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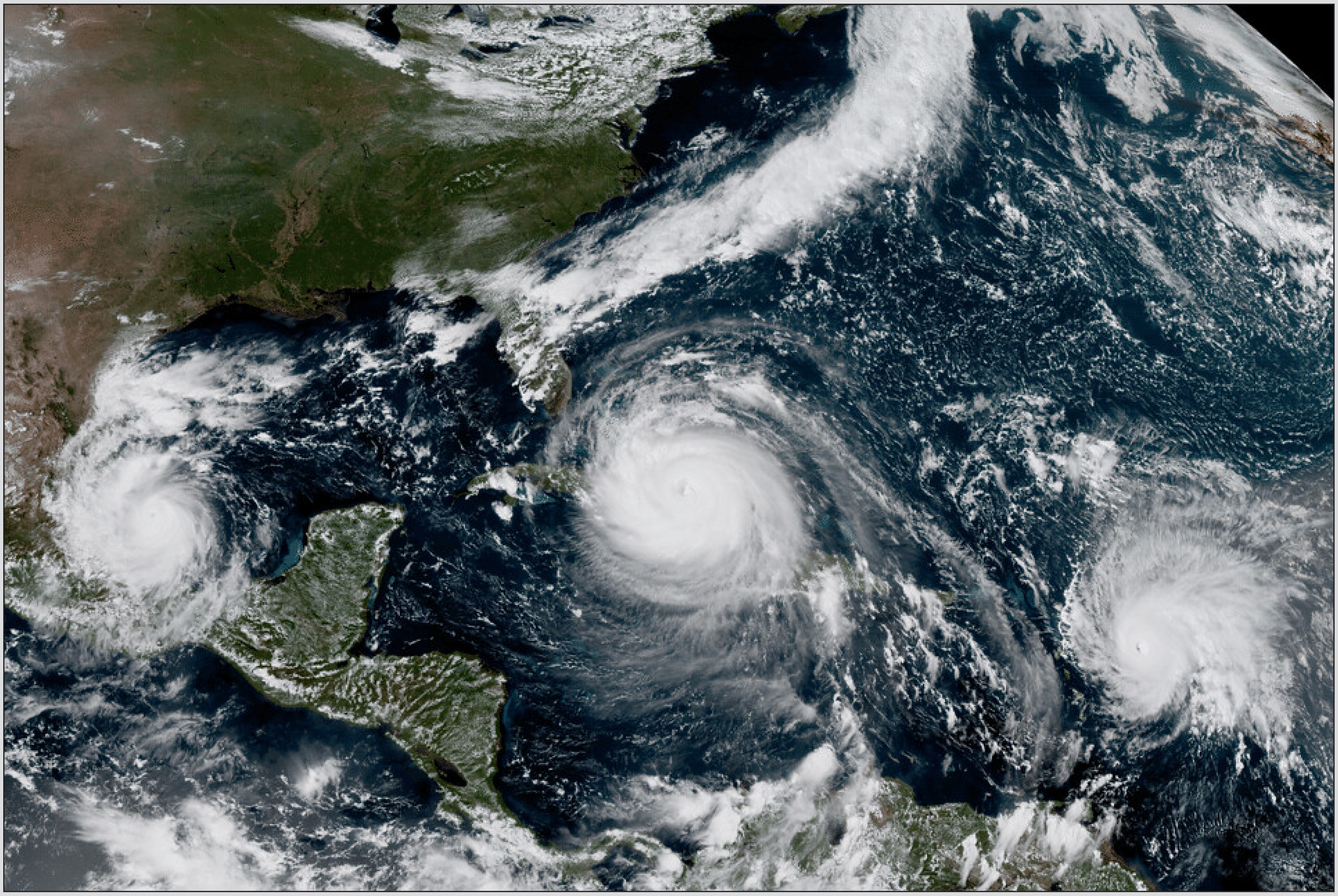

Open-File Report 2024–1048

U.S. Department of the Interior
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Cover. Goes-16 satellite geocolor image of three hurricanes in the Gulf of Mexico and Atlantic Ocean on September 8, 2017. Hurricanes shown from left to right are, Hurricane Katia, Hurricane Irma, and Hurricane José. Image from Cooperative Institute for Research in the Atmosphere, 2017.

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Preface

Coastal storm activity has become stronger, more frequent, and more unpredictable over the past decades. Intense coordination among U.S. Geological Survey (USGS) Mission Areas and other Federal agencies has led to improved products to predict and assess impacts of coastal storms on physical hazards. We recognize herein the need to consider impacts of coastal storms on water-quality hazards as well, and advance understanding of water-availability impacts that are influenced by watershed conditions and changing water levels, the primary focus of current USGS monitoring and modeling.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Velocity	
foot per second (ft/s)	0.3048	meter per second (m/s)
inch per hour (in/h)	0.0254	meter per hour (m/h)
inch per hour (in/h)	2.54	centimeter per hour (cm/h)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Mass flow	
pound per cubic foot (lb/ft^3)	0.1602	kilogram per liter (kg/L)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Velocity	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per hour (m/h)	39.37	inch per hour (in/h)
centimeter per hour (cm/h)	0.3937	inch per hour (in/h)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)
	Mass flow	
kilogram per liter (kg/L)	62.428	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

APT	Antecedent Precipitation Tool
CDAT	Coastal Data and Analysis Tool for Water Resources Management
CDI	Community for Data Integration
CDT	conductivity-temperature-depth
CFWSC	USGS Caribbean-Florida Water Science Center
CISA	Carolinas Integrated Sciences Assessments
CO_2	carbon dioxide
COAWST	Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System
CONUS	contiguous United States
CoSMoS	Coastal Storm Modeling System
CRMS	coastwide reference monitoring sites
CSI	Coastal Salinity Index
DEWS	Drought Early Warning System
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EDEN	Everglades Depth Estimation Network
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FEV	USGS Flood Event Viewer
HWM	high-water mark
ICCOH	Interagency Coordinating Committee on Hurricanes
ICAMS	Interagency Council for Advancing Meteorological Services

IWAA	USGS Integrated Water Availability Assessment
LMGWSC	USGS Lower Mississippi–-Gulf Water Science Center
NAVD 88	North American Vertical Datum of 1988
NAWQA	National Water-Quality Assessment Project
NCEP	National Centers for Environmental Prediction
NERR	NOAA National Estuarine Research Reserve
NGVD 29	National Geodetic Vertical Datum of 1929
NGWOS	Next Generation Water Observing System
NHP	National Hurricane Program
NIDIS	NOAA National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service
NWIS	USGS National Water Information System
NWS	National Weather Service
OTWSC	USGS Oklahoma–Texas Water Science Center
ppm	parts per million
RDG	real-time rapid-deployment gage
SAWSC	USGS South Atlantic Water Science Center
STORET	USGS STOrage and RETrieval Data Warehouse
STN	USGS Short-Term Network
STS	mobile storm-tide sensors
SWaTH	USGS Surge, Wave, and Tide Hydrodynamics Network
TCORF	Tropical Cyclone Observations and Research Forum
TIFF	Texas Integrated Flooding Framework
TWDB	Texas Water Development Board
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WARC	USGS Wetland and Aquatic Research Center
WISO	EPA Watershed Index Online
WMA	USGS Water Resources Mission Area
WSC	USGS Water Science Center

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Introduction and Rationale

Tropical cyclones (which include tropical depressions, tropical storms, and hurricanes) cause landscape-scale disturbances that can lead to impaired water quality and thus reduce water availability for use. Hereinafter referred to as hurricanes, the storm surge and high precipitation rates of these pulsed weather events can lead to altered surface-water and groundwater flow paths, flooding, and erosion, and inland penetration of ocean water can alter the freshwater/saltwater balance in ecosystems and water supplies. As a result, the quality of both surface-water and groundwater, including key metrics of salinity, temperature, suspended sediment, and nutrients, can be substantially altered on multiple timescales, including short- (weeks or less) and long-term (months or more) periods. Additional topics of concern to residents and policymakers are the release of anthropogenic contaminants and contaminant mobility and transport during and after such extreme events.

Hurricanes of the southeastern United States have caused tens to thousands of deaths, and single-event costs have reached more than tens of billions of dollars (table 1). Hurricanes Harvey (2017) and Katrina (2005), and recently Ian (2022), are especially notable for rainfall, property damage, and deaths. Impacts increase considerably if a larger region is considered, with single storms covering large territories—such as Ida (2021) migrating through the Appalachian and northeastern States—and (or) lingering in neighboring territories—such as Irma (2017) lingered in Puerto Rico for more than 2 weeks and was subsequently followed by Maria (2017). Although windspeeds can cause great damage to infrastructure, historically, 90 percent of hurricane fatalities on the U.S. Atlantic Coast were attributed to flooding (Rappaport, 2014).

Multiple climatic drivers working on decadal scales complicate the interpretation of century-scale trends in hurricane strength. However, over the past four decades, the intensity and proximity of these events to U.S. coasts have increased (Vecchi and others, 2021), and these trends in location and intensity are predicted to continue (Knutson and others, 2010; Coumou and Rahmstorf, 2012). Moreover, ongoing sea-level rise is expected to increase the vulnerability of coastal water supplies and ecosystems to hurricane events (Sweet and others, 2022). Thus, the ability to measure and predict the impacts of hurricanes on water quality is critical for policymakers to assess and plan for the availability of water of adequate quality for human consumption, ecosystems, and other uses in coastal watersheds. The potential retreat of millions of residents from coastal zones in coming decades (Hauer and others, 2020) and the role that water quality plays in maintaining the habitability of coastal zones makes this work especially urgent.

Although many Federal, State, and local entities assess hurricane impacts to property and infrastructure and there has been substantial research into water-quality impacts at local scales (for example, LaMontagne and others, 2022), a regional and comprehensive understanding of the impacts of hurricanes on surface-water and groundwater quality—and thus water availability—is lacking in both coastal and inland areas affected by hurricanes. As the U.S. Geological Survey (USGS) considers development of tools to predict the extent to which water-quality impacts of hurricanes affect water availability, an assessment of the state of the science of hurricane impacts is needed. This will entail identification of critical gaps in measuring and modeling the spatial extent, magnitude, and timing of water-quality impacts, including the ability to couple existing models of coastal processes with surface-water and groundwater models that integrate flow and quality. For both watersheds and aquifers, an assessment of the impacts of different physical components of hurricanes (intensity and duration of storm surge, rainfall, and winds) on water availability also is needed.

Table 1. Hurricanes that made landfall in 2000–2022 in the southeastern United States, including within the coastal Atlantic States, lower Mississippi Gulf States, and the U.S. Caribbean territories of Puerto Rico and the Virgin Islands.

[Impact demonstrated in terms of estimated cost of damages and deaths. Data from Smith (2020)]

Hurricane	Category at time of U.S. landfall	Coastal landfall site	Date	Estimated cost of damages (in billions)	Number of deaths
Fiona	1	Puerto Rico	Sept. 2022	$2.6	25
Ian	5	Florida	Sept. 2022	$30	160
Nicholas	1	Texas	Sept. 2021	$1.1	0
Ida	4	Louisiana	Aug. 2021	$79	96
Zeta	2	Louisiana	Oct. 2020	$4.9	6
Delta	2	Louisiana	Oct. 2020	$3.2	5
Sally	2	Alabama	Sept. 2020	$8.1	5
Laura	4	Louisiana	Aug. 2020	$26	42
Isaias	1	North Carolina	Aug. 2020	$5.3	16
Hanna	1	Texas	July 2020	$1.2	0
Dorian	1	North Carolina	Sept. 2019	$1.8	10
Michael	5	Florida	Oct. 2018	$29	49
Florence	1	North Carolina	Sept. 2018	$27.8	53
Irma	4	Florida, U.S. Virgin Islands	Sept. 2017	$59.5	97
Maria	4	Puerto Rico, U.S. Virgin Islands	Sept. 2017	$109.8	2,981
Harvey	4	Texas	Aug. 2017	$148.8	89
Matthew	1	South Carolina	Oct. 2016	$12.10	49
Arthur	2	North Carolina	July 2014	$39.5	0
Isaac	1	Louisiana	Aug. 2012	$3.5	9
Irene	1	North Carolina	Aug. 2011	$17.4	45
Ike	2	Texas	Sept. 2008	$40.2	112
Gustav	2	Louisiana	Sept. 2008	$8	53
Dolly	2	Texas	July 2008	$1.7	3
Wilma	3	Florida	Oct. 2005	$27.9	35
Rita	3	Louisiana, Texas	Sept. 2005	$27.2	119
Katrina	3	Louisiana, Mississippi, Texas	Sept. 2005	$186.3	1,833
Dennis	3	Florida	July 2005	$3.7	15
Jeanne	3	Florida	Sept. 2004	$11.5	28
Ivan	3	Alabama	Sept. 2004	$31.6	57
Frances	2	Florida	Sept. 2004	$15.1	48
Charley	4	Florida	Aug. 2004	$24.6	35
Isabel	2	North Carolina	Sept. 2003	$8.7	55
Lili	1	Louisiana	Sept. 2002	$1.9	2

We report herein a strategic review of current knowledge (including publications and invited presentations) and assets within the USGS to assess the impacts of hurricanes on water quality with a focus on the southeastern United States. We argue that an unfilled niche exists in predicting water-availability impacts from hurricanes that result from water-quality impacts, and that the USGS Water Resources Mission Area (WMA), in partnership with USGS Water Science Centers (WSC), has the skills and capabilities to develop a strategic and extensive collaboration in coastal watersheds. This report is structured sequentially as follows:

1. State of the science on measurements of water-quality impacts of hurricanes.

2. State of the science on modeling of water-quality impacts of hurricanes.

3. Emergent opportunities to address and prioritize gaps in measurements and models for hurricanes in coastal watersheds.

State of the Science on Measurements of Water-Quality Impacts of Hurricanes

Monitoring Framework and USGS Tools and Approaches

Understanding the quality of surface water and groundwater is fundamental to assessing water availability. Designing a monitoring network requires consideration of multiple factors, including the selection of constituents to be measured, spatial extent and density of sampling locations, frequency of data collection, and accuracy of instrumentation and measurement techniques. It is important that the design of a monitoring network is tailored to meet stakeholders' needs for data to inform their management decisions regarding the quality and quantity of water available for use. Those uses may range from public supply to industrial cooling to agricultural irrigation to ecological support. Predicting the influence of an extreme event like a hurricane on water availability for a specific use is highly uncertain, depending on the magnitude, extent, and location of the event and the nature of the impact (for example, flow, fire, flood, and wind).

We have reviewed current abilities to monitor and model hurricane impacts on water quality in the southeastern United States. The results indicate the need for a comprehensive regional program of data collection or model development to address this growing concern. The results also indicate that notable stakeholder and scientific interests exist in improved water-quality predictions and measurements. We discuss herein the state of measurements within the USGS, past and ongoing, as well as a curated understanding of water-quality measurements publicly available through the interagency USGS Water Quality Portal (https://www.usgs.gov/tools/water-quality-portal) or published literature.

There is currently no comprehensive water-quality monitoring system in place, for any agency, for assessing the impact of coastal storms on water supplies, both surface and groundwater (Robert Mason, USGS Extreme Events Coordinator, February 20, 2022).

Hurricanes can have a wide range of impacts on water quality due to strong physical forcings of wind and water and existing hydrologic components and land uses within a watershed (fig. 1). These forcings drive the direction and rates of flows, which are made especially complex in populated and low gradient (little topographic relief) coastal watersheds. Compound flooding,

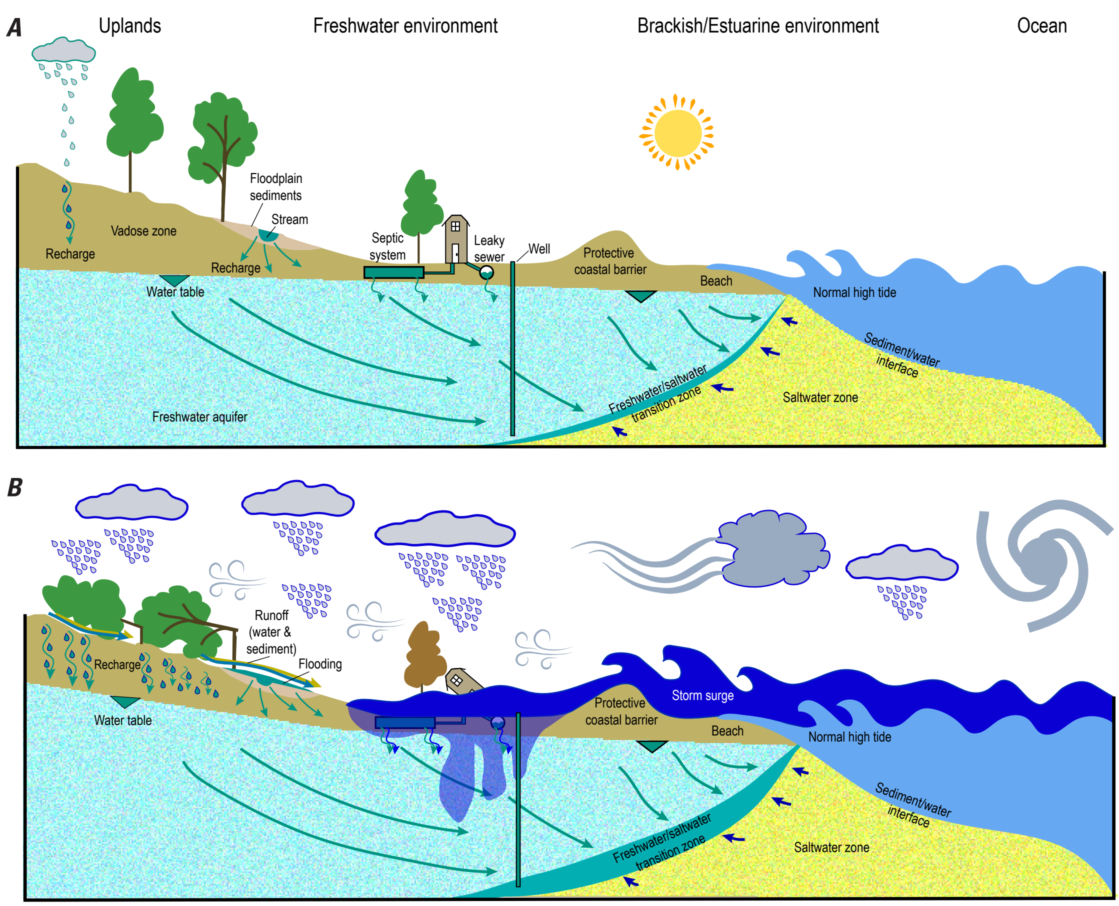


Figure 1. Diagrams of coastal storm impacts on hydrology of coastal watersheds illustrating (*A*) pre-storm conditions and (*B*) potential storm impacts.

in particular, commonly occurs where surface water, ocean water, groundwater, and atmospheric waters interact directly and (or) indirectly during and after storm events (for example, reduced or reversed discharge via storm surge). Water quality can be altered when established patterns of drainage ("plumbing") are disrupted, both in terms of residence time (faster or slower flows) or routes (sewer lines and drainage canals). As illustrated in figure 1, the intensity of hydrologic and hydrodynamic forcings is a distinct hallmark of acute water-quality impacts, which can lead to long-term impairment of wells and water supplies.

All hurricanes are similar in their atmospheric origins, but each hurricane has unique impacts. Improved hurricane tracking, from formation to dissipation, has increased the leadtime and confidence in predicting hurricane tracks, rates, and magnitude categorization (for example, Hurricane Analysis and Forecast System, https://www.emc.ncep.noaa.gov/hurricane/HFSA). Thus, although the spatial extent, duration, and magnitude of wind and water forcings may be predictable, a wide range of water-quality impacts are possible. Hydrologic processes respond not just to these physical forcings but also to antecedent conditions and localized watershed characteristics and infrastructure (for example, Woodruff and others, 2013). These preexisting conditions, whether from natural weather patterns (for example, recent rainfall), ecological vulnerability (for example, forest structure), or flood-mitigation infrastructure (for example, storm drains), often exert greater control of water-quality impacts than storm characteristics alone.

Common water-quality metrics can be impaired in many specific and combined ways (table 2). Specific hazards and modes of impairment lead to short- or long-term impacts, which can broadly affect the availability of water for specific uses.

Location of landfall and trajectories of coastal storms strongly influence their impacts. Figure 2 illustrates the changing nature of hurricane intensity during the life of a storm. There were 392 tropical cyclones in the North Atlantic basin from 2000 through 2021 (Knapp and others, 2010, 2018). Of these, 117 intersected the U.S. coastline, with intensities classified as tropical depressions, tropical storms, hurricanes with categories ranging from 1 to 5, and extratropical storms (North Atlantic). Hurricane projections of location and intensity have markedly improved since 2000 (Cangialosi and others, 2020), especially owing to advances in satellite observations and model development. Hurricane landfall locations are now routinely estimated within an error margin of 100 miles (mi) at 3 days before impact (National Oceanic and Atmospheric Administration, 2023), as compared with 300 mi of error in 1992. Currently (2023), locational errors are estimated at 39 nautical miles within a 24-hour period (https://www.nhc.noaa.gov/verification/verify5.shtml). Although average economic losses from hurricanes are normalized to approximately $17 billion annually (Weinkle and others, 2018), investments in hurricane forecasting have paid for themselves with reduced property damages and deaths (Martinez, 2020). Although predictions of hurricane tracks and their physical impacts are likely to see less uncertainty with improved observations and models (Smith and Matthews, 2015; Cangialosi and others, 2020), when compared with other weather and climate disasters, hurricanes remain the single most costly natural disaster (Smith and Katz, 2013; National Oceanic and Atmospheric Administration, 2024).

Table 2. Four major parameters of water availability sensitive to hurricane event forcing.

Parameter	Specific hazards/modes of impairment	Impacts	Water uses with affected availability
Temperature	Precipitation with warmer temperatures Cloud cover	Stratification Groundwater warming or cooling Detriment to ecological community structure, including invasive species and migration Coastal mixing	Ecological Industrial
Salinity	Coastal inundation due to storm surge Inland migration of saltwater in coastal canals/rivers due to storm surge Freshwater flooding and rapid groundwater recharge due to extreme precipitation	Changes in salinity in estuaries and coastal wetlands (salinization due to storm surge or freshening due to extreme precipitation) Salinization of industrial intake water Salinization of groundwater	Industrial Drinking water Ecological Agricultural
Nutrients	Loading from excessive overland flows Flooding or dam breaks of retention ponds/treatment basins/manure storage pits	Hydrocarbons Microbial pathogens from sewage Algal growth Oxygen depletion Harmful algal blooms/toxins Groundwater/inland water sources Nitrate contamination of drinking water Carbon loading to drinking water	Ecological Drinking water Agricultural
Suspended sediment	Overland flow Channel erosion	Turbidity/visibility/physical destruction of habitats Increased treatment cost to remove sediment Loss of long-term storage in reservoirs Shipping/boating	Ecological Drinking water Industrial Agricultural

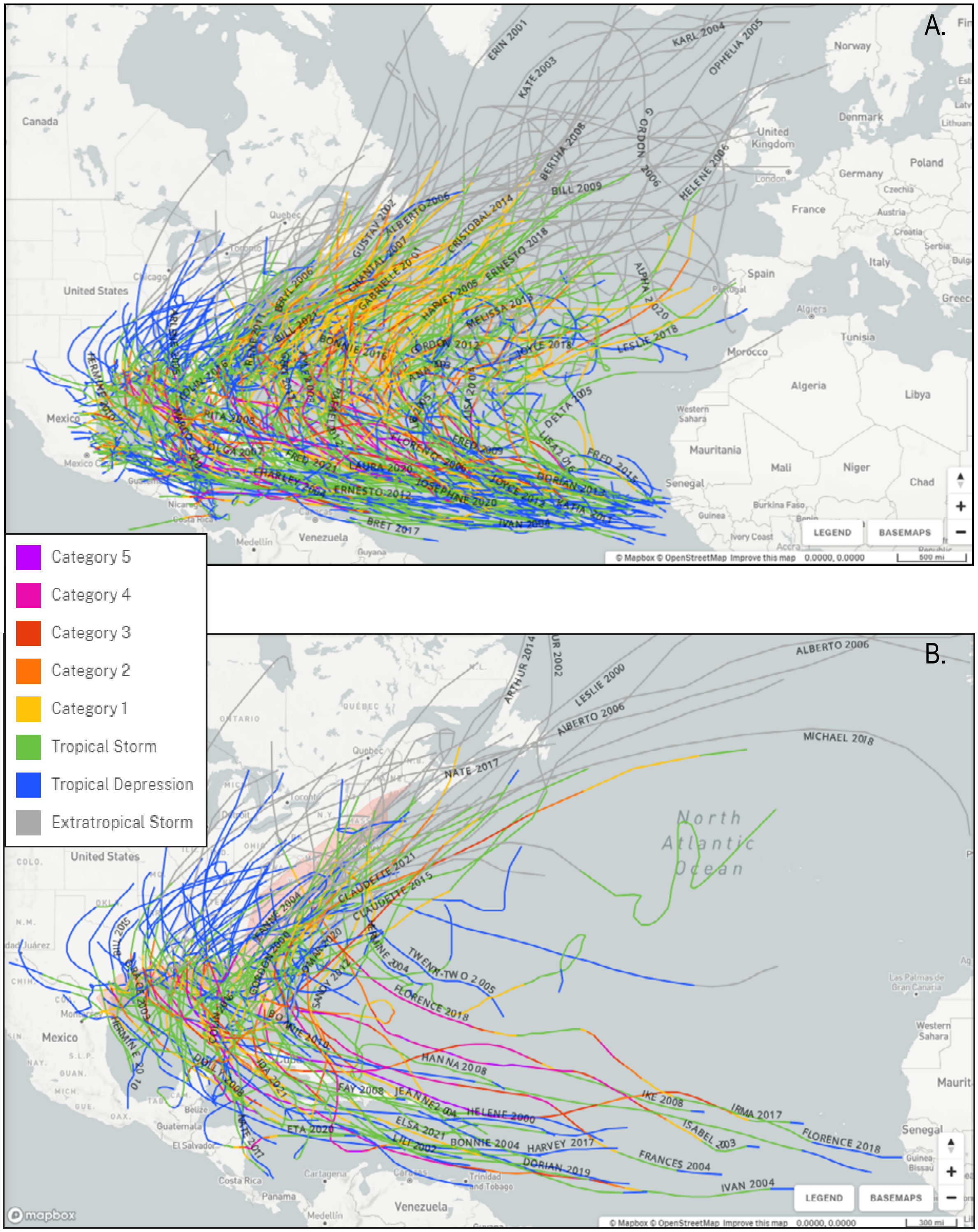


Figure 2. Maps of tropical cyclone tracks (and their dynamic windspeed characterization based on the Saffir-Simpson Hurricane Wind Scale) in the North Atlantic basin. *A*, All historical hurricane tracks from 2000 to 2021 in the North Atlantic basin (n=392). *B*, The subset of historical hurricane tracks from 2000 to 2021 that intersected the contiguous United States (n=117). From the National Oceanic and Atmospheric Administration Historical Hurricane Tracks webpage (https://coast.noaa.gov/hurricanes), based on Knapp and others (2010, 2018).

The long-term development of the geomorphology and hydrology of many coastal watersheds has been substantially influenced by multiple landfalls of tropical cyclones and the strong physical forces associated with these storms (Greening and others, 2006; Patrick and others, 2020). Human use of surface-water and groundwater resources in coastal watersheds also has changed over time, as have operational structures and human settlement distributions (Ledford and others, 2020). Thus, predictions of the hydrologic (water quality and availability) impacts of hurricanes are constrained by our understanding of and ability to model the impacts of impervious surfaces, industrial hazards, diversions, wells, and other alterations of the geomorphic landscape.

The USGS is one of multiple U.S. Federal agencies that contribute to monitoring and modeling efforts for assessing coastal storm impacts and hazards. The Interagency Coordinating Committee on Hurricanes (ICCOH) includes the USGS, U.S. Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), U.S. Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), and the Department of Defense (DOD). In particular, the USGS Coastal Storm Team coordinates measurements and model projections across all USGS Mission Areas for pre-, syn-, and post-storm water levels. Current data sharing focuses on high-water marks (HWM), flooding hazards, and total water levels (table 3). Agency-specific missions and capabilities determine the focus of monitoring and response, with annual integration provided through the Federal ICCOH framework.

After Hurricane Sandy made landfall in New Jersey in October 2012, the USGS formally began the development of the overland Surge, Wave, and Tide Hydrodynamics (SWaTH) Network (https://www.usgs.gov/mission-areas/water-resources/science/surge-wave-and-tide-hydrodynamics-swath-network) along the northeastern Atlantic Coast from North Carolina to Maine (Verdi and others, 2017). This network, developed collaboratively with local, State, Tribal, and Federal agency partners, features the integration of long-term NOAA National Ocean Service and USGS real-time tide gages; mobile, rapidly deployable, but temporary, real-time rapid-deployment gages (RDGs); and mobile storm-tide sensors (STSs). A central tenet of the SWaTH Network is that most locations for the mobile RDGs and STSs have been presurveyed to the National Geodetic Vertical Datum of 1988 and equipped with receiving brackets that permit rapid installation of instrumentation in the hours and days prior to a storm. Following Hurricane Joaquin off the Atlantic Coast in October 2015, the SWaTH Network expanded to include additional sites in the Atlantic (South Carolina to Texas, and Puerto Rico), Eastern Pacific (Washington to California), and Central Pacific (Hawaiian Islands).

Water-level data collected via the SWaTH Network are typically stored and maintained through the USGS Short-Term Network (STN, https://stn.wim.usgs.gov/STNWeb), which is a national-scale application and database generally designed to support USGS event-based sensor deployments and HWM data collection efforts. The STN database is specifically designed to encourage repeated visits to temporary sensor deployment (wave or water level) or HWM locations. A system that encourages repeated, as-needed deployments in the same locations facilitates the development of longer term datasets of storm events than would be feasible by relying on field personnel’s memories of previous deployments or interpretations of paper records alone. Such efficient responses have become a cornerstone of the USGS hazards response.

Water-level and HWM data collected, stored, and maintained within the USGS STN are accessible and can be displayed via the USGS Flood Event Viewer (FEV), which is an online mapping and display application that provides long-term access to data collected from short-term storm events, including hurricanes (Flood Event Viewer, https://stn.wim.usgs.gov/FEV). Developed in conjunction with the USGS STN, the FEV displays the water-level data for a particular storm that can be selected from a drop-down list of historical events (for example, fig. 3).

As previously noted, however, SWaTH Network, STN database, and FEV application data focus on water levels of coastal waters following a storm surge at landfall as well as streams and rivers following inland river flooding that occurs after heavy rainfall commonly associated with hurricanes. These tools do not presently accommodate water-quality data that could be collected in response to hurricanes. This data gap provides an opportunity to develop a program for the systematic collection and display of water-quality data in response to hurricanes and other flood events.

USGS capabilities to monitor hurricane effects have been demonstrated through pre-, syn-, and post-storm visits to prepare for and detect impacts, which have consisted of mostly responses of surface-water extent and height (for example, Stockdon and others, 2023). Examples of USGS cross-Mission Area responses since 2018 (Hurricane Florence) through 2022 (Hurricane Ian) have been documented internally (USGS internal Hurricane Coordination Network). The Pacific Coast has only recently (January 2023) been included in this response effort, as the focus has been on the eastern United States and Caribbean territories. The multiple USGS programs for coastal storm preparedness and response are coordinated through a Coastal Storm Team, with representatives from the WMA and the Natural Hazards Mission Area (Coastal and Marine Hazards and Resources Program, https://www.usgs.gov/programs/cmhrp). Recent tools used to assess total water level include RDGs and HWMs, with data and visualizations available through the following contiguous United States (CONUS)-scale web pages.

1. National Water Information System (NWIS, https://waterdata.usgs.gov/nwis): Water-quality and flow data repository for all USGS water-resource monitoring of groundwater and surface water.

2. WaterWatch (https://waterwatch.usgs.gov): A statistical representation of current and historical data for evaluation of flood stage dynamics since 1901.

Table 3. Data tools and resources used by U.S. Geological Survey and partner agencies for hurricane (coastal storm) response, updated as of 2022.

[DOE, U.S. Department of Energy; FEMA, Federal Emergency Management Agency; NCEP, National Centers for Environmental Prediction; NOAA, National Oceanic and Atmospheric Administration; NWS, National Weather Service; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; WSC, USGS Water Science Center; –, no data]

Agency	Tool or program name	Tool type	Purpose/description	Begin date	Location extent
USGS	Short Term Network (STN) (https://stn.wim.usgs.gov/stnweb/#)	Field data collection and delivery	To collect storm or flood event-related water-level information	2005	Nationwide United States
USGS	Flood Event Viewer (FEV)[1] (https://stn.wim.usgs.gov/fev)	Web visualization	Display application for short-term network water-level data and for storm tide data	–	Nationwide United States
USGS	Flood Inundation Mapper (https://fim.wim.usgs.gov/fim)	Web visualization	Allows users to explore the full set of inundation maps that show where flooding would occur given a selected stream condition.	–	Contiguous United States
USGS	Data Visualization Laboratory, Hurricane Water Footprint Visualizations (https://www.usgs.gov/products/web-tools/data-visualizations)	Web visualization	Animated graphic incorporating hurricane path, rainfall amounts, and stage changes at affected USGS streamgages (search visualizations for water footprints for Hurricanes Harvey, Irma, Maria, and Matthew)	–	Storm specific
USGS	Coastal Salinity Index (CSI) (https://apps.usgs.gov/sawsc/csi/index.html)	Web data delivery and visualization tool	Monitor and model changes in coastal salinity in response to hydrologic events and provide data to evaluate ecological, industrial, and public water supply availability.	2012	Atlantic Coast of the continental United States
USGS	Surge, Wave, and Tide Hydrodynamics (SWaTH) Network (https://www.usgs.gov/mission-areas/water-resources/science/surge-wave-and-tide-hydrodynamics-swath-network)	Field data collection station network	Monitoring of tides, waves, and storm surge from large coastal storms	2012	Originally Atlantic Coast of the northeastern United States. Now includes all continental contiguous U.S. coasts and Hawai‘i
USGS	Coastal Storm Modeling System (CoSMoS) (https://www.usgs.gov/centers/pcmsc/science/coastal-storm-modeling-system-cosmos)	Model	Multifactor models of coastal flooding, waves, tides, and atmospheric conditions. Tied to local elevations for modeling flood extents.	2018	Global storm conditions. Local flooding based on elevation data. Implemented primarily along the California coast.
USGS	Coastal Data and Analysis Tool for Water Resources Management (https://fl.water.usgs.gov/mapper)	–	Provide data, analyses, and visualizations to assist coastal water managers; data types include groundwater level, and salinity, surface water stage, flow, salinity, and the CSI.	–	Southeastern United States, Gulf Coast, and Puerto Rico
NOAA, NWS	National Hurricane Center (https://www.nhc.noaa.gov)	–	Improve watches, warnings, forecasts, and analysis of tropical weather to save lives and property.	1943	–
FEMA	National Hurricane Program (NHP) (https://www.fema.gov/emergency-managers/risk-management/hurricanes)	–	Preparedness, operational tools, and risk information.	–	–

Table 3. Data tools and resources used by U.S. Geological Survey and partner agencies for hurricane (coastal storm) response, updated as of 2022.—Continued

Agency	Tool or program name	Tool type	Purpose/description	Begin date	Location extent
FEMA	Sea, Lake, and Overland Surge from Hurricanes (SLOSH) (https://www.nhc.noaa.gov/surge/slosh.php)	Model	Storm surge prediction based on physical features and physics equations.	–	–
NOAA, NWS, National Hurricane Center, USACE, FEMA	HURREVAC (https://www.hurrevac.com)	Web browser-based decision support tool	Identifies vulnerable coastal populations and predicts their evacuation times based on storm scenarios.	–	U.S. Atlantic and Gulf of Mexico coastlines. Hawai‘i, Puerto Rico, U.S. Virgin Islands, and the Bahamas
Oklahoma–Texas WSC, USACE, and Texas Water Development Board	Texas Integrated Flooding Framework (TIFF) (https://www.texasflood.org/tools-library/tiff/index.html)	–	Support flood planning and mitigation. Formed in support of Hurricane Harvey response.	2020	Gulf Coast of Texas
USGS	Hazard Exposure and Reporting Analytics (HERA) (https://www.usgs.gov/apps/hera)	–	Data and maps provided to help local managers determine community risk.	2016	California
USGS	National Water Dashboard (https://dashboard.waterdata.usgs.gov/app/nwd/en/?aoi=default)	Web visualization tool, information rich	Used to view provisional data from all USGS real-time water data collection systems.	–	–
USGS	Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST) (https://www.usgs.gov/centers/whcmsc/science/coawst-coupled-ocean-atmosphere-wave-sediment-transport-modeling-system)	Integrated modeling system for coastal change	Integrates the ocean, atmosphere, wave and sediment models to produce hourly forecasts of modeled parameters such as sea temperature, wave height, sediment, wind, and currents.	2008	–
USGS	NGWOS Real-Time Flood Impact Map pilot (https://test.wim.usgs.gov/thresholds/#)	Web visualization tool and local elevation collection program	Web tool to report the inundation status of local points of interest (bridges, roadways, parking lots, buildings, parks, and so on) adjacent to existing streamgages. Plan to integrate with HURREVAC tool.	Pilot in 2021	Coincident with the existing USGS streamgage network; potentially with the STN
USGS	Integrated Water Prediction science program (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-prediction-iwp#:~:text=The%20USGS%20Integrated%20Water%20Prediction,water%20constituents%2C%20and%20ecological%20conditions)	Model development capability	Development of advanced models for forecasting multiple water quality and quantity attributes.	–	Entire United States

Table 3. Data tools and resources used by U.S. Geological Survey and partner agencies for hurricane (coastal storm) response, updated as of 2022.—Continued

Agency	Tool or program name	Tool type	Purpose/description	Begin date	Location extent
DOE, U.S. Global Change Research Program, and others	Coastal Integrated Hydro-Terrestrial Modeling Workshop	Model development capability	Challenges of modeling and evaluating coastal landscapes of coevolving human and natural systems subject to influences and stressors, including extreme weather events.	2020	Global
USGS, NOAA, NWS, and NCEP	Total Water Level and Coastal Change (TWL&CC) Forecast Viewer and API (https://coastal.er.usgs.gov/hurricanes/research/twlviewer)	Web visualization tool and forecast data	Forecast total water level and determine the probability of dune erosion, overwash, and inundation/flooding.	2016	Coastline of continental United States
NOAA	Nearshore Wave Prediction System (https://polar.ncep.noaa.gov/nwps)	Forecast data	5-day wave predictions	–	Sandy coastlines of United States
USACE	Antecedent Precipitation Tool (APT) (https://www.epa.gov/wotus/antecedent-precipitation-tool-apt)	Desktop and web tool	Incorporates existing climatic and weather data to support decisions as to whether field data collection and other site-specific observations occurred under normal climatic conditions.	2020	United States
University of North Carolina at Chapel Hill, University of Notre Dame, and others	ADCIRC Prediction System (https://www.adcircprediction.org)	Model	Algorithms of fluid motion used to evaluate water levels and wave heights in coastal environments. Can be used for storm surge and flooding prediction.	–	–
Multiple Federal atmospheric and earth science agencies	Interagency Council for Advancing Meteorological Services (ICAMS) Tropical Cyclone Observations and Research Forum (TCORF) Interdepartmental Hurricane Conference	Annual conference	Brings together Federal agencies that have missions related to data collection for hurricanes.	–	–

[1]Flood Event Viewer (FEV) described further in appendix 2.

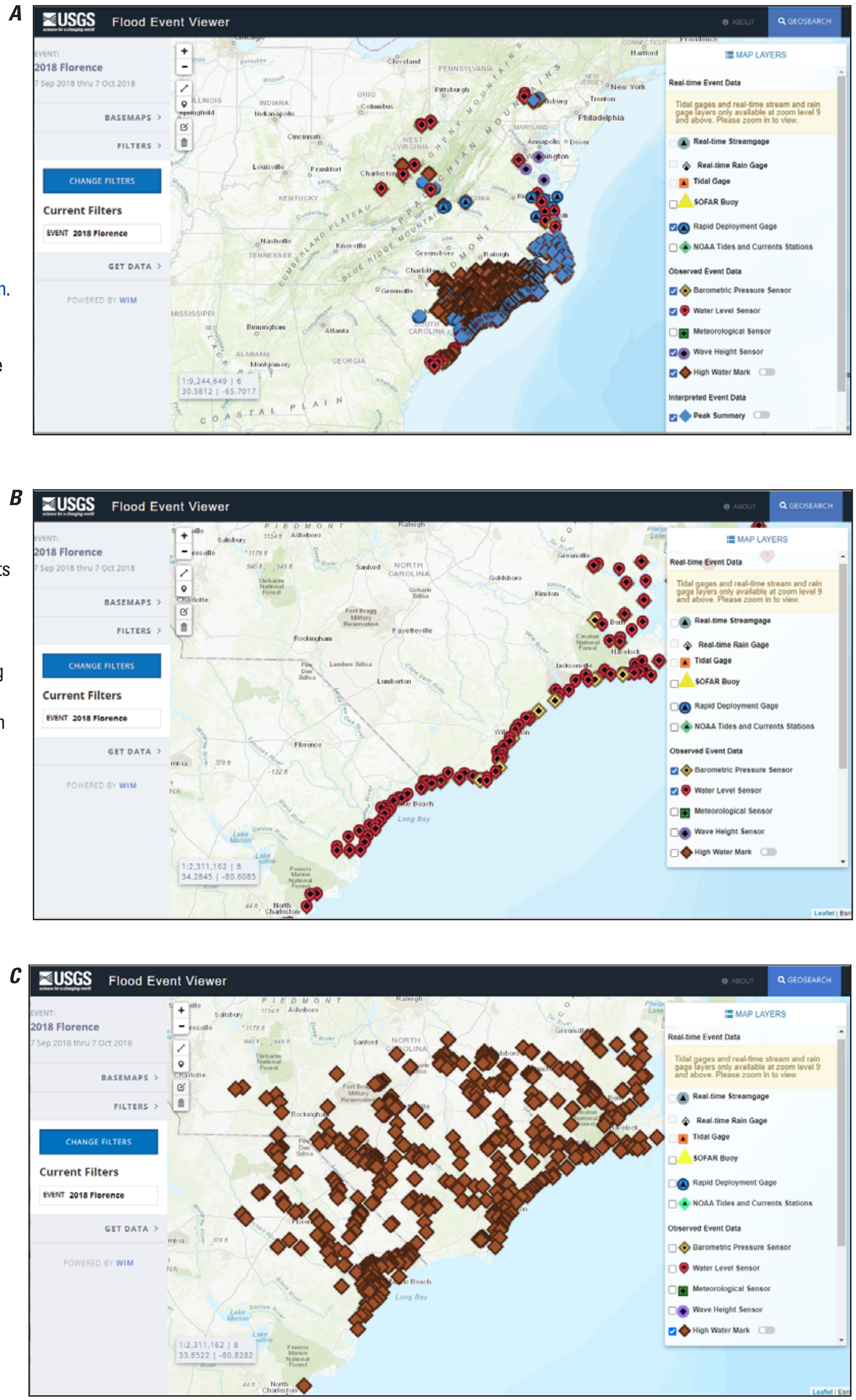


Figure 3. Screen captures of U.S. Geological Survey (USGS) Flood Event Viewer (FEV) examples for Hurricane Florence in 2018 (https://stn.wim.usgs.gov/FEV/#2018Florence). *A*, All data collected and displayable for this event (scale 1:9,244,649). *B*, Zoomed-in map (scale 1:2,311,162) showing locations of water-level and barometric pressure sensors deployed before the storm. *C*, Zoomed-in map showing locations of high-water marks collected after the storm in parts of eastern North Carolina and South Carolina. Nationwide mapping allows FEV to track storms, such as Florence, along the central and eastern United States as remnants of the storm tracked northward in the days following landfall.

3. National Water Dashboard (https://dashboard.waterdata.usgs.gov): An interactive spatially explicit tool for access to current conditions at USGS NWIS stations.

4. USGS Flood Event Viewer (FEV, https://stn.wim.usgs.gov/FEV): An interactive mapping interface to visualize data and imagery of current and past flood events.

Although continuous measurements from USGS streamgages are currently reported in real time on the National Water Dashboard (https://dashboard.waterdata.usgs.gov), extreme events are supported with additional response tools such as the FEV. During expected events, the FEV provides map-based access to water level and meteorological data from targeted field sites that can be used by scientists and stakeholders to help forecast risk and inform decisions about deployment locations for additional water-level monitoring. Map layers on the FEV are updated daily. The focus of USGS and partner agencies has largely been total water levels. In particular, HWM mapping has been a hallmark of USGS storm response since at least 2005 and is used post-storm for developing predictive capacity of flood extents across populated landscapes in relation to in-channel monitoring gages and infrastructure. On the interagency FEV platform, real-time data are available from streamgages, rain gages, tidal gages, SOFAR buoys, and NOAA tide and current gages. The recent addition of RDGs to USGS storm monitoring efforts has made additional water-level measurements from targeted locations available for emergency managers and model development. Rapid return of these FEV mapped data allows for near instantaneous predictions of flooding risks to property and lives. These data are made publicly available across a wide region, with increased data representation as the user zooms in to the county level. RDGs are deployed quickly by local WSC teams on a temporary basis to augment existing long-term data collection networks during storm events. RDG data are released immediately through NWIS on a provisional basis. Virtually no RDG monitoring is performed on groundwater levels or quality because of the focus on flooding responses of surface waters. Furthermore, no water-quality metrics are reported from RDGs. Nonetheless, water-quality data could contribute to addressing community interest in understanding compound flooding and thus the relative water sources and flow rates in flooding waters.

Prior to the landfall of Hurricane Rita across the Louisiana and Texas coasts in September 2005, the USGS deployed short-term networks of storm-surge gages and water-level pressure transducers in surface waters along with nearby barometric pressure transducers during selected hurricane events. The transducers collected data during these events to document the storm surge and changes in water levels as the selected storms made landfall and moved inland across affected coastal regions. Hurricane Rita marked the USGS's efforts to begin formalizing a strategy and program to locate and deploy sensors in advance of selected hurricanes and to retrieve and process the data (including HWMs) after the storms pass. Consistent with the historical surface-water focus of USGS data collection, the collection of hurricane-related data was focused on surface water-level and storm-surge data. Water-quality and groundwater-level data collection generally was limited to specific points of interest as part of other USGS efforts in cooperation with local or State cooperators. The USGS has not historically conducted spatially broad sampling campaigns designed to capture changes in surface-water or groundwater quality caused by the approach and passage of hurricanes. As such, there has been little to no data collected or coordinated efforts to monitor water-quality conditions during storm passages or to document post-storm water-quality impacts and recovery, for either surface water or groundwater.

In general, coastal watersheds are densely populated with high use of water resources, and most uses are likely to be impacted by adverse effects on water quality. The 2018–2021 WMA Water Quality Gaps project identified significant impacts of altered water quality on ecological, industrial, agricultural, and public-supply uses (Tesoriero and others, 2024) and further identified extreme events as poorly constrained for water-quality predictability (Harvey and others, 2024). Additionally, surface-water datasets have a wider array and deployment of monitoring tools than groundwater datasets with respect to water quality. Predictions of key water-quality metrics are typically modeled under long-term (annual) or spatially explicit relations, that may be altered by acute storm-induced changes in flows and flow paths (Lisa Lucas, USGS, written commun., 2023). The largely physical impacts from hurricanes include alterations of flows through direct changes to the hydrologic cycle and coastal hydrodynamics as well as indirect effects on water-control structures and other engineered components of the landscape. Physical disturbance can lead to changes in water flows, residence time, connectivity of different water bodies, contamination, and thus impacted use. Extreme events are not currently a focus of USGS WMA modeling development, but a literature review highlights the need for expanding the discipline. For example, Patrick and others (2020) highlight the importance of extreme events in ecological forecasting, especially in aquatic habitats. Because modeling success is strongly linked to the quality and density of observations, the USGS is poised to substantially contribute to these resource management projections and needs.

Literature Review of Coastal Storm Impacts on Water Quality

We reviewed the readily available scientific literature to provide insight into the nature and focus of the state of knowledge and available tools for addressing coastal storm impacts on water quality. The relevant literature was identified through the search feature on the USGS Publications Warehouse (https://pubs.usgs.gov), as well as targeted web search engines (PubMed, GoogleScholar), relevant scientific journal publisher sites (American Geophysical Union journals, ScienceDirect), and general Internet searches. We restricted our searches to include only peer-reviewed literature that describes studies involving one or more coastal States in the southeastern continental United States, Puerto Rico, or the U.S. Virgin Islands. The searches were conducted in mid-2022; therefore, the review compilation does not include more recently published literature. The resulting list of

85 papers and reports (appendix 1), published from 1991 to 2022, is not a comprehensive list of all relevant literature but provides a representative overview of the focus of research interests related to the impacts of coastal storms on water quality. Most (91 percent, *n*=77) of the reviewed studies were published in scientific journals. These peer-reviewed papers were spread across 43 different journals only 3 of which (Frontiers in Marine Science, Estuaries and Coasts, and Journal of Coastal Research) published 5 or more. The other 9 percent (*n*=8) of the publications are USGS scientific products and reports produced by other agencies.

Table 4 provides summary information about each of the reviewed studies, which includes investigations into the impacts of coastal storms on a wide variety of water-quality constituents (table 5). Nutrients, microbial contaminants, dissolved oxygen, chlorophyll, organic matter, and suspended sediment received the most attention in the literature; however, various other constituents, including salinity and both naturally occurring and anthropogenic contaminants also were researched. Many of the studies addressed more than one water-quality constituent; 50 percent considered at least two constituents and 35 percent considered three or more constituents.

More research has focused on surface water affected by hurricanes compared to groundwater. Approximately 81 percent of the papers we reviewed addressed the impact of coastal storms on surface-water quality whereas only 19 percent addressed groundwater quality. Estuaries (38 percent of the papers) and

Table 4. Summary of study area locations investigated in the literature review (by State/territory and region or water body).

[Percentages sum to greater than 100 percent due to rounding]

Region or water body	Percentage of papers reviewed (*n*=85) that addressed specified water body
Florida	
Apalachicola Bay	5
Big Pine Key	1
Biscayne Bay	2
Cape Canaveral Barrier Island Complex	2
Charlotte Harbor Watershed	1
Everglades National Park	2
Florida Keys	1
Freedom Park Wetland System	1
Indian River Lagoon	5
Lake Okeechobee	2
Pellicer Creek	2
Pensacola Bay	1
Southern Florida region	2
St. Lucie Estuary	4
West Central Florida Region	1
Georgia	
Altamaha River	1
Cabretta Island	1
Sapelo Sound	1
Louisiana	
Atchafalaya River Basin	1
Gonzales-New Orleans Aquifer	1
Lake Pontchartrain and surrounding canals	4
New Orleans	2
Pointe au Chene Swamp	1
Southwestern Louisiana region	1
St. Tammany Parish	2
Upper Ponchatoula Aquifer	1
Mississippi	
Pearl River	2
Puerto Rico	
La Parguera Natural Reserve	1
Lago Loìza River Basin	1
Luquillo Experimental Forest	2
North coast region	1
Various	4
North Carolina	
Buxton Woods Aquifer	2
Cape Fear River Basin	5
Herrings Marsh Run Watershed	1
Lumbee River Basin	1
Lumber River Basin	1
Neuse River Basin	4
Neuse River Estuary	7
Pamlico Sound	5
Tar River Basin	5
South Carolina	
Cooper River	1
Hobcaw Barony	1
Pee Dee River	1
Waccamaw River	1
Texas	
Clear Lake	1
Galveston Bay	6
Guadalupe Estuary	1
Gulf coast and inland along Guadalupe River	1
Houston	1
Lavaca-Colorado Estuary	1
Nueces Estuary	1
Southeast region	1
U.S. Virgin Islands	
St. Thomas	1

rivers (21 percent of the papers) were the focus of much of the research, but wetlands, beaches, and tap water (from various sources) also received research attention. Studies commonly investigated multiple water bodies rather than focusing exclusively on a single water body. Water-quality surveys of multiple water sources following storm-induced flooding also were common in the literature.

Most of the reports and papers (72 percent) addressed storm-induced water-quality impacts on in-situ uses of the water resource (for example, ecosystem services, fishing, and swimming). The impacts of water-quality changes on consumptive uses (for example, private or domestic and municipal water supplies) received less attention (16 percent of the studies). Several of the studies (12 percent) considered how storm-induced water-quality changes affect multiple types of water use.

The reviewed studies investigated the water-quality impacts of 26 named storms (table 6) ranging from tropical storms to Category 5 hurricanes that occurred from 1989 to 2018. Hurricanes Katrina, Harvey, and Irma were the only storms that were the focus of more than 10 percent of papers and reports. Several studies compared the water-quality impacts of two or more storms. The geographic extent or location of study was necessarily dependent on where the storms made landfall, but it was apparent that study areas also were selected to take advantage of existing water-quality monitoring networks and pre-storm datasets. More of the papers and reports focused on Florida (34 percent; *n*=29) and North Carolina (31 percent; *n*=26) than on other States and territories. In terms of individual water bodies, Galveston Bay in Texas, Apalachicola Bay and Indian River Lagoon in Florida, and Pamlico Sound and the Cape Fear and Tar River Basins in North Carolina received the most research attention (table 4).

The objectives of the reviewed studies were varied and included, but were not limited to, surveys of post-storm contamination to assess health risk, pre-and post-storm water-quality comparisons, identifying contaminant sources and transport pathways, and comparison of the water-quality impacts of different storms. The approaches and methods used also varied, although most of the papers included statistical summaries of water-quality data and many also used statistical methods to identify trends and shifts in water-quality data. Only a few of the papers used a modeling

Table 5. Summary of water-quality constituents investigated in the literature review.

[Percentages sum to greater than 100 percent because some papers addressed multiple constituents]

Water-quality constituent(s)	Percentage of papers reviewed (*n*=85) that addressed specified constituent(s)
Nutrients	37
Microbial contamination	28
Dissolved oxygen	25
Chlorophyll/harmful algal blooms	21
Organic matter	21
Suspended sediment/turbidity	20
Salinity/chloride/specific conductance/total dissolved solids	19
pH	14
Temperature	9
Major ions	9
Trace elements	7
Fuel compounds	6
Pesticides/pharmaceuticals	6

Table 6. Summary of named storms investigated in the literature review.

[Percentages sum to greater than 100 percent because some papers considered multiple storms]

Storm name	Year	Category at time of U.S. landfall	Percentage of papers reviewed (*n*=85) that addressed specified storm (sum is greater than 100 percent as some papers consider multiple storms)
Katrina	2005	3	14
Harvey	2017	4	13
Irma	2017	4	12
Maria	2017	4	7
Rita	2005	3	6
Matthew	2016	1	6
Jean	2004	3	6
Hugo	1989	4	6
Frances	2004	2	5
Wilma	2005	3	4
Ivan	2004	3	4
Irene	2011	1	4
Gustav	2008	2	4
Charley	2004	4	4
Fran	1996	3	2
Floyd	1999	2	2
Emily	1993	3	2
Dennis	2005	3	2
Tammy	2005	Tropical storm	2
Andrew	1992	5	1
Bertha	1996	2	1
Fay	2008	Tropical storm	1
Ike	2008	2	1
Isaac	2012	1	1
Michael	2018	5	1
Tammy	2005	Tropical storm	1

approach. Twenty percent (*n*=17) of the studies included process-based modeling, of which 53 percent (*n*=9) focused on groundwater, most of which used dual-density groundwater flow models to evaluate the influence of storm surge on groundwater salinity. In addition to the papers that took a process-based modeling approach, four used geochemical mixing models to identify constituent sources and transport pathways and two applied geospatial modeling techniques to identify areas most impacted by storm-induced water-quality changes.

The literature review points to many predictive relations among impacts. We summarize these below for the four primary focus constituents of the USGS WMA Integrated Water Availability Assessments (IWAAs) Program (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-availability-assessments) as a framework for prioritizing modeling opportunities for water-quality constituents:

- Salinity/conductivity,
- Nutrients (nitrogen, phosphorus, and carbon),
- Temperature, and
- Suspended sediment.

Salinity/Specific Conductance

Salinity is a water-quality constituent related to the dissolved salts in a quantity of water (McCleskey and others, 2023). Although there are many definitions and means of measuring salinity—each specific to certain fields of oceanography, limnology, chemistry, and other fields—a typical salinity value might be in grams of salt per kilogram of water. In seawater, the dissolved salts are predominantly sodium and chloride, but across saline, brackish, and fresh water, there are other important dissolved constituents, including calcium, magnesium, sulfate, bicarbonate, as well as many trace elements. Commonly in coastal regions, groundwater and surface-water salinity are a function of freshwater mixing with seawater, but there are other important sources and processes related to salinity, including wastewater, urban runoff, water-rock interaction, basinal brines, and dissolved inorganic carbon generated by biologic respiration.

Freshwater salinization is a growing challenge in the 21st century. Salinity changes in groundwater in coastal regions are a widespread and important problem exacerbated by growing populations and climate-change driven sea-level rise (for example, Steyer and others, 2007; Anderson, 2002). In the southeastern United States, important drivers of changes in surface-water and groundwater salinity include sea-level change, increasing freshwater withdrawals or diversions for human activities, and current and projected changes in hydrology related to climate change, such as changes in precipitation amount and intensity, represented in part by storm events like hurricanes. Saltwater migrating up coastal canals and entering aquifers through canal leakage is a particular problem during storm surge and is a known threat to municipal well fields in Florida (Prinos and others, 2014; also see Feher and others, 2023).

Saltwater displacement by increased freshwater flow into groundwater in coastal regions (also known as freshening) is another important process (Vengosh, 2014). Displaced saline groundwater flows seaward, and fresh groundwater enters the system. Typically, freshwater has elevated concentrations of calcium and magnesium, which can displace sodium sourced from seawater, leading to elevated salinity of sodium-bicarbonate type groundwater.

Impacts on water use can be directly related to salinity, such as chloride in drinking water. A maximal threshold of 1,000 milligrams per liter (mg/L) is a general requirement for chloride availability for human use (drinking water, agricultural, and industrial uses), but the EPA guideline (secondary drinking water standard) for chloride in drinking water is 250 mg/L, which is about 1 percent of the typical concentration in seawater (U.S. Environmental Protection Agency, 2012). Removal of chloride from water requires expensive treatment methods (such as reverse osmosis, distillation, or ion exchange), and thus seawater contamination can be a costly and long-term impact of storm surge. Issues also can be indirect through changes in salinity causing corrosion of drinking-water infrastructure (Belitz and others, 2016; Stets and others, 2018), affecting the chemical mobility of contaminants such as radium (Lindsey and others, 2021) or mixtures of contaminants sometimes referred to as “chemical cocktails” (Kaushal and others, 2022). Changes in salinity also can change the physical properties of aquifers, affect the fate and transport of carbon and nutrients, mobilize contaminants, affect soil stability, affect the biogeochemical processes occurring in coastal sediment, alter distribution of invasive species (including harmful algae), and cause changes in coastal plant communities that transform nutrients and protect coastlines from erosion (Lindsey and others, 2021; Harvey and others, 2024).

A broad recent USGS study of salinity predictions for CONUS water resources identifies knowledge gaps, their importance to water uses, and proposed approaches to meet these gaps (Harvey and others, 2024; Tesoriero and others, 2024; Lisa Lucas, USGS, written commun., 2023). In general, these approaches include:

- Developing the ability to distinguish various salinity sources and multiple transport pathways from sources to receptors, including watershed or aquifer mass balance approaches combined with flow modeling to better understand the interactions between surface water, the unsaturated zone, and groundwater.
- Building understanding of hourly, seasonal, and long-term changes in sources, peaks, and trends of salinization, such as monitoring salinity with high-frequency sensors and developing long-term continuous datasets.

- Understanding the importance of salt ions and mixtures, including a survey of data on major-ion ratios and trace elements related to salinity in fresh and brackish water resources and developing predictive models for groundwater quality based on local geologic, hydrologic, and climatic conditions.

- Developing water-quality observations and research to understand how salinity affects coastal carbon sequestration, invasive species, and loss of plant communities anchoring coastal wetlands that transform nutrients and stabilize coastlines.

In a recent study prioritizing and ranking watersheds for study (HUC4, Van Metre and others, 2020), the importance of the coastal region may be understated because of the spatial factors considered and the national scope. Beyond the landfall impacts of hurricanes on coastal settings, we emphasize here the need for focal assessments on direct coastal watersheds (for example, HUC8) given their density of human population, economic yield, and substantial challenges from urbanization and sea-level rise.

Coastal Salinity Index—An Operational USGS Southeastern United States Monitoring Network for Salinity Responses

To aid in tracking salinity responses in coastal watersheds, the Coastal Salinity Index (CSI, https://apps.usgs.gov/sawsc/csi/index.html) was developed in 2017 as a long-term monitoring tool that uses salinity as the primary stressor to assess coastal drought (Conrads and Darby, 2017). Motivation for a coastal drought index grew from the NOAA National Integrated Drought Information System (NIDIS) Drought Early Warning System (DEWS) for coastal North Carolina and South Carolina. The tool utilized an approach similar to the Standardized Precipitation Index (McKee and others, 1993) to develop a probability distribution for salinity, instead of precipitation, at a given location. The CSI classifies the salinity at a water-quality gage relative to historical measurements to indicate the changing severity of the saline (or drought) conditions at that location. Initial development focused on two USGS water-quality stations located in large watersheds of North Carolina, South Carolina, and Georgia. Preliminary results indicated the CSI can characterize both saline (drought) and freshwater (wet) conditions as well as time intervals that represent short- to long-term conditions (Conrads and Darby, 2017).

Funding from NIDIS in 2017 allowed expansion of the CSI beyond the two original sites (Petkewich, Lackstrom, and others, 2019; Petkewich, McCloskey, and others, 2019). During that phase of development, the USGS, in cooperation with NIDIS and Carolinas Integrated Sciences and Assessments (CISA), developed a unified CSI software platform, computed static (that is, average condition) CSI results for 97 coastal gages in the southeastern United States and Gulf of Mexico, and created a real-time CSI website for 17 USGS stations served by the South Atlantic WSC (SAWSC). Funding from the Greater Everglades Priority Ecosystem Sciences Program allowed dissemination of real-time CSI results for 11 USGS gages within the Coastal Everglades Depth Estimation Network (EDEN) in 2017. Funding provided from the USGS Community for Data Integration (CDI, https://www.usgs.gov/centers/community-for-data-integration-cdi) in 2020 expanded the SAWSC network to 130 gages located from Maine to Texas and in Puerto Rico by including additional real-time salinity gages from the USGS, the National Park Service (NPS) in Everglades National Park, and the National Estuarine Research Reserve (NERR) System (fig. 4). The CSI website can be used as a monitoring, forecasting, and decision-making tool to evaluate real-time disturbance events as they unfold. The CSI includes sites with more than 14 years of data, currently collecting data, and located on the eastern and Gulf Coasts. Beyond these Tier 1 sites, additional sites from the Pacific Coast and those that have fewer years of coverage are worthy of consideration as the network matures.

Despite its southeastern United States focus and recent expansion, our initial analysis of representativeness of the CSI tool illustrates multiple spatial gaps for representation in the southeastern United States. Of 128 coastal southeastern United States HUC8 watersheds, 111 have no continuous real-time salinity measurements monitored by the USGS. Gages from the NPS and NERR provide additional coverage but are focused on estuarine mixing zones, rather than locations above the fall line (that is, where an upland region and coastal plain meet). Three States contain 83 percent of all CSI gages (Florida, Louisiana, and South Carolina). An expansion of sites to improve representativeness of the CSI gage network is recommended.

Coastal Data and Analysis Tool for Water Resources Management (CDAT)—A USGS Product Providing Data, Analyses, and Visualizations for Coastal Areas

The Coastal Data and Analysis Tool for Water Resources Management (CDAT; https://fl.water.usgs.gov/mapper) is a prototype USGS website that provides data, analyses, and visualizations relevant to coastal water-resources management, including surface-water and groundwater salinity data. CDAT incorporates components of the CSI website described above and the USGS Water Level and Salinity Analysis Mapper website. Users can access a wide variety of data, analyses, and visualizations for groundwater and surface-water sites on CDAT. Data types include groundwater levels, chloride concentrations, and specific conductance in groundwater, surface-water stage, surface-water flow, surface-water salinity, surface-water specific conductance, and the CSI. The website includes a map interface. Users can select which data type to view and also select information the map symbols communicate (for example, recent changes in values or long-term trends) (fig. 5).

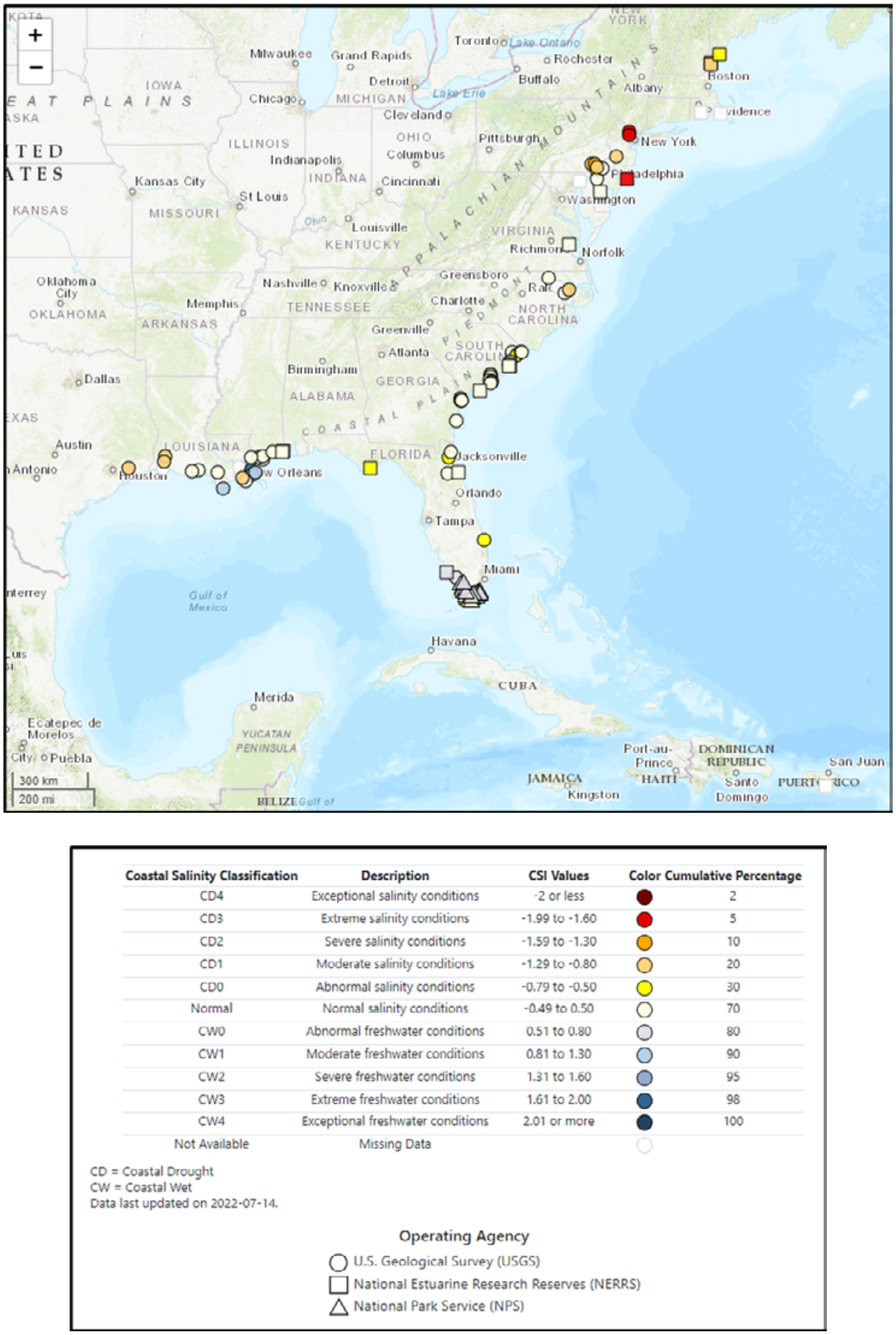


Figure 4. Screen capture showing Coastal Salinity Index (CSI) stations and classifications (accessed July 14, 2022, at https://apps.usgs.gov/sawsc/csi/index.html). The CSI is further detailed in appendixes 3 and 4.

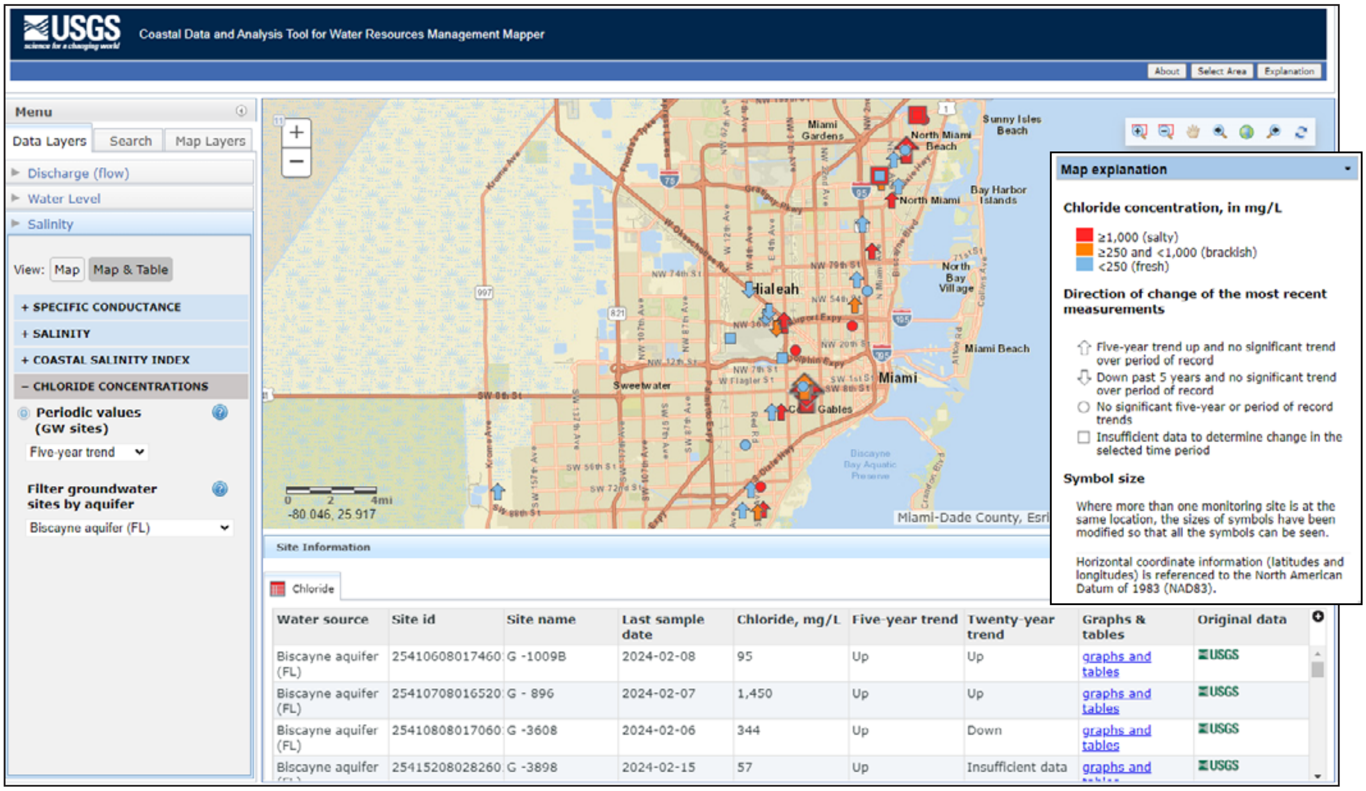


Figure 5. Screen capture showing data from the Coastal Data and Analysis Tool (CDAT) dashboard for groundwater chloride concentration and trends (accessed April 10, 2024, at https://fl.water.usgs.gov/mapper).

For each site, the CDAT also provides a series of plots and data tables to help users visualize long-term trends and short-term shifts in data, such as those caused by coastal storm impacts (for example, fig. 6).

CDAT R-scripts are run daily to retrieve data, perform statistical analyses, and generate the visualizations and tables provided on CDAT. Because Miami-Dade County is the primary source of funding for CDAT, the website is heavily focused on southern Florida. A 2021 grant from the USGS CDI enabled the expansion of scripts to demonstrate applicability to a wider variety of data tables and a wider geographic area. Currently CDAT includes more than 750 sites from 16 Atlantic and Gulf of Mexico States and Puerto Rico. The R-scripts and website have been designed to be flexible so that the number of sites, types of data, and geographic region covered by CDAT can continue to expand as needs and opportunities arise.

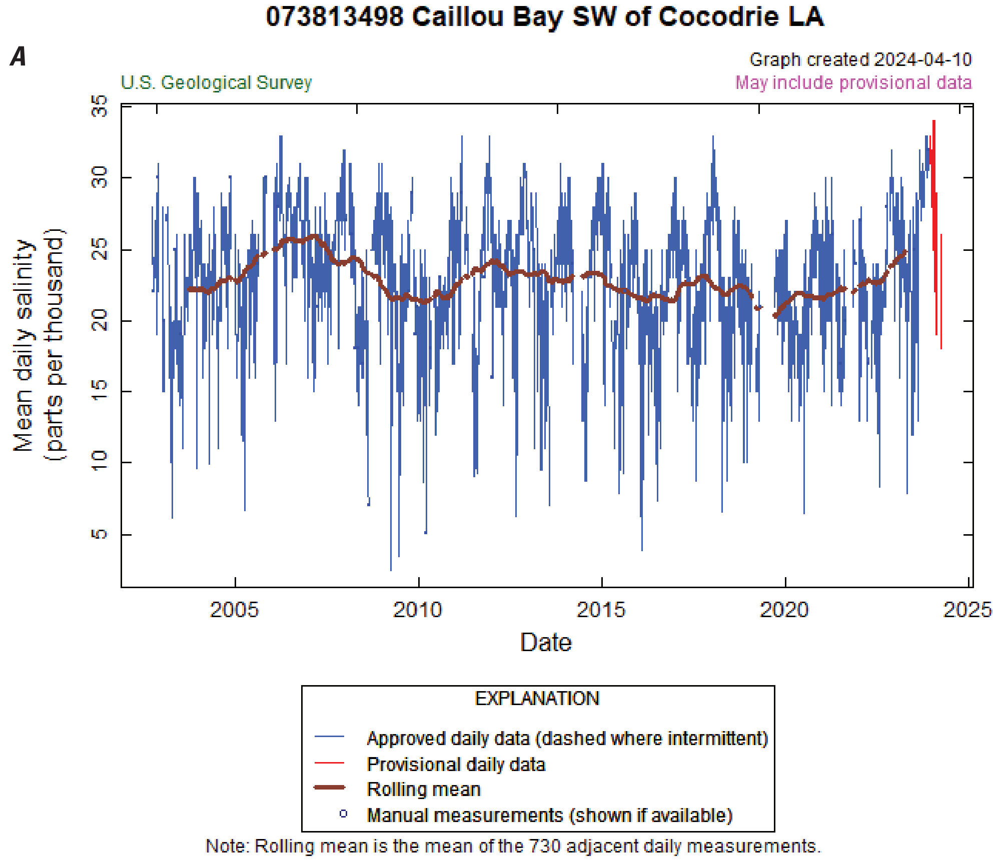
Nutrients

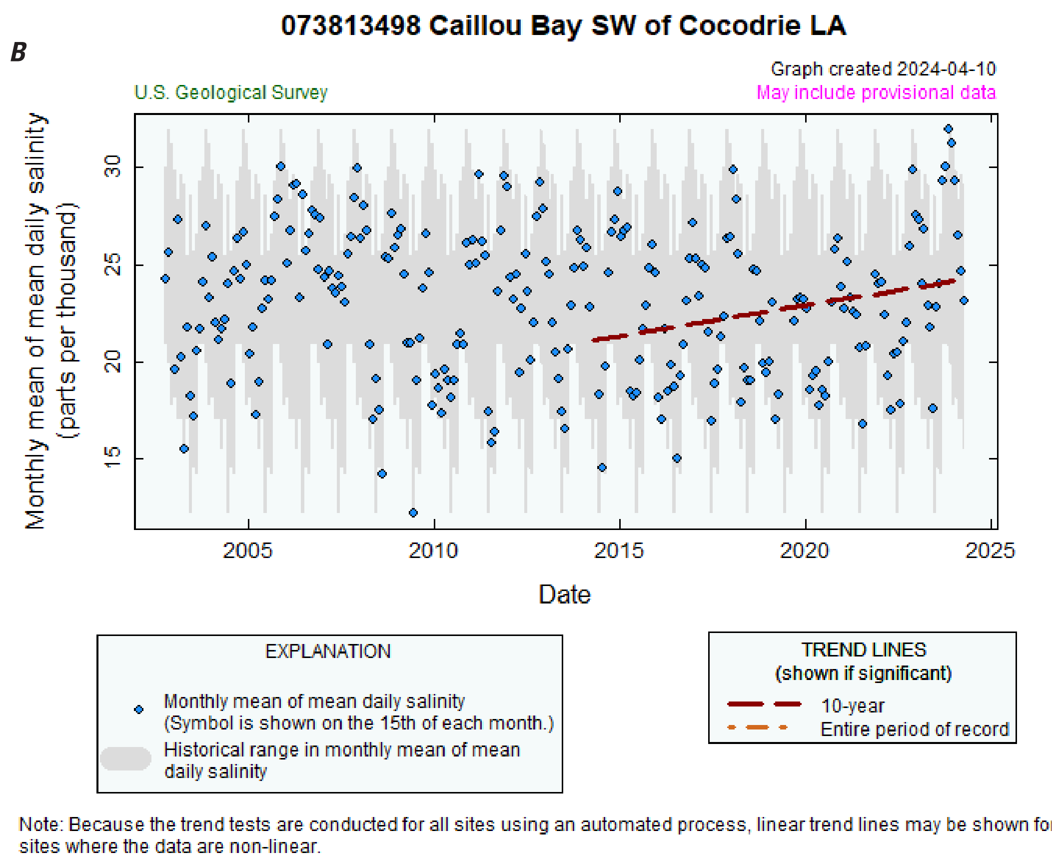
Following a hurricane, both nutrient concentrations and speciation may be altered relative to pre-hurricane conditions. These shifts have cascading effects on water quality, such as algal blooms and increased atmospheric CO_2 fluxes. Although some broad trends have been established, there are still substantial gaps in knowledge regarding phosphorus, nitrogen, and carbon cycling post-hurricane (see Blood and others, 1991; Gardner and others, 1991).

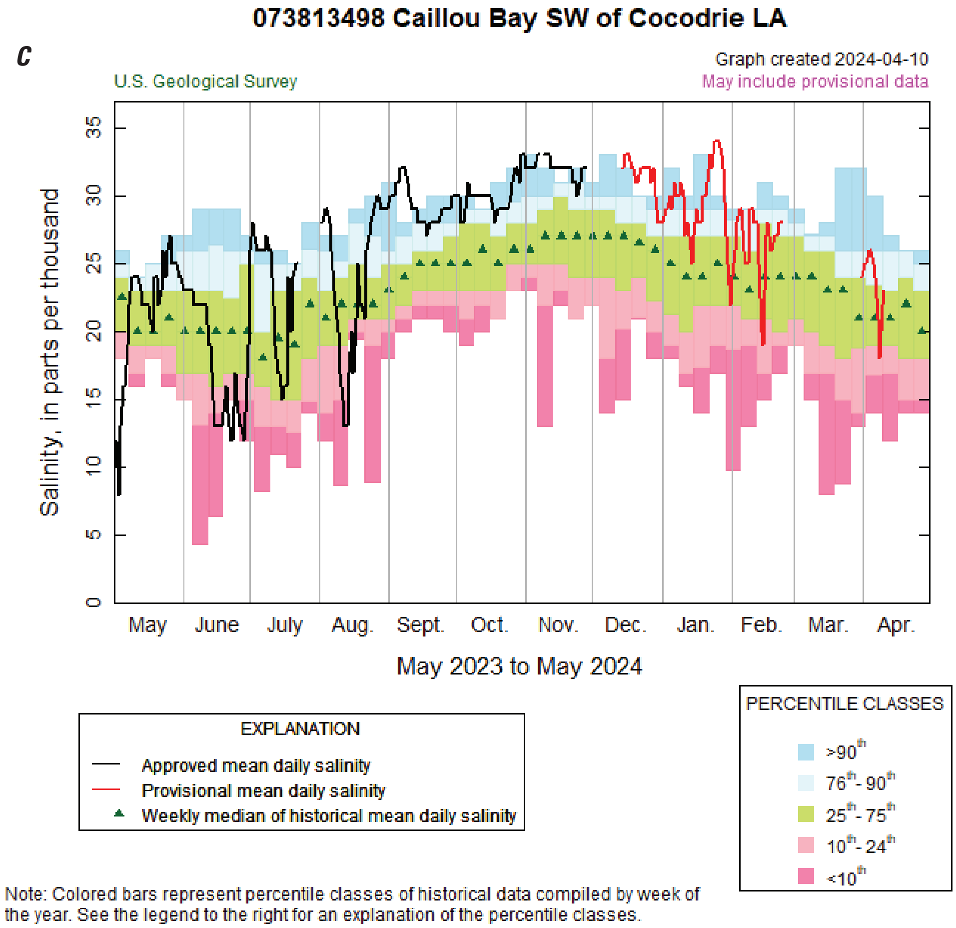
Typically, nutrient concentrations in surface waters increase immediately through overland flow after a hurricane and can remain elevated for extended periods depending on subsequent weather events, biogeochemical cycling, and the local physical environment. For example, major storms can cause a doubling of annual nitrogen and a tripling of annual phosphorus concentrations compared to non-storm years (Paerl and others, 2018). After Hurricane Fran (1996), nitrogen and phosphorus were measured to be 1–3 percent of the mean annual load in a single day in the Tar and Neuse Rivers (North Carolina) (Bales and others, 1996). During a 36-day flood period after hurricane Floyd (1999), nitrogen and phosphorus loads ranged from 50 to 90 percent of long-term average annual loads in the Neuse River (Bales, 2003). Elevated concentrations of nitrogen and phosphorus measured throughout the 2004–2005 hurricane season in southeast Florida in the St. Lucie estuary demonstrated the compounding impact that several storms may have on nutrient concentrations in surrounding water bodies (Lapointe and others, 2012).

Similar to inorganic nutrients, dissolved organic carbon concentrations also are commonly elevated in post-hurricane water bodies. In North Carolina coastal waters after Hurricane Matthew (2016), 25 percent of the annual carbon loading was measured, and wetland-derived terrestrial organic matter persisted in coastal waters for several months (Osburn and others, 2019). Terrestrial organic matter also was rapidly mobilized because of Hurricane Irene (2011) in North Carolina (Paerl and others, 2018).

Figure 6 (pages 18 and 19). Graphs showing results from the Coastal Data and Analysis Tool (CDAT) output for salinity trends at U.S. Geological Survey site 073813498 (Caillou Bay SW of Cocodrie, LA) for selected period of record. *A*, Mean daily salinity. *B*, Temporal trends in monthly mean of mean daily salinity. *C*, Two years of mean daily salinity data relative to historical frequency analysis. *D*, Two years of mean daily salinity data relative to the historical range in values. Data accessed April 10, 2024.







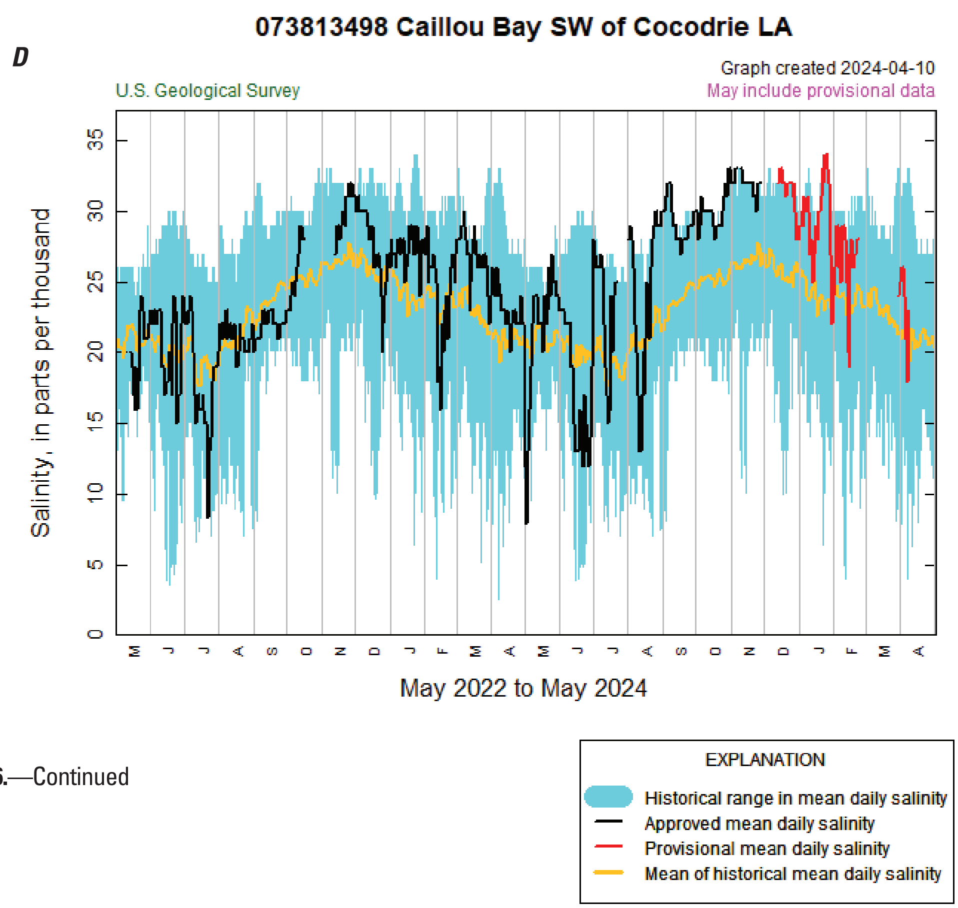


Figure 6.—Continued

In response to both Hurricanes Irene and Matthew, this shift in dissolved carbon speciation led to an increase in vertical CO_2 effluxes in these areas owing to microbial degradation and other biological processes. In addition to gaseous and dissolved carbon phases, particulate organic carbon also has been demonstrated to increase post-hurricane relative to non-storm conditions (Dhillon and Inamdar, 2014).

The length of time until nutrient concentrations return to pre-hurricane levels varies widely and is dependent on various factors. For example, elevated concentrations of phosphorus, nitrogen, and carbon decreased across Galveston Bay over the course of 4 weeks after Hurricane Harvey (2017) (Steichen and others, 2020). Conversely, as mentioned above, sustained increased nutrient concentrations have been measured for weeks and even months post-hurricane. For example, following Hurricanes Joaquin (2015) and Matthew (2016) in North Carolina, dissolved carbon concentrations were elevated for months, and sustained CO_2 effluxes were correspondingly measured (Paerl and others, 2018). In the Pamlico Sound of North Carolina, three sequential hurricanes occurred in autumn 1999 and post-hurricane water quality was subsequently measured for 2.5 years (Peierls and others, 2003). Because the Pamlico Sound is isolated from the ocean by barrier islands, the impacts of the direct storm surge were minimal; however, increased concentrations of nutrients occurred and did not return to pre-hurricane levels for 1–2 months.

High nutrient loadings not only degrade water quality and have the potential to increase greenhouse gas emissions, but also have ecological effects such as shifts in microbial communities, fecal coliform concentrations, and harmful algal blooms (HABs). Increased nitrogen concentrations in particular have been repeatedly linked to increased phytoplankton biomass after Hurricanes Fran (1996), Irene (2011), Dennis (2005), and Floyd (1999) (Burkholder and others, 2004). After Hurricane Harvey (2017), an estimated 500,000 Texas residents may have had their drinking-water supplies affected by bacterial contamination (Pieper and others, 2021). A comparison of two separate water distribution systems with direct and no direct effects on water flows in response to Hurricane Harvey illustrates impacts of microbial contamination for about 70,000 people (Landsman and others, 2019). High fecal and total coliform levels have been measured not only post-Hurricane Harvey (Steichen and others, 2020; LaMontagne and others, 2022) but also after several hurricanes in southeast Florida (Lapointe and others, 2012), and fecal coliform bacteria have been listed as a top concern in terms of ecological effects post-hurricane (Mallin and Corbett, 2006). Another documented biological effect resulting from increased nutrient concentrations post-hurricane is fish kills (Mallin and Corbett, 2006). Hurricanes also have been linked to red tides off the coast of Florida through increased nutrient delivery by submarine groundwater discharge (Hu and others, 2006). Increased biological oxygen demand, eutrophication, and hypoxia all contribute to added stress on ecological communities and, consequently, decreases in biodiversity. Nutrient and microbial impacts on groundwater supplies—especially increased nutrient, carbon, and bacteria loading to recharge—are even less studied or understood.

From the literature, it is clear that more monitoring and data are needed to understand the many factors that contribute to nutrient concentrations, speciation, and recovery in post-hurricane water bodies. Long-term data, in addition to event-based data, are needed to better understand and predict post-hurricane water quality.

Temperature

The effects of temperature changes related to hurricane or storm events on water quality do not appear to have yet garnered much attention in the scientific literature. In contrast, there is a substantial body of knowledge related to sea-surface temperature and hurricane strength. Regardless, one potential topic of interest is the transient temperature pulses created in streams associated with large rain events, which has predominantly been explored in urban settings (Zeiger and Hubbart, 2015; Zahn and others, 2021). Although not directly related to water-quality determinations, thermal changes of the land surface have been observed and associated with defoliation after Hurricane Maria in 2017 (Scholl and others, 2021) and Hurricane Laura in 2020 (Reesman and Miller, 2023). In the case of Hurricane Maria, the defoliation was linked to local changes in the water cycle, cloud formation, and precipitation in eastern Puerto Rico. Thus, the post-hurricane effects on the forest affected water availability. In the case of Hurricane Laura, defoliated land surface was linked to increased heat index, a measure of heat stress or human perceived temperature, in southwestern Louisiana.

Suspended Sediment

Elevated suspended-sediment concentrations are a substantial water-quality impairment for multiple water resource uses. High flows and landslides can lead to substantial post-hurricane contributions of sediments to surface waters. Several publications highlight the specific hurricane-induced enhancement of suspended-sediment concentration, which can be associated with nutrients (phosphorus), mobilized toxic constituents, and (or) physical geomorphic restructuring. Six example publications were reviewed to explore a range of impacts across ecological and consumptive uses. These case studies illustrate the need for physical modeling to predict the likely enhancement of erosion and deposition with more frequent and higher intensity rainfall events during hurricanes.

Example 1 (Du and others, 2019).—The dramatic sediment responses to Hurricane Harvey were primarily driven by extreme precipitation and its influence on elevated water levels. High channel velocities, exceeding 3 meters per second (m/s), led to intense sediment scouring and subsequent deposition of sediment downstream with huge sediment plumes extending miles offshore. For reference, the estimated freshwater load to Galveston Bay during Hurricane Harvey and the following month was 11.1 billion cubic meters (m^3), which is approximately three times the standing water volume of Galveston Bay.

Example 2 (Liu and others, 2018).—Modeled sediment flux in the Gulf of Mexico's Terrebonne and Barataria Basins associated with Hurricane Gustav (2008) required a coupled hurricane wind, storm surge, wave, and sediment transport modeling system as well as an extensive set of field observations along the coast. Model simulations, in good agreement with measures of fresh sediment deposition (Tweel and Turner, 2012), illustrated that the sediment suspension and redistribution primarily occurred with mud on the mud-dominant Louisiana coast; in contrast, the transport of sand was relatively negligible during the hurricane. High (and highly uncertain) erosion rates played a critical role in sediment accretion within the coastal wetland complex, suggesting the importance of suspended-sediment concentrations in wetland resilience. Additional monitoring of suspended-sediment properties, for constraining settling velocity and shear stress, was recommended to assess hurricane impacts and the fate of suspended sediment.

Example 3 (Zang and others, 2018).—This study modeled sediment dynamics during Hurricane Gustav, but with a more general hydrodynamic modeling framework (using the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System, COAWST; https://www.usgs.gov/science/coawst-a-coupled-ocean-atmosphere-wave-sediment-transport-modeling-system) applied to Gustav's dynamic ocean influence in the Gulf of Mexico. Sediment concentrations were excessive (greater than 1 kilogram per liter [kg /L] and strongly driven by asymmetric winds). With the loss of estuarine stratification, high wave energy and strong bottom shear led to suspended-sediment fluxes exceeding 11 kg/m/s, and deposition rates more than 26-fold greater than during normal ocean conditions. Not accounting for these extreme and episodic geomorphic alterations, including landward migration, limits both predictive understanding (forecasting) and landscape interpretation (hindcasting) of hurricane impacts.

Example 4 (Gellis, 2013).—In Puerto Rico, 120 storm events were assessed to illustrate the role of sediment source location in terms of predicted suspended-sediment concentrations and their hydrologic loading in time and across basins. Rather than storm intensity, antecedent events and basin types were the best predictors of hysteresis in sediment loads. Whereas cropland basins had high sediment availability outside channels, the forest- and pasture-dominated basins saw sediment loads responsive to in-channel sources. Urbanized basins saw stormwater runoff diluting suspended-sediment concentrations on the rising limb, with upland sediment arriving during the hydrograph recession. The statistical approaches reported for Puerto Rico are helpful in generating hypotheses of the location and delivery of watershed sediment sources and targeting modeling and monitoring approaches.

Example 5 (Yellen and others, 2014).—The utility of rating curves for sediment transport predictions during Hurricane Irene (2012) were examined. Extreme precipitation altered expected relations owing to added and preferential transport of previously unmobilized fin-grained glacial sediment from upland catchments in the steep post-glacial tributaries of the western Atlantic slope. These winnowed clays and silts from upland sources were unexpected, suggesting that high magnitude, low frequency events (such as hurricanes) can be strong drivers of suspended sediment into lower order tributaries. Furthermore, this result was the opposite of rating curve patterns in the Pacific Northwest, where specific sediment yields in intense rainfall events increase with decreasing drainage area.

Example 6 (Dellapenna and others, 2020).—The toxicity of sediments mobilized and accumulated in response to the extreme rainfall and record flooding extent of Hurricane Harvey (2018) was examined. In addition to the industrial wastewater loads of metals (for example, mercury) and petrochemical constituents, historical subsidence in the basin drove rapid flows and more than 2 meters (m) of sediment accumulation in subsided basins. Concentrations of total mercury in sediment exceeded 51 micrograms per gram (µg/g), which is 1,000-fold higher than background concentrations and 20-fold higher than measured anywhere in the Galveston Bay region. Detailed profile assessment illustrated two phases of the flood event for the San Jacinto River—an initial 12–16 days followed by reservoir releases that led to 53 days of flooding in Buffalo Bayou. Erosion during rising flood waters was followed by a long period of deposition, with elevated mercury in fine sediments poised for methylation in the more surficial layers.

To summarize, the impacts of coastal storms on water quality are substantial and are controlled by the acute and diverse physical forcings associated with hurricane events. Furthermore, these primary metrics of water-quality impact have strong implications on toxicity and contaminant transport, whether organic, inorganic, or microbial. Hurricane impacts on water use can have long (multiyear) recovery times if not permanent impairment (for example, groundwater) leading to surface water or aquifers becoming unusable for humans or wildlife. Monitoring efforts typically have been limited to single well-studied sites, with specific questions. The more generalized repeated measurements reported across multiple monitoring programs by the Water Quality Portal (sourced by NWIS and the USGS STOrage and RETrieval Data Warehouse [STORET]) are an initial entrée to understand historical variability and predict antecedent conditions but are much more useful when continuous and provided in real time. The CSI example shows a statistical use of real-time continuous data that allows immediate interpretation, and thus responsive modeling potential for chloride and other associated contaminants. Given the diversity of landscape settings, hydrologic connections, and storm characteristics, the monitoring needed to support prediction of water-quality impacts and recovery at watershed scales is nearly insurmountable. A more integrated and representative network of model-supporting datasets, including remotely sensed support, is needed. Monitoring data are the first and most lacking component of a predictive approach, as applications will require understanding of local hydrology, water control infrastructures and their resilience, historical and planned human alteration of floodplains and recharge locations, and scenario-testing capabilities to test storm impacts based on varied landfall location, intensity, and duration.

State of the Science on Modeling Water-Quality Impacts of Hurricanes

The USGS recognizes a need for predictive models to help managers plan for and respond to a myriad of water-availability and water-quality impacts in response to hurricanes. A general spectrum of approaches to water-quality modeling includes mechanistic, statistical, and hybrid modeling (figs. 7 and 8). Model development to inform water-resource management is a primary USGS WMA goal, which includes understanding and developing strategies for building models capable of predicting water-quality impacts resulting from hurricanes.

Model Choice

Mechanistic models also are referred to as process-based or physically based models. These types of models use mathematical formulations to represent a response (for example, a change in chemical composition) to a stressor (such as a hurricane or extreme weather event) (Baker and others, 2018). Mechanistic models are particularly valuable for improving understanding of the chemical and physical processes that lead to water-quality changes and can be used for scenario testing to predict how water quality might respond to the stressors associated with hurricanes (extreme wind, storm surge, and so on). However, the mathematical formulations that are the foundation of mechanistic models are often not capable of fully representing heterogeneities in natural systems or the myriad of complex interwoven physical and chemical processes that influence water quality, which can lead to uncertainties and inaccuracies in model predictions (Muniruzzaman and Pedretti, 2021). Additionally, parameterizing, calibrating, and validating complex mechanistic models can be time intensive and expensive (Schneider and others, 2022).

Statistical models are data-based. Rather than attempting to model individual processes, they focus on statistical relations between input and output parameters. Statistical models, sometimes referred to as data-driven models, tend to be less useful than mechanistic models for improving understanding of causal relations; however, statistical models are commonly used for estimating data in place of routine monitoring (Safaie and others, 2016) and also can be useful for predicting water quality in circumstances where there is a limited understanding of the physical system or where it is not practical for mechanistic models

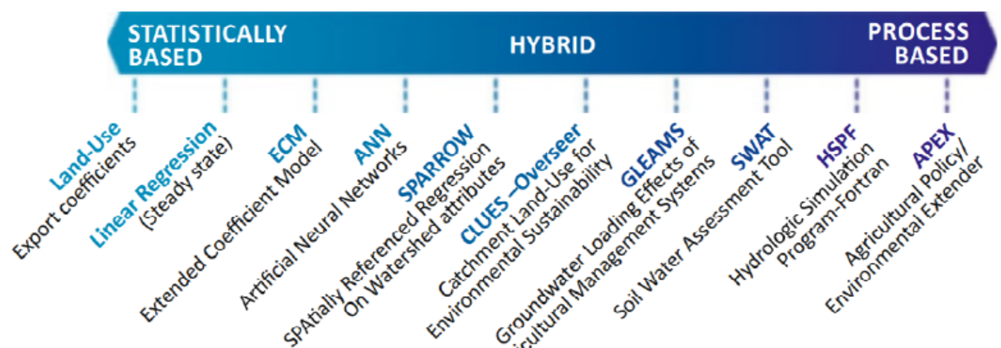


Figure 7. Diagram showing conceptual flow of modeling approaches from empirical (statistically based) to parameterized (process based) processes (modified from Parshotam and Robertson, 2019).

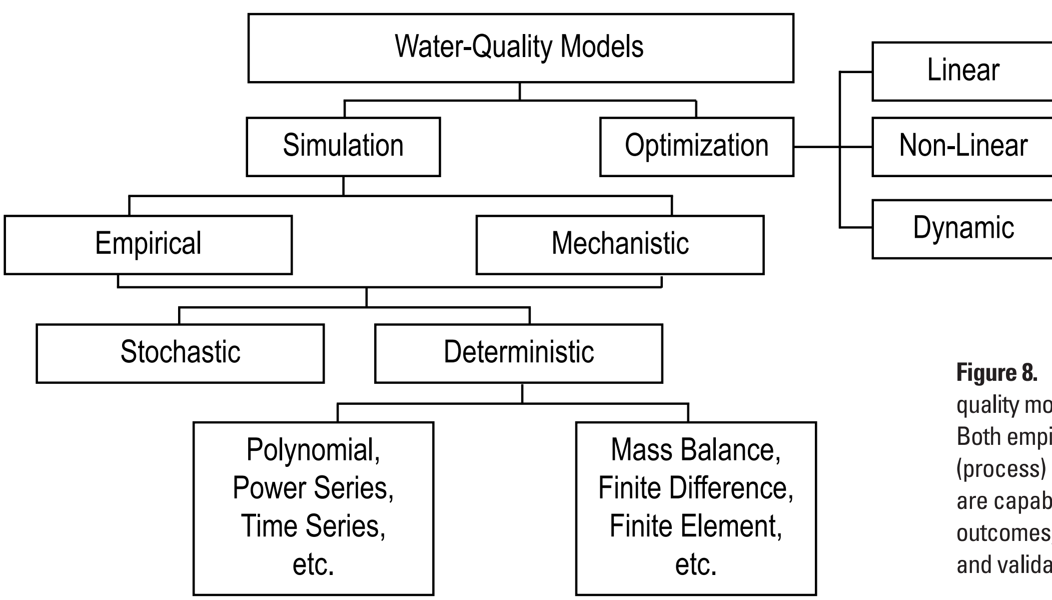


Figure 8. Diagram showing range of water-quality models designed for specific tasks. Both empirical (statistical) and mechanistic (process) models for water-quality prediction are capable of stochastic and deterministic outcomes, given sufficient parameterization and validation.

to fully capture heterogeneities and complex system interactions (Muniruzzaman, and Pedretti, 2021). Common types of statistical models include regression models and probability models. Machine learning and deep learning algorithms also are being increasingly applied for water-quality prediction.

When applied to a limited range of system conditions, statistical models can produce more accurate predictions than mechanistic models. However, mechanistic models tend to be more robust than statistical models when extrapolating predictions over a wide range of system conditions. Thus, hybrid models, which aim to combine the strengths of both statistical and mechanistic models, are increasingly being used for water-quality prediction (Qaughebeur and others, 2022).

Recent Case Study for Hindcasting/Predicting Water Quality Effects of Hurricanes—Hurricane Maria

Hurricane Maria made landfall as a Category 4 storm in Puerto Rico on September 20, 2017. The storm caused severe flooding and had devastating impacts on the island's natural environment as well as its infrastructure, including electricity, water, and wastewater systems. Several studies were conducted to assess the impact of Hurricane Maria on the island's drinking-water quality (Lin and others, 2020; Keenum and others, 2021; Warren and others, 2023). These studies included widespread sampling campaigns, toxicity assays, and microbial genome sequencing. Although predictive modeling was not a focus of these studies, statistical analyses were performed to evaluate differences in water quality pre- and post-hurricane and to identify the areas on the island where water quality was most impacted. Such sampling campaigns and statistical analyses are necessary to identify the contaminants of greatest concern and the most at-risk geographic areas for water-quality impacts from hurricanes. This type of information is essential for developing hypotheses and designing models that can help predict the water-quality impacts of future hurricanes.

Hurricane Maria's impact on Puerto Rico serves as an example of the complexity of interrelated processes that can influence water quality and of the challenges inherent in modeling such processes. Bessette-Kirton and others (2019) documented more than 40,000 landslides that occurred because of hurricane Maria, providing a source of readily mobilized sediment for months after the event. Miller and others (2019) observed that post-Hurricane Maria sediment loads to nearshore waters were still higher than normal 4 months after Hurricane Maria's landfall. Hall and others (2020) documented forest loss including defoliation, stem loss, and uprooting to be about 23 percent of pre-hurricane forest above-ground biomass for the island, and Leitold and others (2021) compared light detection and ranging (lidar) measurements to determine that forests were shorter and more open 3 years after the hurricane. The widespread defoliation altered the thermodynamics of the lower atmosphere, which led to a post-hurricane period of altered cloud dynamics and energy balance, with precipitation at normal levels (Scholl and others, 2021). McDowell and Potter (2022) described spikes in nitrate, phosphorus, and potassium in soil solution and (or) streamflow following leaf and branch deposition from the defoliation, and suggested long-term changes in nutrient balances as a result of disturbance. These studies indicate that models of water quality after hurricane disturbance need to represent the effect of changes in forest cover on runoff processes, nutrient export, and sediment mobilization; few modeling studies to date have focused on interactions between sudden land-cover change and water quality (except for wildfire, for example, Ebel and others, 2023; Murphy and others, 2023).

Williams and others (2013) used two mechanistic models, the Agricultural Policy/Environmental eXtender (APEX) and the Riparian Ecosystem Management Model (REMM) models, to simulate both the hydrology and water quality of agricultural areas near the Jobos Bay National Estuarine Research Reserve in Puerto Rico. They used the models to estimate water, sediment, and nutrient transport to mangrove wetlands in Jobos Bay. Their simulations indicated that both tropical storms and hurricanes play an important role in sediment and nutrient transport to the wetlands. The USGS evaluated constituent loads during storm events in four Puerto Rico watersheds as part of the Water, Energy, and Biogeochemical Budgets program (WEBB) (Murphy and Stallard, 2012). The water quality and stream discharge data for this project were collected from 1991 to 2005. Both simple regression models and the computer program LOADEST (Runkel and others, 2004) were used to model the relation between constituent loads and stream discharges. The models were then used to estimate constituent loads over specific time intervals. This study found that runoff from hurricanes in Puerto Rico is commonly exceptionally high in chloride, which is likely due to the inland deposition of windborne sea salt from the ocean during hurricanes. Additionally, higher than normal potassium concentrations were observed in some runoff samples for extended periods after hurricanes. These elevated potassium concentrations are likely the result of runoff interacting with the large amounts of leaf litter that are deposited during hurricanes.

Water-Quality Model Options in USGS Products

Model options are varied among USGS validated products. Mechanistic water-quality models are tools that mathematically describe some or many mechanisms that cause changes in water quality and lead to useful relations to assess cause and effect. Mechanistic water-quality models are limited currently to salinity-intrusion models (for example, COAWST), as solute transport models have had limited development. Rather, advanced particle tracking in MODFLOW (https://www.usgs.gov/software/modflow-6-usgs-modular-hydrologic-model) today may provide feedback to constrain flow effects on water quality. The Precipitation Runoff Modeling System (PRMS) (https://www.usgs.gov/software/precipitation-runoff-modeling-system-prms) can supply information on rainfall-runoff partitioning, evapotranspiration, and soil moisture dynamics, but can only provide a water balance to work with and possibly test out different flow scenarios. Mechanistic models, which can integrate compound flow and transport functions, have some advantages for addressing questions of hydrology-related water-quality impacts from hurricanes, such as:

- Support of increased mechanistic understanding of water-quality dynamics;
- Supply of quantitative information on cause-and-effect relations;
- Interpretability of datasets and drivers; and
- Transferability to other systems, time periods, or conditions that can lead to predictive capabilities under unusual conditions, if adequately calibrated and validated.

Empirical models are commonly thought of as black-box models (for example, machine-learning models). Purely empirical models, such as many statistical models, allow description of the fixed relations between input data and output results with a minimum process-based understanding about how the system works. Still, purely data-driven approaches (machine learning) can identify important parameters about processes that aid in mechanistic model development. Statistical models estimate parameters through statistical analysis and then check the adequacy of the model. One of the principal restrictions of empirical models is that they cannot be implemented for other systems or for conditions out of the range used for creation of the model (Martin and McCutcheon, 1998). From the practical point of view, water-quality management models will have empirical characteristics, especially because of the need for initial development, parameterization, and validation.

Deterministic models (for example, for stage-discharge relations) have a fixed relation between input data and output results and may be empirical or mechanistic. They represent essential components of hybrid approaches such as USGS SPAtially Referenced Regression On Watershed attributes (SPARROW) modeling (https://www.usgs.gov/mission-areas/water-resources/science/sparrow-modeling-estimating-nutrient-sediment-and-dissolved) (for example, Brakebill and others, 2011).

Stochastic models contain some random elements and can be used to ask questions of representativeness of extreme events, such as hurricanes. Stochastic models include steady-state Monte Carlo simulation models, often using a mass-balance model, which generate an output result with varying input conditions in the form of a frequency distribution, and dynamic time-series simulation of component responses to illuminate boundaries of model applicability.

Interviews with USGS scientists who have expertise in water-quantity and water-quality modeling in 2022 led to some valuable conclusions. Approaches to assessing trends and their drivers with respect to extreme events are largely statistical. They are improved by machine learning that allows relations to vary nonlinearly in accordance with rich time series of data (Jory Hecht, USGS, oral commun., 2023). Similarly, parameterized by long-term spatiotemporal response datasets, SPARROW model approaches are deterministic hybrid approaches to predict water quality by flow responses to landscape characteristics (Noah Schmadel, USGS, oral commun., 2023; Jared Smith, USGS, oral commun., 2023). Future physical modeling approaches, such as those being pursued in the WMA Integrated Water Prediction (IWP) Program (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-prediction-iwp), are based on first principles of hydrologic fluxes, leading to large parameterization needs, again relying on rich time series of data (Lisa Lucas, USGS, oral commun., 2023). Finally, COAWST, a mechanistic modeling framework driven by physical hydrodynamics, is an impressive time-dependent, multidimensional partial differential transport equation. As shown for divergent storm and tidal impacts, it is capable of predicting water quality such as surface water salinity and mixing along a tidal river (Cook and others, 2023), but in its simplest form is fundamentally a mass conservation model relying heavily on a dense network of sampling points, which is achievable for conductivity and potentially temperature because of their physical conservatism and constraints (Salme Cook, USGS, oral commun., 2023). Even with dense nutrient and sediment data, other less-conservative water-quality parameters may be difficult to address with the physical COAWST framework. In most water-quality applications associated with external drivers, the data density needed for model development is insufficient for regionally accurate predictions. Specific sites are well outfitted for specific impacts (for example, salinity-intrusion-front mapping in the Biscayne aquifer in Miami-Dade County, Florida), but hurricane timing and magnitude and antecedent conditions require far too large a parameterization dataset (and validation dataset) to develop a regional modeling approach. Several high-performance models are available within the USGS or from USGS partners (see examples from the Texas Integrated Flooding Framework [TIFF] at https://www.texasflood.org/tools-library/tiff/index.html) but the parameterization is weak, especially for mixing water sources owing to compound flooding. Difficulties in upscaling water-quality modeling from local, single-process studies to regional-scale and multiprocess situations are persistent, with multiple issues of parameterization and numerical model applicability. The greatest challenges to model implementation are the frequency and spatial density of data collection, the ability to use data in real time to assess management responses, and both the data and the model representativeness for statistical modeling. Rather than focus on preselected directions for predictive modeling, we describe conceptual models that make clear the parameterization necessary to determine factors of risk and resilience for predicting impacts of concern to stakeholders.

Conceptual Model Framework

A conceptual model approach is used here to explore the effects of hurricane drivers, and what their impacts are on water availability. Similar to the concepts provided by Mallin and Corbett (2006), we developed a conceptual framework (fig. 9) to examine five major hurricanes since 2000 (Hurricanes Ivan, Rita, Harvey, Florence, and Ian). Comparison of these five major hurricanes, and their unique aspects that led to differential impacts on water availability, provides a mechanism to identify where model parameterization is needed for future exercises in predicting

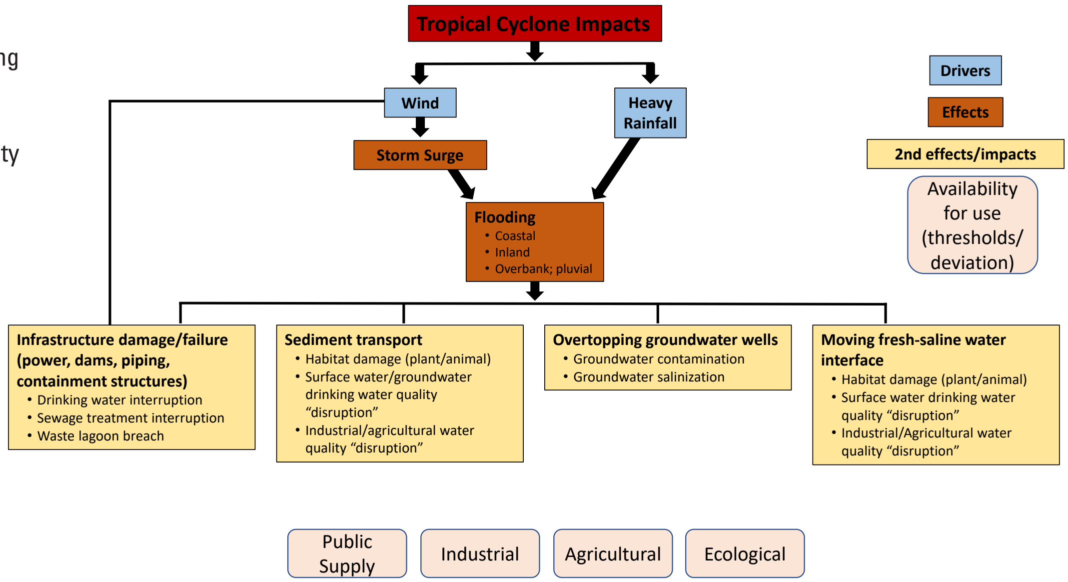


Figure 9. Diagram showing conceptual framework of hurricane drivers and their impacts on water availability through thresholds and deviations in water quality.

water-quality impacts. Hurricane tracks and coastal salinity anomalies are detailed in appendix 5.

Hurricane Ivan (2004)

Hurricane Ivan made landfall on September 16, 2004, as a Category 3 storm along coastal Alabama during an exceptionally busy 2004 hurricane season. Although this storm precedes hurricane response actions and reporting in the USGS Flood Event Viewer, the impacts were notable with substantial wind bursts, and an unusual and record-setting 23-day track that progressed north through Pennsylvania, returned through southern Florida as a tropical depression, and made a final push across the Gulf of Mexico into Texas as a tropical storm. Infrastructure damage closed Interstate 10 in Alabama for weeks, but successful pre-event population evacuation appeared to limit immediate health impacts. Coastal water quality was characterized by high flushing rates and sediment transport, but salinity alterations were not long lived. With Hurricane Frances (August 2004) setting high antecedent soil saturation and water levels, inland flooding from Hurricane Ivan was particularly long lived, as were wastewater- treatment plant failures, leading to significant bacterial contamination of private wells and public water supplies. As Hurricane Ivan traveled inland, major effects also were observed across the eastern United States, including historical rates of sedimentation and phosphorous accumulation in the Susquehanna River Basin (Langland, 2015).

Hurricane Rita (2005)

Hurricane Rita (2005) made landfall at the Texas-Louisiana border as a Category 3 storm after reaching Category 5 status (112–129 mile per hour [mph] winds) over the Bahamas. Arriving less than a month after Hurricane Katrina (2005), Hurricane Rita had localized effects distinct to its industrialized landfall location and antecedent conditions. Significant storm surge (17–18 feet [ft]) and excessive rainfall (exceeding 10 inches per hour) dominated impacts from eastern Texas to Alabama, with secondary storm-surge impacts as far as the Florida Keys. Inundation up to 15 ft above ground level was observed along large portions of eastern Texas to the Florida coast (https://stn.wim.usgs.gov/FEV/#2005Rita). Coastal flooding led to substantial infrastructure damage to the energy sector, from petroleum to electrical transmission lines, as well as to municipal water systems, such as wastewater treatment (Reed and others, 2010). Secondary effects of moving surface water, fresh-saline interfaces included significant salinity intrusion and vegetation stress along wetlands of the Louisiana coast (Steyer and others, 2010). Alligator populations also decreased with initial salinity intrusions, which were followed by a 4-month drought that hyper-salinized substantial extents of freshwater wetlands at the Texas-Louisiana border (Lance and others, 2010). Agricultural stresses of saline flooding from Hurricane Rita included sugarcane crop losses (Beuzelin and others, 2009) and aquaculture failures (for example, crayfish; Buck, 2005) that exceeded freshwater damages to 90 percent of Louisiana's coastal oyster beds. Although surge waters clearly contaminated many private wells near Lake Pontchartrain, Louisiana, recovery of groundwater availability occurred within a month of impact (Van Biersel and others, 2007).

Hurricane Harvey (2017)

Hurricane Harvey made landfall on August 25, 2017, as a Category 4 hurricane north of Corpus Christi, Texas, in Aransas County, and despite its remnants continuing northward to Tennessee, the impacts of Hurricane Harvey were hyper-localized (https://stn.wim.usgs.gov/FEV/#2017Harvey). As one of the costliest U.S. hurricanes ever (costs exceeded $125 billion, as of 2022), the storm stalled near the Texas coastline due to confinement by two high pressure atmospheric events, leading to torrential and unprecedented amounts of rainfall over Texas (greater than 1.5 m) over a short 4-day period. The deluge (more than 100 billion cubic meters of rain, in total) led to significant ecological shifts, such as the alteration of the estuarine biotic community into a primarily freshwater biotic community for several months after the flooding event (Steichen and others, 2020). On land, the deluge was exacerbated by poor geologic drainage of the region, with new (greater than 2 centimeters) elevation loss adding to historical subsidence (Milliner and others, 2018), and current urbanization features that promoted long-term flooding and water treatment failures. Storm surge was modest but prolonged (Blake and Zelinsky, 2018), leading to compound flooding that prevented accurate flood depth modeling. The extent of contaminant mobilization was measured in core-estimated sedimentation rates (Kiaghadi and others, 2021) and evidence of far sediment transport (Shore and others, 2021), which led to extensive ecosystem and aquaculture damage in Galveston Bay. With the Trinity and San Jacinto Rivers delivering greater than 70 percent of the freshwater inflow into Galveston Bay, contamination from Superfund sites and compromised wastewater-treatment systems, industrial facilities, oil refineries, and chemical plants released raw sewage and toxic chemicals still being accounted for today. The creation of the interagency Texas Integrated Flooding Framework (TIFF, https://www.texasflood.org/tools-library/tiff/index.html) was a direct response to the limited predictive capacity of research and regulatory agencies to produce a comprehensive risk assessment in real time. Our conceptual model highlights how water level and flow-path modeling establish a foundation for understanding the impacts of the storm on hydrologic processes, but water-quality impacts result primarily from infrastructure breaching, damage, and delayed recovery of pre-storm hydrologic conditions that are not accounted for in traditional mechanistic hydrologic models.

Hurricane Florence (2018)

Hurricane Florence made landfall as a Category 1 storm in South Carolina on September 14, 2018, with record wind damage to trees and the electrical grid and storm surges exceeding 10 ft. Despite heavy wind gusts and coastal dune erosion, the most notable impacts were through torrential rains breaking State records in North and South Carolina (30 in. and 23 in. over 24 hours, respectively, https://stn.wim.usgs.gov/FEV/#2018Florence). Historical flooding led to nine river gages across the Carolinas exceeding their peaks of record, and these high flows led to massive log jams that further increased off-channel flows, leading to multiple water-quality impacts. Infrastructure failures—including damage to wastewater-treatment plants, confined animal feeding operations (CAFOs), retaining dams, and coal-ash storage sites—led to some of the longest boil water advisories on record (more than 2 months). Direct discharges of wastewater to groundwater at onsite wastewater treatment systems occurred as a result of raised groundwater levels in the Coastal Plain (Humphrey and others, 2021). High turbidity and post-storm debris poised multiple reaches for significant increases in biological oxygen demand and decreases in dissolved oxygen concentration, affecting aquatic ecosystem health. Impacting human health, more than 330,000 private wells were identified in flooded counties with 15 percent of those tested yielding positive for contamination with fecal coliform (North Carolina Department of Environmental Quality, 2019). Hurricane Florence was the first extensive test of RDGs (48 retrieved) following a hurricane, yielding actionable data for response teams as well as for parameterizing water-level models to account for compound flooding (Leijnse and others, 2021).

Hurricane Ian (2022)

After crossing Cuba and intensifying to a Category 5 storm, Hurricane Ian made its first CONUS landfall in Florida on September 28, 2022, with 155 mph winds as a Category 4 hurricane. The resulting storm surge on the east coast of Florida was profound (12–15 ft estimated at Daytona Beach), yet winds pushed coastal waters offshore (reverse storm surge) on the west coast of Florida near Tampa (Clearwater; https://stn.wim.usgs.gov/FEV/#2022Ian). Very disparate responses, coupled with more than 20 in. of rain, caused different water-quality responses along with major flooding across the Florida peninsula. Hurricane Ian crossed east across Florida in less than 48 hours then turned northward and re-strengthened to a Category 1 hurricane before its final landfall on the South Carolina coast near Georgetown on September 30, 2022. Based on Hurricane Ian's initial classification as a Category 5 storm (although it was downgraded to a Category 4 at landfall), and its similar projected trajectory to Hurricane Charley (2004), RDGs were placed as far north as Washington D.C., but water-level effects appeared to be limited to the Florida peninsula and Atlantic Coast as far north as South Carolina. In Florida, all rivers across Hurricane Ian's path reached flood stages, with eight reaches near Tampa showing record flood levels. Scientific publications are still forthcoming but significant water contamination was expected due to power failures and over-capacity flows, and thus, extensive boil-water advisories were put rapidly into effect across the State. To date, contaminant point sources have been identified, included raw sewage overflows, that exceed 73 million gallons (Mgal) (Orlando to Indian River Lagoon), 13 Mgal of wastewater into the Manatee River (Bradenton), and 2,300 gallons of sodium hypochlorite into public supply (Polk County). Dispersed sources of gasoline (storage, personal boats, and so on) were expected to further contaminate drinking water. As of July 2023, Manatee County water wells were still suspected of contamination from infiltration of bacteria-laden waters. To date (2023), Hurricane Ian remains one of only a few near-Category 5 or Category 5 hurricanes to hit U.S. shores, and recovery continues.

Emergent Opportunities to Address and Prioritize Gaps in Measurements and Models for Hurricanes in Coastal Watersheds

"Every storm is its own beast." Scott McBride, USGS Caribbean-Florida Water Science Center, April 26, 2022

Our review of literature, databases of available measurements, published modeling approaches, and interviews with modeling and topical experts in the southeastern USGS WSCs, across the WMA, and the Coastal and Marine Hazards Resources Program (https://www.usgs.gov/natural-hazards/coastal-marine-hazards-and-resources) leads to a summary of knowledge gaps and prioritization of opportunities for improved predictions of water-quality impacts. This section has three components:

1. Coordinated discussions with other USGS programmatic needs.
2. Direct feedback from USGS Water Science Centers on lessons learned from past hurricanes.
3. Model opportunities and data needs.

We conclude that water-quality prediction for risk reduction to water availability and use is both necessary and achievable within USGS programmatic boundaries. Our conclusion identifies the key components of a strategic plan to prioritize and improve water-quality assessment from impacts of hurricanes on coastal watersheds of the southeastern United States.

Coordinated Discussions with Other USGS Programmatic Needs

Annual reporting at the National Hurricane Conference (previously known as Interagency Coordination Conference on Hurricanes [ICCOH]) is a USGS requirement, and associated USGS townhall discussions in recent years have illustrated the lack of any agency pursuing water-quality metrics along with water level, oceanic data, and atmospheric information. Within the USGS, a Hurricane Coordination workgroup has monthly workshops for updates from USGS and associated Federal agency program leaders and presentations on advances in USGS products being used or considered for the FEV framework. Monitoring advances include automated HWM generation using smartphone technology and improved conductivity-temperature-depth (CTD) sensor technology and deployment approaches. Limited model discussion is presented for either water levels or water quality, as the emphasis has been primarily on monitoring and response.

An emergent proposal from discussion in the Hurricane Coordination workshops is one advanced by the USGS Coastal Storm Team leads (Athena Clark and Bryce McClenney) to broaden the national network of measurements and report in the FEV for immediate access. The national CTD data network proposed by the Coastal Storm Team (https://www.usgs.gov/special-topics/hurricanes) is a significant and more representative advance from historical USGS gages, which currently provide essential long-term records for predictive modeling. Although the existing USGS gages provide the long-term historical data necessary for determining baseline conditions and detecting changes, they are generally part of monitoring networks designed to provide site-specific data needed by local policymakers and resource managers. Thus, the proposed national CTD network would enhance the existing USGS network of historical gages with more than 250 additional gages that have higher temporal resolution and broader geographic coverage needed to parameterize regional-scale predictive models. This national network would be added to the USGS Groundwater and Streamflow Program of the Federal Priority Streamgage Network, which serves as a backbone of the greater National Streamgage Network to meet ongoing Federal priorities for streamgaging data. Sites would be selected at coastal communities, to augment the National Ocean Service Tide gages. Sites installed along bays and estuaries will include specific conductance sensors, to monitor the trends and impacts of coastal storm surge on salinity.

Direct Feedback from USGS Water Science Centers on Lessons Learned from Past Hurricanes

On May 24, 2022, a USGS workshop was held to hear feedback and suggestions from WSC scientists who have experience in monitoring or modeling hurricane impacts on water quality and associated stakeholder concerns (for example, contamination or endangered species) (table 7). Although water-quality responses have not been a focus of post-hurricane assessments, ideas were explored for predictive modeling based on water quality for impacts on ecology, hydrology, and water uses.

With respect to ecological impacts of hurricane alterations of water flows, **Jamie Barichivich** (Wetland and Aquatic Research Center [WARC]) illustrated amphibian population responses in regional wetland complexes to the many storms (357 over 22 years) that have hit Florida and South Carolina. Pointing out that there can be little recovery time between storms, Jamie Barichivich highlighted that relatively small storms (for example, Hurricane Debbie in 2012) can have bigger effects than large storms (for example, Hurricane Michael in 2018) due to location and antecedent conditions. He also demonstrated a limited role of water salinity in mapping population storm responses (Walls and others, 2013), showing instead that hydrologic parameters that influence fish populations (namely habitat connectivity and dissolved oxygen) can exert a larger influence on amphibians through predation by carnivorous fish.

Scott Mize (Lower Mississippi Gulf WSC [LMGWSC]) also suggested there is limited recovery of water-quality conditions between storms in Florida and Louisiana, and there is "limited data" available to assess water-quality impacts and recovery trajectories, especially in a varied landscape of impounded and

Table 7. Presentations at Hurricane Water Science workshop, May 24, 2022.

Session	Speaker	USGS Science Center	Title
Water Quality and Ecological Impacts	Jamie Barichivich	Wetland and Aquatic Research Center	Threats to southeastern biota from coastal storms: How do we better monitor, predict, and mitigate?
Water Quality and Ecological Impacts	Scott Mize	Lower Mississippi Gulf	Hurricane storm event impacts on water quality and ecology in northern Gulf of Mexico
Water Quality and Ecological Impacts	Celeste Journey	South Atlantic	Hurricane water-quality impacts across Georgia, South Carolina, and North Carolina: Perspectives from a recently retired USGS water-quality specialist
Storm Monitoring	Corey Whittaker	Caribbean-Florida	Storm surge water quality data collection and monitoring of canals in southeast Miami-Dade County
Storm Monitoring	Scott McBride	Caribbean-Florida	Post-hurricane samples—Hurdles and roadblocks
Storm Monitoring	Bryce McClenney	South Atlantic	Rapid deployment conductance sensors for identifying saltwater intrusion during coastal storm events
Integrated Use	Athena Clark[1]	South Atlantic	How far did storm tide go up a river system?
Integrated Use	Sam Rendon	Oklahoma-Texas	An overview of the Texas Integrated Flooding Framework (TIFF)
Integrated Use	Kirk Rodgers	Lower Mississippi Gulf	Baseline flow, gage analysis, and on-line tool development supporting bay and estuary restoration in Gulf of Mexico States

[1]Presented by Bryce McClenney.

non-impounded environments. Considering other water-quality concerns (harmful algal blooms), storms may actually impede algal growth by removing stratification and enhancing turbidity. Robust data networks for conductivity (for example, Grand Pass near Mississippi Sound) and improved use of isotopes to source water inputs (Mississippi versus local Lake Ponchartrain sources) were identified as necessary monitoring advances.

Celeste Journey (Emeritus, South Atlantic WSC [SAWSC]) identified some potential improvements to expand beyond water-level recording and leverage hydrologic monitoring data to inform impact assessments. Dissolved oxygen is a key component of the fishery and tourist industry, and hurricanes generally lead to reduced dissolved oxygen concentration through biological oxygen demand and nitrogen loading, as well as high flushing of nutrients that prevent aquatic transformations (for example, denitrification). With examples from Hurricanes Fran, Floyd, and Irene, Celeste Journey suggested development of a hurricane monitoring system for water quality to address the impacts of concern to stakeholders, including microbial contamination risk of well waters. To develop actionable monitoring, a targeted assessment is needed to determine which sites (currently and potentially) provide the most information for specific human uses (agriculture, fisheries, public supplies, industry, or ecosystems).

Corey Whittaker (Caribbean-Florida WSC [CFWSC]) described risks affecting the Biscayne aquifer. In Miami-Dade County, canals that allow salty ocean water to move into freshwater regions inland are regulated by salinity control structures that restrict tidally driven inland migration of ocean water. During storms, the salinity control structures are typically opened to allow the canals to flow freely to the ocean to minimize the risk of inland flooding during high rainfall events. Thus, during hurricanes, storm surge and wind can readily drive ocean water inland through the canals and the salt water can then infiltrate from the canals to the underlying Biscayne aquifer, which is the primary source of public supply in southeast Florida. The USGS currently deploys CTD sensors (for example, Van Essen CTD Divers) in housings attached to bridge supports to monitor "return to normal" conditions in the canals after storms. These CTD data from the canals, as well as continuous monitoring of groundwater levels and conductivity are needed for models that predict how storms impact salt-water concentrations in the Biscayne aquifer.

Scott McBride (CFWSC) identified multiple problems with post-hurricane water-quality sampling. These include USGS protocols that cannot be met under urgent conditions, partnerships that are not optimized for data sharing, and most importantly, logistics whereby agencies need to cooperate rather than compete for community needs, gear, and personnel support. Using examples from the hurricane-dense 2004 USGS National Water-Quality Assessment Project (NAWQA) sampling effort (Hurricanes Charley, Jean, and Ivan), Scott McBride identified the uniqueness of each storm, and in particular the issue of landscape vulnerabilities (factors of risk for water supply and demand) in making predictions. A resonant question was the need to clarify the role of the USGS in these settings, given the active involvement already of many local and Federal regulatory agencies. Scott McBride also described some of the logistical hurdles inherent in deploying personnel to monitoring sites post-storm. These hurdles include post-storm safety issues (downed power lines, flooded conditions, debris-blocked roadways, telecommunications outages, and so on). The availability of personnel trained in data collection might be limited because personnel stationed in the impacted area also might be subject to storm impacts on their personal property and family, whereas lodging for personnel coming from outside of the storm-affected area might be limited because of a combination of storm damage to hotels and the demand for lodging for other storm responders (for example, search and rescue and utility workers restoring power and telecommunications). Scott McBride also noted that, although USGS WSCs are uniquely well-suited to engage in post-storm data collection (properly trained personnel, necessary equipment, knowledge of local areas and monitoring networks, existing relations with local and State agencies, and so on), the funding model under which WSCs operate does not typically provide for post-storm data collection unless an existing agreement is in place for such work prior to the storm event. Such agreements are uncommon because it is not feasible for cooperating agencies to commit funding to a data collection effort for an event that has not yet occurred, may not occur, and that if it does occur will have uncertain impacts and an uncertain geographic scope.

Bryce McClenney (SAWSC) described the need to enhance the measurement capability of RDGs to include specific conductance sensors as well as water level. Saltwater intrusion and wind driven vectors are important to disentangle sources of flooding. When specific conductance and water height peak at the same time, storm surge is occurring and can be quantified alongside floodplain contributions and traditional channel discharge. These differences are not just important for modeling water-quality impacts but also have implications for FEMA responses. Some improved CTD sensors with data collection and telemetry include the in-situ AquaTroll to monitor salt wedges along channel bottoms and provide similar but harmonized data with more common USGS-deployed CTD sensors.

Athena Clark (SAWSC) clarified the distinct need for long-term specific conductance data to identify pulses and understand their drivers. Knowing how far upstream a storm surge travels can demonstrate hydrologic sensitivity of reaches, their likely sources of contamination, and their response to climatic or operational drivers. Tracking temperature at one site (Bay la Fourche, Louisiana) provided an example of initial rain causing a hydrograph peak (warm, landscape-derived river water), which was then followed by a storm tide coming in from the colder ocean. Together, salinity and temperature are essential components of modeling compound flooding, and today they can be maintained at low cost alongside water-level gages. Athena Clark identifies this as a missed opportunity for USGS.

Sam Rendon (Oklahoma-Texas WSC [OTWSC]) introduced the Texas Integrated Flooding Framework (TIFF, https://www.texasflood.org/tools-library/tiff/index.html), and its key need to improve modeling and implications of compound flooding, where many interacting sources affect water quantity and quality. Examples from Hanes County, Texas, showed clear evidence of river sources dominating Hurricane Harvey flooding, not storm surge, with a longer duration and spatially extensive flooding. The TIFF was created with a December 2020–2024 charter so that cooperators (Texas Water Development Board [TWDB], USGS, and USACE), stakeholders, modelers, and active observation networks can communicate, leverage, and develop data, models, and science with trusted relations, and also support $4 million of outreach activities. The primary lesson learned was that partners were not asking the right questions of compound flooding models and needed “component champions” to clarify challenges and opportunities for different data streams (for example, social, physical, and ecological) and different approaches (for example, mechanistic versus empirical models). In the end, USGS is the data-monitoring “component champion” for TIFF and allows the TWDB to visualize information for city managers in the most useful ways for planning and response. USGS’ role as an honest broker of data is an important feature to bridge stakeholder priorities.

Kirk Rodgers (LMGWSC) described the extensive, and yet incomplete, southeast network of NWIS sites for trend analysis in the northern Gulf of Mexico and Coastwide Reference Monitoring Sites (CRMS). Leveraging long-term data, evidence was shown of flow alterations from hurricane impacts and examples of water-quality impacts (specific conductance, temperature, and dissolved oxygen) of varying magnitude and extent. In the complicated operational environment of the northern Gulf of Mexico, location on one side or the other of a levee has fundamental effects on flow and water exchanges, and thus measurement location is key to model development. Kirk Rodgers suggests that a first assessment could include a HUC12 analysis of where more gages would benefit model improvement, not just for gage height and flows but also for key water-quality constituents, such as conductivity and temperature.

Model Opportunities and Data Needs

Quantitative approaches to prioritizing where to monitor and evaluate the effects of tropical cyclones on coastal basins could be performed based on existing conceptual models and datasets. Recently the USGS WMA conducted a quantitative assessment of 163 basins in 18 hydrologic regions across the continental United States to prioritize basins for the USGS Integrated Water Science Basins studies (https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-science-iws-basins) (Van Metre and others, 2020). A conceptual model of attributes to consider when assessing aquatic environmental damage caused by hurricanes is presented by Mallin and Corbett (2006). Factors leading to the relatively more severe effects include population of landfall location, floodplain type (urban, rural, wetland), floodplain use (industrial, combined animal feeding operations, wastewater treatment, traditional agriculture), and hurricane speed, trajectory, and rainfall attributes.

Although hurricane trajectory and rainfall attributes for any given location are difficult to predict a priori, excellent datasets exist for population, floodplain type, land use, and other factors. Thus, predictive models could be developed using basin-scale characterization of responses. For example, the EPA maintains a free, publicly available data library of watershed attribute data (Watershed Index Online [WSIO, https://www.epa.gov/wsio/wsio-indicator-data-library). These data are available at the HUC12 level, and include such information as percentage of land under urban or agricultural land uses in the riparian zone within the basin (from the 2019 National Land Cover Database), predicted coastal flooding from sea-level rise or percentage of land in Hurricane Storm Surge Zone for a given category (projections from NOAA’s Sea Level Rise Viewer), Toxic Release Inventory Site Count in HUC12 (from EPA Facility Registry Service geodatabase), and socioeconomic data such as percentage of low-income population in HUC12 (from U.S. Census American Community Survey, 2016–2020). A quantitative spatial analysis of selected data could be performed to prioritize basins for water-quality monitoring. Prior to detailed HUC12 characterization (2,942 watersheds), initial statistics from EPA consolidated watershed characteristics illustrate the very different vulnerabilities between watersheds that can be seen at HUC8 scale (241 watersheds). Coastal watershed characteristics vary strongly, with areas ranging from 200 square kilometer (km^2) (Lower Rio Grande, Texas) to 11,459 km^2 (Everglades, Florida), and with hydrologic connectivity of the watershed ranging from 15 (Reagan-Sanderson, Texas) to 100 percent (Lake Pontchartrain, Louisiana). Considering the relative distribution of land-use types that are contiguous with surface-water channels and waterbodies within each watershed illustrates how neighboring watersheds can be extremely different (fig. 10). For example, in the southeastern United States from the Carolinas to Louisiana, wetland acreage is a dominant land use along waterways. In contrast, the border of Texas (Buffalo-San Jacinto) waterways are dominated by urban/developed land uses and the remaining Texas coastal watersheds are dominated by agriculture. Other critical factors of risk to consider are National Pollutant Discharge Elimination System (NPDES) permits, which for 2019 totaled 4,549 permits for the Buffalo-San Jacinto watershed—42-fold higher than the median NPDES count of 108 per watershed. Additional factors of risk, such as infrastructure age and geomorphic conditions (low gradient slopes, poorly drained hydric soils, levee presence) are available but likely to be extremely site specific and thus require a finer spatial scale of analysis.

Rather than focus only on water-quality indicators, water demand is an additional factor of risk, especially for unaccounted water sources (for example, private or domestic wells). Differences among watersheds in water uses (agricultural, industrial, drinking water, ecosystem) are equally profound with orders of magnitude variability. An update to 2016 values is ongoing for watershed components likely significant in watersheds in the southeastern United States, such as canal density, ground water intake to public supply, toxics release inventory, and septic system count.

Toward predictive model development, integrated monitoring datasets that are representative of compound flooding dynamics both temporally and spatially are key datasets that USGS can contribute to stakeholder efforts to manage and interpret hurricane impacts. Water-quality data are necessary from a larger range of coastal watersheds than are currently available, and real-time gage availability is essential for response and assessing antecedent conditions, including CSI integration. In fiscal year 2020, the USGS Groundwater and Streamflow Information Program received Department of the Interior priorities funding to (1) test autonomous telemetry technologies and capacity, which can provide real-time water-level and meteorological data during a coastal storm event, and to (2) develop a transition plan for the delivery of real-time tide and wave data. The USGS formed a working group to fulfill this priority and tested the delivery of real-time storm tide data using low-power, low-cost data transmission technology with successful demonstration during 2022 Hurricane Ian. The Storm Tide Monitoring team (Athena Clark and Bryce McClenney) plans to addresses this data gap and the unique role of the USGS among interagency hurricane coordination efforts. Leadership by the SAWSC but with local decisions and maintenance by each CONUS coastal county (n=250) will assure optimal rates of data collection and quality of sensor data for sharing, maintenance, and applicability to models and response teams.

The CSI tool is a useful forensic approach to observe past storm effects on salinity and predict future impacts (see appendix 3). Feher and others (2023) recently used CSI records since 2000 for four sites in coastal Louisiana to examine natural and operational effects on water quality of Barataria Bay. They found that effects of hurricanes were highly variable, with some storms leading to elevated salinities throughout the entire estuary (for example, Hurricanes Katrina and Rita in 2005), whereas other storms led to elevated salinities for some but not all stations (for example, Hurricanes Gustav and Ike in 2008 or Hurricane Isaac in 2012). Despite its statistical utility, CSI representativeness shows alarming gaps in data availability for the southeastern United States and for the larger Atlantic and Gulf of Mexico region (fig. 11). Across the entire eastern and Gulf Coasts, there are currently 130 stations registered in the CSI. Of those stations, 20 stations no longer submit current or new data, either due to instrument error, site retirement, or transmission error (9 stations collect data currently but these data are not successfully transmitting to CSI). From North Carolina through the Gulf of Mexico, only 93 stations have optimal 14+ years of salinity data in the CSI. Of the 128 HUC8 watersheds in these southeastern States, 111 have no real-time gages with long (greater than 10 years) records of data to support interpretation of water-quality anomalies. Of the 17 populated HUC8s, only 2 in southern Florida have the majority of datasets active. Of the 176 HUC8 watersheds of the CSI current domain, 152 lack real-time gages. Establishment of long-term records and national scale networks, including on the Pacific Coast (total = 241 HUC8s), is an initial modeling contribution that can be met with direct USGS investment and also by partnering with agencies that also monitor water quality (critical parameters at https://github.com/USGS-R/CSI).

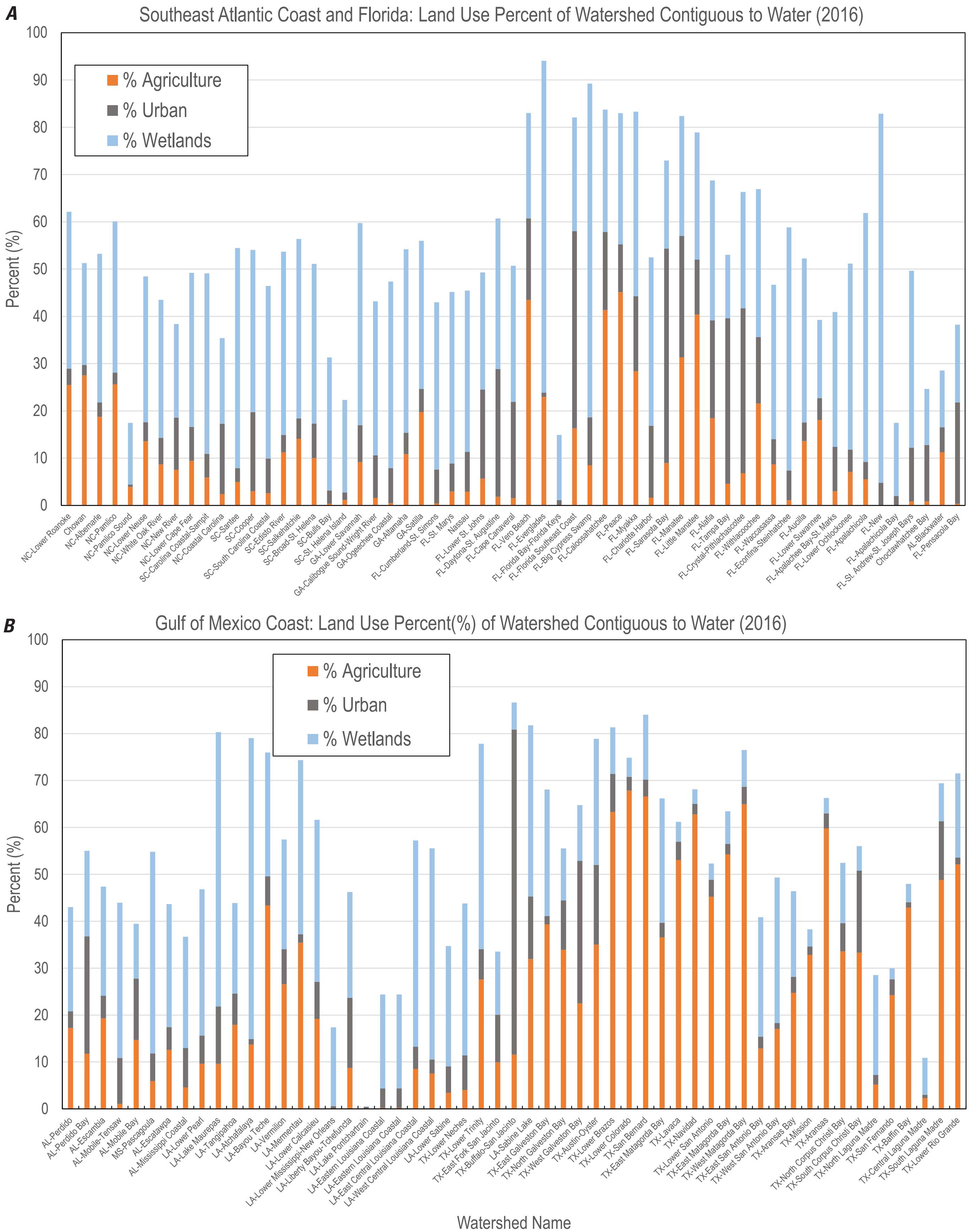
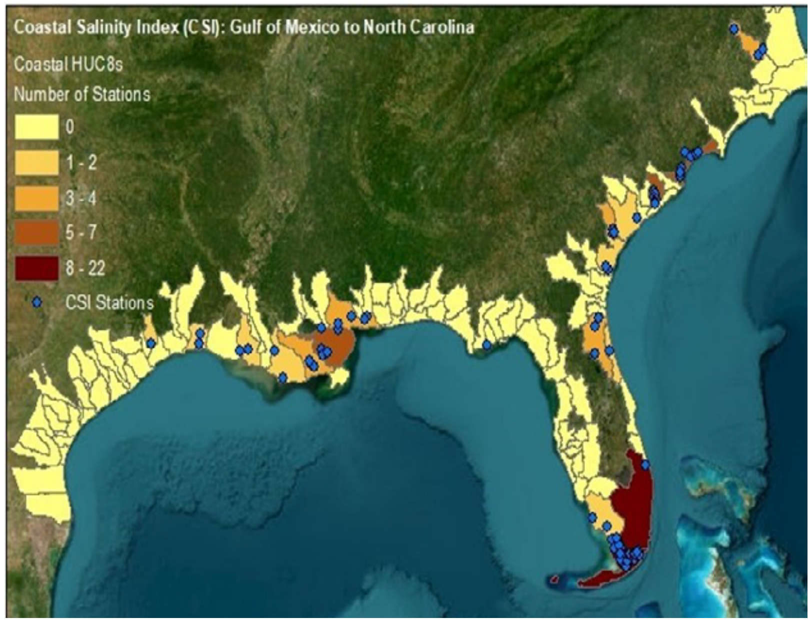
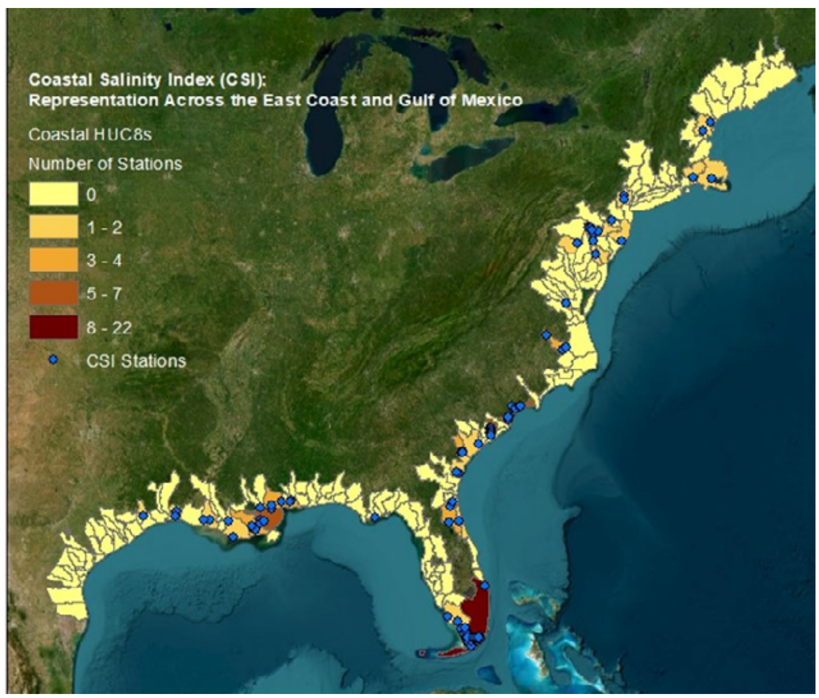


Figure 10. Graphs showing watershed characteristics of southeastern United States. Coastal HUC8s (n=115) in proximity to NHDv2 waterways (2016) (data from the EPA Watershed Index Online, WSIO, https://www.epa.gov/wsio/wsio-indicator-data-library). *A*, Atlantic States from North Carolina to Florida. *B*, Gulf of Mexico States from Alabama to Texas.

A



B



C

State	Number of Stations (Tier 1)	Number of Proposed Stations (Tier 2)	Nautical Coastline (miles)	Tidal Coastline (miles)	Stations per 100 miles of nautical coastline (Tier 1)	Stations per 1,000 miles of tidal coastline (Tier 1)
North Carolina	3	1	301	3,375	1.0	0.9
South Carolina	17	2	187	2,876	9.1	5.9
Georgia	4	0	100	2,344	4.0	1.7
Florida	48	3	1,350	8,436	3.6	5.7
Alabama	0	0	53	607	0	0
Mississippi	4	1	44	359	9.1	11.1
Louisiana	13	7	397	7,721	3.3	1.7
Texas	1	0	367	3,359	0.3	0.3

Figure 11. Real-time, long-term (greater than 10-year) data representativeness in the Coastal Salinity Index (CSI) tool illustrating locations from the Gulf of Mexico to North Carolina (*A*), expanded perspective including along the East Coast (*B*), and calculations illustrating the coverage of the coastline and tidal coastline by CSI gages (*C*).

Conclusions and Directions for Improved Understanding of Hurricane Impacts

Water-quality impacts of hurricanes are a substantial hazard that is not currently monitored by any Federal agency, nor currently predicted with a comprehensive modeling effort. Stakeholders and scientists at local and national scales have illustrated a need for understanding the risks to water quality of extreme coastal storm events. This assessment of USGS capabilities and opportunities focused only on the southeastern coastal States, but hurricanes have large impacts on water quality in northeastern and western coastal States as well. Based on consideration of the state of the science, our gap analysis, and prioritization of data and science needs, the following potential needs and opportunities are identified to improve future forecasting of hurricane impacts on water quality, which in turn impacts water availability.

1. Spatial-temporal assessment of factors of risk within prioritized waterways. The EPA Watershed Index Online (WSIO; https://www.epa.gov/wsio) allows exploration of spatial and decadal variability among coastal watersheds, but in itself is insufficient for predictive modeling of tipping points and infrastructure resilience.

2. A basic, dispersed, and NWIS maintained network of real-time CTD gages, with equitable representation among coastal HUC8s (*n*=241 in CONUS), to monitor in real-time the varied water-quality effects of a single hurricane event and sequential hurricane events.

3. A topical focus beyond the southeastern United States due to the larger costs and impacts occurring in ill-prepared regions with limited recent history of hurricane impacts (including the northeastern and western coastal States).

4. A model focus on reducing uncertainty in the contributing elements of compound flooding, especially in low gradient watersheds with limited drainage networks.

5. Attention to potential groundwater impacts and contamination and recovery rates, rather than surface-water levels alone.

We considered two specific potential future directions that would help advance these goals.

1. A spatial risk framework for storm impacts working from landscape and infrastructure characteristics—natural and managed—that influence susceptibility to contaminant sources and compound flooding. A watershed (or subwatershed) assessment of risk factors can be communicated as a risk score (for example, low, moderate, or high) for hurricane impacts. Leveraging existing data sources (for example, EPA WSIO) and current CONUS-scale HUC12 basin analyses by recent USGS studies (Lisa Lucas, USGS, written commun., 2023), a hurricane risk framework could include characteristics such as:

   A. Population.

   B. Population density.

   C. Infrastructure density and age (such as dams, reservoirs, septic systems, sewage treatment plants, industrial facilities, agricultural operations, and so on).

   D. Sources and characteristics of public-water supply (for example, groundwater, surface water, or mixed or variable sources, geochemical characteristics of water supply). If groundwater, additional characteristics might include shallow groundwater, deep groundwater, depth to groundwater resource, and groundwater age.

   E. Sources and characteristics of domestic water supply. If groundwater wells, consider similar features as above along with density of domestic wells (for example, Johnson and others, 2019).

   F. Climate and landscape characteristics (for example, slope, elevation, contiguous runoff pathways, land use, vegetation, impervious cover, floodplain characteristics, landslide potential), near-shore or offshore features (reefs, estuary biota, and so on), ecological features or sensitivities (for example, endangered species and their habitat needs).

   G. Hurricane characteristics might include:

      I. Category (windspeed throughout storm duration),

      II. Trajectory (direction throughout storm duration),

      III. Rainfall data (throughout storm duration), and

      IV. Storm-surge data (magnitude and timing with astronomical tides).

   Once landscape characteristics are defined, a forensic approach could be initially applied to historical storms to compare the modeled framework with actual recorded water-quality impacts to determine sensitivities of the model and data density. Basin-by-basin assessment can be used to refine the approach and better predict historical storm impacts as functions of watershed structure (natural and managed), antecedent conditions, and storm characterization. Further, the direction of analysis could be reversed, with an assessment of vulnerable watersheds, as seen by past responses, such as long-recovery times of drinking water through public supply. Resultant data-driven, refined models of hurricane features and localized impacts and recovery could then be applied across areas of interest or impact for future storms.

2. A paired subwatershed (HUC8 or HUC12) comparative approach in a USGS focal Next Generation Water Observing System (NGWOS; https://www.usgs.gov/mission-areas/water-resources/science/next-generation-water-observing-system-ngwos) basin at risk for hurricane

impacts (one potential example pair in the newly [2023] selected NGWOS Trinity-San Jacinto Basin in Texas is the industrially dominated Buffalo-San Jacinto watershed and the wetland dominated Lower Trinity watershed). Equivalent monitoring infrastructure for paired surface water and groundwater quality in each basin would allow direct comparison of their responses to physical storm forcings. Differences could support an initial framing of model needs to assess compound flooding and optimal data needs to predict hurricane impacts to water quality and their timelines of recovery.

These USGS recommendations are best addressed with USGS WSC topical experts connected with local and regional stakeholder needs, as they are best prepared to perform the following action items in targeted locations:

1. Mine existing databases for water-quality information that may represent historical storm influence periods.
2. Combine maps of wind and rain extents with georeferenced water-quality data (both continuous and discrete).
3. Build a coastal and inland water-quality network to collect baseline and storm changes.
4. Identify vulnerable infrastructure, ecological systems, and source waters for industry and public supply.
5. Use hurricane characterization products and visualizations (for example, NASA Scientific Visualization Studio 2022 Hurricane Season; https://svs.gsfc.nasa.gov/5097), such as previous eyewall track, wind, surge, and flood data to parameterize past events.
6. Use spatial and historical analysis of watershed characterization along with local USGS and stakeholder input to prioritize and optimize monitoring locations.
7. Identify critical points of interest in the hydrologic system (for example, water-control structures, intakes, storage, and natural hydrologic components), which will provide maximum information to evaluate risks to the vulnerable areas.
8. Instrument as many of the priority locations as possible. To support remotely sensed assessments, basic constituents that are easily monitored would be primary (specific conductance, temperature, and depth), and consider high-demand data instruments (dissolved oxygen, chlorophyll a, turbidity, nitrate, fDOM [fluorescent dissolved organic matter]) for select locations and periodic validation of water-quality proxy relations.
9. Locate other points of interest with existing streamgages or historical data where the network could be expanded immediately prior to hurricane impacts.

All the actions and directions described above will expand datasets and approaches available to model water-quality impacts from storms and provide near-real-time data to help protect valuable water needs (adjusting industrial and municipal source water intakes or treatments, extra protective measures for sensitive ecological systems). The patchiness and unpredictability of storm effects limits potential benefits of a single station but the network allows real-time tracking of disparate effects, such as the opposing effects of winds and rain observed on the eastern and western Florida coasts in response to Hurricane Ian (2022). Storm paths remain difficult to predict, although predictions have greatly improved (https://www.nhc.noaa.gov/verification/verify5.shtml). We suggest that the heterogeneity of physical geography across the southeastern United States can be considered a testbed of conditions for model development. The proposed Coastal Storm Team National Network Real-Time Coastal Gage (deployment and maintenance of real-time conductivity, temperature, and depth sensors in 250 coastal counties) is the logical, locally relevant, and gap-filling next step for improving predictability of water-quality and water-availability impacts of hurricanes in the southeastern United States. As coastal storms continue to intensify and travel long distances through interior States, expanding our knowledge of hurricane impacts will include harmonizing our understanding from coastal settings toward broader flood mapping and compound flood modeling efforts.

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Appendixes 1–5

Appendix 1. Summary of Literature Review by Water-Quality Constituents

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
Temperature					
Bonvillain and others, 2011	River	Ecosystem	Gustav	2008	Statistical
Cai and others, 2013	Rive	Ecosystem	Gustav, Ike	2008	Geochemical mixing
Hampel and others, 2019	Lake and estuary	Ecosystem	Irma	2017	Statistical
Lapointe and others, 2012	Estuary	Ecosystem	Various	Various	Statistical
Phlips and others, 2020	Estuary and lake	Ecosystem	Various	Various	Statistical
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Walker and others, 2021	Estuary	Ecosystem	Harvey	2017	Statistical
pH					
Bales and others, 2000	River and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bonvillain and others, 2011	River	Ecosystem	Gustav	2008	Statistical
Cai and others, 2013	River	Ecosystem	Gustav, Ike	2008	Geochemical mixing
Hampel and others, 2019	Lake and estuary	Ecosystem	Irma	2017	Statistical
Humphrey and others, 2019	River	Ecosystem	Matthew	2016	Statistical
Landsman and others, 2019	Municipal supply	Municipal supply	Harvey	2017	Statistical
Presley and others, 2006	Various	Various	Katrina	2005	None
Roca and others, 2019	Coastal beaches	Ecosystem	Irma	2017	Statistical
Shiller and others, 2012	River	Ecosystem	Katrina	2005	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Wachnicka and others, 2020	Coastal canals and coastal bay	Ecosystem	Irma	2017	Statistical
Walker and others, 2021	Estuary	Ecosystem	Harvey	2017	Statistical
Dissolved oxygen					
Bales and Childress, 1996	River	Ecosystem	Fran	1996	None
Bales and others, 2000	River and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bonvillain and others, 2011	River	Ecosystem	Gustav	2008	Statistical
Burkholder and others, 2004	Estuary	Ecosystem	Various	Various	None
Hagy and others, 2006	Estuary	Ecosystem	Ivan	2004	Geochemical mixing
Hampel and others, 2019	Lake and estuary	Ecosystem	Irma	2017	Statistical
Humphrey and others, 2019	River	Ecosystem	Matthew	2016	Statistical
LaMontagne and others, 2022	Estuary	Ecosystem	Harvey	2017	Statistical/geochemical mixing
Lapointe and others, 2012	Estuary	Ecosystem	Various	Various	Statistical
Mallin and Corbett, 2006	River, bay, and estuary	Ecosystem	Various	Various	None
Mallin and others, 1999	River and estuary	Ecosystem	Bertha, Fran	1996	None
Mallin and others, 2002	River and estuary	Ecosystem	Various	Various	None
Presley and others, 2006	Various	Various	Katrina	2005	None
Rybczyk and others, 1995	Wetland	Ecosystem	Andrew	1992	None
Schuck-Kolben and Cherry, 1995	River	Ecosystem	Hugo	1989	None

Appendix 1—Continued

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Tomasko and others, 2006	River and estuary	Ecosystem	Charley, Frances, Jean	2004	None
Wachnicka and others, 2020	Coastal canals and coastal bay	Ecosystem	Irma	2017	Statistical
Walker and others, 2021	Estuary	Ecosystem	Harvey	2017	Statistical
		Suspended sediment, turbidity			
Cai and others, 2013	River	Ecosystem	Gustav, Ike	2008	Geochemical mixing
Chen and others, 2009	Estuary	Ecosystem	Frances	2004	Statistical
D’Sa and others, 2019	Estuary	Ecosystem	Michael	2018	Process-based modeling with remote sensing
Gellis, 1993	Reservoir	Municipal supply	Hugo	1989	None
Landsman and others, 2019	Municipal supply	Municipal supply	Harvey	2017	Statistical
Lapointe and others, 2012	Estuary	Ecosystem	Various	Various	Statistical
Roca and others, 2019	Coastal beaches	Ecosystem	Irma	2017	Statistical
Schafer and others, 2020	River and estuary	Ecosystem	Irma	2017	Statistical
Shiller and others, 2012	River	Ecosystem	Katrina	2005	Statistical
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Sobel and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Steward and others, 2006	Estuary	Ecosystem	Charley, Frances, Ivan, Jeanne	2004	None
Tomasko and others, 2006	River and estuary	Ecosystem	Charley, Frances, Jean	2004	None
Wachnicka and others, 2020	Coastal canals and coastal bay	Ecosystem	Irma	2017	Statistical
Zang and others, 2018	Ocean	Ecosystem	Gustav	2008	Process-based
Ziervogel and others, 2016	Estuary	Ecosystem	Isaac	2012	Statistical
		Salinity, chloride, total dissolved solids, specific conductance			
Anderson, 2002	Groundwater	Water supply for human use	Emily	1993	Process-based
Anderson and Lauer, 2008	Groundwater	Water supply for human use	Emily	1993	Process-based
Bales and others, 2000	River and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bonvillain and others, 2011	River	Ecosystem	Gustav	2008	Statistical
Brown and others, 2014	Estuary	Ecosystem	Irene	2011	Process-based
Burkholder and others, 2004	Estuary	Ecosystem	Various	Various	None
Cai and others, 2013	River	Ecosystem	Gustav, Ike	2008	Geochemical mixing
Carlson and others, 2007	Groundwater	Water supply for human use	Katrina, Rita	2005	Statistical and process-based
Dix and others, 2008	River	Ecosystem	Charley, Frances, Jeanne, Ivan	2004	None
D’Sa and others, 2019	Estuary	Ecosystem	Michael	2018	Process-based modeling with remote sensing
Du and Park, 2019	Estuary	Ecosystem	Harvey	2017	Process-based
Du and others, 2019	Estuary	Ecosystem	Harvey	2017	None
Edmiston and others, 2008	Estuary	Ecosystem	Various	Various	None

Appendix 1—Continued

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
Gardner and others, 1991	Groundwater	Ecosystem	Hugo	1989	None
Hagy and others 2006	Estuary	Ecosystem	Ivan	2004	Geochemical mixing
Hampel and others, 2019	Lake and estuary	Ecosystem	Irma	2017	Statistical
Huang and others, 2014	Estuary	Ecosystem	Dennis	2005	Process-based
Humphrey and others, 2019	River	Ecosystem	Matthew	2016	Statistical
Kiflai and others, 2020	Groundwater	Ecosystem	Irma	2017	None
Krohn and others, 2020	Various	Various	Various	Various	Process-based
LaMontagne and others 2022	Estuary	Ecosystem	Harvey	2017	Statistical/geochemical mixing
Landsman and others, 2019	Municipal supply	Municipal supply	Harvey	2017	Statistical
Langevin and others, 2005	Coastal wetland	Ecosystem	Irene	1999	Processed-based
Lapointe and others, 2012	Estuary	Ecosystem	Various	Various	Statistical
Mahmoodzadeh and Karamouz, 2019	Groundwater	Various	Various	Various	Processed-based
Paerl and others, 2018	Estuary	Ecosystem	Various	Various	Statistical
Paldor and Michael, 2021	Groundwater	Various	Various	Various	Process-based
Phlips and others, 2020	Estuary and lake	Ecosystem	Various	Various	Statistical
Presley and others, 2006	Various	Various	Katrina	2005	None
Roca and others, 2019	Coastal beaches	Ecosystem	Irma	2017	Statistical
Schafer and others, 2020	River and estuary	Ecosystem	Irma	2017	Statistical
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Smith and others, 2008	Estuary and groundwater	Groundwater	Tammy, Wilma	2005	Processed-based
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Song and others, 2022	Groundwater	Various	Various	Various	Process-based
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Steward and others, 2006	Estuary	Ecosystem	Charley, Frances, Ivan, Jeanne	2004	None
Steyer and others, 2007	Wetland	Ecosystem	Katrina, Rita	2005	None
Swain and others, 2015	Various	Various	Various	Various	Process-based
Tomaszewski and Lovelace, 2007	Groundwater	Private water supply wells	Katrina	2005	None
Van Biersel and others, 2007	Groundwater	Water supply for human use	Katrina, Rita	2005	Statistical
Walker and others, 2021	Estuary	Ecosystem	Harvey	2017	Statistical
Wilson and others, 2011	Groundwater	Ecosystem	Fay	2008	None
Xiao and others, 2019	Groundwater	Various	Jeanne	2004	Process-based
Xiao and Tang, 2019	Groundwater	Various	Jeanne	2004	Process-based
Zhang and others, 2009	Coastal water	Ecosystem	Katrina, Wilma	2005	None
Ziervogel and others, 2016	Estuary	Ecosystem	Isaac	2012	Statistical
Major ions					
Gardner and others, 1991	Groundwater	Ecosystem	Hugo	1989	None
Landsman and others, 2019	Municipal supply	Municipal supply	Harvey	2017	Statistical
Mapili and others, 2022	Groundwater	Private water supply wells	Various	Various	Statistical

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
McDowell and others, 1996	Groundwater	Ecosystem	Hugo	1989	Statistical
Schaefer and others, 2000	Rivers	Ecosystem	Hugo	1989	None
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Tomaszewski and Lovelace, 2007	Groundwater	Private water supply wells	Katrina	2005	None
Van Biersel and others, 2007	Groundwater	Water supply for human use	Katrina, Rita	2005	Statistical
		Nutrients			
Bales and Childress, 1996	River	Ecosystem	Fran	1996	None
Bales and others, 2000	River and Estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bales, 2003	River and Estuary	Ecosystem	Floyd	1999	None
Burkholder and others, 2004	Estuary	Ecosystem	Various	Various	None
Cai and others, 2013	River	Ecosystem	Gustav, Ike	2008	Geochemical mixing
Chen and others, 2019	River	Ecosystem	Harvey, Irma	2017	Statistical
Davis and others, 2018	Wetland	Ecosystem	Katrina, Wilma	2005	Statistical
Dix and others, 2008	River	Ecosystem	Charley, Frances, Jeanne, Ivan	2004	None
Gardner and others, 1991	Groundwater	Ecosystem	Hugo	1989	None
Hampel and others, 2019	Lake and estuary	Ecosystem	Irma	2017	Statistical
Hu and others, 2006	Coastal waters, river, groundwater	Ecosystem	Various	Various	None
Humphrey and others, 2019	River	Ecosystem	Matthew	2016	Statistical
LaMontagne and others, 2022	Estuary	Ecosystem	Harvey	2017	Statistical/geochemical mixing
Lapointe and others, 2012	Estuary	Ecosystem	Various	Various	Statistical
Mallin and Corbett, 2006	River, bay, estuary	Ecosystem	Various	Various	None
Mallin and others, 2002	River and estuary	Ecosystem	Various	Various	None
Mallin and others, 1999	River and estuary	Ecosystem	Bertha, Fran	1996	None
McDowell and others, 1996	Groundwater	Ecosystem	Hugo	1989	Statistical
Nesbit and Mitsch, 2018	Constructed wetland	Ecosystem	Irma	2017	Statistical
Neville and others, 2021	River	Ecosystem	Matthew	2016	Statistical
Novak and others, 2007	Wetland	Ecosystem	Various	Various	Statistical
Paerl and others, 2018	Estuary	Ecosystem	Various	Various	Statistical
Presley and others, 2006	Various	Various	Katrina	2005	None
Rybczyk and others, 1995	Wetland	Ecosystem	Andrew	1992	None
Schaefer and others, 2000	River	Ecosystem	Hugo	1989	None
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Wachnicka and others, 2020	Coastal canals and coastal bay	Ecosystem	Irma	2017	Statistical
Walker and others, 2021	Estuary	Ecosystem	Harvey	2017	Statistical
Wilson and others, 2011	Groundwater	Ecosystem	Fay	2008	None

Appendix 1—Continued

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
Zhang and others, 2009	Coastal water	Ecosystem	Katrina, Wilma	2005	None
Chlorophyll, harmful algal blooms, cyanobacteria					
Burkholder and others, 2004	Estuary	Ecosystem	Various	Various	None
Dix and others, 2008	River	Ecosystem	Charley, Frances, Jeanne, Ivan	2004	None
D'Sa and others, 2019	Estuary	Ecosystem	Michael	2018	Process-based modeling with remote sensing
Hagy and others, 2006	Estuary	Ecosystem	Ivan	2004	Geochemical mixing
Hampel and others, 2019	Lake and estuary	Ecosystem	Irma	2017	Statistical
Hernández and others, 2020	Coastal waters	Ecosystem	Irma, Maria	2017	Statistical
Hu and others, 2006	Coastal waters, rivers, groundwater	Ecosystem	Various	Various	None
Mallin and Corbett, 2006	River, bay, estuary	Ecosystem	Various	Various	None
Mallin and others, 2002	River and estuary	Ecosystem	Various	Various	None
Paerl and others, 2018	Estuary	Ecosystem	Various	Various	Statistical
Phlips and others, 2020	Estuary and lake	Ecosystem	Various	Various	Statistical
Schafer and others, 2020	River and estuary	Ecosystem	Irma	2017	Statistical
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Steward and others, 2006	Estuary	Ecosystem	Charley, Frances, Ivan, Jeanne	2004	None
Wachnicka and others, 2020	Coastal canals and coastal bay	Ecosystem	Irma	2017	Statistical
Walker and others, 2021	Estuary	Ecosystem	Harvey	2017	Statistical
Zhang and others, 2009	Coastal water	Ecosystem	Katrina, Wilma	2005	None
Ziervogel and others, 2016	Estuary	Ecosystem	Isaac	2012	Statistical
Organic matter					
Asmala and others, 2020	Estuary	Ecosystem	Various	Various	Statistical
Bales and others, 2000	River and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bales, 2003	River and estuary	Ecosystem	Floyd	1999	None
Brown and others, 2014	Estuary	Ecosystem	Irene	2011	Process-based
Cai and others, 2013	River	Ecosystem	Gustav, Ike	2008	Geochemical mixing
Chen and others, 2019	River	Ecosystem	Harvey, Irma	2017	Statistical
D'Sa and others, 2019	Estuary	Ecosystem	Michael	2018	Process-based modeling with remote sensing
Humphrey and others, 2019	River	Ecosystem	Matthew	2016	Statistical
Landsman and others, 2019	Municipal supply	Municipal supply	Harvey	2017	Statistical
Letourneau and Medeiros, 2019	River and estuary	Ecosystem	Matthew	2016	Statistical
Ortiz-Rosa and others, 2020	Coastal water	Ecosystem	Irma, Maria	2017	Statistical
Osburn and others, 2019	Estuary	Ecosystem	Matthew	2016	Statistical
Paerl and others, 2018	Estuary	Ecosystem	Various	Various	Statistical
Rudolph and others, 2020	Estuary	Ecosystem	Matthew	2016	Geospatial/statistical/geochemical mixing
Schafer and others, 2020	River and estuary	Ecosystem	Irma	2017	Statistical
Shiller and others, 2012	River	Ecosystem	Katrina	2005	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical

Appendix 1—Continued

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
Ziervogel and others, 2016	Estuary	Ecosystem	Isaac	2012	Statistical
		Microbes			
Bacosa and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Bales and others, 2000	Rivers and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bales, 2003	Rivers and estuary	Ecosystem	Floyd	1999	None
Demcheck and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Humphrey and others, 2019	River	Ecosystem	Matthew	2016	Statistical
Jiang and others, 2020	Various	Various	Irma, Maria	2017	Statistical
Keenum and others, 2021	Municipal supply source and tap water	Municipal supply	Maria	2017	Statistical
LaMontagne and others, 2022	Estuary	Ecosystem	Harvey	2017	Statistical/geochemical mixing
Landsman and others, 2019	Municipal supply	Municipal supply	Harvey	2017	Statistical
Lapointe and others, 2012	Estuary	Ecosystem	Various	Various	Statistical
Mallin and Corbett, 2006	River, bay, estuary	Ecosystem	Various	Various	None
Mallin and others, 2002	Rivers and estuary	Ecosystem	Various	Various	None
Mapili and others, 2022	Groundwater	Private water supply wells	Various	Various	Statistical
Pieper and others, 2021	Groundwater	Private water supply wells	Harvey	2017	Geospatial
Presley and others, 2006	Various	Various	Katrina	2005	None
Roca and others, 2019	Coastal beaches	Ecosystem	Irma	2017	Statistical
Schwab and others, 2007	Surface water and tap water	Municipal supply	Katrina	2005	None
Sevillano and others, 2021	Municipal supply	Municipal supply	Maria	2017	Statistical
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Tomaszewski and Lovelace, 2007	Groundwater	Private water supply wells	Katrina	2005	None
Van Biersel and others, 2007	Groundwater	Water supply for human use	Katrina, Rita	2005	Statistical
Yu and others, 2018	Various	Various	Harvey	2017	Statistical
Ziervogel and others, 2016	Estuary	Ecosystem	Isaac	2012	Statistical
		Pesticides, pharmaceuticals			
Bales and others, 2000	River and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bales, 2003	River and estuary	Ecosystem	Floyd	1999	None
Lin and others, 2020	Tap water	Tap water	Maria	2017	Statistical
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
		Fuel compounds			
Bacosa and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical
Bales and others, 2000	River and estuary	Ecosystem	Dennis, Floyd, Irene	1999	None
Bales, 2003	River and estuary	Ecosystem	Floyd	1999	None
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	Statistical
Steichen and others, 2020	Estuary	Ecosystem	Harvey	2017	Statistical

Appendix 1—Continued

References	Types of water body	Impact	Storm	Year of storm	Modeling approach
Trace elements					
Lin and others, 2020	Tap water	Tap water	Maria	2017	Statistical
Mapili and others, 2022	Groundwater	Private water supply wells	Various	Various	Statistical
Presley and others, 2006	Various	Various	Katrina	2005	None
Shiller and others, 2012	River	Ecosystem	Katrina	2005	Statistical
Skrobialowski and others, 2007	Lake and canals	Ecosystem	Katrina, Rita	2005	None
Smith and others, 2009	Lake and coastal water	Ecosystem	Katrina	2005	None

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Appendix 2. Flood Event Viewer (FEV) and Available Datasets

The U.S. Geological Survey (USGS) Flood Event Viewer (FEV; https://stn.wim.usgs.gov/FEV) (fig. 2.1) has evolved to be a go-to clearinghouse of USGS data, partner agency information, and crowd-sourced imagery, providing actionable data for event response through real-time data, even as they are reported provisionally. Key data layers include the following:

- Rapid deployment gages (RDGs)—Storm-deployed, provisional water levels at 15-minute increments.
- National Oceanic and Atmospheric Administration (NOAA) tides and currents stations—Coastal water levels and historical conditions.
- Barometric pressure sensors.
- Water level sensors—National Water Information System (NWIS) stations with active maintenance and long-term records.
- Wave height sensors—Used for total water-level impacts (see USGS Coastal Change Hazards Portal at https://www.usgs.gov/tools/coastal-change-hazards-portal).
- High-water mark (HWM) results (post-storm data)—Field-validated water elevations off channel.

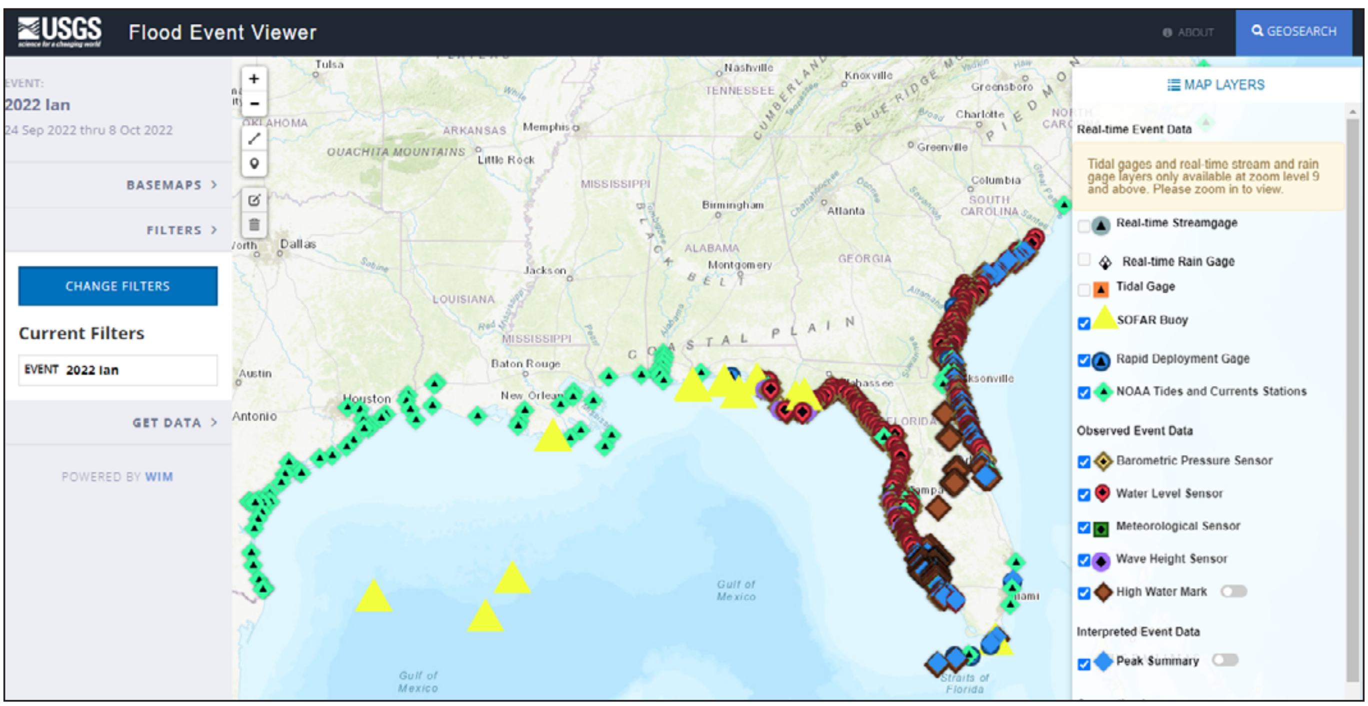


Figure 2.1. Screen capture of the U.S. Geological Survey Flood Event Viewer (FEV) showing an example with selected map layers for Hurricane Ian (2022).

Appendix 3. Coastal Salinity Index (CSI) Forensic Prediction of Hurricane Impacts

Potential uses for the Coastal Salinity Index (CSI) include predicting impacts based on previous observations. This was explored for Hurricane Ian (September 2022) when its track was determined to be similar to Hurricane Charley (August 2004). Water-quality impacts and, in particular, salinity shifts to fresher or more saline conditions were examined for coastal watersheds with CSI representation. A similar CSI analysis is reported for Barataria Bay by Feher and others (2023). Preliminary results (fig. 3.1) indicate that some significant CSI classification changes occurred because of Hurricane Charley (2004). These surface-water data indicate rates of change and recovery potential of wind effects versus storm surge versus freshwater runoff, allowing a blueprint for potential impacts of extreme hurricane events. Furthermore, an antecedent hurricane may set up the area (gage) for extended extreme conditions if the weather that follows is wetter than normal but not directly associated with the hurricane itself. Although CSI currently focuses only on salinity, and thus cannot detect water-quality changes when conditions are fresh and remain fresh, the statistical approach, and use of historical data may be applicable to longer term records of other continuous real-time data, such as dissolved oxygen or temperature.

Note that flooding and freshening after Hurricane Ian was observed for the same 2-month window as Hurricane Charley, suggesting past events can inform future predictions of impact duration (fig. 3.1).

A

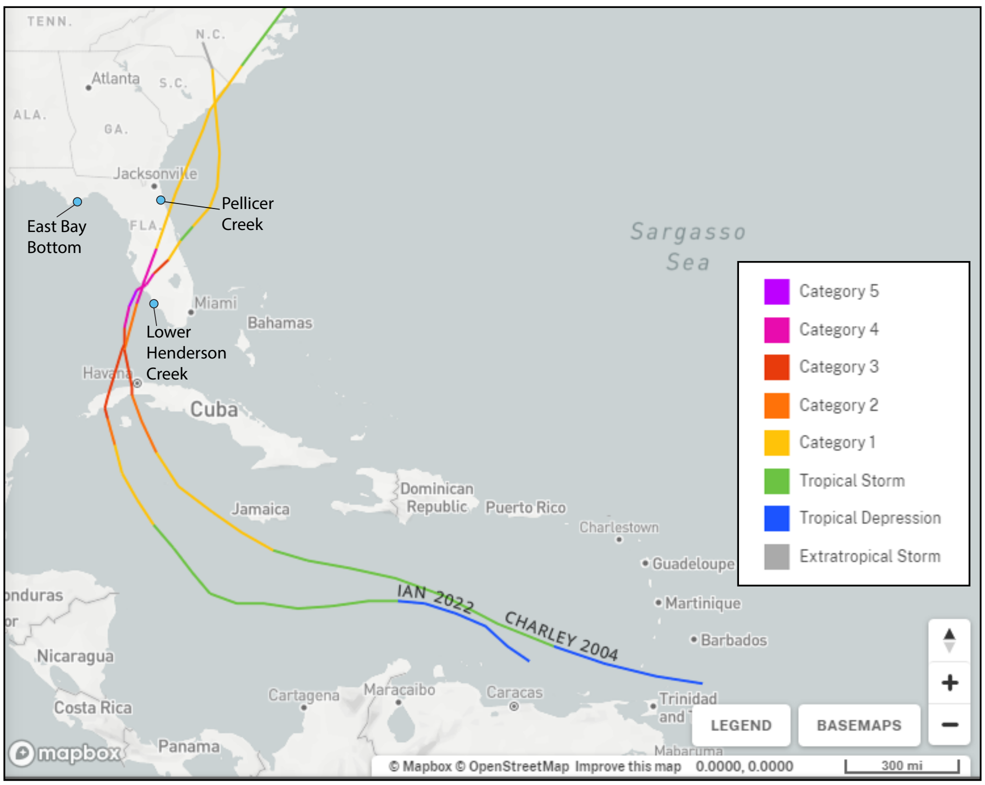
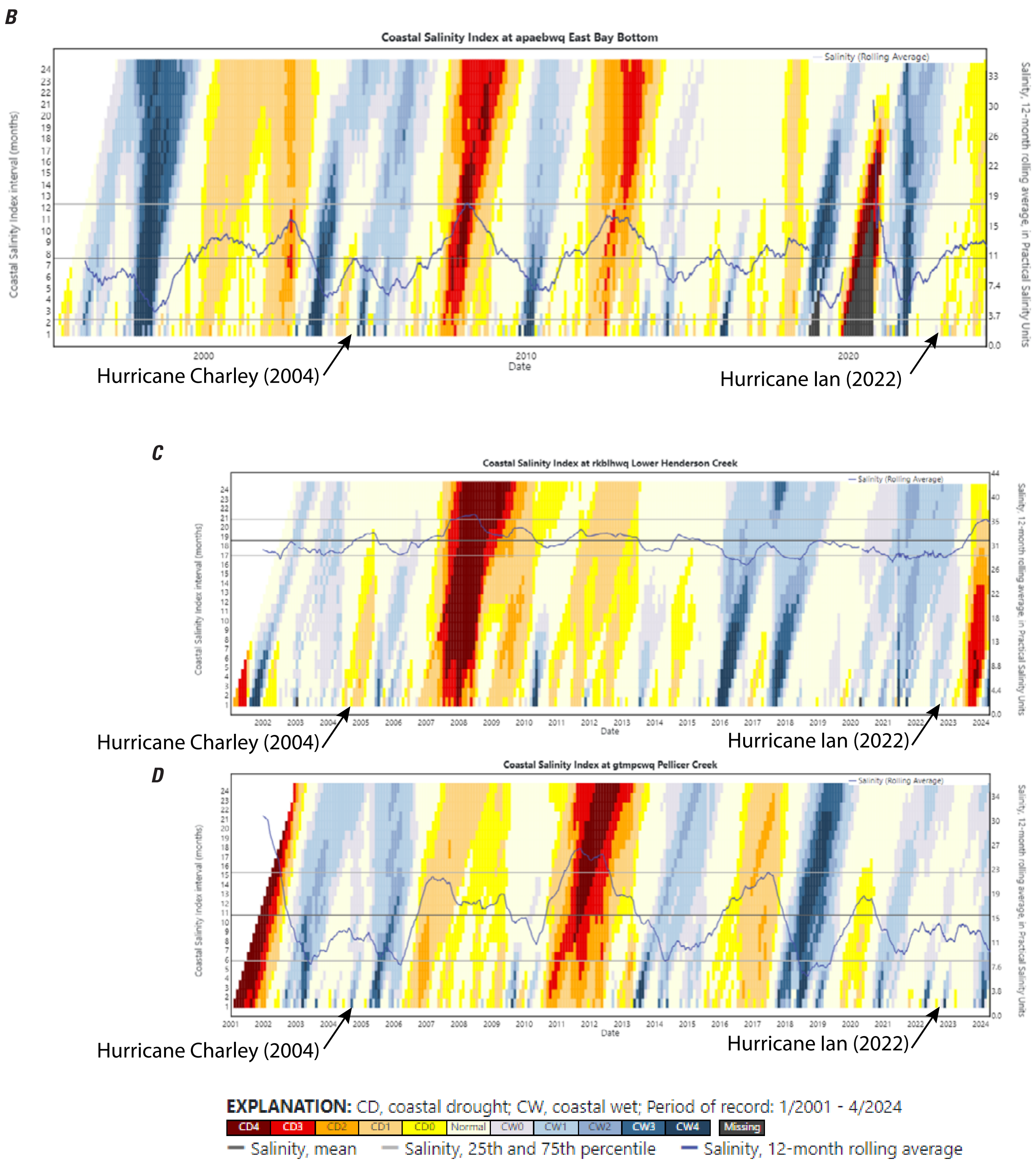


Figure 3.1 (pages 54 and 55). Comparison of surface-water salinity records at three stations relevant to Hurricane Charley (2004) and Hurricane Ian (2022), which followed similar paths across Florida. Data from the Coastal Salinity Index (CSI) database (https://apps.usgs.gov/sawsc/csi/index.html). *A*, Screen capture showing storm tracks from the National Oceanic and Atmospheric Administration Historical Hurricane Tracks web page (https://coast.noaa.gov/hurricanes), based on Knapp and others (2010, 2018). *B*, *C*, *D*, Plots of surface-water salinity records for three sites (locations in *A*) maintained by the National Estuarine Research Reserve: East Bottom Bay (site apaebwq) (*B*), Lower Henderson Creek (site rkblhwq) (*C*), and Pellicer Creek (site gtmpcwq) (*D*). Warmer colors indicate surface-water salinization anomalies and cooler colors indicate freshening anomalies across multiyear records. The x-axis represents monthly time periods and the y-axis is continuous time across months. CSI classifications change markedly from the month prior to and after the hurricanes. In particular, CSI changes at Pellicer Creek (*D*), located on the east coast of Florida, were three standard deviations and very short term for CSI-1 (only 1 month) after Hurricane Charley. This event appears to have a small ripple effect for the CSI-2 month and longer periods. Changes associated with freshening were evident but short-term for Lower Henderson Creek (*C*), located in western Florida (CSI-1 changed for 1-month; CSI-2 changed for 2 months). In contrast, salinization was apparent at the East Bottom Bay gage (*B*), located in the Florida Panhandle, in response to Hurricane Ian (2022), which persisted for more than 2 months.


B
Coastal Salinity Index at apaebwq East Bay Bottom
Salinity (Rolling Average)
Coastal Salinity Index interval (months)
Salinity, 12-month rolling average, in Practical Salinity Units
Date
Hurricane Charley (2004)
Hurricane Ian (2022)
C
Coastal Salinity Index at rkblhwq Lower Henderson Creek
Salinity (Rolling Average)
Coastal Salinity Index interval (months)
Salinity, 12-month rolling average, in Practical Salinity Units
Date
Hurricane Charley (2004)
Hurricane Ian (2022)
D
Coastal Salinity Index at gtmpcwq Pellicer Creek
Salinity (Rolling Average)
Coastal Salinity Index interval (months)
Salinity, 12-month rolling average, in Practical Salinity Units
Date
Hurricane Charley (2004)
Hurricane Ian (2022)
EXPLANATION: CD, coastal drought; CW, coastal wet; Period of record: 1/2001 - 4/2024
CD4 CD3 CD2 CD1 CD0 Normal CW0 CW1 CW2 CW3 CW4 Missing
Salinity, mean
Salinity, 25th and 75th percentile
Salinity, 12-month rolling average

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Appendix 4. Coastal Salinity Index (CSI) Monitoring Sites

Number	Site number	Station name	State	Longitude	Latitude
		U.S. Geological Survey			
1	01481500	Brandywine Creek at Wilmington, DE	DE	−75.576694	39.7695
2	01482800	Delaware River at Reedy Island Jetty, DE	DE	−75.568259	39.5009454
3	02244040	St. Johns R at Buffalo Bluff near Satsuma, FL	FL	−81.683138	29.5963582
4	02277110	St. Lucie River at Speedy Point, Stuart FL	FL	−80.2587833	27.2048
5	02277110	St Lucie Estuary at A1A (Steele Pt) Stuart FL	FL	−80.207444	27.1990278
6	02290930	Turner River nr Chokoloksee Island, FL	FL	−81.341667	25.8286111
7	251003080435500	McCormick Creek at Mouth Near Key Largo, FL	FL	-80.73358889	25.16819444
8	251127080382100	Taylor River at Mouth near Homestead, FL	FL	−80.639053	25.1905944
9	251209080350100	Mud Creek at Mouth nr Homestead, FL	FL	−80.584111	25.2033028
10	251241080385300	Upstream Taylor River near Homestead, FL	FL	−80.647667	25.2102972
11	251253080320100	Trout Creek at Mouth near Key Largo, FL	FL	−80.533506	25.2148972
12	251355080312800	Joe Bay 2E, near Key Largo, FL	FL	−80.524867	25.232625
13	251433080265000	West Highway Creek near Homestead, FL	FL	−80.447572	25.2421083
14	301124081395901	St. Johns River Buckman Bridge at Jacksonville, FL	FL	−81.666205	30.1902405
15	302309081333001	St Johns R Dames Point Bridge at Jacksonville, FL	FL	−81.558147	30.3860727
16	02198840	Savannah River I-95 near Port Wentworth, GA	GA	−81.151083	32.2354722
17	02198920	Savannah River at GA 25, at Port Wentworth, GA	GA	−81.154917	32.1653333
18	022035975	Hudson Creek at Meridian Landing, near Meridian, GA	GA	−81.362778	31.4533333
19	073745257	Crooked B. NW of L. Cuatro Caballo near Delacroix	LA	−89.719507	29.7082661
20	073745258	Cow Bayou at American Bay nr Pointe-A-La-Hache, LA	LA	−89.703952	29.5707699
21	07374526	Black Bay nr Snake Island nr Pointe-A-La-Hache, LA	LA	−89.563669	29.633544
22	07374526	Northeast Bay Gardene near Point-A-LA-Hache, LA	LA	−89.6060434	29.58600378
23	07374527	Barataria Bay N of Grand Isle, LA	LA	−89.9506268	29.42272045
24	073802512	Hackberry Bay NW of Grand Isle, LA	LA	−90.041184	29.3985551
25	07380335	Little Lake Near Cutoff, LA	LA	−90.1814655	29.5177174
26	07381349	Caillou Lake (Sister Lake) SW of Dulac, LA	LA	−90.9211111	29.24916667
27	073813498	Caillou Bay SW of Cocodrie, LA	LA	−90.871389	29.0780556
28	073814675	Bayou Boeuf at Railroad Bridge at Amelia, LA	LA	−91.099722	29.6683333
29	07387040	Vermilion Bay near Cypremort Point, LA	LA	−91.880398	29.7132658
30	07387050	Vermilion Bay (B. Fearman) nr Intracoastal City, LA	LA	−92.135556	29.6744444
31	08017044	Calcasieu River at I-10 at Lake Charkes, LA	LA	−93.2473764	30.23714987
32	08017095	North Calcasieu Lake near Hackberry, LA	LA	−93.299599	30.0318786
33	08017118	Calcasieu River at Cameron, LA	LA	−93.349043	29.8157762
34	291929089562600	Barataria Bay near Grand Terre Island, LA	LA	−89.9405	29.3247222
35	292800090060000	Little Lake near Bay Dosgris E of Galliano, LA	LA	−90.1	29.4666667
36	292859090004000	Barataria Waterway S of Lafitte, LA	LA	−90.0111111	29.48305556
37	2951190901217	L. Catacouatche at Whiskey Canal S of Waggaman, LA	LA	−90.2047222	29.85527778
38	300722089150100	Mississippi Sound near Grand Pass	LA	−89.250278	30.1227778
39	301104089253400	Mississippi Sound at USGS St. Joseph Island Light	MS	−89.4222222	30.19083333
40	301429089145600	Mississippi Sound at USGS Merrill Shell Bank Light	MS	−89.242819	30.2382541
41	302318088512600	Biloxi Bay at Point Cadet Harbor at Biloxi, MS	MS	−88.857222	30.3883333
42	0208062765	Roanoke River at Halifax, NC	NC	−77.580278	36.3311111
43	02081022	Roanoke River Near Oak City, NC	NC	−77.21527778	36.0136111
44	02081094	Roanoke River at Jamesville, NC	NC	−76.892778	35.8130556
45	0208114150	Roanoke River at NC 45 nr Westover, NC	NC	−76.722778	35.915
46	01388000	Ramapo River at Pompton Lakes NJ	NJ	−74.28	40.9919444
47	01389005	Passaic River below Pompton Riv at Two Bridges NJ	NJ	−74.269167	40.8963889
48	01463500	Delaware River at Trenton NJ	NJ	−74.778056	40.2216667
49	01467200	Delaware R at Ben Franklin Bridge at Philadelphia	PA	−75.1393603	39.946402
50	01477050	Delaware River at Chester, PA	PA	−75.366302	39.8367793

Appendix 4.—Continued

Number	Site number	Station name	State	Longitude	Latitude
51	01480617	West Branch Brandywine Creek at Modena, PA	PA	−75.801334	39.9617734
52	01480870	East Branch Brandywine Creek below Downingtown, PA	PA	−75.673272	39.9687191
53	01481000	Brandywine Creek at Chadds Ford, PA	PA	−75.593262	39.8698328
54	02110704	Waccamaw River at Conway Marina at Conway, SC	SC	−79.043722	33.8326111
55	02110755	AIW at Briarcliffe Acres at N. Myrtle Beach, SC	SC	−78.75307469	33.7985057
56	02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, SC	SC	−78.866693	33.7407276
57	02110770	AIW at Grand Strand Airport N. Myrtle Beach, SC	SC	−78.718629	33.8212835
58	02110777	AIW at Highway 9 at Nixons Crossroads, SC	SC	−78.655848	33.8515612
59	021108125	Waccamaw River near Pawleys Island, SC	SC	−79.126987	33.5065572
60	02110815	Waccamaw R nr Hagley Land, nr Pawleys Island, SC	SC	−79.173934	33.4446125
61	02172020	W Branch Cooper R at Pimlico nr Moncks Corner, SC	SC	−79.9489708	33.0935042
62	02172040	Back River at Dupont Intake nr Kittredge, SC	SC	−79.958472	33.0569722
63	02172050	Cooper R nr Goose Creek, SC	SC	−79.936193	33.0576713
64	02172053	Cooper R at Mobay nr N Charleston, SC	SC	−79.922861	32.9835058
65	021720677	Cooper River at Filbin Creek at North Charleston, SC	SC	−79.962865	32.8904523
66	021720698	Wando River above Mt Pleasant, SC	SC	−79.896196	32.8590638
67	021720709	Cooper River at U.S. Hwy 17 At Charleston, SC	SC	−79.910087	32.8023984
68	021720710	Cooper R at Customs House AUX at Charleston, SC	SC	−79.923699	32.7804544
69	021989784	L Back River above Lucknow Canal, nr Limehouse, SC	SC	−81.11789	32.1857575
70	021989791	Little Back River at F&W Dock, near Limehouse, SC	SC	−81.117639	32.171
71	08067252	Trinity Rv at Wallisville, TX	TX	−94.731309	29.8124434
72	301001089442600	Rigolets at Hwy 90 near Slidell, LA	LA	−89.740556	30.1669444
National Estuarine Research Reserve					
73	acespwq	St. Pierre	SC	−80.433332	32.4833314
74	cbmocwq	Otter Point Creek	MD	−76.243567	39.4462198
75	cbvtcwq	Taskinas Creek	VA	−76.714125	37.4165339
76	delslwq	Scotton Landing	DE	−75.46044	39.08507
77	gndbhwq	Bayou Heron	MS	−88.4054	30.4178
78	apaebwq	East Bay Bottom	FL	−84.87569	29.78631
79	gndblwq	Bangs Lake	MS	−88.4629	30.3571
80	grblrwq	Lamprey River	NH	−70.9344	43.08
81	grborwq	Oyster River	NH	−70.911	43.134
82	grbsqwq	Squamscott River	NH	−70.9118	43.0524
83	gtmpcwq	Pellicer Creek	FL	−81.25754	29.66657
84	jacb6wq	Buoy 126	NJ	−74.33558	39.50801
85	jacnewq	Chestnut Neck	NJ	−74.4608	39.5479
86	job09wq	Station 9	PR	−66.2385833	17.9430556
87	job20wq	Station 20	PR	−66.211472	17.930317
88	nartbwq	T-Wharf Bottom	RI	−71.32109	41.57895
89	niwdcwq	Debidue Creek	SC	−79.16718	33.36048
90	niwolwq	Oyster Landing	SC	−79.18912	33.34958

Appendix 4.—Continued

Number	Site number	Station name	State	Longitude	Latitude
91	rkblhwq	Lower Henderson Creek	FL	−81.73371	26.02762
92	sapldwq	Lower Duplin	GA	−81.29688	31.4176
93	welinwq	Inlet	ME	−70.56361	43.3203
94	welsmwq	Skinner Mill	ME	−70.549217	43.344711
95	wqbmhwq	Menauhant	MA	−70.54795	41.55249
National Park Service					
96	BA	Bob Allen Keys	FL	−80.681	25.027
97	BK	Buoy Key	FL	−80.834	25.119
98	BN	Butternut Key	FL	−80.519	25.087
99	BR	Broad River	FL	−80.989	25.478
100	BS	Blackwater Sound	FL	−80.438	25.178
101	BSC	Big Sable Creek	FL	−81.162	25.266
102	CN	Canepatch	FL	−80.942	25.422
103	CW	Clearwater Pass	FL	−81.013	25.297
104	DK	Duck Key	FL	−80.49	25.18
105	GB	Garfield Bight	FL	−80.801	25.167
106	GI	Gunboat Island	FL	−81.029	25.378
107	HC	Highway Creek	FL	−80.444	25.254
108	HR	Harney River	FL	−81.06	25.424
109	JB	Joe Bay	FL	−80.541	25.224
110	JK	Johnson Key	FL	−80.904	25.053
111	LB	Little Blackwater Sound	FL	−80.432	25.214
112	LM	Little Madeira Bay	FL	−80.633	25.176
113	LN	Lane Bay	FL	−80.894	25.284
114	LO	Lostmans River	FL	−81.169	25.556
115	LR	Little Rabbit	FL	−80.826	24.982
116	LS	Long Sound	FL	−80.457	25.235
117	MB	Manatee Bay	FL	−80.422	25.239
118	MD	Miami-Dade	FL	−80.396	25.289
119	MK	Murray Key	FL	−80.942	25.106
120	NR	North River	FL	−80.911	25.338
121	PK	Peterson Keys	FL	−80.747	24.918
122	SR	Shark River	FL	−81.1	25.352
123	TB	Terrapin Bay	FL	−80.722	25.155
124	TC	Trout Cove	FL	−80.533	25.213
125	TE	Tarpon Bay East	FL	−80.964	25.41
126	TP	Thursday Point	FL	−80.372	25.203
127	TR	Taylor River	FL	−80.65	25.217
128	WB	Whipray Basin	FL	−80.735	25.072
129	WE	White Water Bay East	FL	−80.938	25.232
130	WW	Willy Willy	FL	−81.044	25.587

Appendix 5. Focal Conceptual Models for Selected Storms with Hurricane Tracks and Responses at Selected Coastal Salinity Index (CSI) Gages

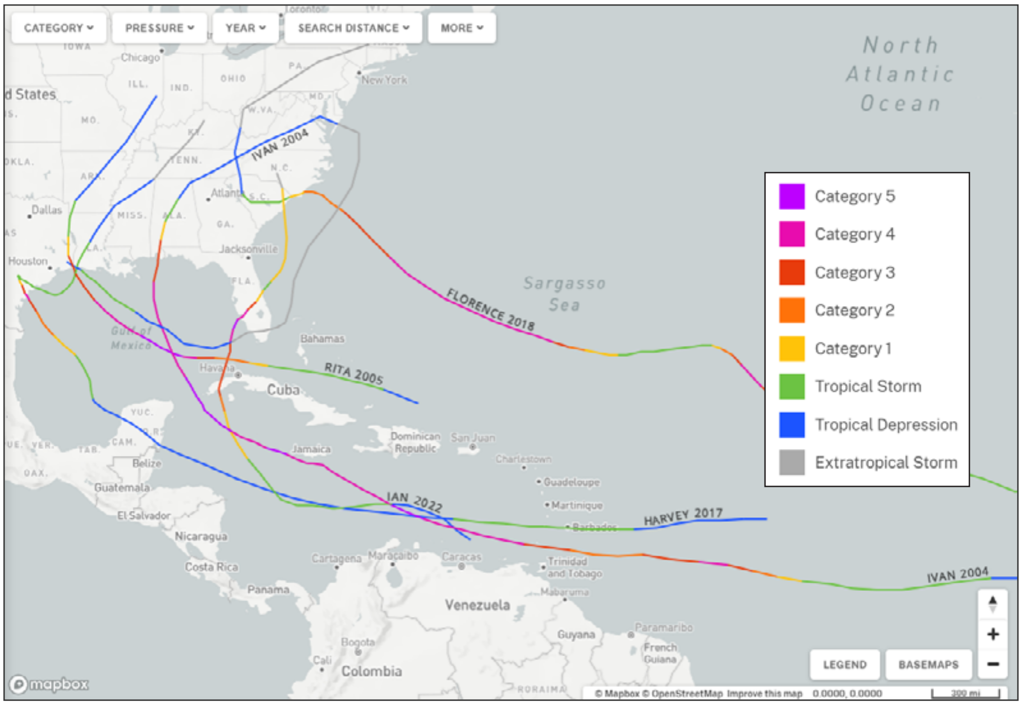

Figure 5.1. Screen capture showing a map of storm tracks for Hurricanes Ivan (2004), Rita (2005), Harvey (2017), Florence (2018), and Ian (2022) from the National Oceanic and Atmospheric Administration Historical Hurricane Tracks web page (https://coast.noaa.gov/hurricanes) based on Knapp and others (2010, 2018).

Figures 5.2 through 5.6 were generated by exporting data from the Coastal Salinity Index (CSI) database with a request for values of CSI-1 (1-month timescale). All CSI-1 values were classified on a scale of −5 to +5 using the thresholds listed in the CSI legend (https://apps.usgs.gov/sawsc/csi/index.html). Classifications are as follows CD4 = −5, CD3 = −4, CD2 = −3, CD1 = −2, CD0 = −1, Normal = 0, CW0 = 1, CW1 = 2, CW2 = 3, CW3 = 4, CW4 = 5. CSI differences were then calculated by subtracting the CSI-1 value for a given month from the value for the previous month. For example, the CSI-1 values for Brandywine Creek at Wilmington, Delaware (USGS site 01481500), is −1 for September 2022 and +1 for October 2022; the CSI-1 difference calculated for October 2022 is 2 (−1 to +1 equals 2). This CSI-1 difference represents the magnitude of change between salinity conditions for the two months. A difference of 0 would mean no change, whereas a positive difference (+1 to +5) indicates a freshening of the water (less salinity) with the value of +5 indicative of a more significant freshening event. A difference of −1 through −5 indicates increased salinization of the water with the value of −5 being a more significant salinity event. The difference values were assigned a color code based on colors similar to the CSI legend in the online database. Resulting data were filtered for time periods and areas of interest affected by specific hurricanes of interest.

A

Site Number	Station Name	State	6/1/2004	7/1/2004	8/1/2004	9/1/2004	10/1/2004	11/1/2004	12/1/2004	1/1/2005
301104089253400	Mississippi Sound at USGS St Joseph Island Light	MS	0	2	0	0	0	0	2	0
301429089145600	Mississippi Sound at USGS Merrill Shell Bank Light	MS	0	2	0	0	0	0	3	0
302318088512600	Biloxy Bay at Point Cadet Harbor at Biloxi, MS	MS	1	0	0	-1	0	2	2	0
gndbhwq	Bayou Heron	MS	1	0	-1	0	0	5	5	1
gndblwq	Bangs Lake	MS	0	0	-2	-1	0	2	5	1
wkbfrwq	wkbfrwq	AL	0	0	-1	0	0	4	5	0
apaebwq	East Bay Bottom	FL	0	0	0	0	5	2	4	0

B

Site Number	Station Name	State	6/1/2004	7/1/2004	8/1/2004	9/1/2004	10/1/2004	11/1/2004	12/1/2004
02277100	St Lucie River at Speedy Point, Stuart FL	FL	-1	-2	0	4	5	1	0
02277110	St Lucie Estuary at A1A (Steele Pt) Stuart FL	FL	-2	-2	-1	5	5	1	0
02290930	Turner River nr Chokoloskee Island, FL	FL	-1	-2	0	0	0	0	-1
251003080435500	McCormick Creek at Mouth near Key Largo, FL	FL	-1	-2	-2	-2	-2	-3	-3
251127080382100	Taylor River at Mouth near Homestead, FL	FL	-2	-2	-2	-2	-2	-2	-2
251209080350100	Mud Creek at Mouth nr Homestead, FL	FL	-2	-2	-3	-3	-3	-2	-4
251241080385300	Upstream Taylor River near Homestead, FL	FL	-2	-3	-2	-2	-1	0	0
251253080320100	Trout Creek at Mouth near Key Largo, FL	FL	-2	-3	-2	-3	-3	-2	-3
251433080265000	West Highway Creek near Homestead, FL	FL	-2	-3	-2	-2	-2	0	-1
BA	Bob Allen Keys	FL	-2	--	-2	-2	-5	-5	-5
BK	Buoy Key	FL	-5	-1	1	0	-1	-2	-2
BN	Butternut Key	FL	0	-1	-1	-2	-3	-2	-3
BR	Broad River	FL	-3	-3	2	-5	0	5	0
BS	Blackwater Sound	FL	-2	-2	-2	-3	-4	-3	-3
BSC	Big Sable Creek	FL	-2	-1	1	2	0	0	0
CA	CA	FL	0	-2	0	0	-1	0	0
CN	Canepatch	FL	-4	-3	1	-5	1	1	0
CW	Clearwater Pass	FL	-2	-2	-1	-1	0	0	0
DK	Duck Key	FL	-1	-2	-1	-2	-2	-3	-3
GB	Garfield Bight	FL	-2	-2	0	-1	-2	-2	-2
GI	Gunboat Island	FL	-4	-2	2	-1	0	2	2
HC	Highway Creek	FL	-3	-4	-1	-3	-1	0	0
HR	Harney River	FL	-2	0	5	0	0	2	1
JB	Joe Bay	FL	-2	-3	-2	-3	-4	-2	-2
JK	Johnson Key	FL	-2	-3	2	1	0	-2	-2
LB	Little Blackwater Sound	FL	-2	-2	-2	-3	-3	-2	-2
LM	Little Madeira Bay	FL	-1	-2	-2	-2	-3	-2	-3
LN	Lane Bay	FL	-2	-3	0	-1	0	0	0
LO	Lostmans River	FL	-2	-2	0	-2	0	0	1
LR	Little Rabbit	FL	-3	-4	0	0	-1	-3	-2
LS	Long Sound	FL	-3	-3	-2	-2	-2	-1	-2
MB	Manatee Bay	FL	-2	-3	-3	-2	-3	-3	-4
MD	Miami-Dade	FL	-3	-4	-3	-2	-3	-2	-3
MK	Murray Key	FL	-1	-1	2	1	-1	-1	0
NR	North River	FL	-2	-3	0	-3	0	0	0
PK	Peterson Keys	FL	-1	-3	0	0	-2	0	-3
rkblhwq	Lower Henderson Creek	FL	-1	-2	0	-2	-2	-2	-2
SR	Shark River	FL	-3	-2	1	0	0	0	0
TB	Terrapin Bay	FL	-1	-2	-2	-2	-3	-3	-3
TC	Trout Cove	FL	-2	-2	-2	-2	-2	-2	-2
TE	Tarpon Bay East	FL	-4	-3	1	-5	-1	1	0
TP	Thursday Point	FL	-2	-2	-2	--	--	-4	-4
TR	Taylor River	FL	-2	-4	-2	-3	-1	0	0
WB	Whipray Basin	FL	-1	-3	0	0	-2	-3	-3
WE	White Water Bay East	FL	0	-2	-2	-2	-2	0	0
WP	WP	FL	-1	-2	0	0	-1	0	0
WW	Willy Willy	FL	-1	-2	0	-2	0	0	0

EXPLANATION

Classification

−5	CD4
−4	CD3
−3	CD2
−2	CD1
−1	CD0
0	Normal
1	CW0
2	CW1
3	CW2
4	CW3
5	CW4
--	No data

Figure 5.2. Coastal Salinity Index data for sites located near the landfall area of Hurricane Ivan. *A*, First landfall September 16, 2004, near Gulf Shores, Alabama, as a Category 3 storm. *B*, Landfall on September 21, 2004, crossing South Florida as an extratropical storm. Color in heat maps are for change in CSI-1 values over a 1 month period.

Site Number	Station Name	State	7/1/2005	8/1/2005	9/1/2005	10/1/2005	11/1/2005	12/1/2005	1/1/2006	2/1/2006	3/1/2006
08067252	Trinity Rv at Wallisville, TX	TX	-2	-2	-2	-1	-2	-2	-3	0	-1
07387040	Vermilion Bay near Cypremort Point, LA	LA	0	0	-1	--	-2	-2	-2	-4	-3
07387050	Vermilion Bay(B. Fearman) nr Intracoastal City, LA	LA	-1	0	-2	--	--	-1	-5	-4	-3
08017044	Calcasieu River at I-10 at Lake Charles, LA	LA	-1	-1	-2	--	-2	-1	-2	0	-2
08017095	North Calcasieu Lake near Hackberry, LA	LA	-2	-1	-1	--	-2	-2	-3	-2	-3
08017118	Calcasieu River at Cameron, LA	LA	-1	0	-1	-2	-2	-4	-4	-3	-2

Figure 5.3. Coastal Salinity Index data for sites in Texas and Louisiana located near the landfall area of Hurricane Rita, September 24, 2005.

Site Number	Station Name	State	7/1/2017	8/1/2017	9/1/2017	10/1/2017	11/1/2017	12/1/2017	1/1/2018	2/1/2018	3/1/2018
08067252	Trinity Rv at Wallisville, TX	TX	1	2	3	2	1	0	0	1	1
07374526	Black Bay nr Snake Island nr Pointe-A-La-Hache, LA	LA	2	1	3	0	0	-1	-1	-1	1
07374527	Northeast Bay Gardene near Point-A-LA-Hache, LA	LA	4	3	5	2	2	0	-1	-2	--
07380251	Barataria Bay N of Grand Isle, LA	LA	3	1	2	2	0	0	-3	-4	0
07380335	Little Lake Near Cutoff, LA	LA	2	1	5	0	2	0	-2	-2	0
07381349	Caillou Lake (Sister Lake) SW of Dulac, LA	LA	2	0	4	0	0	0	0	-3	0
07387040	Vermilion Bay near Cypremort Point, LA	LA	1	0	3	2	0	-1	0	-1	0
07387050	Vermilion Bay (B. Fearman) nr Intracoastal City, LA	LA	2	0	4	2	0	0	0	0	0
08017044	Calcasieu River at I-10 at Lake Charles, LA	LA	3	2	4	0	-1	-2	-2	1	0
08017095	North Calcasieu Lake near Hackberry, LA	LA	3	2	5	0	0	-1	-2	1	2
08017118	Calcasieu River at Cameron, LA	LA	3	2	5	0	0	0	--	0	2
73745253	73745253	LA	--	--	0	0	0	-1	-2	0	--
073745257	Crooked B. NW of L. Cuatro Caballo near Delacroix	LA	2	2	1	1	1	-1	-3	-2	0
073745258	Cow Bayou at American Bay nr Pointe-A-La-Hache, LA	LA	3	2	3	0	2	0	0	1	3
073802512	Hackberry Bay NW of Grand Isle, LA	LA	4	1	4	0	0	0	-2	-3	0
073813498	Caillou Bay SW of Cocodrie, LA	LA	0	1	0	0	0	0	-4	-2	-1
073814675	Bayou Boeuf at Railroad Bridge at Amelia, LA	LA	3	2	2	0	1	0	0	0	0
2951190901217	L. Cataouatche at Whiskey Canal S of Waggaman, LA	LA	0	1	2	1	1	1	0	0	2
291929089562600	Barataria Bay near Grand Terre Island, LA	LA	3	2	2	0	0	-1	-3	-1	0
292800090060000	Little Lake near Bay Dosgris E of Galliano, LA	LA	3	0	4	0	0	0	-4	-5	0
292859090004000	Barataria Waterway S of Lafitte, LA	LA	3	2	3	0	0	0	-4	-5	0
300722089150100	Mississippi Sound near Grand Pass	LA	3	2	1	0	0	0	-1	0	1
301001089442600	Rigolets at Hwy 90 near Slidell, LA	LA	4	2	3	1	2	1	0	1	2
301104089253400	Mississippi Sound at USGS St Joseph Island Light	MS	2	2	1	0	0	--	--	0	1
301429089145600	Mississippi Sound at USGS Merrill Shell Bank Light	MS	0	2	0	0	0	0	-2	0	--
302318088512600	Biloxi Bay at Point Cadet Harbor at Biloxi, MS	MS	4	4	2	2	1	0	-1	2	0
gndbhwq	Bayou Heron	MS	5	1	2	3	0	0	-2	0	0
gndblwq	Bangs Lake	MS	5	2	2	2	0	0	-1	0	0
wkbfrwq	wkbfrwq	AL	3	2	2	2	0	-1	-2	-1	0

Figure 5.4. Coastal Salinity Index data for all Gulf of Mexico sites (Texas, Louisiana, Mississippi, and Alabama) for Hurricane Harvey, which made landfall in August, 2017.

Site Number	Station Name	State	6/1/2018	7/1/2018	8/1/2018	9/1/2018	10/1/2018	11/1/2018	12/1/2018	1/1/2019	2/1/2019	3/1/2019
02110704	Waccamaw River at Conway Marina at Conway, SC	SC	2	2	2	0	2	1	2	1	0	0
02110755	AIW at Briarcliffe Acres at N. Myrtle Beach, SC	SC	2	2	2	0	2	2	2	2	2	1
02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, SC	SC	2	1	2	1	2	2	2	3	1	1
02110770	AIW at Grand Strand Airport N. Myrtle Beach, SC	SC	2	1	2	-1	2	2	2	2	1	2
02110777	AIW at Highway 9 at Nixons Crossroads, SC	SC	2	0	2	0	5	4	5	3	0	2
02110815	Waccamaw R nr Hagley Land, nr Pawleys Island, SC	SC	2	0	2	0	2	2	1	1	1	2
2172020	W Branch Cooper R at Pimlico NR Moncks Corner, SC	SC	0	0	0	2	0	2	3	4	3	3
02172040	Back River at Dupont Intake nr Kittredge, SC	SC	0	0	0	0	0	0	3	2	2	3
02172050	Cooper R nr Goose Creek, SC	SC	0	-1	0	-2	0	0	4	2	0	0
02172053	Cooper R at Mobay nr N Charleston, SC	SC	-1	-1	0	-2	0	0	2	0	0	0
021108125	Waccamaw River near Pawleys Island, SC	SC	0	1	0	1	1	1	1	2	2	2
021720677	Cooper River at Filbin Creek at North Charleston, SC	SC	-2	-1	-1	-4	-3	1	4	2	0	0
021720698	Wando River above Mt Pleasant, SC	SC	-4	2	2	-1	1	2	4	3	1	0
021720709	Cooper River at U.S. Hwy 17 At Charleston, SC	SC	0	0	0	2	-1	2	0	5	0	0
021720710	Cooper R at Customs House AUX at Charleston, SC	SC	0	2	2	0	2	2	4	4	1	0
021989784	L Back River above Lucknow Canal, nr Limehouse, SC	SC	1	-2	0	-2	-2	0	2	2	1	0
021989791	Little Back River at FW Dock, near Limehouse, SC	SC	2	-2	1	0	-2	0	2	2	1	1
acespwq	St. Pierre	SC	0	0	3	-1	0	2	5	5	0	0
niwdcwq	Debidue Creek	SC	0	2	1	5	5	3	5	5	0	0
niwolwq	Oyster Landing	SC	0	2	0	5	5	2	5	5	0	0

Figure 5.5. Coastal Salinity Index data for sites near the landfall of Hurricane Florence, which made landfall in North Carolina, September 14, 2018.

A

Site Number	Station Name	State	6/1/2022	7/1/2022	8/1/2022	9/1/2022	10/1/2022	11/1/2022	12/1/2022	1/1/2023
apaebwq	East Bay Bottom	FL	0	0	0	1	0	-2	-1	-1
02290930	Turner River nr Chokoloskee Island, FL	FL	1	2	0	-2	0	0	0	1
251003080435500	McCormick Creek at Mouth near Key Largo, FL	FL	1	1	0	-1	0	0	0	0
251127080382100	Taylor River at Mouth near Homestead, FL	FL	2	0	-1	-3	-2	-2	-2	-1
251209080350100	Mud Creek at Mouth nr Homestead, FL	FL	2	0	-2	-4	-1	-1	0	0
251241080385300	Upstream Taylor River near Homestead, FL	FL	1	2	-1	-4	0	-2	-2	0
251253080320100	Trout Creek at Mouth near Key Largo, FL	FL	1	0	-2	-3	-1	0	-1	0
251355080312800	Joe Bay 2E, near Key Largo, FL	FL	0	0	-1	-4	-2	-2	-2	-1
251433080265000	West Highway Creek near Homestead, FL	FL	0	0	-2	-3	-2	-2	-2	-1
BA	Bob Allen Keys	FL	2	0	0	-1	-1	-1	0	0
BK	Buoy Key	FL	0	0	-1	-2	-1	0	0	0
BN	Butternut Key	FL	0	0	0	-1	-1	-1	0	0
BR	Broad River	FL	0	0	-2	-4	-3	-2	0	0
BS	Blackwater Sound	FL	0	0	-1	-2	-2	-1	0	0
BSC	Big Sable Creek	FL	NA	NA	NA	NA	NA	NA	NA	NA
CA	CA	FL	0	0	0	-2	3	0	-1	0
CN	Canepatch	FL	3	1	0	0	1	0	1	1
CW	Clearwater Pass	FL	0	1	-2	-1	0	0	0	0
DK	Duck Key	FL	0	0	-1	-1	-1	0	0	0
GB	Garfield Bight	FL	1	0	-1	-3	-1	-2	-1	0
GI	Gunboat Island	FL	2	0	-4	-1	0	-1	-1	0
HC	Highway Creek	FL	0	0	-4	-4	-2	-2	-2	-1
HR	Harney River	FL	2	0	-3	-2	0	-2	-1	0
JB	Joe Bay	FL	1	0	-2	-4	-2	-2	-2	-1
JK	Johnson Key	FL	1	-1	-4	-3	-1	0	0	0
LB	Little Blackwater Sound	FL	0	0	-1	-2	-2	-2	-1	-1
LM	Little Madeira Bay	FL	2	1	0	-2	-2	-1	-1	0
LN	Lane Bay	FL	1	2	-2	-2	1	0	0	0
LO	Lostmans River	FL	0	1	-3	-3	0	-1	0	0
LR	Little Rabbit	FL	1	0	-2	-4	0	0	0	0
LS	Long Sound	FL	0	0	-1	-3	-2	-2	-1	-1
MB	Manatee Bay	FL	2	1	0	-1	-1	-2	-2	0
MD	Miami-Dade	FL	2	1	0	-1	-1	-2	0	0
MK	Murray Key	FL	0	-1	-4	-2	0	1	0	0
NR	North River	FL	2	2	-2	0	2	0	0	1
PK	Peterson Keys	FL	1	0	0	-2	0	0	0	0
rkblhwq	Lower Henderson Creek	FL	2	2	0	2	1	0	0	0
SR	Shark River	FL	0	0	-4	-2	0	0	0	0
TB	Terrapin Bay	FL	1	0	0	-2	0	-1	-1	0
TC	Trout Cove	FL	1	0	-2	-4	-1	0	0	0
TE	Tarpon Bay East	FL	2	1	-2	-2	0	-2	0	1
TP	Thursday Point	FL	2	0	0	-1	-1	-1	0	0
TR	Taylor River	FL	1	2	-1	-5	-2	-2	-2	1
WB	Whipray Basin	FL	1	0	0	0	0	0	0	0
WE	White Water Bay East	FL	0	1	0	-1	0	0	0	0
WP	WP	FL	1	1	0	-3	0	0	0	0
WW	Willy Willy	FL	1	1	-2	-5	1	0	1	1

B

Site Number	Station Name	State	6/1/2022	7/1/2022	8/1/2022	9/1/2022	10/1/2022	11/1/2022	12/1/2022	1/1/2023
02244040	St. Johns R at Buffalo Bluff near Satsuma, FL	FL	0	0	1	0	1	4	4	2
02277110	St Lucie Estuary at A1A (Steele Pt) Stuart FL	FL	0	-1	-3	-2	0	0	0	0
301124081395901	St. Johns River Buckman Bridge at Jacksonville, FL	FL	-1	0	0	0	0	0	2	1
302309081333001	St Johns R Dames Point Bridge at Jacksonville, FL	FL	-1	0	0	0	2	2	0	2
gtmpcwq	Pellicer Creek	FL	0	0	-1	0	1	5	0	0

Figure 5.6. Coastal Salinity Index data for sites potentially impacted by Hurricane Ian. *A*, Western and southern Florida gages near Ian's September 28, 2022, landfall area. *B*, East coast of Florida gages near Ian's land exit on September 29, 2022. *C*, North Carolina and South Carolina sites near Ian's September 30, 2022, landfall.

C

Site Number	Station Name	State	6/1/2022	7/1/2022	8/1/2022	9/1/2022	10/1/2022	11/1/2022	12/1/2022	1/1/2023
02081094	Roanoke River at Jamesville, NC	NC	0	0	0	0	-1	0	0	-1
0208062765	Roanoke River at Halifax, NC	NC	0	0	0	0	0	0	0	1
0208114150	Roanoke River at NC 45 nr Westover, NC	NC	0	-4	-3	-3	-3	-1	1	0
noczbwq	noczbwq	NC	-2	0	0	-1	-2	-2	-2	-2
02110704	Waccamaw River at Conway Marina at Conway, SC	SC	0	0	0	0	-1	-2	-2	-2
02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, SC	SC	0	-1	-1	-2	-2	-2	-1	-1
02110770	AIW at Grand Strand Airport N. Myrtle Beach, SC	SC	0	0	-2	-1	0	0	0	0
02110777	AIW at Highway 9 at Nixons Crossroads, SC	SC	-1	0	-1	-1	-2	-1	-1	-1
02110815	Waccamaw R nr Hagley Land, nr Pawleys Island, SC	SC	-1	0	0	0	0	-1	0	0
02172040	Back River at Dupont Intake nr Kittredge, SC	SC	1	0	0	0	0	0	0	0
02172050	Cooper R nr Goose Creek, SC	SC	0	1	0	1	0	0	0	0
02172053	Cooper R at Mobay nr N Charleston, SC	SC	0	0	-1	-1	-2	-2	-1	-2
021108125	Waccamaw River near Pawleys Island, SC	SC	0	0	0	0	0	0	0	0
021720677	Cooper River at Filbin Creek at North Charleston, SC	SC	-2	0	-4	-1	-2	-5	--	-2
021720698	Wando River above Mt Pleasant, SC	SC	-2	0	5	4	0	0	-1	-2
021720709	Cooper River at U.S. Hwy 17 At Charleston, SC	SC	0	2	0	0	0	-1	0	-1
021720710	Cooper R at Customs House AUX at Charleston, SC	SC	0	1	-1	0	-1	-5	-5	-2
021989784	L Back River above Lucknow Canal, nr Limehouse, SC	SC	0	1	2	0	-1	-1	0	2
021989791	Little Back River at FW Dock, near Limehouse, SC	SC	0	1	2	0	0	0	0	2
acespwq	St. Pierre	SC	-1	0	0	0	0	-1	-1	-1
niwdcwq	Debidue Creek	SC	0	0	0	-2	4	-2	-2	-1
niwolwq	Oyster Landing	SC	-2	0	0	-2	-1	-2	-2	-1

Figure 5.6 (pages 63 and 64). Coastal Salinity Index data for sites potentially impacted by Hurricane Ian. *A*, Western and southern Florida gages near Ian's September 28, 2022, landfall area. *B*, East coast of Florida gages near Ian's land exit on September 29, 2022. *C*, North Carolina and South Carolina sites near Ian's September 30, 2022, landfall.—Continued

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