Drought and Aquatic Ecosystems in the Southeast Workshop:

Informing drought response and ecological resilience to future low-flow events

January 7–8, 2025
North Carolina State University, Raleigh, North Carolina

Prepared by Catherine A. Nikiel and Meredith Muth
NOAA Technical Report OAR-NIDIS-004

Drought and Aquatic Ecosystems in the Southeast Workshop:

Informing drought response and ecological resilience to future low-flow events

Cooperator Report: A Joint Workshop from the NOAA National Integrated Drought Information System (NIDIS) Southeast Drought Early Warning System and the U.S. Geological Survey Southeast Climate Adaptation Science Center (SE CASC)

NOAA Technical Report OAR-NIDIS-004

Report Authors

Catherine A. Nikiel, U.S. Geological Survey, National Climate Adaptation Science Center
Meredith F. Muth, NOAA National Integrated Drought Information System

Recommended Citation

Nikiel, C. A., & Muth, M. F. (2025.) *Drought and Aquatic Ecosystems in the Southeast Workshop: Informing drought response and ecological resilience to future low-flow events.* U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Integrated Drought Information System; U.S. Geological Survey, Southeast Climate Adaptation Science Center (SE CASC). USGS Cooperator Report, SE CASC. NOAA Technical Report OAR-NIDIS-004. DOI: 10.25923/9d8f-gf25.

Cover images: Lake Lanier with low water levels exposing tree roots (credit: Sandra Burn, Shutterstock); attendees at the Southeast Aquatic Ecosystems in the Southeast Workshop (credit: Keri Dawn, SE CASC); a view of the marsh on Cumberland Island, Georgia (credit: Stacy Funderburke, Shutterstock).

Executive Summary

Given the broad interest and need to better understand and plan for ecological drought in the Southeast, the U.S. Geological Survey (USGS) Southeast Climate Adaptation Science Center (SE CASC) and National Oceanic and Atmospheric Administration (NOAA) National Integrated Drought Information System (NIDIS), in support of the Southeast Drought Early Warning System (SE DEWS), convened a 2-day Workshop in January 2025, bringing together scientists and managers from diverse fields, to address drought and low-flow in the Southeast and its impacts to aquatic systems across the region.

The Workshop was organized around three themes:

- Theme 1: Understanding drought/low-flow ecosystem impacts and water resources management in the context of the Southeast.
- Theme 2: Ecological drought monitoring and response in the near-term
- Theme 3: Incorporating drought/low flow in long-term resilience and adaptation planning

Individual sessions were organized to address specific Workshop objectives. This table identifies tangible deliverables to meet each objective, that can be further utilized by regional partners to strengthen resilience of aquatic ecosystems to future drought.

Workshop Objective	Agenda Item	Deliverables in This Report
Identify barriers and opportunities to improve preparedness to future droughts	Breakouts (Session 8) and World Café	• Action 1: List of near-term opportunities by (1) communications & coordination; (2) understanding physical-biological interactions; (3) monitoring current conditions, and (4) projecting future conditions (Table 1 on pg. 10; Appendix F) • Action 2: Science needs for incorporating drought into long-term adaptation planning (Table 2, on pg. 13; Appendix G)
Identify management information needs	World Café, Sessions 3, 5	• Action 2: Science needs for incorporating drought into long-term adaptation planning (Table 2, on pg. 13; Appendix G) • Presentations and discussions by regional partners (pg. 20, slides on website)
Understanding drought and hydrology in the Southeast	Breakouts (Session 4); Sessions 1, 3; Poster Session	• Action 3: List of indicators used to recognize hydrological drought (Table 3 on pg. 16; Appendix F) • Poster presenters (Appendix C) • Presentations and discussions by regional partners (pg. 20, slides on website)

Highlight recent advancements in hydroclimate research and tools	Tools and Resource Fair; Poster Session; Sessions 4, 10	• List of tools and resources for (1) drought and climate monitoring, (2) natural resource management, (3) streamflow and water monitoring, (4) water supply and management, and (5) Climate Projections (Appendix B; Appendix D) • Presentations and discussions by regional partners (pg. 20, slides on website) • Poster presenters (Appendix C)
Identify case studies that incorporate low-flow conditions into response and planning	Sessions 6, 11	• Presentations and discussions by regional partners (pg. 20, slides on website)
Identify current and future impacts of drought and low flow	Breakouts (Session 4 and 8); Sessions 2, 4, 5, 10	• Presentations and discussions by regional partners (pg. 20, slides on website) • Action 1: List of near-term opportunities by (1) communications & coordination; (2) understanding physical-biological interactions; (3) monitoring current conditions, and (4) projecting future conditions (Table 1 on pg. 10; Appendix F) • Action 3: List of indicators used to recognize hydrological drought (Table 3 on pg. 16; Appendix F)

Common themes and lessons from the Workshop include the following:

- There are significant near-term opportunities that can provide high impact value to the region for relatively low effort. In particular, communicating and increasing awareness of what already exists.
- The Southeast has a substantial number of existing resources, data, and tools to support drought preparedness, response, and planning.
- Significant work is already being done by scientists, managers, and policymakers that take advantage of the broad range of data, tools, and information available. Existing resources should be utilized and leveraged before considering the creation of new tools.
- Science needs for incorporating drought into long-term adaptation planning should include expanding the coverage and usability of existing data sources and information.
- Additional synthesis and integrated data sharing is necessary to effectively understand and address long-term science needs. This would also highlight what is missing in terms of ecological indicators and markers of aquatic health and resilience in the face of drought and support adaptation planning.

- Streamflow and precipitation are necessary indicators but not sufficient for characterizing ecological drought in aquatic ecosystems. A wide variety of indicators are used that span hydrology, climatology, ecology, agriculture, and socioeconomics, and are used to assess impacts and potential risks to aquatic ecosystems.
- Effective response and planning understanding and trusted relationships across disciplines and missions as well as science.

This Workshop provided an opportunity to share available science, resources, and best practices across the Southeast; to jointly identify key management priorities and research questions across disciplines and perspectives; and provided information to help expand the region's ability to respond to and prepare for future droughts.

Visit the Workshop website to view the full agenda and presentations.

Table of Contents

Introduction

The Southeast region has experienced several periods of exceptional drought in the 21st century and is a hot spot for drought events that rapidly intensify (flash droughts). Competing water demands stress supply even in this humid region.

Historically, drought has been characterized in terms of its agricultural, hydrological, and socioeconomic impacts. How drought affects ecosystems and the services they provide human communities has only recently been emphasized as an important area of research and socio-economic impact. The U.S. Geological Survey (USGS) Southeast Climate Adaptation Science Center (SE CASC) held an ecological drought Workshop in 2016 to better understand drought management challenges in a regional context (summary here). A critical need was understanding the impacts of low streamflow and drought on aquatic systems to inform future research needs, management practices, and adaptation planning. Given recent advancements and drought events in the Southeast, the time is ripe to weave together and articulate what we have learned so far from the science and management community, identify if there are some commonalities across different parts of the region, and identify scientific priorities driven by management and planning needs to inform future research investments.

Given the broad interest and need to better understand and plan for ecological drought in the Southeast, the USGS Southeast Climate Adaptation Science Center (SE CASC) and NOAA's National Integrated Drought Information System (NIDIS) in support of the Southeast Drought Early Warning System (SE DEWS), convened a 2-day Workshop in January 2025, with scientists and managers from diverse fields to address the impacts of drought and low-flow on aquatic systems in the Southeast.

This Workshop provided an opportunity to share available science, resources, and best practices; jointly identify key management priorities and research questions; and expand the region's ability to respond to and prepare for future droughts.

Workshop Objectives

The Workshop objectives were:

1. Increase **understanding of drought and hydrology in the Southeast, and how it is changing** in the context of regional water demand and changing climate.
2. Highlight recent **advancements in hydroclimate research and tools** for monitoring and predicting in-stream flows across multiple time scales (short-term forecasting, seasonal outlooks, and medium- and long-term projection).
3. **Assess vulnerability and identify current and future impacts of drought and low-flow** streamflow conditions on aquatic and estuarine ecosystems and surrounding human communities; this includes considerations of water quality, reservoir operations, water withdrawals, and permitting.
4. **Identify management information needs** related to all types of droughts (rapid onset droughts or flash droughts, intermittent flows, and longer chronic droughts).

5. **Identify case studies** that effectively incorporate low-flow conditions into response and planning.
6. **Identify barriers and opportunities** to improve our understanding of, and preparedness to, future drought and low-flow events.

Workshop Organization and Agenda

The Workshop was organized around three themes:

- **Theme 1:** Understanding drought/low-flow ecosystem impacts and water resources management in the context of the Southeast.
- **Theme 2:** Ecological drought monitoring and response in the near-term
- **Theme 3:** Incorporating drought/low-flow in long-term resilience and adaptation planning

The Workshop agenda (Appendix A) included four sessions of presentations from 11 presenters, four sessions of panels with 19 panelists, one poster session with 20 participants (Appendix C), a tool and resource fair with 11 participating groups and organizations (Appendix D), two working sessions consisting of 8 habitat themed groups, and one World Cafe session with seven topic tables. Federal, Tribal, state, local, government, industry, academic, and non-governmental perspectives were represented in the Workshop agenda.

Presentations, posters, and additional resources can be found on the meeting website.

Workshop Participants

Participants represented the Southeast region as defined by the overlap of the Southeast CASC and the Southeast DEWS (Alabama, Arkansas, Georgia, Florida, Mississippi, North Carolina, South Carolina, Tennessee, Virginia). The participants engaged in-person with limited virtual attendees during plenary sessions. In-person participation included 104 individuals representing 73 organizations or agencies including local, state and federal agencies, private industry, academia, Tribes, and NGOs. Virtual participants nearly doubled the number of represented organizations (an additional 61). The list of meeting attendees and affiliations are found in Appendix E.

A broad range of natural resource management professionals were represented in the following areas: threatened and endangered species, invasive species, native and common species, recreational fishing, habitat and conservation, estuary and coastal systems, and freshwater wetlands and peatlands. Over a quarter of participants identified as graduate students, post-docs or early career (less than five years). The meeting successfully increased regional awareness and connections with the SE CASC and NIDIS. Through a poll of in-person and virtual attendees during the Workshop introduction, 64% had never attended a NIDIS or SE CASC event before (total of 105 respondents).

Actions to Increase Drought Resilience, Preparedness, and Planning in the Southeast

Needs and opportunities for near- and long-term actions were identified through several working group sessions with participants. These addressed the Workshop objectives related to identifying management information needs and barriers as well as opportunities to improving understanding of, and preparedness to, future drought and low-flow events. Sessions gathered information on both the short-term monitoring and response needs as well as adaptation needs for a longer time horizon.

Action 1: Address near-term needs and opportunities that can provide high value

In Session 8, participants were asked to come up with **needs and opportunities** to address impacts and support actions identified in the previous breakout, phrased as “if we had ___, we could do ___ better”. This was intended to center the discussions around actionable, management-relevant outcomes. Answers fell under five categories: (1) communication, coordination and policy, (2) understanding of biological/ecological/physical interactions and response, (3) future conditions including near-term forecasting and longer-term projections, and (4) current conditions including monitoring, data collection, and indicators. A fifth category captured any other uncategorized submissions.

Participants then placed these responses on an impact-effort grid and discussed placement. For example, a tool that has broad regional applicability may be high in **impact** while a tool that is very useful but limited in application would be low impact. If the same tool would take significant time and resources to develop or would need other inputs to be developed first then it may also be high **effort.** Participants were then also asked to identify which actions they considered most important to pursue to improve future drought response and preparedness in aquatic environments.

Many shared themes emerged among the groups. **Here we identify actions that fell in the high-impact/low-effort quadrant, as they represent actions that could be addressed by the region in the near-term, with some specific examples highlighted.**

Communication, Coordination, and Policy

- More structured data-sharing, collaboration, and communication across agencies and sectors will increase learning, leverage existing efforts, avoid redundancy and increase efficiency.
    - *Examples: Rapid response networks of scientists that characterize drought impacts; continuation and expansion of workshops to share ideas and build a professional "drought network" for aquatic systems.*
- Integrated data sharing and management will lead to better decision making and leverage the robust monitoring and response networks maintained by individual states and organizations.
    - *Examples: Develop AI tools to compile, screen and look for patterns within and across datasets; build an integrated [regional?] database accessible to all colleagues to improve communication and strategic planning.*
- Partnership and outreach efforts will further engage stakeholders, building public trust, and enhancing effectiveness, both during and outside of drought events.
    - *Examples: Build on successful examples (like GA-FIT, CERP, etc.); maintain communication outside of drought events; lead with people, not models; develop a tiered method of drought risk on a coarse and fine geographic scale*

and then communicate at different scales (using resource agencies); work with university extension programs to educate about water conservation.

- Improving communication with non-scientists will increase connections with the public and increase the effectiveness of efforts to shape policy.
    - *Examples: Build policy literacy among scientists; build understanding of who the end users are and what they want; highway electronic sign communication about water conservation measures.*
- Developing monitoring efforts, tools, and communication that are focused on impacts to broad public interests will maximize drought response and planning decisions.
    - *Examples: More information about the role of native species and landscaping in water conservation; outreach on the locations and importance of high-quality waters; USGS gage water level alert system as a connection to the community and public risk awareness.*

Understanding of Biological/Ecological/Physical Interactions and Response

- Improved and expanded real-time monitoring of ecological indicators would improve response to developing drought events.
    - *Examples: Develop alerts based on thresholds in existing monitoring networks and use them to trigger communication across different sectors; real-time monitoring of species "responses" to current conditions to supplement release strategies; identification of early vegetative indicators (e.g. riverweed in Georgia).*
- More engagement, data and knowledge sharing, and strong system level interdisciplinary understanding will improve understanding of the cross-sector implications of drought.
    - *Examples: Need better understanding of key "pinch points" in life cycles; assemblage data in intermittent streams; better monitoring of fish ages, fish spawn and vegetation responses to river flow; monitoring site conditions during all times (wet, dry); more cross-discipline engagement; 1 page fact sheets on traditional species and their thresholds for drought.*

Current Conditions: Monitoring, Data Collection, and Indicators

- Cross-agency and sector collaboration will support communication and data collection efforts to reduce redundancies and increase the effectiveness of actions.
    - *Examples: Multi-agency/NGO coordinated social media/public outreach on drought and water conservation; collaboration/sharing standardized data across agencies; focusing monitoring efforts and reducing duplication.*
- Leveraging public outreach and engagement (education, citizen science) will both bolster the ability to understand current conditions and bolster communication and public buy-in during and outside of drought events.
    - *Examples: Organize community science observations; crowdsourcing data collection (CoCoRaHS style, etc.); employ social scientists to address water conservation measures.*
- Applying new technologies and methodologies may improve data coverage and quality.
    - *Examples: Aerial photos of streams and rivers at different flow levels; remote flow sensing; quality control and QA; standardized sampling; remotely sensed data regarding plant conditions.*

● Utilizing existing/traditional methods of data collection still provides an opportunity to maximize data per dollar with easy-to-use, low-cost tools. ○ *Examples: Easy to deploy stream gages and soil moisture gages; point source monitors to monitor soil condition and crop health.* ● Both new and old technologies should be used to increase gage and sensor infrastructure to enhance monitoring coverage (spatially and temporally). ○ *Examples: Increase sensor infrastructure on strategic habitat units, e.g. identified stream reaches for imperiled species; coastal salinity index data in more places; model and measure groundwater and surface water better; more precipitation gauges to resolve precipitation distribution.* ● Better integration, translation and reporting of existing information will facilitate more confident and efficient decision making, especially in cases where a lack of information is not the core issue. ○ *Examples: More integrated data management would make answering our questions and understanding everything we're working on much clearer, e.g. an integrated GIS database for data exploration and comparison; put the puzzle pieces together: use what we have with additional resources, synthesis, and effective reporting and application to inform predictions and models.*
Future Conditions: Near-Term Forecasting and Longer-Term Projections
● More robust monitoring of low-coverage inputs such as groundwater and water withdrawals will improve forecasting, models, and tools. ○ *Examples: Forecasts of upstream water use; monthly reporting of water withdrawals and returns; groundwater input forecasts; antecedent conditions: pre-season indicators for specific vulnerable species stages.* ● Communication of changing future conditions to policymakers is critical to inform policy and increase support for future work. ○ *Examples: Communicate with legislators; science-based policies and legislation for greater resources, planning, and management; improved communication tools and approaches; communication to D.C. to facilitate informed policy.*

Table 1: Grouped responses from the High Impact - Low Effort quadrant of the Impact-Effort grid developed in Breakout Session 2 (Session 8). Responses are grouped based on the four discussion topics (Communication, Coordination, and Policy; Understanding of Biological/Ecological/Physical Interactions and Response; Current Conditions: Monitoring, Data Collection, and Indicators; Future Conditions: Near-Term Forecasting and Longer-Term Projections). Grouped topics are paired with specific response examples from groups. For a full set of responses during this exercise, see Appendix F.

Action 2: Address science needs for incorporating drought into long-term adaptation planning

A World Cafe style session was held to better understand how drought is being considered in long-term adaptation planning (years to decades) for ecosystems, what tools and approaches could be applied, and what science gaps exist that need to be addressed. The session was centered around a set of similar questions asked at seven topic tables (Species Management, Hydrologic Data Collection and Delivery, Conservation and Restoration, Water Quality, Ecological Modeling, Hydrologic Modeling, and Climate Information and Projections). Participants were asked a range of questions at each table including what tools they currently use and why, what future research and development is needed, and what would be a useful topic for synthesis and evaluation. Participants rotated through the tables, adding their own responses or reacting to the responses of others. The tables were chosen to capture topics that were important to organizers and attendees but were not a focus of other sessions. Outcomes will inform the Southeast Climate Adaptation Science Center (SE CASC) understanding of what science is most needed to help partner agencies manage fish, wildlife, water, land, and people in the long term. Full questions and details on the World Cafe session can be found in Appendix G.

A few common themes emerged from the World Cafe discussions:

1. State and federal governments are the primary source for data (both observations and modeled). These **data are robust but are also often not available for representative locations or time periods**. For example, monitoring networks are often geographically biased towards lowlands (vs. mountains) and more populated areas, are biased towards areas that already have monitoring, and do not cover unique or difficult to access and monitor locations such as springs, caves, and groundwater.
2. Data (observations and models) would be more useful if they were accessible in **web-based dashboards**, rather than data catalogs for download only. This would allow users with different levels of technical skill to access, explore, and apply the data as well as integrate information from different sources to provide better spatial and temporal coverage. Tools should also include **relevant ecological and management-relevant thresholds** to provide context and foster use for planning and decisions.
3. Additional research and development are broadly needed to better understand **ecological responses to drought across various species and habitats**, but especially for “umbrella” or “indicator” species and habitats.
4. There is a need to **synthesize** existing information on known ecological responses to drought. There is also a need to **systematically compare** the various datasets, models, and processes available for scientists and resource management agencies. Related, there was a common need for **summaries of best practices** to select and use the best data and models for various applications.

Summaries of responses from individual tables are captured below:

Theme	Source of Info	What is needed to increase the usefulness of existing information and data?	Additional R&D Needed	Synthesis Needs
Hydrological Modeling	• Government (robust/little support) • Consultants (tailored/use mutations of “one size fits all” tools)	• Accessible dashboards • Standardized Formats • Pre-developed/calibrated models	• Process for data/model selection • Model intercomparison • Connection to ecology and	• Scale and Resolution necessary to capture high intensity/small scale events

	• University & open source • USGS gauges and StreamStats		environmental quality • Simulations validated for intermittent or zero flow • Representation of development/management	
Climate Info & Projections	• Federal, state agencies, Universities (robust data but spatial and temporal scales not always useful for ecological applications)	• Integrated management thresholds • Application-specific metrics/variables • Training and translation tools • Process for data/model selection	• Resolve convection/very local scale storms • Regional earth system integrated models • Local- to regional-scale drought projections	• Model intercomparison • Summary of pros/cons for various model applications
Conservation & Restoration	• US Drought Monitor • USGS gauges • Localized tools (e.g. ACF basin dashboard)	• 50-year projections at HUC 12 • Integrated habitat vulnerability index/ metrics	• Understand if/how agricultural practices affect groundwater recharge • Ecoflow thresholds for "umbrella" species • Efficacy of restoration projects on ecosystem function	• How hydro variables related to biological/ ecological indicators • Methods of cross-sector communication
Ecological Modeling	• Govt agencies (consistent data, limited coverage) • Universities (analysis packages)	• Web-based models/ dashboards • Integrated management thresholds • User involvement in model/tool development	• Assemblage data for larger rivers • Ecological thresholds for species (e.g. temperature, salinity, flow, soil moisture, precipitation) and lag responses • Biotic-abiotic interactions • Better linkage between model development and field data collection	• Comparison across ecosystems • Trends in ecoflow/ecodrought
Species Management	• USFWS (quality data but limited) • USGS flow data (quality record, not available in small streams except for small scale deployments)	• Dashboards • Tools scaled to local conditions • Tools that scale to species range	• Long-term species surveys • Spawning conditions • Species interconnections (e.g. mussel/host) • Ecological thresholds • Surface-groundwater interactions	• Projections of habitat conditions • Impacts of disturbance to systems
Water Quality	• FWS/USGS water quality reporting tool (centralized) • USGS stream gages (variable record) • EPA (standards, monitoring) • State govts (consistent, robust/limited in space and time)	• Diurnal patterns • Integrated management thresholds • More sites, long-term data monitoring	• Impacts of compound stressors (nutrients + temperature + dissolved oxygen + drought) and covariation of flow + quality • Adaptive/assimilative capacity of stream reaches	• Emerging compounds (PFAS, pharmaceuticals, metals, etc.) instream under drought • Tolerance of umbrella species • Impacts of drought in coastal rivers

			• Impacts of high flow/flush after drought • Ecological thresholds under low flow	
Hydrologic Data Collection & Monitoring	Useful data are: • Open source • Good metadata • Peer reviewed • Easy to visualize/share • Scaled to issues	• Integrated portal with env quality data + training • Contextual data - what does a data value mean? • Groundwater integration	Monitoring Needs: • Real-time • Groundwater • Consumptive use • In cave systems, headwaters, springs/seeps, non-urban • Integrated ecological/hydrological monitoring to understand eco response • Evapotranspiration / Fluxes	• Surface-groundwater interactions • Long-term changes to base flows, seasonality • How habitat availability changes with flow levels

Table 2: Synthesized responses from World Cafe tables. Each row presents synthesized information from one of the topic tables (left) grouped by question (columns). Questions and transcribed answers from the exercise can be found in Appendix G.

Actions to Increase the Efficiency and Application of Existing Tools, Resources, and Information

Workshop participants had varied professional experience and understanding of core needs and issues related to drought in aquatic systems. Therefore, several Workshop objectives centered around information sharing and building a common understanding, including establishing a scientific baseline, assessing vulnerability and impacts, and identifying case studies and advancements with cross-sector applicability. Participants noted that this knowledge sharing and networking was a key outcome and success of the Workshop activities.

Action 3: Utilize a broad range of indicators to monitor drought impacts to aquatic ecosystems

Two breakout sessions (Session 4 & 8) were utilized to document needs, barriers and opportunities to improve drought preparedness and response in the context of aquatic systems. Breakout groups were organized around seven major aquatic habitats present in the Southeast: coastal estuaries, coastal wetlands, inland wetlands, mountainous riverine systems, forested riverine systems, lowland riverine systems (two groups), and urban and working lands.
In the first breakout session (Session 4), participants were asked to identify what **criteria/indicators** (e.g. something that is being monitored or an impact observed) are currently utilized to recognize that a system is approaching or is experiencing hydrological drought? **A wide variety of indicators, spanning hydrology, ecology, agriculture, and socio-economic indicators – not just streamflow and precipitation – are used to assess impacts and potential risks to aquatic ecosystems.** A summary of the topics identified by participants are found in Table 3. Topics marked were those added to the flipcharts and do not indicate that the other elements are not important or are not utilized in these habitats.

	Inland Wetland	Urban/ Working Lands	Forested Riverine	Lowland Riverine A	Coastal Wetland	Lowland Riverine B	Mountain Riverine	Coastal Estuary
Streamflow/Baseflow	x	x	x	x	x	x	x	x
Soil Moisture	x	x		x	x	x		x
Groundwater & Recharge	x		x	x	x		x	x
Reservoir Levels		x	x	x		x		
Sea Surface Temperature					x			
Precipitation	x	x	x	x	x	x	x	x
Snowfall			x					
Temperature		x		x				
Evapotranspiration		x	x					x
Indicator Species Health	x	x						
Documented Mortality or Decreased Abundance of Fauna (e.g. low harvest, fish kills)					x	x		x
Species Behavior Changes (e.g. migration)		x			x	x		x
Vegetation Stress (e.g. NDVI, leaf area)	x	x	x		x	x		x
Wildfire		x	x		x	x		
Crop Yields	x	x	x					

Drought Alerts/Regulatory Triggers	x		x	x	x	x	x	
Citizen Science/Stakeholder Reports		x	x	x	x	x	x	
Water Temperature						x	x	x
Salinity					x			x
Harmful Algal Blooms						x		x

Table 3: Topics mentioned in Breakout Session 1 (Session 4) for indicators and criteria of drought. Topics are broadly grouped by hydrology (blue), climate (yellow), ecology (green), human interaction and policy (red) and water quality (orange).

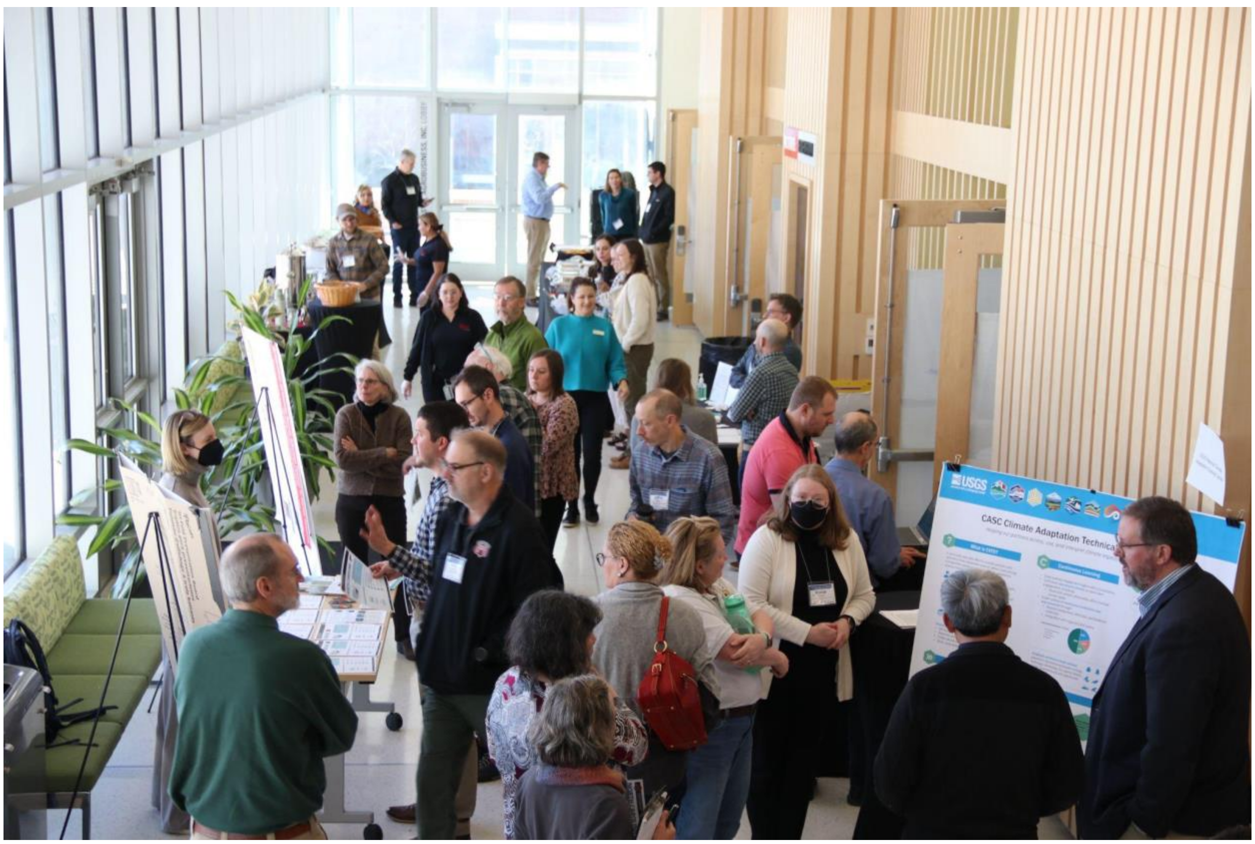
As drought conditions worsen, groups noted that communication and coordination increases, triage of response becomes more critical, and the focus narrows (from broad to fine scale).

Next, groups were asked to catalogue the **impacts** of drought on systems that are being observed and what **actions** are being taken to address reduced water availability during a drought. Summarized responses are included in Appendix F.

Action 4: Utilize existing tools and resources to maximize efficiency

A primary goal of this Workshop was to identify and communicate existing resources in the Southeast that can be applied more readily by the region. Sharing information between information providers and users across states and sectors was identified as a key need throughout the Workshop for improving drought response and planning in drought monitoring, water management, and natural resource management.

Federal, state, Tribal, academic, industrial and non-governmental institutions and organizations in the region contribute to the development and dissemination of most resources and knowledge. Appendix B identifies a range of tools and resources identified during the Workshop including web tools, datasets, funding opportunities, reports, organizations, information repositories, code, and policy documents. These are organized across several categories: 1) Drought and Climate Monitoring 2) Natural Resource Management 3) Streamflow and Water Monitoring 4) Water Supply and Management and 5) Climate Projections.



Key Takeaways from Individual Sessions

Session 1: Setting the stage - drought and water trends in the Southeast

This session set the stage for the Workshop with presentations that provided an overview of hydro-climate trends and drought in the Southeast as well as a discussion about the importance of proactive regional drought planning.

Jeff Lineberger (Duke Energy) (*Regional Importance of a Current Drought Plan*) spoke first about the history of drought planning at Duke Energy in North Carolina and South Carolina. Communication with the public about conservation measures was noted as a key challenge, and he noted that communication should be constant and actions should be consistent and objective. Key points included:

- Proactive, long-term drought planning and actions are essential.
- Effective plans must consider science and stakeholder/community needs.
- Systems should learn from drought events to improve plans and increase efficiency.
- Communication (especially consistency of messages) and public education on water conservation and drought response are critical for success.

Lee Ellenburg (Alabama State Climate Office/University of Alabama) (*Precipitation and Droughts in the Southeast*) spoke about the hydro-climate of the Southeast and the complexity of drought. Key points included:

- Droughts are complex and unique in the Southeast, complicated by tropical storms, rising temperatures, and baseline high levels of water availability.
- Better monitoring and predictive models are essential for addressing rapid-onset "flash droughts."
- Understanding drought timing and impacts is critical and drought effects often extend beyond individual events, complicating recovery and management.
- Understanding and documenting ecosystem impacts remains a gap in drought monitoring.

Caleb Mitchell (USGS) (*Trends of Annual Minimum 7-day Average Flow in Georgia, South Carolina, and North Carolina, Climate Years 1932–2021*) shared work being done by the USGS South Atlantic Water Science Center on analyzing historical streamflow trends in North Carolina, South Carolina, and Georgia and their connections with historical climate patterns and trends. Key points included:

- Natural annual variability and seasonal low-flow periods are important considerations when characterizing droughts.
- Although we are already seeing historical trends in some climate variables, trends in streamflow are less straightforward. Most streams had no significant trends in streamflow over the last 30 years (1992-2021), but those that did more often showed downward (i.e. drying) trends.

- Long term monitoring networks are essential for understanding how the system is changing.
- There is a critical difference between analyzing a direct metric of interest (streamflow) versus other proxies (temperature and precipitation).

Session 2: Impacts of low-flow conditions on Southeast aquatic species and habitats

This session provided an overview of our current understanding of how different aquatic species and ecosystems may be impacted by drought and low-flow conditions. The panelists were asked to introduce themselves, how their focal system responds to drought, and any pathways of drought impacts on their system or resource.

Jennifer Archambault (USFWS) spoke about the U.S. Fish and Wildlife Service's mission to administer the Endangered Species Act and her view of drought coming from a scientific background of freshwater mussel research, especially the critical nature of compound heat and water availability stress. **Dan Magoulick** (USGS/University of Arkansas) spoke on his fieldwork on disturbance ecology and ecological flow monitoring. Seasonal and supra-seasonal drought stresses systems differently (groundwater) and impacts fish and crayfish populations. **Rainee Tetreault** (Eastern Band of Cherokee Indians) spoke about the importance of water quality standards for the Eastern Band of Cherokee Indians which allow them to respond quickly and consistently to drought and other adverse conditions. **Seth Wenger** (University of Georgia) spoke about long-term river ecosystem services and sustainable resource management across sectors to maintain sustainable water use even in drought periods. **Mike Osland** (USGS) spoke about drought's impact on coastal wetlands through salinity changes. He highlighted the usefulness of the Coastal Salinity Index (CSI) which tracks salinity extremes, supports drought impact monitoring, and informs management strategies.

Key Points:

- Preparing for and responding to drought requires an emphasis on resilience and nature-based solutions.
- Challenges in preparing for drought exist due to funding and timing constraints and interactions between drought and other stressors (e.g., urban development, invasive species).
- High heterogeneity across systems and species makes management difficult. Impact thresholds, levels of adaptability and resilience, and recovery rates are all space, time, and species dependent.
- More stream gauges, real-time salinity monitoring, and data on intermittent streams will help managers and scientists understand drought in different systems.
- Drought patterns are changing, with observed shifts in flow variability and hydrological responses over decades.

Session 3: Understanding water management in low flow conditions

This session provided an overview of the U.S. Army Corps of Engineers (USACE) operations and environmental considerations across the region, and highlighted emerging partnerships to address aquatic ecosystem needs in the context of water management operations.

Matthew Parrish (USACE) (*Overview of the U.S. Army Corps of Engineers Operations During Low Flow Conditions in the Southeast*) gave an overview of USACE operations in the South Atlantic region including authorized purposes. Key points included:

- The scale of USACE operations in the Southeast is extensive and guided by a broad range of management and water-related official policies and procedures including drought contingency plans and federal legislation.
- During drought, appropriate drought contingency plans set metrics and triggers to identify drought conditions and their resolution.

Troy Ephriam (USACE) (*Apalachicola-Chattahoochee-Flint Basin Status and Drought Level Response*) discussed USACE Mobile District operations including at specific reservoirs throughout the region. Key points included:

- The 27 projects in the district serve a variety of purposes including flood control, hydropower, recreation, fish and wildlife, navigation, water supply, and water quality.
- In extreme drought conditions, water is only allowed to meet critical water needs (water supply). In other conditions, reservoirs can meet water supply, water quality, and endangered species usage needs.
- Plans are stress tested and responsive to changing conditions. They are developed with the most up-to-date information at the time and are changed to meet operational needs that were not sufficiently addressed in previous droughts.

Ashley Hatchell (USACE) (*Sustainable Rivers Program at Work in USACE-Wilmington District*) spoke about district operations and the partnership work occurring on Jordan Lake and Dam and the Cape Fear River through the Sustainable Rivers Program (SRP). Key points included:

- Drought contingency plans, like those developed for Jordan Lake, are collaborative and adaptive management strategies, and can feature increased proactivity, potentially allowing for increased water storage for longer periods of time.
- The SRP is a formal agreement between the USACE and The Nature Conservancy to identify, refine and implement environmental strategies for the USACE (learn and adapt): In the Roanoke River, the SRP is helping to validate operational expectations and identify adaptive management strategies after recent changes to flood operations. It is also working to mitigate water quality and fish migration issues in the Cape Fear River exacerbated by downstream locks and dams.

Session 4: Integrating science and management needs for drought in aquatic systems

These presentations focused on discussing drought and low-flow in the context of integrating science and management, especially in low-information contexts. This includes how data and monitoring can be identified and incorporated to prepare and respond for drought.

Daren Carlisle (USGS) (*Estimating Ecological Vulnerability to Drought: A Case Study in the Cascades and Sierras*) discussed a project investigating the relationship between the severity of hydrologic drought and ecological degradation as well as the factors that may serve to ameliorate ecological drought. Key points included:

- Groundwater recharge is a critical variable for predicting ecological vulnerability to drought but the data have limited spatial availability.
- The predictive model showed that biological degradation (with specific impacts on macroinvertebrates) was influenced by drought conditions.

Laura Rack (University of Georgia) (*Defining and Applying Ecologically Based Low Flow Thresholds in a Management Context*) discussed a project in the Flint/Iconia River Basin in Georgia trying to integrate ecological flow thresholds for water management. Key points included:

- Five functional flow thresholds provide a framework for how water supply, recreation, and ecology are limited during drought conditions.
- Three themes for integrating flows in management: 1) Identifying and understanding the local actors and settings for water resources decision-making, 2) Identifying an e-flow approach and developing quantitative metrics and thresholds as a starting point for evaluating river ecosystem needs alongside other water uses, 3) Providing the necessary information to evaluate and interpret ecological metrics alongside other water uses.
- Regardless of the uncertainties, it is important to start somewhere and there is still a lot of science to do: how low, how long, and how often? However, metrics that represent flow-related ecosystem functions can help to integrate ecosystem needs with other uses.

Session 5: Response during low-flow conditions and incorporating ecological needs into decisions

This session shared how water managers and natural resource managers monitor and respond during a drought and provided examples of effective practices for incorporating ecological needs into decision making during low-flow conditions.

Wei Zeng (Georgia Department of Natural Resources Environmental Protection Division) spoke about his work in Georgia developing and implementing regulations for rivers, lakes, municipal, industrial and agricultural water uses. **Jennifer Sharkey** (Tennessee Valley Authority) spoke about the integrated network of dams managed by the Tennessee Valley Authority and the six objectives for all the dams (power generation, navigation, water control, water supply, recreation, and flood control). **Harold Brady** (North Carolina Department of Environmental Quality) spoke about water planning in North Carolina and the importance of incorporating industrial water use and local water supply planning considerations. **Bernie Kuhajda** (Tennessee Aquarium) spoke about his work as a habitat conservation specialist with the

Tennessee Aquarium and their operations on emergency rescue in low-flow conditions in 2024 and previously. **Sonia Mumford** (USFWS) spoke about hatchery habitat and the collaborative nature of managing species between the hatchery and natural settings and between partners with different objectives.

Key Points:

- Many of the organizations (State of Georgia, Tennessee Valley Authority, State of North Carolina) have done a considerable amount of planning for low-flow conditions in the past 20 years. However, there are still knowledge and operational gaps in incorporating environmental flow into the plans. In some cases, these plans do not move quickly enough to allow for urgent conservation action.
- The importance of building long-time and well-maintenance partnerships cannot be overstated. It's important to have consistent communication (permittees, the public, local governments, etc.) especially with partners that might not usually be at the table or that may have competing interests (industry, farmers, etc.).
- More biology-ecology studies are needed and should be incorporated into decision making as much as possible because they increase defensibility of decisions.

Session 6: Case studies on collaborative planning and management

This session highlighted specific approaches and solutions towards addressing challenges of balancing water demand and ecosystem health during low-flow events, and lessons learned that can be applied across the region with a focus on connecting science, policy, and stakeholder engagement. Two large initiatives were represented in a panel discussion:

The **Comprehensive Everglades Restoration Plan**: Amanda Kahn and Walter Wilcox, from the South Florida Water Management District spoke about *Collaborative Planning and Management across South Florida Ecosystems*. They highlighted the balance between providing mutual benefit for human water supply and ecosystem benefits within the project. Also key is the continuous monitoring and assessment feedback loop that happens after individual project components are implemented. One critical component of the planning has been an integrated modeling framework.

The **Georgia Flow Incentive Trust (GA-FIT)**: Mark Masters and Steve Golladay from the Georgia Water Planning and Policy Center, and Anna Truszczynski from the Georgia Department of Natural Resources Environmental Protection Division spoke about their work coordinating policy across the Lower Flint Region. They highlighted that stakeholder engagement on the ground has been key, especially given that the initiative blends policy with on the ground data collection in aquatic habitats.

Key Points:

- Communication across agencies and collaborators is crucial even with different interests within the same ecosystem. Both cases span large geographic areas and incorporate varied interests (agricultural, municipal and industrial water supply, ecological) so approaches must be tailored.

- Clear and continuous engagement is especially important and difficult in these kinds of projects that span decades and involve hundreds of participants – where turnover is inevitable.
- Both projects have developed a set of tools that work well with different layers of complexity, from monitoring and heterogeneity in policy approaches, to integrated modeling efforts across groups. Access and continued improvement of tools for multifaceted applications are essential components needed for reaching ecosystem goals.
- Both projects are complex and have long lifespans and therefore both understand the need for iterative approaches that learn from successes and failures and allow for updates and modifications (e.g. in permitting rules and decisions).

Session 7 (Tool and Resource Fair) information can be found in Appendix D. Session 8 (Breakout) is discussed in Action 1 and Appendix F. Session 9 was eliminated from the program due to scheduling constraints.

Session 10: Applications of future low-flow models in the Southeast

This session showcased examples of how future flow projections are currently being developed and used across the Southeast. Presentations aimed to share broad assumptions and data limitations that exist in their development and application.

Catherine (Kasia) Nikiel (USGS/Oak Ridge Institute for Science and Education (ORISE) Research Participation Program) (*Hydroclimate Futures of the Southeast*) spoke about how climate projections can be incorporated into management decisions despite competing pressures and limited biological and ecological knowledge for some species and systems. Key points included:

- While there is climate model spread and emissions scenario uncertainty, trends indicate that Southeast temperatures will increase and rain will fall in heavier events. This will translate to several patterns that may perpetuate longer, more frequent and more intense drought events.
- Connecting hydroclimatic change to on the ground impacts is challenging and there are confounding factors (including teleconnections, tropical storms, and the impacts of vegetation) that contribute additional uncertainty.
- Changes in the hydrologic cycle are increasingly captured in large-scale hydrologic modeling but there are tradeoffs between scale and detail and the representation of certain system features (dams, withdrawals, groundwater, etc.).
- Managers and scientists will need to accept complexity and move forward with best practices for using climate and hydrology data including scenario planning. As scientists, it is key to understand what information is most useful to a given management need and how to communicate uncertainty.

Taylor Woods (USGS) (*Low Flow Impacts on Chesapeake Bay Ecological Communities (And Beyond)*) spoke on the application of USGS modeling to understand future flow changes and their impacts on aquatic biota (specifically freshwater fish) at several key watersheds in the United States. Key points included:

- An interdisciplinary team is critical for this project, including specialists in hydrology, aquatic ecology, and geospatial analytics. This supports a high level of data utilization, integration, and development of new connections.
- Connecting with local partners was key to understanding their concerns about changes to the system and deciding project objectives. Each watershed has its own set of diverse needs.
- Integrating the data needed to run models is a huge task and relies on robust technical infrastructure (like USGS high-performance computing).

Michele Eddy (RTI International) (*Modeling Flow-Ecology Changes in South Carolina and Across the Region*) spoke about the application of the RTI International WaterFALL model, a highly detailed watershed model that can be applied to answer questions related to future flow, nature-based solutions, and water quality. Key points included:

- The model packaging and nature of RTI International projects make it so that new projects can be transferred to a new area and initiated in a streamlined way. However, funding and time are still mitigating factors.
- It is important to communicate inputs and outputs in a way that is meaningful to the end user. This helps to build confidence in any outputs produced by the model.
- Decisions on scenario planning and inputs should address the needs of the end user while utilizing best practices for applying climate data and scenario planning.

Session 11: Working towards aquatic resilience and adaptation to future low-flow events

This panel session highlighted case studies, strategies, actions and approaches being utilized to plan for future drought and low-flow events in aquatic systems.

Robert Burgholzer (Virginia Department of Environmental Quality) spoke about the importance of monitoring water availability, and especially groundwater storage, which is often overlooked. Operational modeling at the state of Virginia level has helped to understand water availability in the state and prepare for the next drought event even when it may look substantially different than any historical drought. **Erin Rivenbark** (USFWS) spoke about listing and recovery work in the U.S. Fish and Wildlife Service and how they try to approach managing their biodiversity in the region largely through scenario planning. While many of the currently petitioned species have very little life history information, scenario planning allows the Service to incorporate the best available science and plan for a range of outcomes. This involves working with teams of collaborators to assess risks and uncertainties. **Dave Penrose** (Penrose Environmental Consulting, LLC) spoke about the risks to macroinvertebrates in the aquatic system and how they are some of the most important components to understanding ecosystem health. He argued for the importance of in-depth ecological and taxonomic knowledge for these species and the training of the next generation of scientists. **Zack Edwards** (Working Lands for Wildlife) spoke about his work with the Working Lands for Wildlife organization and their framework for enhancing aquatic resource connectivity across 16 states.

Key Points:

- More can be done to incorporate historical and future climate in planning efforts. One aspect that was highlighted as a planning priority is the risk of consecutive drought years or events.
- Uncertainty in future climate projections can complicate decision making. Scenario planning, and design frameworks that account for a range of projected futures is key – especially when a characteristic of future hydroclimatic conditions is increased variability.
- Collaboration with academic and local institutions is encouraged to fill gaps in species data and develop new risk assessment frameworks.

Conclusion: Strengthening Regional Collaboration and Looking Forward

This Workshop highlighted the tremendous amount of work being done to increase resilience to ecological drought events in the Southeastern United States. It also showed that a whole systems approach is necessary and requires engagement from water supply managers, scientists, natural resource managers, and sectors dependent on water that are committed to finding interdisciplinary solutions.

There are substantial **near-term opportunities** to build cross-sector resilience to drought in aquatic ecosystems. Increased communication, collaboration, monitoring, data sharing and integration, and clearer public education were indicated as high-impact, near-term efforts. Additional synthesis and integrated data sharing is necessary to effectively understand and address **long-term science needs**. These developments can also help the community to further quantify what is missing in terms of ecological indicators and markers of aquatic health and resilience in the face of drought and support adaptation planning.

Significant work is already being done, with scientists, managers, and policymakers taking advantage of the broad range of data, tools, and information available. Streamflow and precipitation are necessary but not sufficient indicators for characterizing ecological drought in aquatic ecosystems. A variety of **indicators** are used to recognize drought occurrence and assess impacts and risks in aquatic ecosystems, including hydrology, ecology, agriculture, and socio-economic factors. The Southeast has a substantial number of **existing resources, data, and tools** to support drought preparedness, response and planning. A catalog of those mentioned during the Workshop are included in Appendix B.

Ultimately, this Workshop succeeded in convening a unique community of professionals concerned about the impacts of drought on aquatic ecosystems and providing knowledge sharing and networking opportunities that often lead to future work and collaboration. Additionally, this joint SE CASC and NIDIS gathering helped integrate management communities on this issue and provided a dedicated venue for discussing issues related to drought in aquatic ecosystems with a Southeast focus.

Key information and actionable takeaways are included in the main text, but additional details and resources are included in several appendices that will be useful to attendees and the broader region:

- Appendix A: Meeting agenda with session objective and participants
- Appendix B: Tool and resource list with short descriptions and links.
- Appendix C: Poster session participants with titles, abstracts, and co-authors
- Appendix D: Tool and resource fair presenters
- Appendix E: List of in-person Workshop participants with their affiliations and emails.
- Appendix F: Responses from breakout sessions (Session 4 and 8) including summaries and impact-effort grids.
- Appendix G: World Cafe questions and responses

Acknowledgements

We thank all those who attended and contributed to the event's success, including the following: the Plant Sciences Building staff at North Carolina State University; the Southeast CASC staff for assisting with meeting logistics and operations including Michelle Jewell, Maira Brondizio and Cari Furiness; the University Corporation for Atmospheric Research (UCAR) Cooperative Programs for the Advancement of Earth System Science (CPAESS) staff including Keri Dawn Solner and Tania Sizer. The Workshop was co-organized by Catherine (Kasia) A. Nikiel and Meredith Muth.

The Workshop steering committee included the following organizations: NOAA's National Integrated Drought Information System (NIDIS) Southeast Drought Early Warning System; U.S. Geological Survey (USGS) Southeast Climate Adaptation Science Center; USGS National Climate Adaptation Science Center; North Carolina Department of Water Quality, Division of Water Resources; USGS South Carolina Cooperative Fish and Wildlife Research Unit/Clemson University; University of South Carolina; USGS Lower Mississippi Gulf Water Science Center Corey Dunn, USGS North Carolina Cooperative Fish and Wildlife Research Unit/North Carolina State University; Alabama State Climatology Office/University of Alabama Huntsville; American Rivers; USGS South Atlantic Water Science Center; Southeast Aquatic Resources Partnership; U.S. Army Corps of Engineers (USACE) South Atlantic Division; NOAA Southeast Regional Climate Center; U.S. Department of Agriculture (USDA) Southeast Climate Hub; Georgia Water Planning and Policy Center; NOAA Southeast River Forecast Center; The Jones Center at Ichauway; USGS Wetland and Aquatic Research Center; Native American Fish and Wildlife Society; U.S. Fish and Wildlife Service Science Applications; U.S. Forest Service Southern Research Station/NCSU; South Carolina Department of Natural Resources. Specific steering committee members can be found on the Workshop website.

We would also like to acknowledge the session moderators and breakout facilitators who contributed to session development and facilitated engaging and fruitful discussions. Session moderators were Meredith Muth, Corey Dunn, Todd Hamill, Barrett Smith, Kasia Nikiel, Rachel McGuire, Ryan Boyles, and Katherine Smith. Breakout session facilitators included Ryan Boyles, Greg Carbone, Elliot Wickham, Luke Bower, Brianne Minton, Ben Emanuel, Will Farmer, and Meredith Muth. World Cafe facilitators included Klaus Albertin, Ge Sun, Halina Pyzdrowski, Mileisha Velazquez, Kasia Nikiel, Michael Gavazzi, and Asumi Saito.

We thank the 2024-2025 SE CASC Global Change Research Fellows for note taking, helping to run the meeting, assembling tools and resources, and producing session recaps, including: Grace Choi, Bigyapti Nepal, Christopher Oates, Halina Pyzdrowski, Asumi Saito, and Mileisha Velazquez. Thank you to Lydia Campbell, Cari Furiness, and Ryan Boyles for providing additional synthesis support for this summary.

Thank you to Michelle Jewell (NCSU SE CASC) and Kelsey Satalino Eigsti (CIRES / NOAA NIDIS) for providing editing and formatting support. Thank you to Katherine Smith (USGS) and Will Farmer (USGS) for providing peer review.

The report resulting from the 2025 Drought and Aquatic Ecosystems in the Southeast Workshop reflects the dialogue and discussion of attendees, and does not represent official Administration policy or position. This report has been peer reviewed and approved for publication consistent with USGS Fundamental Science Practices (https://pubs.usgs.gov/circ/1367/). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Information about Conveners

The NOAA/NIDIS-led Southeast Drought Early Warning System (SE DEWS) and the Southeast Climate Adaptation Science Center (SE CASC) are two regional entities that have built cross-state partnerships and relationships with stakeholders that allow them to bring together key knowledge producers and users.

The Southeast Drought Early Warning System (DEWS) is a collaborative federal, regional, state, and local interagency effort to improve drought early warning capacity and build long-term drought resilience throughout the region. Launched in 2020, this regional network includes Tennessee, Virginia, North Carolina, South Carolina, Georgia, Florida and Alabama. This is one of eight regional DEWS networks across the nation and is coordinated by the National Integrated Drought Information System (NIDIS) at the National Oceanic and Atmospheric Administration (NOAA). The 2022-2025 Southeast DEWS Strategic Action Plan is here.

The Southeast Climate Adaptation Science Center (SE CASC) is part of a network of nine Climate Adaptation Science Centers managed by the U.S. Geological Survey National Climate Adaptation Science Center. Our mission is to deliver science to help fish, wildlife, water, land, and people adapt to a changing climate. The current SE CASC footprint covers Tennessee, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Arkansas, Puerto Rico and the U.S. Virgin Islands. The National and nine regional CASCs are federal-university partnerships made up of a consortium of institutions, including university, Tribal, and non-profit organizations. See the Summary of the 2016 Southeast Workshop and the National CASC Synthesis document.