Chapter 10

Impacts of Climate Change and Variability on Water Resources in the Southeast USA

COORDINATING LEAD AUTHOR

Ge Sun (gesun@fs.fed.us; Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

CONTRIBUTING AUTHORS

Sankar Arumugam (Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina)

Peter V. Caldwell (Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

Paul A. Conrads (US Geological Survey, South Carolina Water Science Center, Raleigh North Carolina)

Alan P. Covich (Odum School of Ecology, University of Georgia, Athens, Georgia)

James Cruise (Department of Civil and Environmental Engineering, University of Alabama- Huntsville, Huntsville, Alabama)

John Feldt (NOAA/NWS/SERFC, Peachtree City, Georgia)

Aris P. Georgakakos (School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia)

Richard T. McNider (Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama)

Steven G. McNulty (Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

Daniel A. Marion (Center for Bottomland Hardwoods Research, USDA Forest Service, Hot Springs, Arkansas)

Vasu Misra (Meteorology Department, Florida State University, Tallahassee, Florida)

Todd C. Rasmussen (Warnell School of Forestry and Natural Resources, The University of Georgia, Athens, Georgia)

Luigi Romolo (Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana)

Adam Terando (Climate Change Science Center, North Carolina State University, Raleigh, North Carolina)

The Southeast (SE) and Caribbean encompasses of a large geographic region including 11 states, and Puerto Rico and US Virgin Island. The region is known for warm climate, abundant water resources, and rich ecosystems and biodiversity. Many areas of the SE have seen population increases between 45% and 75% during the past three decades. The population is projected to increase 50% in the next 50 years, representing one of the most dynamic economies in the nation (Wear and Greis 2011). The region relies on water resources to maintain this growing economy that is largely based on forestry, recreation, manufacturing, tourism, agriculture, power generation, fisheries, and navigation.

However, in recent decades the 'water rich' SE region has experienced periodic water shortages due to recurring severe droughts and the increasing levels of consumptive water use from multiple sources (Sun et al. 2008). Water stress is especially critical in the large metropolitan areas such as Atlanta and Charlotte. Thus, any additional stresses implied by climate changes are beginning to concern all economic sectors (Caldwell et al. 2012).

Climate change is hydrologic change. Water is essential to life. Hydrologic alterations due to climate change have profound impacts to ecosystems and society. The objectives of this chapter are (1) to document the consequences of climate change and variability in altering the quantity, quality, and timing of water supplies at multiple scales during the past and the next 50 years; (2) to present case studies showing how climate change has affected regional water resources; and (3) to discuss water resource management strategies to mitigate and adapt to climate change across the southeastern region.

Key Findings

- Future climate warming likely will increase water loss through evapotranspiration (ET) due to increased evaporative potential and plant species shift. Greater ET can decrease total streamflow, groundwater recharge, flow rate, and regional water supplies.
- Water supply stress is projected to increase significantly by 2050 due to hydrologic alteration caused by climate change and increased water use by key economic sectors, such as domestic water supply, irrigation agriculture, and power plants. Water supply stress will become most severe in the summer season when normal rainfall is typically not sufficient to meet evaporative demand of the atmosphere.
- Declining runoff and increasing demands for water resources are likely to increase the pressure on the existing reservoirs, leading to deeper and longer lasting drawdowns.
- Runoff and soil erosion potential are projected to increase in some areas due to changes in rainfall that either increase rainfall erosivity or decrease vegetative cover protection.
- Inland water temperature is projected to increase with increases in air temperature, resulting in possible adverse impacts on coldwater fish habitat in the Appalachians.

- Salinity intrusion in coastal fresh water systems likely will increase in response to sea level rise and potential decreases of fresh water inputs from uplands due to climate change.
- Ecosystem restoration, including afforestation, has the potential to mitigate or reduce adverse impacts of hydrologic extremes (droughts or floods) and water quality caused by climate change.
- Large knowledge gaps exist about how future climate change and other stressors—such as human population growth, land use change, energy security, and policy shifts—will interactively affect both surface and ground water availability.
- Consequences of proposed adaptation management options, such as increase in irrigated agriculture and bioenergy development, must be carefully evaluated to maximize their effectiveness and cost-benefit.

10.1 Water Resources in the Southeast

The 2009 National Climate Assessment suggests that droughts, floods, and water quality problems are likely to be amplified by climate change in the SE (Karl et al. 2009). More descriptions of climate change in the SE region can be found in Chapter 2 of this volume. Projected demographic and socioeconomic changes associated with rapid population growth further threaten water resources (Lockaby et al. 2011, Marion et al. 2012). Recent drought experience in many areas of the USA indicate that even small changes in drought severity and frequency may have major impact on agricultural production and ecosystem services, including drinking water supplies (Easterling et al. 2000). Unique to the SE are the 8000 km long, mostly populated, low-lying coastal areas that are vulnerable to salt water intrusion, flooding, erosion, water quality degradation, and wetland losses in addition to projected sea level rise and intensified tropical storms (Lockaby et al. 2011). Recent modeling studies suggest that the frequency of major hurricanes (Categories 3 to 5) likely will increase in the future, while the overall number of tropical cyclones will likely decrease (see Chapter 2). The devastating consequences of Hurricane Katrina in 2005 indicate the severity of what extreme climate impacts might be on coastal zones. The large range of hydrometeorological and socioeconomic characteristics across the region implies that responses to climate change in the SE require a multifaceted adaptation and mitigation management strategy (Marion et al. 2012).

10.2 Key Constraints to Water Resources in the Southeast

Changing Climate

Climate change alters stream water quantity and quality by altering hydrometeorological patterns, elevating ET potential, and disrupting biological processes. Climate variability, growing water demands, and limited storage capacity exacerbate the risk of water shortages during droughts. In addition, buildup of dissolved phosphorus and cyanobacteria in drinking water reservoirs and rivers is a major threat to public health (Meybeck 2004, Osidele and Beck 2004). Damage from tropical and winter storms has also increased dramatically. As a result, the region is faced with the need to develop new infrastructure, such as reservoirs and water treatment facilities; management strategies; and planning policies to respond to these challenges. Climate-related hazards, particularly tropical storms and drought, are the most frequently occurring natural hazards in the Caribbean. Projected increase of drought frequency is of vital concern for the Caribbean islands, which already have limited freshwater sources (Farrell et al. 2011).

Sea Level Rise

If global temperatures continue to increase, sea levels are expected to rise as much as 2 ft by 2050 in the coastal areas in the SE (Titus et al. 2009, Obeysekera et al. 2011). Water resources in coastal areas in Louisiana, Mississippi, Alabama, Florida, and the Caribbean Islands are vulnerable to saltwater intrusion and flooding. Some of the major economic and environmental consequences of saltwater intrusion into freshwater aquifers and drainage basins include the degradation of natural ecosystems and the contamination of municipal, industrial, and agricultural water supplies (Bear et al. 1999). Changes to patterns of coastal flooding as a result of sea level rise may increase damage to forests and wetlands, and property and infrastructure (Heimlich et al. 2009). In addition, sea level rise will have significant effects on river form and processes and may alter channel behavior far upstream of the estuaries and coastline.

Rising Water Use for Energy Generation

The relationship between water and energy, called the "water-energy nexus," represents a critical business, security, and environmental issue (Glassman et al. 2011). The growing population and irrigated agriculture in the SE has increased the demand for energy by orders of magnitude over the past decades. Power production by nuclear, coal, gas, and hydropower is the largest overall user of water resources in the region (Kenny et al. 2009). Water availability is a large concern in the SE, especially during drought conditions when cumulative effects of thermal discharges reduce the assimilative capacity of streams and the sensitivity of aquatic organisms during periods of high temperatures and low dissolved oxygen (Webb et al. 2008). Loss of dissolved oxygen for aquatic species is further accelerated by eutrophication and the accumulation of nutrients from outdated wastewater treatment plants and agricultural fertilizer runoff from feed lots and eroding farmlands. Competition between water use for energy and other water uses, such as drinking water and irrigation, are most severe during droughts. During the 2007-2008 drought, water providers from Atlanta, GA, to Raleigh, NC, urged residents to conserve water while power plants struggled to avoid blackouts. In North Carolina, water woes forced Duke Energy to reduce output at its G.G. Allen and Riverbend coal plants on the Catawba River (Averyt et al. 2011). In Alabama, the Browns Ferry nuclear plant had to drastically reduce its output to avoid exceeding the river temperature limit and killing fish in the Tennessee River (Averyt et al. 2011).

Increasing Water Use for Irrigation

The 2008 US Farm Bill established the Agricultural Water Enhancement Program (AWEP) to encourage more efficient and effective irrigation and water conservation measures. In order to maintain a robust agricultural economy and food prices, there is a large potential to expand irrigated agriculture in the SE, especially in South Carolina and Alabama. Florida, Georgia, and Mississippi have substantially expanded irrigation in the last 40 years, but irrigation withdrawals impair summer stream flows and threaten riverine ecosystems. Increasing existing water storage is being considered as a potential strategy to restore environmental flows. For example, Alabama farmers have recently begun to build off- stream reservoirs to store water during the winter, when streamflows are greatest, for use during the spring and summer crop season (Curtis and Rochester, 2012).

Changing Land Use and Land Cover

The conversion of forest lands and wetlands to residential, commercial, industrial, and agricultural uses likely will exacerbate the impacts of climate change (Lockaby et al. 2011, Sun and Lockaby et al. 2012). For example, large areas of the North Carolina Pocosin system in the Atlantic Coastal Plain region have been modified into an extensive network of drainage canals to make agricultural production feasible in the normally hydric soils. These canals have altered the hydrology, lowered the water table, and increased the vulnerability of the system to long-lived fires. As the climate warms, droughts likely will be more severe, more frequent, or both, thus increasing the exposure to fires that can burn for many weeks (Liu et al. 2012). Climate change influences streamflows differently from land use change (Wang and Hejazi 2011). In the Appalachian region, the influence of recent climatic trends is larger than the influence of direct human impacts from urbanization or agriculture. However, in the Piedmont and Coastal Plain regions, direct human impacts on streamflow have generally been larger than the impacts of recent climatic trends (Wang and Hejazi 2011).

Insufficient Water Storage

Unlike the western USA, most of the reservoir-reliant water supply systems in the SE are within-year systems that store water during the high-flow fall and winter season and release it during the low-flow spring and summer season. The smaller size of these systems makes them more vulnerable to any substantial increase or decrease in annual runoff due to climate change. Detailed uncertainty analyses of climate change impact on the vulnerability of water supply systems are important tools for adaptation and mitigation. Currently, the high level of uncertainty in precipitation and runoff projections does not warrant application of projections for major long-term investment decisions, such as building a new reservoir to respond to drought or flood over the next 50 years. However, it is important to develop strategies to reduce the vulnerability of systems if projected climate changes occur or projections become more certain.

Unique Biodiversity

Native ecosystems in the SE are among the most diverse and unique in the world. Few areas on the planet have such biodiversity and few face as great a threat of destruction. Trying to reconcile regional development against the backdrop of fragile and fragmented ecosystems is a key sustainability issue (Richter et al. 2003). Allocating proper environmental streamflows is essential to protect the aquatic resources.

Unique Cultures

The racial legacy in the SE has left an imprint on educational institutions both from segregation and desegregation, and environmental perceptions. Trying to bridge the old versus the new South will require the development of communication and collaboration mechanisms that are relevant to important subcultures, not only the existing African-American and rural communities, but also the emerging Latin-American communities. In addition, there is increasing evidence that the poor and elderly in the SE have unequal access to natural resources, including water (John et al. 2012).

10.3 Historical Climate Trends

Observed and projected climate change in the SE is spatially complex due to the interacting influences of global climate change and natural large scale climate oscillations including El Niño-Southern Oscillation (ENSO), Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) (Li L. et al. 2011, see Chapter 2). Across the region, mean air temperature increased 0.9ºC between 1970 and 2008 (Karl et al. 2009). During the 20th century, annual rainfall amounts increased 20% to 30% or more for some portions of the SE, although other portions experienced declines in rainfall amounts. The amount of very heavy rainfall (more than 2 in per event) increased 15% to 20% from 1958 to 2007. The SE summer rainfalls have exhibited higher interannual variability with more frequent and intense summer droughts and anomalous wetness in the recent 30 years (1978 to 2007) than earlier in the 20th century (1948 to 1977) (Karl et al. 2009, Wang et al. 2010). The number of abnormally wet and dry summers in the SE region doubled over the last few decades (Li W. et al. 2011). As anthropogenic forcing continues to increase and the North Atlantic Subtropical High (NASH) climate system continues to intensify, the SE will experience more frequent wet and dry summers during positive Pacific Decadal Oscillation phases (Li W. et al. 2011). Average annual temperatures in the region are expected to increase by an additional 2.5°C to 3.5°C over the next 50 years (McNulty et al. 2012). More discussion about climate change in the SE can be found in Chapter 2.

10.4 Uncertainty in Predicting Future Climate and Hydrologic Impacts

Most global climate models (GCMs) predict that as the climate warms, the frequency of extreme precipitation will increase across the globe (O'Gorman and Schneider 2009). However, less than two-thirds of GCMs agree on the predicted change in direction of future precipitation events for the eastern USA (IPCC 2007). The uncertainty of predicting local, regional, global precipitation patterns at different temporal scale is well recognized (Chapter 2, Chan and Misra 2009, Misra et al. 2009).

Climate change impacts hydrologic processes and water resources directly through precipitation, evapotranspiration, groundwater recharge, peak flow, and water yield; and indirectly through water quality and water use by irrigation. Many of the responses are not unidirectional and can be additive or cancel each other. For example, increase in atmospheric CO_2 concentration may increase plant water use efficiency and reduce ET demand. But increase in air temperature is likely to increase potential water loss through ET and stimulate plant growth when soil moisture and nutrients are not limited. (See Chapters 7 and 11 for more details.) So the net hydrologic effects can be uncertain. Similarly, agricultural abandonment followed by reforestation tends to increase ET and reduce streamflows (Wu et al. 2007, Cruise et al. 2010), thus mitigating the impacts of extreme climate and hydrology (e.g., flooding) (Ford et al. 2011). Consequently, projections of timing and spatial distribution of climatic variables, such as radiation and cloudiness, and climate impacts on ET and precipitation remain difficult.

10.5 Water Resources Impacts of Climate Change

This section reviews historical trends and future projections for water quantity for average and extreme events, including low flow conditions and drought. The review then focuses on issues of water quality including temperature, erosion and sedimentation, impacts on aquatic biota and salinity intrusion.

Water Supply

Streamflow rates from 1940 to 1999 show statistically significant increasing trends in the Appalachians and Mississippi Alluvial Valley regions, and to a lesser extent in the Coastal Plain and Piedmont regions (Lins and Slack 1999, 2005). The increasing trends in streamflows occurred as a result of a steep increase in precipitation beginning around 1970 (Groisman et al. 2003, McCabe and Wolock, 2002).

The uncertainty of future climate and the interactive relationship between hydrological cycle and land use change and human water demand means the future of water supplies in the SE cannot be precisely predicted at this time (Sun et al. 2008, Caldwell et al. 2012). The Apalachicola-Chattahoochee-Flint (ACF) river basin in the three-state area of Alabama, Florida, and Georgia is one example of how climate change will interact with other factors such as land use changes. For example, for the Flint River Basin in Georgia, modeling results suggest a declining streamflow trend relative to current conditions (Viger et al. 2011, Walker et al. 2011, Georgakakos et al. 2010). However, under a "business-as-usual" scenario of continued urbanization, some of these streamflow declines may be offset due to increasing surface runoff from impervious surfaces.

Recently, Moreau (2007) provided an excellent review on the projected climate changes by various coupled global circulation models (CGCMs) over the SE. Moreau compared the change in precipitation suggested by various models from 1980 to 1999 and concluded that there is no agreement between the CGCMs on either the magnitude and the direction of change in precipitation over the SE. Most importantly, the review shows that the differences among CGCMs are largest during the summer season, which is the most critical for the SE water supply. Despite disagreements among models on precipitation, Krakauer and Fung (2008) argued that climate change will ultimately decrease future streamflows across the USA due to increased evapotranspiration.

Sankarasubramanian et al. (2001) predicted that streamflow in the SE would increase 2% for every 1% increase in precipitation, which was estimated based purely on the observed records of precipitation and temperature over the last 50 years. Bates et al. (2008) reported that the changes in runoff over many watersheds are not consistent with changes in precipitation. Milly et al. (2005) combined runoff downscaled from different climate models and also found that the streamflow over the SE is expected to increase 2% for a 1% increase in precipitation.

Multiple CGCMs and multiple scenarios are required to quantify the uncertainty in projections. For instance, it has been shown that combining multiple models optimally reduces model uncertainty and improves seasonal climate and streamflow forecasts (Devineni et al. 2008). Multimodel combination algorithms for reducing model uncertainty in atmospheric general circulation models (AGCMs) also has improved seasonal climate forecasts (Barnston et al. 2003, Devineni and Sankarasubramanian 2010). Greene et al. (2006) show that developing multimodel combinations of atmospheric-ocean global circulation models (AOGCMs) using Bayesian hierarchical modeling provide better correspondence with regional air temperature under climate change projections.

To understand water resource issues, both water supply and water demand must be examined simultaneously at a basin scale (Sun et al. 2008, Caldwell et al. 2012). The same study defined Water Supply Stress Index (WaSSI) as the ratio of human related water use by all economic sectors (for example, thermoelectric, irrigation, domestic water withdrawal) to the total water supply, such as surface and groundwater. Climate change affects both water supply and demand dynamics, thus greatly influencing WaSSI values. The importance of integrated climate assessments for water planning and management is exemplified in the Apalachicola-Chattahoochee-Flint case study presented later in this chapter (Georgakakos et al. 2010).

Groundwater is a major source for water supply and use, especially for costal areas in the SE (Kenny et al. 2009). As 'one water', surface water and groundwater are connected in many cases. Climate change and human influences on surface water also affect groundwater. This is especially true in regions, such as Florida, where karst topography creates a unique hydrogeology. There are many issues to consider for a comprehensive review of climate change and watershed management including groundwater withdrawal for domestic use and irrigation, inland wetland and coastal habitats, storm water management, and salt water intrusion (Heimlich et al. 2009).

Future projections for water yield. Using the mean water yield response output from four climate models, the CSIRO-A1B, CSIRO-B2, HAD-B2, and MIROC-A1B climate projections, the WaSSI model results project that annual water yield across the SE as a whole will decline in the first half of the 21st century (Caldwell et al. 2012, Marion et al. 2012). The annual decrease is predicted to be approximately 10 mm per decade (3.7% of 2001 to 2010 mean annual water yield) or 50 mm (18% of 2001 to 2010 levels) by 2060 (Figure 10.1). There is considerable interannual variability in the projected water yield, but the general trend is a statistically significant decrease ($p < 0.05$). Likewise, there is considerable variability in the magnitude of water yield changes among the four climate projections; however, all four projections considered in this study exhibited decreasing trends. The projected trend in the mean water yield varies considerably across the SE as well (Caldwell et al. 2012, Marion et al. 2012), with most watershed projections exhibiting statistically significant declining trends in mean water yield of more than 2.5% per decade (Figures 10.1 and 10.2). Across the region, the mean water yield trend is projected to decline between 2010 and 2025, level off between 2025 and 2045, and decline again after 2045 (Figure 10.1)

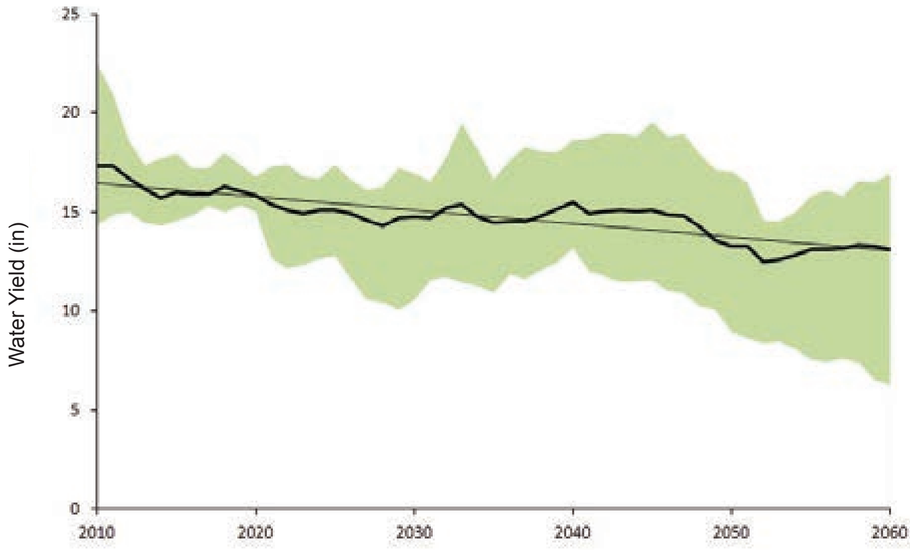

Figure 10.1 Predicted Southeast-wide 10-year moving-mean annual water yield. The wide green band represents the range in predicted water yield over the four climate projections (Marion et al. 2012).

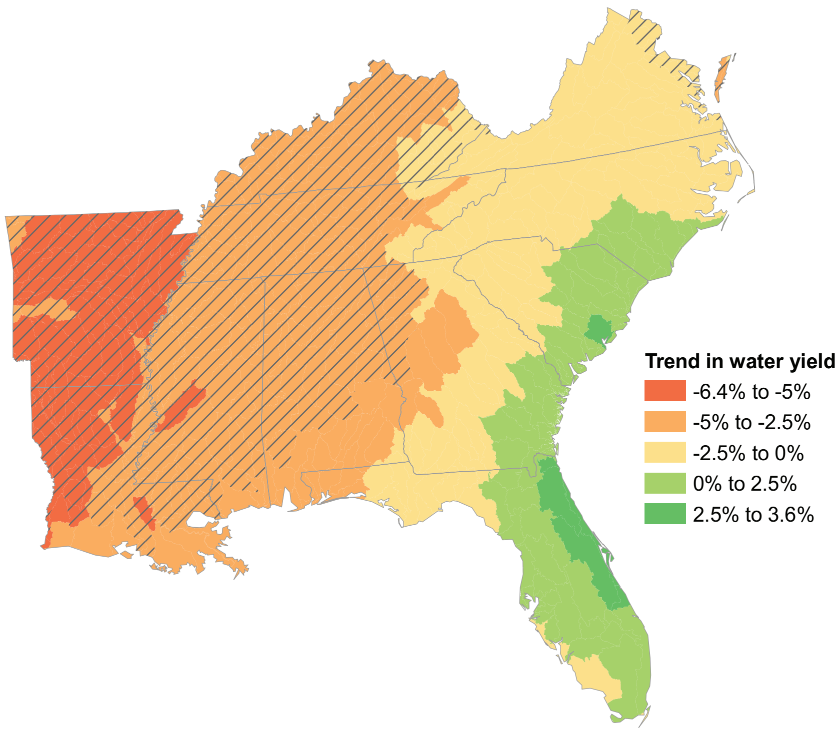

Figure 10.2 Mean trends predicted for 2010 to 2060 in mean annual water yield, normalized by the 2001 to 2010 mean annual water yield. Hatched area represents locations where the predicted trend in water yield is statistically significant ($p < 0.05$) (Marion et al. 2012).

Impacts on water stress. Population growth impacts water demand due to domestic water use, while land use and climate change affect water supply through alteration of the watershed water balances (Sun et al., 2008). The impact of declining water yield and increasing population is projected to increase water supply stress by 2060 in much of the SE, particularly in developing watersheds (Figure 10.3) (Caldwell et al. 2012, Marion et al. 2012). For example, the Upper Neuse River watershed, which provides water supply for the Raleigh-Durham, NC metropolitan area, is projected to experience a 14% decline in water yield due to climate change; at the same time, population growth likely will increase water demand by 21%. This simulation suggests an increase in WaSSI from 0.30 from 2001 to 2010 to 0.44 from 2051 to 2060. A WaSSI value of 0.40 has been used as a general threshold at which a watershed begins to experience water supply stress (Alcamo et al. 2000, Vörösmarty et al. 2000), although stress may occur at lower or higher values depending on local water infrastructure and management protocols.

Low Flows

Low flows levels are an integral component of a flow regime of any river and can occur seasonally or during drought (Smakhtin 2001). Low flows affected by climate change likely will have serious consequences for water supply to reservoirs, transportation, and power generation. In addition, water quality may also be affected in terms of, for example, dissolved oxygen concentration, water temperature, salinity, and nutrient levels, as well as the quality of aquatic habitat.

Previous studies suggested that the low flow characteristics have been changing variably across the SE. For example, Lins and Slack (1999; 2005) reported significant increasing trends in annual minimum and 10th percentile flows between 1940 and 1999 at most sites in the Appalachian-Cumberland, Mississippi Alluvial Valley, and Mid-South (MS) subregions while many sites in the Coastal Plain and Piedmont subregions exhibited significant decreasing trends in low flows. A case study on three forest-dominated headwater watersheds in the Lower Mississippi River Basin suggested that low flows were occurring more frequently over time as the watersheds have become drier in the past 60 to 90 years (Marion et al. 2012).

A continental watershed hydrologic simulation study with the WaSSI model (Sun et al. 2008) showed that monthly mean low flows were projected to decrease 6.1% per decade across the southern USA into the first half of the 21st century under various climate change scenarios (CSIRO-A1B, CSIRO-B2, HAD-B2, and MIROC-A1B); the largest decreases in flow magnitude in the study were in the Appalachian-Cumberland and Mississippi Alluvial Valley (MAV) subregions. The large projected decrease in the MAV was partially due to decreasing flows from streams outside of the study region (Marion et al. 2012).

Water Quality

Climate change affects both water quantity and quality through altering the hydrologic, energy, biogeochemical, and biological cycling of ecosystems. Water quality is highly coupled to water quantity discussed in the previous sections. This section focuses on key water quality parameters that are directly affected by climate change.

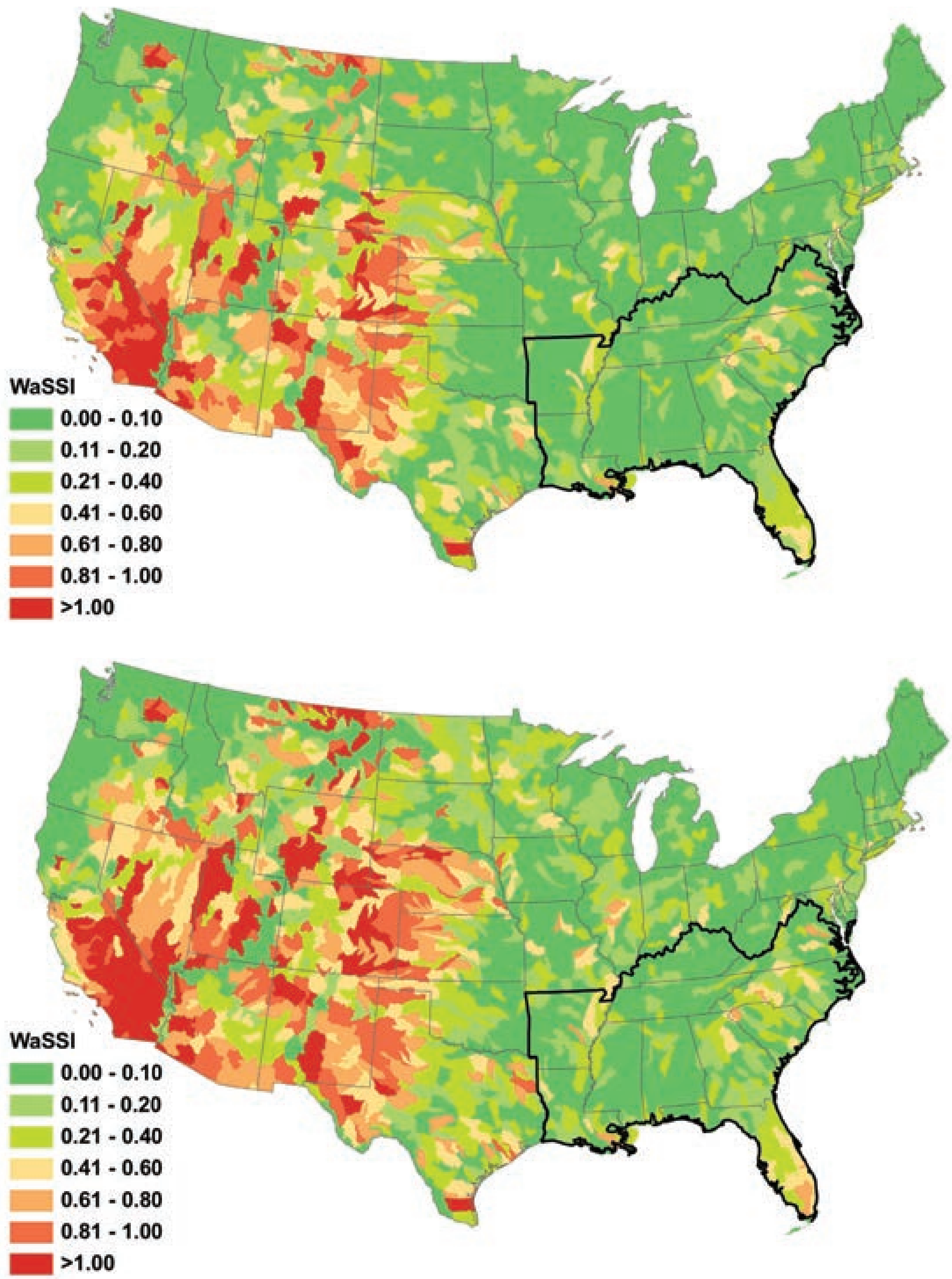

Figure 10.3 Mean annual Water Supply Stress Index (a ratio of water demand/water supply) based on four climate projections for (a) Baseline (2001 to 2010), and (b) Future (2051 to 2060) (Marion et al. 2012).

Water Temperature. Climate change affects water quality as well as water quantity (Cruise et al. 1999, Murdoch et al. 2000, Whitehead et al. 2009). A warming climate may elevate water temperature and decrease instream dissolved oxygen concentrations, which would adversely affect aquatic life (Mohseni and Stefan 1999, Webb et al. 2008, Kaushal et al. 2010). Warmer water is of particular concern for coldwater fish habitats for species such as Eastern Brook Trout (*Salvelinus fontinalis*) in the southern Appalachians. The lethal limit for such species is approximately 25°C (Meisner 1990, Matthews and Berg 1997). Several natural factors influence the extent to which changes in air temperature impact stream temperature, including total stream flow, the relative groundwater contribution to flow (Sullivan et al. 1990, Matthews and Berg 1997, Webb et al. 2008), and canopy cover over the stream. In addition, human-related factors that influence the air-water temperature relationship include runoff from impervious surfaces (Nelson and Palmer 2007), thermal discharges (Webb and Nobilis 2007), and reservoir releases (Webb and Walling 1993). A recent analysis using a monthly air-water temperature model for 91 low-impact sites in the SE was reported in Marion et al. (2012). This modeling study found that 62 of the 91 sites showed significant trends, of increasing mean annual stream water temperature (T_s) between 1960 and 2007. The mean increase in annual stream water temperature across the 62 sites with significant trends was 0.14°C per decade, ranging from 0.08°C to 0.29°C per decade. The largest increasing trends were found in the Appalachian region. More relevant to aquatic ecosystems than mean annual T_s are the extreme temperature conditions, such as the annual maximum monthly T_s. Of the 91 sites, 71 show significant increasing trends in annual maximum monthly T_s between 1960 and 2007. The mean trend in annual maximum monthly T_s for the 71 sites was 0.20°C per decade, ranging from 0.04°C to 0.37°C per decade. Under four future climate change scenarios, all 91 sites were projected to have significant warming trends in mean annual T_s (0.21°C to 0.35°C per decade) from 2011 to 2060. The mean significant warming trend in annual maximum T_s over all sites and climate projections was 0.25°C per decade.

Soil Erosion and Sedimentation. Sediment is one of the primary pollutants affecting water quality in the SE (West 2002). Changes in precipitation amount or storm intensity can affect surface soil erosion potential by changing the runoff magnitude, the kinetic energy of rainfall or the amount and type of vegetation cover resisting erosion. Increased erosion results in increased sediment delivery to streams and lakes. Increases in water temperature and sediment concentrations may occur in combination with decreased flow rates and velocities, magnifying the individual impacts of these factors on fish and other aquatic animals (Henley et al. 2000).

The rainfall-runoff erosivity factor (R-factor) provides an index of the intensity and amount of rainfall occurring at a given location over a long period of time, and as such is directly affected by climate. The R-factor provides a useful surrogate for assessing potential changes in future surface erosion related to climate change. In general, the R-factor value changes modeled showed little consistency for the South (Phillips et al. 1993, Nearing, 2001). Overall, past work evaluating potential R-factor changes provides inconclusive results for the SE (Nearing 2001). A study by Marion et al. (2012) provides a new examination using a somewhat more conservative emission scenario (Hadley GCM and the B2 emission scenario) and a finer-scale climate projection than past studies. This study suggests that large future changes in soil erosion potential concentrate in three major geographic clusters including the Central Gulf Coast, Blue Ridge Mountains, and South Florida (Marion et al. 2012). The modeled effect of R-factor increases on surface erosion within the Blue Ridge Mountains may be amplified by the steeper terrain where landslides are of particular concern.

Aquatic Biota

Changes in water quantity and quality due to climate change in turn affect aquatic systems (see Chapter 11). Species richness and biodiversity rates are sensitive to hydrologic changes, and transformation into altered or qualitatively different states can occur (Kwak and Freeman 2010, Spooner et al. 2011). Degraded ecosystem functions and services that are the product of past human actions that have altered the landscape can also be exacerbated by climate change.

Climate change has cascading effects on watershed and ecosystems in the SE and the Caribbean. For example, in Puerto Rico, large runoff rates result in both periodic and intense sediment discharges and chronic elevated nutrient levels (Larsen and Webb 2009). As in conterminous SE, elevated runoff rates and nutrient levels are related to human land use activities. Sediment discharge in these watersheds is highly episodic and spatially variable. In Puerto Rico, small watersheds with large channel gradients combine with intense rainfall events to transport large amounts of sediment directly to the coast, which threatens coral reef systems (Larsen and Webb 2009). The largest sediment transport events occur when tropical systems pass over the islands and deposit multiple centimeters of rain in one event. Although much uncertainty remains about future trends in precipitation, hurricane frequency, and hurricane intensity, these results suggest that increases in future extreme precipitation events will result in large sediment and nutrient discharges into reef systems. Other reef stressors such as increasing salinity, acidity, and ocean temperatures will compound sediment and nutrient stress (see Chapter 11).

Salinity Intrusion

Saltwater intrusion into freshwater aquifers and drainage basins can degrade natural ecosystems and contaminate municipal, industrial, and agricultural water supplies (Bear et al. 1999). The balance between hydrologic flow conditions within a coastal drainage basin and sea level governs the magnitude, duration, and frequency of salinity intrusion into coastal rivers. Future changes in precipitation patterns have the potential of decreasing streamflow to the coast, which favors salinity intrusion, especially combined with sea level rise (Conrads et al. 2006, 2010a, 2010b).

A study by Conrads et al. (2010a) indicates that future sea level rise can potentially affect salinity intrusion threatening the municipal water supply from two municipal intakes, on the Atlantic Intracoastal Waterway (AIW) and the Waccamaw River near Myrtle Beach along the Grand Strand of the South Carolina Coast. Results suggest that an increase in number of days that specific conductance values, which measure salinity level, exceeded the threshold level of 2,000 $\mu S\ cm^{-1}$ with historic sea level rises and decreases of streamflow. For example, a 1 ft sea level rise combined with a 10% decrease in historical streamflow would increase the days that the intake is unavailable by 25%, or an additional 100 days. A 25% reduction of low streamflows increases the number of days of unavailability to more than 700 days. Conrades et al. (2010b) also examined effects of climate change on salinity intrusion on the lower Savannah River estuary.

Climate Change Implications for River Basin Management: A Case Study of the Apalachicola-Chattahoochee-Flint River Basin

Impacts of global climate change on water resources are site-specific. Prescribing adaptive watershed management strategies and measures requires a comprehensive assessment of the likely influences of climate change on all aspects of the watershed functions. Involvement of local stakeholders and decision makers is essential to the success of sound integrated watershed management in responding to climate change. We use the Apalachicola-Chattahoochee-Flint (ACF) River Basin study, a well-studied basin with high significance in the SE, to demonstrate the processes of climate change assessment and water resource adaptation planning at a large basin scale.

Significance. The Apalachicola-Chattahoochee-Flint (ACF) River Basin drains 19,600 sq mi and receives an average annual rainfall of 1,140 mm of which 25% and 45% becomes runoff for the south and north, respectively. The principle water uses are irrigation at 2.9/0.2 (summer/winter) billion gallons per day (bgd), thermoelectric: 2.5/2.2 bgd, and municipal and industrial: 1.8/1.4 bgd. The ACF includes one nuclear and six fossil fuel power plants. The ACF River system is navigable from the mouth of the Apalachicola in Florida up to Columbus, GA, and is used to transport construction materials. The ACF includes four federal (369 MW) and five private (276 MW) hydroelectric plants, including the South East Power Administration (SEPA) and Southern Company Services. The basin sustains rich ecosystems, including the Apalachicola Bay, which supports 131 freshwater and estuarine fish species and serves as a nursery for many significant Gulf of Mexico species (e.g., the Gulf sturgeon). According to the US Army Corps of Engineers, Lake Lanier and West Point Lake registered more than 15,000,000 visitor days in 2003 with an economic benefit exceeding $300 million. The Apalachicola Bay is a major ecotourism attraction valued at $73 billion per year. The basin is underlain by productive groundwater resources, including the Upper Floridan Aquifer, primarily pumped for irrigation but also for domestic and industrial water supply. Groundwater provides approximately 62% of the region's irrigation.

Integrated Water Resources Assessment and Planning Framework. The ACF climate change assessment is carried out following the integrated water resources assessment and planning framework (Figure 10.4, Georgakakos et al. 2010 and 2011). The assessment process begins with the development and selection of consistent climate, demographic, socioeconomic, and land use and land cover scenarios, which are depicted across the top of Figure 10.4.

Historical (1960-2009) scenarios and responses are analyzed first to establish baseline conditions. The analysis clearly suggests that climatic change is already occurring in the ACF River Basin. Future (2000-2099) climate scenarios are based on GCMs available through the Intergovernmental Panel on Climate Change (IPCC) (A1B and A2 emission scenarios generated by 13 GCMs). Downscaling of GCM outputs through statistical, dynamic, or both methods is applied to generate high resolution (12x12

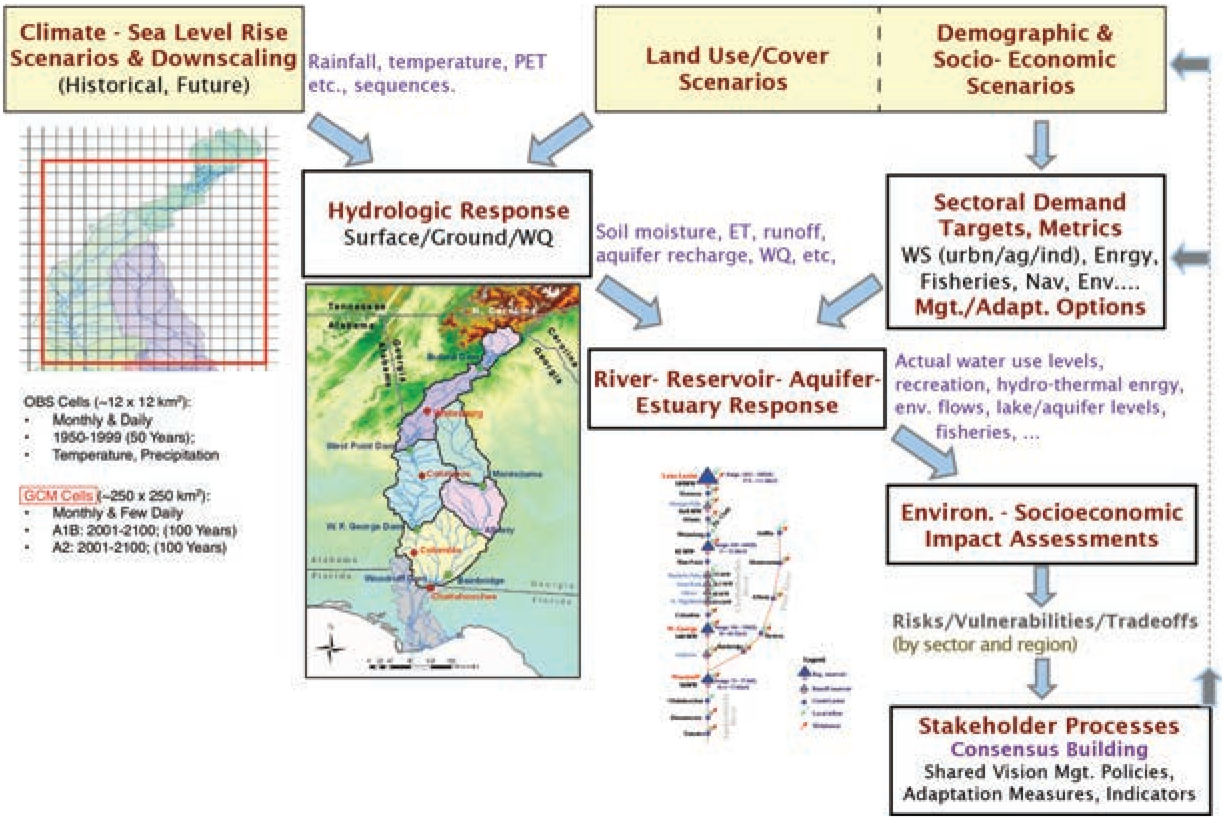

Figure 10.4 Integrated Water Resources Assessment and Planning Framework (Georgakakos et al. 2010 and 2011a).

km) atmospheric forcing, such as rainfall and temperature, over the ACF River Basin watersheds (Zhang and Georgakakos, 2012). Physically based watershed, aquifer, and estuary models are used to quantify the hydrologic and water quality response to alternative climate and land use and land cover scenarios at a basin scale. Water demand assessments are carried out for all water users including environmental and ecological flow and lake level requirements. The goal is to establish desired water use targets, performance metrics, and management and adaptation options. Adaptive optimization methods are used to generate system-wide management policies conditional on inflow forecasts. Subsequently, environmental and socioeconomic impact assessments are carried out to quantify the relative merits, risks, vulnerabilities, and tradeoffs of alternative adaptation and management strategies across the various water sectors and users. The generated information is used to inform stakeholder planning and decision processes aimed at developing consensus on adaptation measures, management strategies, and performance monitoring indicators. The assessment and planning process is driven by stakeholder input and is iterative and sequential.

Water Resources Assessments. Historical and future basin inflow sequences corresponding to A1B and A2 climate change scenarios were used to drive the ACF river basin model that incorporates the river network, all storage projects and hydroelectric facilities, water withdrawals and returns, in-stream flow requirements, and management procedures (Georgakakos et al. 2010). The impact assessment criteria include reliability of water supply for municipal, industrial, and agricultural users; lake levels; environmental and ecological flow requirements; navigation; and hydropower generation. Following is a summary of the assessment conclusions:

- Under the climate change scenarios and with current management procedures that follow rule curve based releases, the ACF River Basin is likely to experience more severe than historical stresses including deeper reservoir drawdowns, greater water supply deficits, less firm energy generation, and more frequent and severe violations of environmental flow requirements. The A2 climate scenario impacts are considerably more severe than those of the A1B.
- Adaptive management procedures and modified operation rules as proposed and tested by Georgakakos et al. (2010) and Georgakakos et al. (2012) prove to be useful to mitigate the impacts of climate change. However, adaptive management procedures and tools have yet to be adopted and made operational by federal and state agencies.

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

The Apalachicola-Chattahoochee-Flint (ACF) River Basin extends from the Blue Ridge Mountains across the Piedmont and Southeastern Plains to the Gulf of Mexico and drains an area of approximately 50,000 square kilometers (Figure 10.1.ACF). The headwaters in the upper ACF basin contain the Chattahoochee National Recreation Area and the Chattahoochee National Forest. The basin provides essential water supply for several million people where access to groundwater aquifers is constrained geologically. The main stem rivers support hydroelectric, thermoelectric and nuclear power production, waste assimilation, recreation, and navigation (in lower half of basin). These flows are managed by three federal and twelve state, or privately operated, main stem dams. Many small impoundments (i.e. lakes, ponds, wetlands) occur throughout the drainage area and provide some degree of flood protection, sediment storage, and local water supplies during prolonged droughts. The lower ACF basin intersects the extensive Floridan aquifer, which provides groundwater for irrigated agriculture over large areas of southwest Georgia.

The Upper Flint and Chattahoochee Rivers are highly valued for recreational hiking, camping, fishing, and boating. Lake Lanier, on the upper Chattahoochee, north of Atlanta, provides multimillion dollar recreational opportunities for bass fishing and boating. The cold-water outflows from the lower depths of Lake Lanier and creates valuable habitat for valuable trout fishing by people throughout the region, especially from metro Atlanta. Additional recreational opportunities and hydropower are available at West Point Lake and Lake Walter F. George on the Chattahoochee River.

The Flint River is one of the longest remaining free-flowing rivers in the contiguous 48 states. The Flint River flows from headwaters south of metro Atlanta, across the Piedmont and onto

Continued on next page

Continued from previous page

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

Coastal Plain before reaching the confluence with the Chattahoochee River and forming Lake Seminole, a main stem impoundment noted for its bass fishing and duck hunting. The Apalachicola River is formed by the outflow from Lake Seminole together with groundwater inputs at the Georgia-Florida border. The river contains a diverse floodplain known for exceptional habitat and species diversity before flowing to the Apalachicola Bay on the Gulf of Mexico, a barrier island estuary designated as a National Estuarine Research Reserve.

The Apalachicola River provides approximately 90% of the freshwater discharge to the Bay. The estuary supports a multimillion dollar production of shellfish (oysters, crabs, shrimp) and finfish. These fisheries depend on a specific salinity range maintained by freshwater inflow from the ACF rivers and groundwater from the Floridan aquifer. Oyster mortality in particular is dependent on an optimal range of salinity (16 to 26 ppt) for growth. Lower salinity values are associated with high river discharges and are thought to reduce mortality from salt-water fish predators. High river flows also bring nutrients into the Bay that contribute to planktonic food production used by oysters.

There have been decades of discussions, sometimes contentious, among water users in Georgia, Florida, and Alabama, the three states that compose the ACF basin. The focus of these ongoing deliberations is competing water interests: municipal supply (especially in upper basin), power plants, irrigated agriculture (lower basin), reservoir recreation and land values, fish and wildlife conservation (river and stream species that includes federally protected species in middle and lower basin), and estuarine fisheries. Specifically the issues rest on municipal water supplies for upstream users, especially metro Atlanta, versus sufficient environmental flows to sustain endangered species. Insuring good nutrient flow and optimal salinity ranges for oyster production within the Apalachicola Bay is also an issue. Consequently, long-term combinations of prolonged droughts, high storm flows from the river, and wind-driven wave action generated by hurricanes are

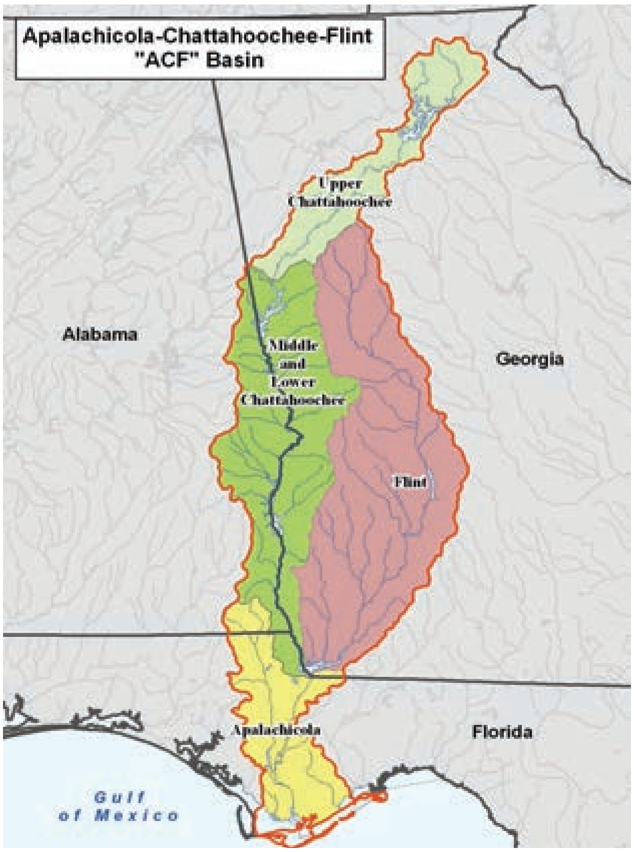

Figure 10.1.ACF Map of the Apalachicola-Chattachoochee-Flint River Basin. The basin includes drainage areas in three states with most of the catchment in Georgia.

Continued on next page

Continued from previous page

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

variables that may prove detrimental coastal fisheries.

Climate change impacts in the ACF likely will exacerbate conflicts among water users and anthropogenic stresses on these interconnected natural systems. Floods throughout the ACF basin are associated with intense, hurricane-derived rainfall. Higher evaporation and evapotranspiration by plants in the freshwater ecosystems likely will decrease water availability and river discharge. In addition, projected increases in extreme variability of rainfall and increased demands for water for irrigation and municipal supplies by rapidly growing regional populations will also likely continue to transform the ACF drainage network. Extremely low flows during prolong droughts and high temperatures combine to concentrate the effects of excessive nutrients from waste-water treatment plants and agricultural runoff that threaten local extinctions. These reduced flows will further threaten the high biodiversity of the freshwater biota. There are recent examples of perennial streams drying up in last decade for first time ever recorded; for example Spring Creek, an inflowing stream to Lake Seminole in southwest Georgia (Figure 10.2.ACF).

The aquatic species diversity in the ACF includes approximately 125 freshwater fishes, 33 unionid mussels, 30 crayfishes, and hundreds of less-well inventoried invertebrates. At least 30 fishes, mussels, and crayfishes (together) are endemic to the system, and new species continue to be discovered, such as a previously undescribed species of bass, Micropterus sp., that occurs in the headwaters of the Chattahoochee River system. In general, freshwater invertebrates are the most endangered group of organisms. Of the nearly 300 native unionid species of freshwater mussels in North America, 278 of them live only in the SE USA, and 33 are in the ACF. Four mussel species in the Lower Flint River and the Apalachicola River are federally listed as endangered (Medionidus pencillata, Pleurobema pyriforme, Amblema neislerii, Hamotia subangulata) (Figure 10.3.ACF).

Figure 10.2.ACF Spring Creek historically flowed into Georgia's Lake Seminole. During recent prolonged droughts, the channel has dried out and formed isolated pools. Photo by: Andrea Fritts, Warnell School of Forestry and Natural Resources, University of Georgia-Athens.

Most freshwater mussels require sufficient flows of high-quality water as well as the presence of particular species of fish that serve as hosts to complete larval development and dispersal within river drainages (Figure 10.4.ACF). These species provide important ecosystem services throughout the SE. For example, mussels filter as much as six gallons of water a day and feed on suspended micro-algae, bacteria and other organic particles. This biofiltration helps to improve water clarity and quality. In addition, since mussels are among the most sensitive, long-lived species that complete their life cycles completely in freshwaters with limited mobility,

Continued on next page

Continued from previous page

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

they are good bioindicators of increases in contaminants such as ammonia in relatively specific locations.

The ACF is an example of how tradeoffs among competing needs for sustainable freshwater resources require well-defined environmental flows that protect biodiversity and ecosystem services. The ACF stakeholders are being increasingly challenged to implement long-term plans because of the recent extreme variability in precipitation. The complex hydrological and economical connectivity of the water sources from upland forested areas with downstream groundwater will continue to require inter-state discussion and collaboration to bring about resolution.

Figure 10.3.ACF Striped mussel (*Hamotia subangulata*), (commonly called shiny rayed pocketbook), is a federally endangered species found in the ACF River Basin. Source: www.discoverlife.org, University of Georgia.

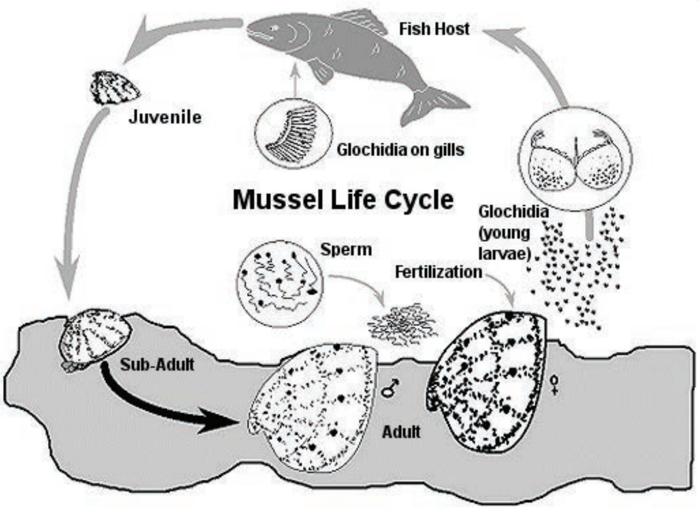

Figure 10.4.ACF Life cycle of freshwater mussels. Adult mussels produce small ectoparasitic larvae that attach to the gills of fish. The larvae grow and are dispersed by the fish to complete their growth in sediments. Some mussel species have evolved specialized mantel tissue resembling small fish that undulate. This movement attracts predatory fish closer to the adult mussel and increases chances of the larvae becoming attached to the fish gills. Source: Diagram from Cummings and Graf, 2009. The MUSSEL Project. http://www.mussel-project.net/. Funded by The National Science Foundation and USGS.

10.6 Mitigation and Adaptation Options

Although global climate model projections for the next several decades do not agree in terms of magnitude or direction of the expected changes for precipitation and some others affecting water resources, the model output all points towards a new climatic regime that the region has not experienced previously (Milly et al. 2008). Climate change already has affected water quantity and quality in several regions in the SE and likely will impact natural ecosystems (Carlisle et al. 2011) and society (Table 10.1) (Marion et al. 2012).

Table 10.1 Potential Adaptation Options for Managing Hydrologic Impact and Risks from Climate Change.

Hydrologic Impacts	**Risks to Ecosystems**	**Adaptation Options**
Water supply stress increase	Water shortage; drying up of drinking wells; Consequences to aquatic ecosystems, socioeconomics, and business	Reduce groundwater and surface water use for agriculture and lawns; enhance water conservation; increase water use efficiency and storage; recycle water; institute adaptive management.
Evapotranspiration increase	Hydrologic droughts; wildfires; insect, disease outbreaks	Use native tree species; reduce tree stocking; reduce water use by crops
Increase of peak flow, Storm flow volume, floods	Flooding; increased soil erosion and sedimentation	Reduce impervious areas; increase stormwater retention ponds; increase evapotranspiration by increasing forest coverage; increase water storage capacity
Low flow decrease; drought	Water quality degradation; fish habitat loss; reduced transportation capacity	Increase water storage; reduce off-stream water withdrawal
Wetland hydroperiod change	Wildlife habitat loss; greenhouse gas (CO_2, CH_4, NO_x) emission	Plug ditches; adjust outflows from reservoirs
Stream water temperature increase	Water quality degradation; loss of cold fish habitat	Maintain riparian buffers and shading
Soil erosion, sedimentation increase	Water quality degradation; siltation of reservoirs; increase cost of water treatment	Enhance best management practices (BMPs); redesign riparian buffers; minimize direct discharge of runoff from roads to streams
Chemical loading increase	Water quality degradation; higher cost of water treatment	Maintain streamflow quantity; applications of BMPs

A limited number of studies have considered adaptation options that might reduce or adapt to the severe consequences of climate changes, such as water supply shortages, habitat loss, and increased forest wildfires. For example, watershed manipulation experiments show that converting a deciduous forest cover to a conifer evergreen forest in the Appalachians can reduce flood risk in extreme wet years (Ford et al. 2011). Adaptation to intensified extreme storms involves consideration of alternative forest covers in future land planning. Current best management practices for reducing nonpoint source pollution may be adapted to better reflect future hydrologic and management conditions. The large area of forests in the SE are expected to have an increasing role to modulate regional climate, maintain water quality, and sequester carbon (Liu 2011, Chen et al. 2012, Lockaby et al. 2011). There is large potential to increase water use efficiency from all major water users, such as the agriculture and energy sectors, including power plants that produce bioenergy.

Facing the uncertainty of climate change, water planning and management organizations and stakeholders must create adaptive frameworks for solutions, re-evaluate past decisions in light of the changing climate, and identify the most effective policies based on the current scientific research and understanding (Rosenhead and Mingers 2001). Some researchers have proposed/tested new decision-making frameworks designed to be responsive to changing climate conditions and scientific understanding. Rosenhead and Mingers (2001) views planning under deep uncertainty as sequential and adaptive decisions made over time. Such an approach helps identify robust solutions, which may not be the best but provide more options for the decision makers in making decisions. Robustness could be thought of as making decisions between optimality and minimizing solutions (Groves 2006). For example, using a stochastic dynamic programming model, Chao and Hobbs (1997) revisit the decision of protecting the Great Lakes shoreline every year in such a way that the expected cost of sand nourishment is minimized under the anticipated probability of lake level change due to global warming. Projections of climate are not regularly represented probabilistically, so it is important that the water management framework explicitly quantify the reservoir yield and releases by assigning reliabilities (Sankarasubramanian et al. 2009a). Sankarasubramanian et al. (2009b) and Georgakakos et al. (2012) also show that updating climate forecasts on a monthly basis, and utilizing the updated forecasts within the seasonal reservoir operation, benefited the system more than an operational policy derived purely based on the climate forecasts at the beginning of the season. Further development of climate forecasts at seasonal and interannual scales could be useful in reducing the vulnerability of water supply systems under future climate change and population growth.

10.7 References

Alcamo, J., T. Henrichs, T. Rosch. 2000. World water in 2025: Global modeling and scenario analysis for the world commission on water for the 21st century. Kassel, Germany: University of Kassel: Center for Environmental Systems Research.

Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, S. Tellinghuisen. 2011. Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. A report of the energy and water in a warming world initiative. Cambridge, MA: Union of Concerned Scientists. November.

Barnston, A.G., S.J. Mason, L. Goddard, D.G. Dewitt, S.E. Zebiak. 2003. Multimodel ensembling in seasonal climate forecasting at IRI. Bulletin of the *American Meteorological Society* 84 (12): 1783–1796.

Bates, B.C., Z.W. Kundzewicz, S. Wu, J.P. Palutikof. 2008. Climate change and water. (2008), Climate Change and Water Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, Switzerland: IPCC Secretariat. 210.

Bear, J., A.H.D. Cheng, S. Sorek, D. Ouazar, I. Herrera. eds. 1999. Seawater intrusion in coastal aquifers–concepts, methods and practices. Dordrecht, the Netherlands: Kluwer Academic Publishers. Dordrecht, The Netherlands.

Cahoon, D.R., S. Williams, B.T. Gutierrez, K.E. Anderson, E.R. Thieler, D.B. Gesch. 2009. The Physical Environment. Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. US Climate Change Science Program. Synthesis and Assessment Product 4.1.

Caldwell, P.V., G. Sun, S.G. McNulty, E.C. Cohen, J.A. Moore Myers. 2012. Impacts of impervious cover, water withdrawals, and climate change on river flows in the Conterminous US, *Hydrology and Earth System Sciences.* Discuss. 9: 4263-4304, doi:10.5194/hessd-9-4263-2012.

Carlisle, D.M., D.M. Wolock, M.R. Meador. 2011. Alteration of streamflow magnitudes, and potential ecological consequences: A multiregional assessment. *Frontiers in Ecology and the Environment* 9 (5): 264-270. doi:10.1890/100053.

Chan, S. and V. Misra. 2009. A diagnosis of the 1979-2005 extreme rainfall events in the southeastern United States with Isentropic moisture tracing. *Monthly Weather Review* 138 (4): 1172-1185.

Chao, P.T. and B.F. Hobbs. 1997. Decision analysis of shoreline protection under climate change uncertainty. *Water Resources Research* 33 (4): 817-829.

Chen, G., M. Notaro, Z. Liu, Y.Q. Liu. 2012. Simulated local and remote biophysical effects of afforestation over SE United States in boreal summer. Journal of Climate (In review). 25 (13): 4511-4522.

Conrads, P.A., E.A. Roehl, R.C. Daamen, W.M. Kitchens. 2006. Simulation of water levels and salinity in the rivers and tidal marshes in the vicinity of the Savannah National Wildlife Refuge, Coastal South Carolina and Georgia: US Geological Survey, Scientific Investigations Report 2006-5187, 134.

Conrads, P.A., E.A. Roehl Jr., C.T. Sexton, D.L. Tufford, G.J. Carbone, K. Dow, and J.B. Cook. 2010. Estimating Salinity Intrusion Effects Due To Climate Change Along the Grand Strand of the South Carolina Coast, Conference Proceedings Paper for the 4th Federal Interagency Hydrologic Modeling Conference Las Vegas, NV June 2010.

Conrads, P.A., E.A. Roehl Jr., R.C. Daamen, J.B. Cook, C.T. Sexton, D.L. Tufford, G.J. Carbone, and K. Dow. 2010. Estimating Salinity Intrusion Effects Due To Climate Change on the Lower Savannah River Estuary. Conference Proceeding Paper of South Carolina Environmental Conference, North Myrtle Beach, South Carolina, March 2010.

Cruise, J.F., A.S. Limaye, N.A. Abed. 1999. Assessment of impacts of climate change on water quality in the southeastern United States. *Journal of the American Water Resources Association* 35: 1539-1550.

Cruise, J.F., C.A. Laymon, O.Z. Al-Hamdan. 2010. Impact of 20 years of land-cover change on the hydrology of streams in the southeastern United States. *Journal of the American Water Resources Association* 46 (6): 1159-1170. DOI: 10.1111/j.1752-1688.2010.00483.x

Curtis, L. and E. Rochester. Water Harvesting for Irrigation: Developing an Adequate Water Supply. ANR-827, New May 1994. http://www.aces.edu/pubs/docs/A/ANR-0827/ANR-0827.html. Data accessed on October 16, 2012.

Devineni, N., A. Sankarasubramanian, S. Ghosh. 2008. Multi-model ensembling of probabilistic streamflow forecasts: Role of predictor state space in skill evaluation. *Water Resources Research* 44 (9), W09404. doi:10.1029/2006WR005855.

Devineni, N. and A. Sankarasubramanian. 2010. Role of ENSO state in developing multimodel combination for improving U.S. Winter Precipitation Improving the prediction of winter precipitation and temperature over the continental United States: Role of ENSO state in developing multimodel combinations. *Monthly Weather Review* 138 (6): 2447-2468.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, L.O. Mearns. 2000. Climate extremes: Observations, modeling, and impacts. Science 289 (5487): 2068-2074. doi:10.1126/science.289.5487.2068

Farrell, D., A. Trotman, C. Cox. 2011. Drought early warning and risk reduction: A case study of the Caribbean drought of 2009-2010. Global Assessment Report on Disaster Risk Reduction. GAR 2011. 22.

Ford, C.R., S.H. Laseter, W.T. Swank, J.M. Vose. 2011. Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Applications* 21 (6): 2049-2067.

Georgakakos, A., F. Zhang, H. Yao. 2010. Climate variability and change assessment for the ACF river Basin, Southeast US. Georgia Water Resources Institute (GWRI) Technical Report sponsored by NOAA, USGS, and Georgia EPD, Georgia Institute of Technology, Atlanta, Georgia, 321.

Georgakakos, A. and F. Zhang. 2011. Climate Change Scenario Sequences and Assessment for ACF, OOA, SO, ACT, TN, and OSSS Basins in Georgia. Georgia Water Resources Institute (GWRI) Technical Report sponsored by NOAA, USGS, and the Georgia EPD; Georgia Institute of Technology, Atlanta, Georgia, USA, 229.

Georgakakos, A.P., H. Yao, M. Kistenmacher, K.P. Georgakakos, N.E. Graham, F.Y. Cheng, C. Spencer, E. Shamir. 2012. Value of adaptive water resources management in northern California under climatic variability and change: Reservoir management. *Journal of Hydrology* on line publication, 412-413 (January): 34-46. doi.org/10.1016/j.jhydrol.2011.04.038.

Glassman, D., M. Wucker, T. Isaacman, C. Champilou. 2011. The water-energy nexus: Adding water to the energy agenda. New York, NY: World Policy Institute. 33.

Greene, A.M., L. Goddard, U. Lall. 2006. Probabilistic multimodel regional temperature change projections. *Journal of Climate* 19 (17): 4326-4343.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, J.H. Lawrimore. 2003. Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* 5 (1): 64-85.

Groves, D.G. 2006. New methods for identifying robust long-term water resources management strategies for California. Pardee RAND Graduate School, Santa Monica, CA. Graduate Thesis.

Heimlich, B.N., F. Bloetscher, D.E. Meeroff, J. Murley. 2009. Southeast Florida's resilient water resources: Adaptation to sea level rise and other impacts of climate change. Boca Raton, FL: Florida Atlantic University. Florida Atlantic University Center for Urban and Environmental Solutions and Department of Civil Engineering, Environmental, and Geomatics Engineering.

Henley, W.F., M.A. Patterson, R.J. Neves, A. Dennis Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resources managers. *Review in Fisheries Science* 8 (2):125-139.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In Core Writing Team, eds. R.K. Pachauri, and A. Reisinger. Climate Change 2007: Synthesis Report. Geneva, Switzerland: IPCC.

Johnson, C.Y. et al. 2012. Climate Change, Human Populations, and Social Vulnerability in the South: An Ecosystem-level Examination of Freshwater Access, 2010-2040. In Climate Change Adaptation and Mitigation Management Options (CCAMMO), ed. J. Vose. CRC Press. (In Press).

Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, R.L. Wingate. 2010. Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment* 8 (9): 461-466.

Keim, B.D. and G.E. Faiers. 1996. Heavy rainfall distributions by season in Louisiana: Synoptic interpretations and quantile estimates. *Journal of the American Water Resources Association* 32 (1): 117-124.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, M. A. Maupin. 2009. Estimated use of water in the United States in 2005, US Geological Survey Circular 1344, 52.

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

Krakauer, N.Y. and I. Fung. 2008. Mapping and attribution of change in streamflow in the coterminous United States. *Hydrology and Earth System Science* 12 (4): 1111-1120.

Kwak, T.J. and M.C. Freeman. 2010. Assessment and management of ecological integrity. *In:* Inland fisheries management in North America, ed. W.A. Hubert and M.C. Quist., editors. *Inland fisheries management in North America*, third edition. Bethesda, Maryland: American Fisheries Society.

Larsen, M.C. and R.M.T. Webb. 2009. Potential effects of runoff, fluvial sediment, and nutrient discharges on the coral reefs of Puerto Rico. *Journal of Coastal Research* 25 (1): 189-208.

Li, L., W. Li, Y. Kushnir. 2011. *Variation of North Atlantic subtropical high western ridge and its implication to the southeastern US summer precipitation. Climate Dynamics* doi:10.1007/s00382-011-1214-y.

Li, W., L. Li, R. Fu, Y. Deng, H. Wang. 2011. Changes to the North Atlantic subtropical high and its role in the intensification of summer rainfall variability in the southeastern United States. *Journal of* Climate 24 (5): 1499-1506.doi: http://dx.doi.org/10.1175/2010JCLI3829.1

Lins, H.F. and J.R. Slack. 1999. Streamflow trends in the United States. *Geophysical Research Letters* 26 (2): 227-230.

Lins, H.F. and J.R. Slack. 2005. Seasonal and regional characteristics of US streamflow trends in the United States from 1940-1999. *Physical Geography* 26 (6): 489-501.

Liu, Y.Q. 2011. A numerical study on hydrological impacts of forest restoration in the southern United States. *Ecohydrology* 4 (2): 299-314. doi:10.1002/eco.178.

Liu, Y.Q., J. Prestemon, S. Goodrick, T. Holmes, J. Stanturf, J.M. Vose, G. Sun. 2012. Future Wildfire Trends, Impacts, and Mitigation Options in Southern U.S Climate Change Adaptation and Mitigation Management Options (CCAMMO), ed. J. Vose. CRC Press. (In Press).

Lockaby, G., C. Nagy, J.M. Vose, C.R. Ford, G. Sun, S. McNulty, P. Caldwell, E. Cohen, J.A.M. Moore Myers. 2011. Water and forests. In: The Southern Forest Futures Project. Technical Report, ed. D. N. Wear and J. G. Greis. Asheville, NC: The Southern Forest Futures Project: Technical Report. USDA Forest Service, Southern Research Station, Asheville, NC. General Technical Report.

McCabe, G.J., and D.M. Wolock. 2002. A step increase in streamflow in the conterminous United States. *Geophysical Research Letters* 29 (24): 2185.

Manuel, J. 2008. Drought in the southeast: Lessons for water management. *Environmental Health Perspectives* 116 (4): A168-A171.

Marion, D., G. Sun, et al. 2012. Managing Forest Water Quantity and Quality Under Climate Change in the Southern U.S. In Climate Change Adaptation and Mitigation Management Options (CCAMMO), ed. J. Vose. CRC Press. (In Press).

Matthews, K.R. and N.H. Berg. 1997. Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. *Journal of Fish Biology* 50 (1): 50-67. doi: 10.1111/j.1095-8649.1997.tb01339.x.

McNulty, S.G., J.M. Myers, P. Caldwell, G. Sun. 2012. Climate Change. In Southern forest future project, ed. D.N. Wear, D.N. and J. G. Gries. Asheville, NC: USDA Forest Service Southern Research Station. Southern Forest Future Project. (In Review).

Meisner, J.D. 1990. Effect of climatic warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis*. *Canadian Journal of Fisheries and Aquatic Science* 47 (6): 1065-1070.

Meybeck, M. 2004. The global change of continental aquatic systems: Dominant impacts of human activities. *Water Science & Technology* 49 (7): 73-83.

Milly, P.C.D., K.A. Dunne, A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438 (7066): 347-350.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, R.J. Stouffer. 2008. Stationarity is dead: Whither water management. *Science* 319 (5863): 573-574.

Misra, V., S. Chan, R. Wu, E. Chassignet. 2009. Air-sea interaction over the Atlantic warm pool in the NCEP CFS. *Geophysical Research Letters*. 36, L15702; doi:10.1029/2009GL038525.

Mohseni, O. and H.G. Stefan. 1999. Stream temperature air temperature relationship: A physical interpretation. *Journal of Hydrology* 218 (3-4): 128-141.

Moreau, D. 2007. What are the experts saying about effects of climate change on rainfall and streamflow in the Southeast? Raleigh, NC: Water Resources Research Institute Publications.

Murdoch, P.S., J.S. Baron, T.L. Miller. 2000. Potential effects of climate change on surface-water quality in North America. *Journal of the American Water Resources Association* 36 (2): 347-366.

Nearing, M.A. 2001. Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. *Journal of Soil and Water Conservation*, 56 (3): 229-232.

Nelson, K.C. and M.A. Palmer. 2007. Stream temperature surges under urbanization and climate change: Data, models, and responses. *Journal of the American Water Resources Association* 43 (2): 440-452.

Obeysekera, J., J. Park, M. Irizarry-Ortiz, P. Trimble, J. Barnes, J. VanArman, W. Said, E. Gadzinski. 2011. Past and projected trends in climate and sea level for South Florida. West Palm Beach, FL: South Florida Water Management District. 3301 Gun Club Road, West Palm Beach, Florida.

O'Gorman, P.A. and T. Schneider. 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proceedings of the National Academy of Sciences of the United States of America 106 (35): 14773-14777. doi:10.1073/pnas.0907610106.

Osidele, O.O. and M.B. Beck. 2004. Food web modelling for investigating ecosystem behaviour in large reservoirs of the south-eastern United States: Lessons from Lake Lanier, Georgia. *Ecological Modelling* 173 (2-3): 129-158.

Phillips, D.L., D. White, C.B. Johnson. 1993. Implications of climate change scenarios for soil erosion potential in the United States. *Land Degradation and Rehabilitation* 4 (2): 61-72.

Rosenhead, J. and J. Mingers. 2001. Rational analysis for a problematic world revisited: Problem structuring methods for complexity, uncertainty, and conflict. Chichester, United Kingdom: Wiley and Sons. Chichester, UK.

Richter, B.D., R. Mathews, D.L. Harrison, R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* 13: 206-224.

Sankarasubramanian, A., U. Lall, F.D. Souza Filho, A. Sharma. 2009a. Improved water allocation utilizing probabilistic climate forecasts: Short term water contracts in a risk management framework. *Water Resources Research* 45, W11409; doi:10.1029/2009WR007821.

Sankarasubramanian, A., U. Lall, N. Devineni, S. Espinueva. 2009b. The role of monthly updated climate forecasts in improving intraseasonal water allocation. *Journal of Applied Meteorology and Climatology* 48 (7): 1464-1482.

South Florida Water Management District. 2009. Climate change & water management in South Florida. West Palm Beach, FL: Interdepartmental Climate Change Group. http://my.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/climate_change_and_water_management_in_sflorida_12nov2009.pdf.

Spooner, D.E., M.A. Xenopoulos, C. Schneider, D.A. Woolnough. 2011. Coextirpation of host-affiliate relationships in rivers: The role of climate change, water withdrawal, and host-specificity. *Global Change Biology* 17 (4): 1720-1732. doi:10.1111/j.1365-2486.2010.02372.x.

Sun, F., M.L. Roderick, G.D. Farquhar. 2012. Changes in the variability of global land precipitation. *Geophysical Research Letters* (39) L19402, 6. doi:10.1029/2012GL053369.

Sun, G., S.G. McNulty, J.A. Moore Myers, E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. *Journal of the American Water Resource Association* 44 (6): 1441-1457.

Sun, G. and G. Lockaby. 2012. Water quantity and quality at the urban-rural interface. In: Urban-Rural Interfaces: Linking People and Nature, eds. D.N. Laband and B.G. Lockaby (In Review). Madison, WI: American Society of Agronomy.

Sullivan, K., J. Tooley, K. Doughty, J.E. Caldwell, P. Knudsen. 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Timber/Fish/Wildlife Rep. No. TFW-WQ3-90-006. Olympia, WA: Washington Department of Natural Resources. Olympia, Washington. 224.

Titus, J.G., K.E. Anderson, D.R. Cahoon, D.B. Gesch, S.K. Gill, B.T. Gutierrez, E.R. Thieler, S.J. Williams. 2009. The physical environment. In: Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region, ed. D.R. Cahoon, S.J. Williams, B.T. Gutierrez, K.E. Anderson, E.R. Thieler, and D.B. Gesch, 9-84. Washington, DC: US Climate Change Science Program.

Viger, R.J., L.E. Hay, S.L. Markstrom, J.W. Jones, G.R. Buell. 2011. Hydrologic effects of urbanization and climate change on the Flint River Basin, Georgia. *Earth Interactions* 15 (20): 1-25.

Vörösmarty, C.J., P. Green, J. Salisbury, R. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289 (5477): 284-288.

Wang, H., R. Fu, A. Kumar, W. Li. 2010. Intensification of Summer Rainfall Variability in the Southeastern United States during Recent Decades, *Journal of Hydrometeorology.*

Walker, J.F., L.E. Hay, S.L. Markstrom, M. Dettinger. 2011. Characterizing climate-change impacts on the 1.5-yr flood flow in selected basins across the United States: A probabilistic approach. *Earth Interactions* 15 (18): 1-16.

Wang, H., R. Fu, A. Kumar, W. Li. 2010. Intensification of summer rainfall variability in the southeastern United States during recent decades. *Journal of Hydrometeorology* 11 (4): 1007-1018.

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* 47, W00J12; doi:10.1029/2010WR010283.

Webb, B.W., D.M. Hannah, R.D. Moore, L.E. Brown, F. Nobilis. 2008. Recent advances in stream and river temperature research. *Hydrological Processes* 22 (7): 902-918. doi: 10.1002/hyp.6994.

Webb, B.W. and F. Nobilis. 2007. Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal* 52 (1): 74-85.

Webb, B.W. and D.E. Walling. 1993. Longer-term water temperature behavior in an upland stream. *Hydrological* Processes 7 (1): 19-32. 1993.

Wehner, M., D.R. Easterling, J.H. Lawrimore, R.R. Heim, R.S. Vose, B.D. Santer. 2011. Projections of future drought in the continental United States and Mexico. *Journal of Hydrometeorology* 12 (6): 1359-1377.

Wear, D.N. and J.G. Greis. 2011. The southern forest futures project: Summary report. Asheville, NC: USDA Forest Service Southern Research Station. Draft. http://www.srs.fs.usda.gov/futures/reports/draft/summary_report.pdf. Date accessed 7 September 2011.

West, B. 2002. Water quality in the South. In *Southern Forest Resource Assessment*, eds. D.N. Wear, J.G. Greis. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. General Technical Report SRS-54: 455-476

Whitehead, P.G., R.L. Wilby, R.W. Battarbee, et al. 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences* 54: 101–123.

Wu, W., C.A.S. Hall, F.N. Scatena. 2007. Modelling the impact of recent land-cover changes on the stream flows in northeastern Puerto Rico. *Hydrological Processes* 21 (21): 2944-2956.

Zhang, F. and A.P. Georgakakos. 2012. Joint variable spatial downscaling. *Journal of Climatic Change* 111 (3-4): 945-972. Online publication, doi:10.1007/s10584-011-0167-9.