Data and Modeling

Hydrologic Response to Climate Change and Habitat Resiliency Illustrated Using Fine-Scale Watershed Modeling

Lorraine E. Flint, Alan L. Flint

Abstract

In the face of rapid climate change, predictions of landscape change are of great interest to land and resource managers who endeavor to develop long-term plans with the goal of maintaining biodiversity and ecosystem services and adapting to extreme changes in the landscape. Climate models, primarily exhibited as increases in air temperature, often support habitat modeling that predicts large-scale migrations, either northward or up in elevation, or extinctions of sensitive species. Current studies rely most dominantly on large spatial scale projections (>10 km) of changes in precipitation and air temperature that neglect the subtleties of topographic shading, geomorphic features of the landscape, and fine-scale differences in soil properties. Climatic parameters downscaled to fine scales has been tested previously with species distribution models and found to improve correlations of vegetation distribution with temperature. For this study, future climate projections were downscaled to 270 m and applied to a hydrologic model to calculate future changes in recharge, runoff, and climatic water deficit for basins draining into the northern San Francisco Bay, CA. Study results provide tools and information for land and resource managers to anticipate potential changes in water availability and landscape stresses for planning purposes.

We generated future watershed hydrology scenarios using a regional coupled climate-hydrology water balance model, Basin Characterization Model (BCM), that predicts water cycle fractions of runoff, recharge, evapotranspiration, streamflow, and changes in soil moisture storage. Primary BCM inputs consist of topography, soil composition and depth, parent geology, and spatially-distributed values (measured or estimated) for air temperature and precipitation. Model calibration is achieved by using historic precipitation and temperature as BCM inputs and comparing model estimates of discharge with streamflow measured at gages. Using estimates of future precipitation and air temperature derived from Global Circulation Models (GCMs) (two models, GFDL and PCM, for two emissions scenarios, A2 and B1) as model input, we describe observed variability over the 20th century and estimate watershed-scale hydrologic response to potential climate change scenarios for the 21st century. Results indicate that by the last 30 years of the 21st century, North Bay scenarios project average minimum temperatures to increase by 1.0°C to 3.1°C and average maximum temperatures to increase by 2.1°C to 3.4°C (in comparison to conditions experienced over the last 30 years, 1981–2010). Precipitation projections for the next century vary between GCMs (ranging from 2 to 15 percent wetter than the 20th century average), and temperature forcings increase the variability of modeled runoff, recharge, and stream discharge, and shift seasonal hydrologic cycle timing. For both high and low rainfall scenarios, by the close of the 21st century warming is projected to amplify late season climatic water deficit (a measure of drought stress on landscapes) by 8–21 percent, however, fine-scale modeling can be used to illustrate local scale resiliency of habitats to climate change. Hydrologic variability within a single river basin demonstrated at the scale of subwatersheds may prove an important consideration for water managers in the face of climate change, and regional fine-scale modeling can provide insights of landscape response from the watershed to local scale for the purposes of resource planning in the face of a changing climate.

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Simulation of Hydrologic Response to Climate and Landscape Change Using the Precipitation Runoff Modeling System in the Apalachicola–Chattahoochee–Flint River Basin in the Southeastern USA

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Abstract

The U.S. Geological Survey (USGS) Southeast Regional Assessment Project (SERAP) was initiated in 2009 to help environmental resource managers assess the potential effects of climate change on ecosystems. One component of the interdisciplinary SERAP program is the development and calibration of a set of multiresolution hydrologic models of the Apalachicola–Chattahoochee–Flint (ACF) River Basin. The ACF River Basin, home to numerous fish and wildlife species of conservation concern, is regionally important for water supply as well as the focus of complementary environmental and climate change research. Hydrologic models of varying spatial extents and resolutions are required to address varied local-to-regional water resource management questions as required by the scope and limitations of potential management actions. In the ACF River Basin, these models (coarse and fine scales) were developed using the USGS Precipitation Runoff Modeling System (PRMS). The coarse-scale model has a contributing area of approximately 50,700 square kilometers. Six fine-resolution models, ranging in size from 396 to 2,690 square kilometers, are nested within the coarse-scale model and have been developed for the following basins: the upper Chattahoochee, Chestatee, and Chipola Rivers and the Ichawaynochaway, Potato, and Spring Creeks. Both coarse- and fine-scale models simulate basin hydrology using daily timesteps, measured climatic data, and basin characteristics, such as land cover and topography. Measured streamflow data are used to calibrate and evaluate computed basin hydrology. Being able to project future hydrologic conditions for this set of models will rely on the use of land cover projections in conjunction with downscaled global climate model results.

Keywords: hydrology, hydrologic modeling, climate change, model optimization

Introduction

To help environmental resource managers assess potential effects of climate change on ecosystems, the U.S. Geological Survey (USGS) Southeast Regional Assessment Project (SERAP) is developing regional models and other science tools (Dalton and Jones 2010). Models and data produced by SERAP will be used in a collaborative process between the USGS, U.S. Fish and Wildlife Service, State and Federal partners, nongovernmental organizations, and academia. Integration of the models developed by SERAP is shown in Figure 1. One component of the SERAP is development and calibration of a set of multiresolution hydrologic models, as highlighted in Figure 1, of the Apalachicola–Chattahoochee–Flint (ACF) River Basin. The ACF River Basin (Figure 2), regionally important as a source of water supply, contains numerous fish and wildlife species of conservation concern; as a result, the ACF River Basin is a focus of complementary environmental and climate change research. Hydrologic models of varying spatial extents and resolutions are required to address varied local-to-regional water resource management questions as required by the scope and limitations of potential

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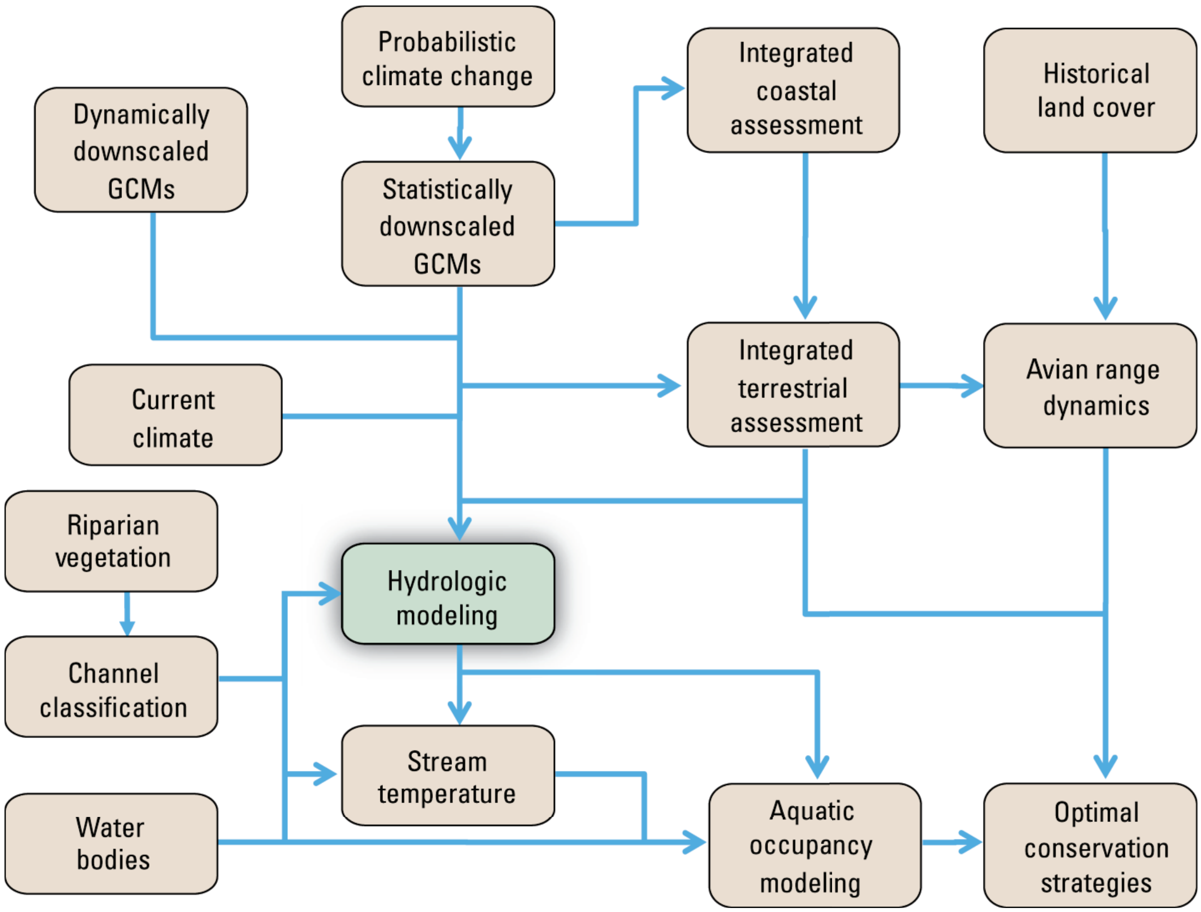

Figure 1. Information flow diagram for the Southeast Regional Assessment Project. The hydrologic modeling team receives information from several project teams and provides output that will be used as input by the stream temperature and aquatic occupancy models. [GCMs, global climate models]

management actions. These models were developed using the USGS Precipitation Runoff Modeling System (PRMS). A coarse-scale hydrologic model of the ACF River Basin (approximately 50,700 square kilometers [km^2]) and six fine-scale models (ranging in size from 396 to 2,690 km^2) were developed as part of this study to simulate natural streamflow in the basin and to compare simulated streamflows at various model scales using climate data from both point and gridded sources. The models simulate natural streamflow for the period 1950–1999 based on a daily timestep.

Description of Study Area

The ACF River Basin includes three major rivers—the Apalachicola, Chattahoochee, and Flint Rivers (Figure 2). The Chattahoochee River begins in the mountains of northeast Georgia and flows southwest through metropolitan Atlanta to the Alabama-Georgia border, where the river flows south to Lake Seminole at the Florida-Georgia border. The Flint River begins in north-central Georgia, just south of Atlanta, and flows south to Lake Seminole. The Apalachicola River begins at Lake Seminole, the confluence of the Chattahoochee and Flint Rivers, and flows south through Florida to the Gulf of Mexico. The Chattahoochee River is highly regulated by four U.S. Army Corps of Engineers reservoirs and several run-of-the-river dams, while the Flint River is relatively unregulated with just two run-of-the-river dams. The lower Flint River Basin also has substantial agricultural land use, for which groundwater and surface water are used for irrigation. The ACF River Basin includes the Blue Ridge, Piedmont, and Coastal Plain Physiographic Provinces (Figure 2). In the ACF River Basin, the Blue Ridge and Piedmont Physiographic Provinces are underlain with crystalline rock; the Coastal Plain Physiographic Province is underlain with sedimentary rocks and unconsolidated sediments (Couch and others 1995).

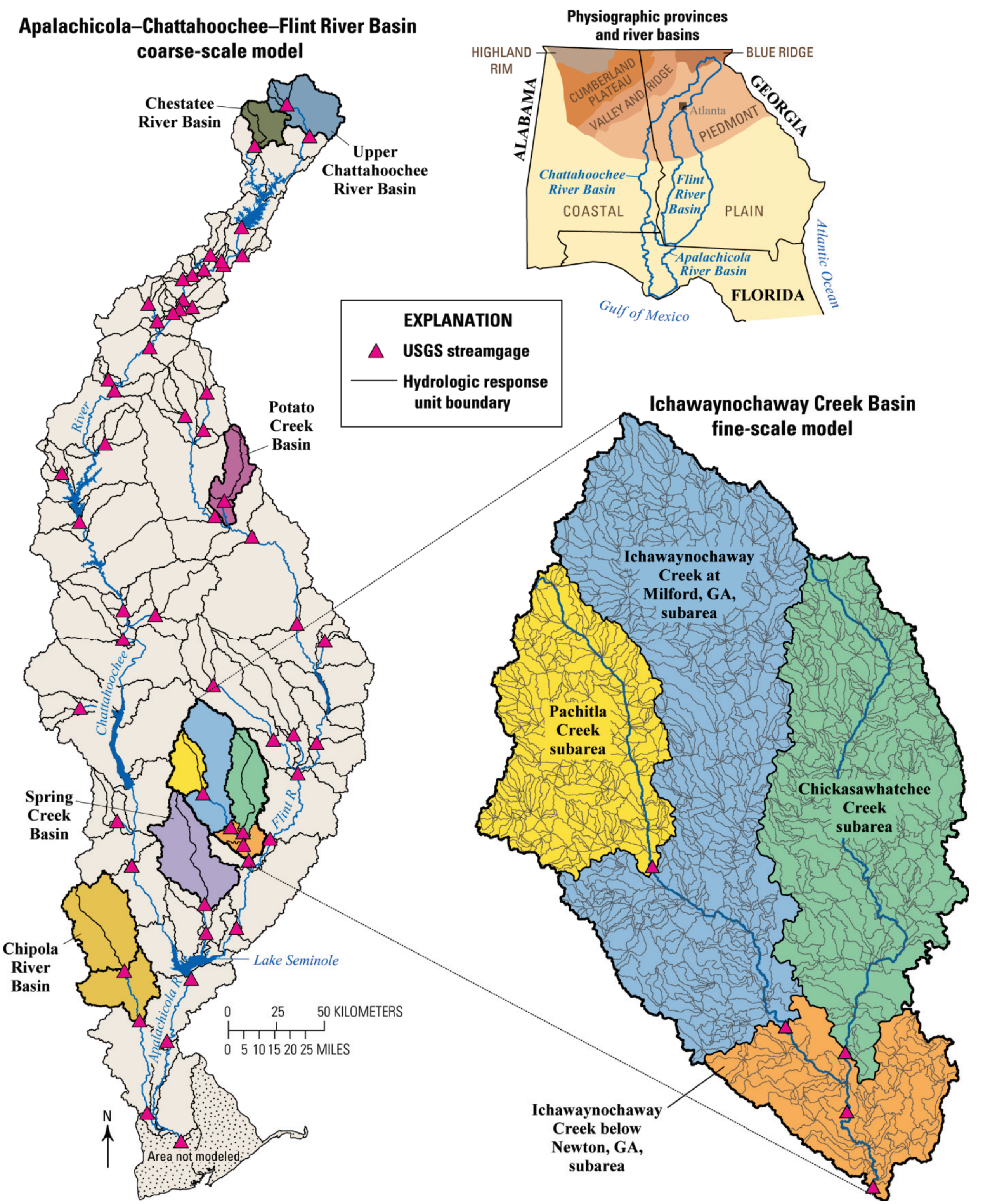

Figure 2. Example of a fine-scale hydrologic model nested within the coarse-scale hydrologic model. Ichawanochaway Creek is located in the lower Flint River Basin and comprises 2,690 square kilometers (km^2). Each of the coarse-scale hydrologic response units (HRUs) in the fine-scale model areas are split into smaller HRUs that provide detailed flow information used by the aquatic occupancy modeling shown in Figure 1. The HRUs range in size from 5 km^2 to 1,900 km^2 for the coarse-scale model and from <0.1 km^2 to 17 km^2 for the fine-scale models.

Description of Precipitation-Runoff Models

The ACF River Basin was modeled using a nested approach composed of a coarse-scale model of the entire basin and six fine-scale models for subbasins of interest (Table 1). The coarse-scale model simulates streamflow to address regional hydrologic questions and provides a regional framework for identifying future fine-scale models in the basin. The fine-scale models simulate streamflow at more points in a given subbasin than the coarse-scale model. In the collaborative process, aquatic occupancy modeling (Figure 1) makes use of the detailed streamflow information simulated by the fine-scale hydrologic models to simulate the presence and persistence of fishes and mussels.

Precipitation-Runoff Modeling System

PRMS is a deterministic, distributed-parameter, physical-process based hydrologic model (Leavesley et al. 1983). There are four primary objectives of this modeling system: (1) simulation of land-surface hydrologic processes, including evapotranspiration, runoff, infiltration, interflow, snowpack, and soil moisture on the basis of distributed climate information (temperature, precipitation, and solar radiation); (2) simulation of hydrologic water budgets at the watershed scale with temporal scales ranging from days to centuries; (3) integration with models used for natural-resource management or other scientific disciplines; and (4) creation of a modular design that allows the selection of alternative hydrologic process algorithms from either the standard module library or user-provided provisional modules.

Delineation and Parameterization

Typically, the delineation of a PRMS hydrologic model is done by overlaying a USGS digital elevation model (DEM) with the study basin using the geographical information system (GIS) Weasel software developed by Viger and Leavesley (2007). The DEM was used to develop the modeled stream network and divide the basin into a series of areas called hydrologic response units (HRUs; Figure 2). HRUs simulate the hydrologic response of the basin (streamflow) to air temperature and precipitation. The stream network is used to route streamflow from the HRUs through the basin. Initially, HRUs were delineated based on the stream network, a maximum area threshold, and changes in elevation from the DEM. These delineations were further refined by including points of interest in the basin, such as locations of streamflow gages, minimum flows, sampling sites, etc. Once the stream network and HRUs were defined, the GIS Weasel software was used to parameterize the model by using terrain, soil, land-cover, impervious-area, and vegetation data. Included in the land cover category is a GIS coverage of surface depressions in the basin. Large numbers of these relatively small waterbodies can have substantial hydrologic effects on streamflow. The simulation of these surface depressions, as discussed in Viger et al. (2009), was used in this set of hydrologic models. Each segment in the stream network and each HRU were treated as a homogeneous entity with parameters that represent an aggregation of the information contained in the data coverages used.

Table 1. Description of coarse- and fine-scale hydrologic models in the Apalachicola–Chattahoochee–Flint River Basin.

Model	Drainage area (square kilometers)	Number of USGS streamgages	Number of stream segments	Hydrologic response unit	Physiographic province
Coarse-scale model					
Apalachicola–Chattahoochee–Flint River Basin	50,700 (approx.)	57	128	258	Blue Ridge, Coastal Plain, Piedmont
Fine-scale model					
Upper Chattahoochee River	815	2	328	600	Blue Ridge, Piedmont
Chestatee River	396	1	168	312	Blue Ridge, Piedmont
Chipola River	2,020	2	778	1,472	Coastal Plain
Ichawaynochaway Creek	2,690	5	824	1,542	Coastal Plain
Potato Creek	616	1	221	427	Piedmont
Spring Creek	1,260	1	345	674	Coastal Plain

Climate Data

PRMS requires the input of daily maximum and minimum air temperatures and daily precipitation data. Climate station data provided by the National Weather Service Cooperative Observer Program (National Oceanic and Atmospheric Administration 2010) typically are used for PRMS models. Initially, 79 of these climate stations were used for the coarse-scale hydrologic model. The model was then adjusted to use climate data from one-eighth-degree (about 12 kilometers [km]) gridded products developed for the conterminous United States by Maurer et al. (2002). A Web-based GIS interface called the Geo Data Portal was then used to spatially transfer the gridded climate data to the model HRUs. The gridded climate data currently available are for the period 1950–1999; however, the gridded climate data and projections are being downscaled for the period 2000–2099 by using statistical and dynamical procedures.

Streamflow Data

The USGS streamflow-gaging network (http://waterwatch.usgs.gov/) was used to obtain daily-flow data for calibration and evaluation of the hydrologic models. For this study, 57 streamgages were selected based on a minimum drainage area of 25 km^2 and a minimum of 10 years of daily-flow record. The spatial distribution of the selected streamgages is shown in Figure 2. Streamflow data are retrieved and formatted for the hydrologic models by using Downsizer, a graphical user interface (GUI) developed by Ward-Garrison and others (2009).

Nested Modeling Approach

Efficient development and interpretation of hydrologic models for the SERAP required that models of varying spatial scales be developed. A single, fine-scale model of the whole ACF River Basin would be time and cost prohibitive. For computational efficiency, the coarse-scale model was developed to (1) represent the overall water balance and hydrologic processes of the system and (2) provide a regional framework for fine-scale hydrologic models. The calibrated coarse-scale model also can provide initial pre-calibration values for some parameters used in the fine-scale models.

By using the coarse-scale HRUs and the stream network, selected fine-scale basins were delineated so the fine-scale HRUs nest within the coarse-scale HRUs, and the fine-scale stream-segment nodes include the coarse-scale stream-segment nodes (Figure 2). By matching the fine- and coarse-scale model delineations, direct comparisons can be made across model scales. In the event that the calibrated fine-scale models outperform the coarse-scale model, outputs from the fine-scale models can be used to refine the coarse-scale model.

Hydrologic Models

Seven hydrologic models were developed for the ACF River Basin—one coarse-scale basinwide model and six fine-scale models. The six fine-scale models simulate two subbasins (upper Chattahoochee and Chestatee Rivers) in the northern part of the ACF River Basin, one subbasin (Potato Creek) in the central part of the basin, and three subbasins (Chipola River and Ichawaynochaway and Spring Creeks) in the southern part of the basin (Figure 2). The subbasins for which fine-scale models were developed were selected based on representing the different physiographic provinces in the ACF River Basin, current and projected urbanization, and critical areas of ecological habitat. The upper Chattahoochee River, Chestatee River, and Potato Creek subbasins are relatively undeveloped in terms of urbanization and agriculture, whereas the Chipola River and Ichawaynochaway and Spring Creek subbasins are heavily developed by agriculture.

The models were calibrated using Luca software, a multi-objective, stepwise, wizard-style graphic user interface (GUI; Hay et al. 2006, Hay and Umemoto 2006). This GUI uses the Shuffled Complex Evolution (Duan et al. 1993) global search algorithm to calibrate parameters for PRMS hydrologic models. A procedure has been developed to calibrate each model by using the following variables: (1) mean monthly solar radiation, (2) mean monthly potential evapotranspiration, (3) annual and monthly flows, (4) timing of daily flows, (5) magnitude of high-flow days, and (6) magnitude of low-flow days. Model parameters were adjusted to optimize the simulation of these six variables for historical climate and streamflow data for the period 1990–1999. Once the models were calibrated, they were evaluated using historical climate and streamflow data for the period 1980–1989. Plots of annual-, monthly-, and daily-flow statistics were used to evaluate the accuracy of the model simulations.

This suite of hydrologic models can be used to study the effects of changing climate and landscape on the hydrologic response of the ACF River Basin. The hydrologic modeling output can also be used as input for stream temperature and aquatic occupancy modeling being done by others in the SERAP collaborative process (Figure 1).

Summary

Multiresolution hydrologic models of the Apalachicola–Chattahoochee–Flint (ACF) River Basin, developed as part of the Southeast Regional Assessment Project (SERAP), are helping assess the potential effects of climate change on ecosystems. Hydrologic models of varying spatial extents and resolutions were developed to address varied local-to-regional water resource management questions as required by the scope and limitations of potential management actions. Seven models were developed by using PRMS.

A coarse-scale model for the ACF River Basin, with a contributing area of approximately 50,700 km^2, is coupled with six fine-scale subbasin models, ranging in size from 396 to 2,690 km^2, for the upper Chattahoochee, Chestatee, and Chipola Rivers and the Ichawaynochaway, Potato, and Spring Creeks. These subbasins were selected based on representation of the different physiographic provinces, current and projected urbanization, and critical areas of ecological habitat. All of the models simulate basin hydrology for the period 1950–1999 using a daily timestep, measured climate data, and basin characteristics, such as land cover and topography. Measured streamflow data from 57 USGS streamgages were used to calibrate and evaluate computed basin hydrology. The ability to project future hydrologic conditions for this set of models will rely on the use of land cover projections in conjunction with downscaled global climate model results.

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