Demonstration of a Unified Hydrologic Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

Report of Results and Next Steps

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List of Figures

2-1. SALCC study boundary watersheds .......................................................... 2
2-2. Overview map of the 60 calibrated gages in the SALCC region .................. 7
2-3. Nash-Sutcliffe Efficiency by drainage area for 46 stream gages under unaltered conditions ........................................... 8
2-4. Flow duration curve for a six-year period of unaltered conditions for Falling River near Naruna, VA ....................................................... 8
2-5. Daily hydrograph for a one-year period for the Chattahoochee River near Cornelia, GA ........................................... 9
2-6. Median monthly flow comparison (calibration period) for Alcovy River above Covington, GA ........................................... 9
2-7. Mean streamflow by month for a three-year period for Reddies River at North Wilkesboro, NC ........................................... 10
2-8. 1970s land use based on digitized aerial photography ................................ 11
2-9. Location of Validation Gage within the Roanoke River Watershed ............ 13
2-10. Flow duration curve for Validation Gage Cub Creek near Phenix, VA ........ 14
2-11. Location of Validation Gage in the Santee River Watershed ..................... 14
2-12. Flow duration curve for Validation Gage Broad River near Boiling Springs, NC ........................................... 15
2-13. WaterFALL estimated flow values plotted against USGS observed flow values for May Low Flows (25th percentile) ........................................... 16
2-14. Local watershed nodes (yellow circles) in the Savannah River Basin (outlined in red) (GA EPD, 2010) ........................................... 17
2-15. Overview map of human alterations in the SALCC study area .................. 18
2-16. Overview map of each dam below a reservoir in the six SALCC watersheds .......... 21
2-17. Illustration of reach gain concept .......................................................... 22
2-18. 2006 land cover used for current condition scenarios in six watersheds .... 22
2-20. Segment of the hydrograph (2002–2004) for Falling Creek altered simulation ........................................... 24
2-23. 2050 land use created from the combination of NLCD 2006 and SLEUTH and SLAMM modeling ........................................... 27
2-24. Estimated County-Level changes in water use between 2005 and 2050 .......... 29
3-1. 1970s land use layer centered on USGS 02335700, Big Creek near Alpharetta, GA ........................................... 30
3-2. 2006 land use layer centered on USGS 02335700, Big Creek near Alpharetta, GA ........................................... 31
3-3. 2050 land use layer centered on USGS 02335700, Big Creek near Alpharetta, GA ........................................... 31
3-4. Baseline scenario FDC (1960-1990) for USGS 02335700, Big Creek near Alpharetta, GA (USGS in red; WaterFALL in blue) ........................................... 32
3-5. Current conditions scenario FDC (1976-2006) for USGS 02335700, Big Creek near Alpharetta, GA (USGS in red; WaterFALL in blue) ........................................... 32
3-6. WaterFALL simulated (blue) and USGS gage (red) hydrograph for USGS 02335700, Big Creek near Alpharetta, GA (2004–2005) ........................................... 33
3-7. Median monthly flow comparisons across four WaterFALL scenarios for USGS 02335700, Big Creek near Alpharetta, GA ........................................... 34
3-8. Mean monthly flow comparisons across four WaterFALL scenarios for USGS 02335700, Big Creek near Alpharetta, GA ........................................... 34
3-9. RPD comparison of August low flow between 1970s baseline and current conditions for the North Carolina extent of the Broad River basin ........................................... 35
3-10. RPD comparison of August low flow between baseline conditions and future scenario B1 for the North Carolina extent of the Broad River basin ........................................... 36
3-11. RPD comparison of August low flow between baseline conditions and future scenario A1FI for the North Carolina extent of the Broad River basin.................................................................36
3-12. 30-year summary of daily average August temperatures for future scenarios for the headwaters of the Second Broad River (one standard deviation represented by shaded area). .................................................................................................................................37
3-13. 30-year summary of daily average August temperatures for future scenarios for the headwaters of the Second Broad River (one standard deviation represented by shaded area). .................................................................................................................................38

List of Tables
2-1. Number of Gages Per Watershed Used in Calibration.................................................................6
2-2. Total Catchments and Area Simulated for Baseline WaterFALL Scenario .............................. 11
2-3. Monthly NSE Performance Metrics............................................................................................26
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

Acronyms and Abbreviations

A1FI Future climate scenario with high greenhouse gas emissions from fossil intensive technology
AWC Available Water Capacity
B1 Future climate scenario with lower greenhouse gas emissions due to resource efficient technology
CCSM3 Community Climate System Model version 3
cfs Cubic feet per second
FDC Flow Duration Curve
GCM Global Climate Model
GIS Geographic Information System
HUC6 (8,12) 6 (8 or 12)-digit hydrologic unit code watershed
IBT interbasin transfer
IHA Indicators of Hydrologic Alteration
IPCC Intergovernmental Panel on Climate Change
LCC Landscape Conservation Cooperative
MGD million gallons per day
NC DENR North Carolina Department of Environment and Natural Resources
NCAR National Center for Atmospheric Research
NHDPlus enhanced National Hydrologic Database
NLCD National Land Cover Dataset
NPDES National Pollutant Discharge Elimination System
NSE Nash-Sutcliffe Efficiency
OVE Overall Volume Error
PEST Parameter Estimation Tool
PET potential evapotranspiration
RCoeff Recession Coefficient
RPD relative percent difference
RTI RTI International
SALCC South Atlantic Landscape Conservation Cooperative
SARP Southeast Aquatic Resource Partnership
Seep seepage coefficient
SERAP Southeast Regional Assessment Project
SLAMM Sea Level Affecting Marshes Model
SLEUTH Urban growth and land use change model (Slope, Land Use, Exclusion, Urban, Transportation, Hillshade)
SSURGO Soil Survey Geographic Database
TNC The Nature Conservancy
USGS U.S. Geologic Survey
VA DEQ Virginia Department of Environmental Quality
WaterFALL® Watershed Flow and Allocation Model
1. Introduction

This project demonstrated the development and application of a hydrologic model for assessing human and climate impacts on daily streamflow for the enhanced National Hydrologic Database (NHDPlus) stream reaches within the boundaries of the South Atlantic Landscape Conservation Cooperative (SALCC). Created by the U.S. Department of the Interior with Secretarial Order No. 3289, the 22 Landscape Conservation Cooperatives (LCCs) across the country seek to better integrate science and management to address climate change and other landscape scale issues. The LCCs also provide a network of resource managers and scientists who share a common need for scientific information and interest in conservation. In 2011, the SALCC instituted a Request for Proposals to develop streamflow estimates for the SALCC region over a range of baseline, altered, and future scenarios. The selected approach to developing streamflows in the SALCC relied on RTI International’s (RTI’s) Watershed Flow and Allocation model, WaterFALL®, which enables interactive, quantitative investigation of water availability at multiple geographic scales. WaterFALL employs an enhanced version of a well-established hydrologic model, the Generalized Water Loading Function (Haith and Shoemaker, 1987), which has been modified to run on the NHDPlus network. WaterFALL functions as an intermediate-level, distributed hydrological model that accounts for spatial variability of the land surface, as well as climatic forcing functions. The watershed model encompasses all major components of the hydrologic cycle using the curve number method for computing runoff and a first-order depiction of infiltration and loss to deep aquifer storage. Enhancements include the representation of human interactions with the natural hydrologic system, allowing for the simulation of altered conditions, and routing routines to transport water from upstream to downstream through the catchment network.

WaterFALL’s distributed model architecture is designed to be scalable and portable. The model can be run anywhere on the NHDPlus network for a single catchment or for any watershed upstream of a user-selected catchment with minimal model set-up, calibration, or additional data inputs for natural stream systems. WaterFALL provides extremely high spatial granularity in its outputs through its distribution across many small NHDPlus catchments, which offers localized sensitivity to geographic variations in land cover and climate across a study region.

RTI, under subcontract to The Nature Conservancy (TNC), used WaterFALL to provide a hydrologic foundation of “unaltered” streamflows for the entire SALCC region dominated by surface water. For six chosen six-digit hydrologic cataloging unit code (HUC6) watersheds within the SALCC region, RTI then conducted a pilot study of current or “altered” conditions, as well as two future scenarios. This report summarizes the findings and outcomes of the project and includes a work plan for the estimation of the streamflow across the SALCC and across the scenarios. As an umbrella hydrologic model for the entire region, WaterFALL can provide a consistent platform for analyses among the many partners, states, and other organizations within the SALCC. As applications extend to other regions, it could also provide a consistent platform between all the LCCs. The final sections of this document constitute a set of focused options for moving forward with WaterFALL in the SALCC and potentially other LCCs.

2. Task Descriptions

2.1 Define Watershed Boundaries

Figure 2-1 shows the 18 watersheds (HUC6 scale) that lie completely or partially within the SALCC boundaries. For the most part, there is relatively good alignment between watershed boundaries and SALCC boundaries. There are only two watersheds, the Apalachicola and the Coosa-Tallapoosa, where a majority of the drainage areas lie outside of the SALCC boundary. Upon concurrence by the SALCC stakeholder group, we included the 16 full HUC6 watersheds delineated in Figure 2-1 in the initial
modeling assessment. The Coosa-Tallapoosa was eliminated from the modeling effort, while the portions of the Apalachicola falling within the SALCC were included in the modeling (i.e., the upper three HUC8s).

![Figure 2-1. SALCC study boundary watersheds.](image)

### 2.2 Complete Model Parameterization

WaterFALL relies on national data sources, where available, to parameterize the climate, land use, and soils parameters necessary to drive the rainfall-runoff simulation mechanisms. The individual data sources used are provided in Appendix A (with the exception of water use data, which are discussed in Section 2.6). This section provides a general overview of the types of data necessary for the hydrologic model.

**Climate:** The rainfall-runoff mechanisms within WaterFALL are simulated on a daily time step. WaterFALL relies on daily temperature and precipitation to drive the model simulation and uses the temperature-based Hamon Method to estimate potential evapotranspiration (PET), in place of a more advanced method that would require cloud cover, relative humidity, and other climate parameters that are less available and more subject to variability and error. The daily, 4-kilometer gridded climate data set obtained from the U.S. Department of Agriculture for the period of 1960 to 2001 (and supplemented by researchers from University of Texas for the years 2002 to 2006) provides the most comprehensive (in terms of spatial and temporal coverage) and spatially explicit representation of precipitation and temperature available for the baseline and altered scenarios. Additional climate data used for the future scenarios is described in Section 2.9.2.
**Land Use:** As a curve number-based model, WaterFALL requires the specification of different land use components with their corresponding hydrologic soil condition. Additional characteristics required of land use, besides the basic type qualification, include the percent imperviousness for developed lands and the percent vegetative cover. Depending on the land use coverage used by scenario, these characteristics were either available as dataset attributes or qualifiers, or were estimated based on the land cover type. Two different land use data sets are employed in the baseline and altered scenarios for this project. The land use data related to future scenarios is described in Section 2.9.1.

**Soils:** The hydrologic condition of the soils underlying each land use within each catchment is required to properly apply a curve number for runoff calculations. Additionally, the subsurface characterization plays a role in determining how fast and at what magnitude water will move through the soils and either enter the deeper groundwater or the stream channel. Although the STATSGO data set has been readily used in hydrologic modeling across the country, for this analysis, we use the more detailed Soil Survey Geographic Database (SSURGO) dataset to obtain more local variances in soils conditions that are better suited to the NHDPlus catchment analysis. We used additional subsurface-based parameters calculated from the combination of SSURGO and land use, obtained from a National Weather Service modeling effort, as a starting point for calibration of the model (Section 2.3).

**Streamflow:** Although WaterFALL does not require observed streamflow inputs to run, these monitored time series can be used to calibrate the model. RTI has compiled a database of U.S. Geologic Survey (USGS) daily streamflow gage observations for this purpose. Additionally, we used some of these observations to represent the releases from dams or alterations caused by other major control structures, which WaterFALL does not explicitly simulate.

### 2.3 Calibrate Model for Unaltered Conditions

A general description of the process used to calibrate WaterFALL simulations is provided below, followed by the specifics of the SALCC calibration for unaltered flows. The actual mathematic calibration process for WaterFALL relies on an automated process that adjusts multiplier values applied to three different model parameters. To set up the process, a pour point on the stream must be chosen where a USGS streamflow gage, or other monitoring device, exists. The daily time series of observations are considered the daily values that should be matched by the model.

#### 2.3.1 Calibration Methods

Theoretically, WaterFALL can be calibrated at any point in the stream characterized by an NHDPlus catchment. However, in practicality, WaterFALL can only calibrated where observed streamflow records exist. The choices for locations of model calibration must be made with regard to several considerations. First, we consider the objective of the model application. For instance, to simulate baseline conditions, USGS streamflow gages that represent “reference” watersheds should be used because these portions of the stream most closely resemble unaltered hydrology. Next, we consider the size and distribution of streams throughout the watershed. Are there gaged locations spread out through several subwatersheds, or are gages concentrated only within one area of the watershed? Are there observations for both tributaries and the main stem of the river? An additional aspect to also consider is whether there is any classification of the USGS gages in the watershed available and, if so, to what class do the potential calibration gages fall (e.g., baseflow-fed, perennial, flashy)? Finally, location selection must account for the major characteristics of the watershed, such as major elevation changes, differences in physiographic regions, locations of cities, etc. Our overall goal for selecting calibration locations is to cover as many different aspects of the watershed as possible. After each individual (or nested) calibration is complete, we extrapolate the final calibrated parameters to the remaining uncalibrated areas of the watershed based on the major characteristics used in the original selection of the locations.
Extrapolation of parameters is possible based on the way the underlying data within WaterFALL have been parameterized and on the design of the calibration process and parameters. WaterFALL is setup in a distributed manner using catchment units ranging from less than 1 square mile to about 7.5 square miles. As a result, the number of catchment units modeled in a full watershed is very large. Calibration of parameters for each catchment individually would be computationally prohibitive. To balance the spatial granularity of the modeling with the computational requirements for calibration, WaterFALL uses an intermediate-level representation of the hydrologic cycle. This level of process-based modeling relies on minimizing the number of model parameters or inputs that can be directly created from physical data and maximizing the number of parameters derived from pure model calibration while still mathematically representing the interconnected hydrologic processes. WaterFALL’s hydrologic representation requires the adjustment of only three model parameters with calibration. Additionally, for two of the parameters, it is not the actual parameter that is adjusted, but a multiplier across the physically based values for the parameter currently available within the WaterFALL database; hence, extrapolation of this multiplier rather than the parameter itself reduces the uncertainty for ungaged streams and preserves the heterogeneity of the physical basis of the parameter across the NHDPlus catchments spanning different soils and land use combinations.

We estimate the values for the two physically based calibration parameters, the available water capacity (AWC) within the unsaturated soils, and the recession coefficient (RCoeff) to define the release of water from the saturated subsurface zone to the stream, from soils (SSURGO) and land use (2001 National Land Cover Dataset [NLCD]) geospatial data layers. Their formulation was developed by the National Weather Service on a 4.67-kilometer grid scale (HRAP grid) across the contiguous United States for use in the Sacramento Soil Moisture Accounting Model (Anderson et al., 2006; Zhang et al., 2011). We overlay and geoprocess the values available for each grid cell against the NHDPlus catchments. Therefore, the values available for each of these two parameters have a physical basis and are adjusted proportionally, up or down, for a calibration region based on the calibrated multiplier to preserve the physical relationship between the soils and land use properties in the region.

The third calibration parameter, the seepage coefficient (Seep), controls the amount of water released from the saturated subsurface into the deep groundwater aquifer. This release constitutes a loss from the system, where the water is no longer available to reach the stream in the temporal context of daily rainfall-runoff modeling. Seepage is controlled in part by the geology within a region and the extent to which the groundwater and surface water are connected. Although related to the geology, the existing national-scale geologic information does not provide enough information to determine quantitative values on which to base this parameter. Therefore, we determine the seepage parameter completely through calibration, although we are guided by the general geology of a region. We hold the value constant over a calibration region.

We provide a range of values (minimum and maximum) and a starting value for each of these three parameters to the program to start the calibration algorithm. We have set up a customized version of the Parameter Estimation Tool (PEST) to interact with WaterFALL and calibrate the parameters through an iterative process. PEST uses a nonlinear estimation technique known as the Gauss-Marquardt-Levenberg method. The strength of this method lies in the fact that it can generally estimate parameters using fewer model runs than any other estimation method. Once interfaced with WaterFALL, PEST’s role is to minimize the weighted sum of squared differences between model-generated values and USGS streamflow gage observations; this sum of weighted, squared, model-to-measurement discrepancies is referred to as the “objective function.” Depending on the purpose of the model, different objective functions are used within WaterFALL’s calibration process:

- Minimize log-transformed differences in daily flows
- Minimize real-space differences in daily flows
- Minimize log-transformed differences in monthly total streamflow
- Minimize real-space differences in monthly total streamflow.

We completed all calibrations with the objective of minimizing the differences in log-transformed daily flows. This objective function gives equal weight to differences in streamflows at the low end of the hydrograph as to the high end of the hydrograph, which often results in better representation of low flows at the expense of potentially underestimating peak streamflows. After completing the model run with the calibrated parameters, we examine the daily hydrograph, monthly median and mean flow, and flow duration curves to assess whether additional subjective adjustments should be made to the calibrated parameters (e.g., a small adjustment to the AWC to reduce daily flashiness).

We use several performance metrics to evaluate the goodness-of-fit for the model. Daily flows were evaluated by an overall volume error (OVE) measure or percent bias and by the Nash-Sutcliffe Efficiency (NSE) (Equations 1 and 2). The OVE quantifies the percent difference in total (summed) daily volume of observations versus model estimates. The NSE ranges from $-\infty$ to 1, where a value of 0 indicates that the model predictions are as accurate as the mean of the observed data. A negative NSE value indicates that the residual variance is larger than the data variance. Both of these daily measures are disproportionately impacted by large storm events where the residual (i.e., difference between observation and model) for a single day with peak flow will cause a larger reduction in these quantitative measures than a difference in a day with low flow. Therefore, we also assess qualitative measures. We balance the quantitative performance metrics related to daily streamflows by matching overall/seasonal trends in the flow duration curve (FDC), daily hydrograph, and monthly median and mean flows.

\[
OVE = \sum_{t=1}^{n} S_t - \sum_{t=1}^{n} O_t \times 100
\]

\[
NSE = 1.0 - \frac{\sum_{t=1}^{N} (S_t - O_t)^2}{\sum_{t=1}^{N} (O_t - \mu_o)^2}
\]

Where

- $S_t$ = Model simulated flow time series
- $O_t$ = Observed flow time series
- $\mu_o$ = mean (average) of observed flow

### 2.3.2 Calibration for the SALCC

We selected 60 gages throughout the SALCC region for model calibration under baseline conditions (Table 2-1 and Figure 2-2). Each HUC6 watershed had at least one calibrated gage, and large watersheds had at least three calibrated gages. Thirty five gages were considered reference gages, meaning that they had very few upstream flow alterations from human activities (e.g., dams, large cities, power plants), and 25 were non-reference gages. Most of the gages were calibrated from 1968–1975, with some variance depending on the USGS time series.
Table 2-1. Number of Gages per Watershed Used in Calibration

<table>
<thead>
<tr>
<th>Watershed (HUC6)</th>
<th>Non-reference</th>
<th>Reference</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albermarle-Chowan</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Altamaha</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Apalachicola</td>
<td>3</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Aucilla-Wacasassa</td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Cape Fear</td>
<td>4</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Edisto</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Lower Pee Dee</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Neuse</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Ochlocknee</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ogeechee</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Pamlico</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Roanoke</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Santee</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Savannah</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>St. Mary’s</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Suwannee</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Upper Pee Dee (Yadkin)</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td><strong>25</strong></td>
<td><strong>35</strong></td>
<td><strong>60</strong></td>
</tr>
</tbody>
</table>
Overall, the model provided a very good estimate of the flow regime at all of the calibrated gages, with the exception of those calibrated gages located in the Karst regions of Florida and coastal Georgia (i.e., Aucilla-Wacasassa, Ochlocknee, St. Mary’s, and Suwannee). This southern SALCC area was not modeled well due to the groundwater interactions that involve the underlying aquifer(s) and related retention of large volumes of water in swamp lands. The processes simulated in the current WaterFALL version employed for the SALCC, which includes surface water and shallow groundwater, did not account for the time-varying gains in streams from deeper or more interactive groundwater, or for the retention of water within large swamplands. These watersheds were eliminated from the current SALCC project and will be considered for a future modeling effort using an updated version of WaterFALL that includes more advanced retention functions and the ability to incorporate existing groundwater model results.

The goodness-of-fit between WaterFALL and the USGS gages for the remaining SALCC study area (n = 46) revealed that there was no consistent bias in the model. We examined model fit through the quantitative NSE (Figure 2-3) and OVE values and through FDCs and daily and monthly hydrographs. Examples of these comparisons are provided in Figures 2-4 through 2-7, respectively.
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

Figure 2-3. Nash-Sutcliffe Efficiency by drainage area for 46 stream gages under unaltered conditions.

Figure 2-4. Flow duration curve for a 6-year period of unaltered conditions for Falling River near Naruna, VA.
Figure 2-5. Daily hydrograph for a 1-year period for the Chattahoochee River near Cornelia, GA.

Figure 2-6. Median monthly flow comparison (calibration period) for Alcovy River above Covington, GA.
2.4 **Generate Unaltered Flow Data (Baseline Scenario)**

We generated flow data representing the baseline unaltered condition for the entire SALCC region. The model was run over a 30-year time period from 1960–1990 (1960 used as a model spin-up year and not reported as results) and used an enhanced historic land cover layer from the 1970s (Figure 2-8). We chose to use this land use/cover data set because it is one of the first national-scale representations of historic land cover that predates most urban/suburban development. Other options for setting baseline land cover would have involved assumptions on pre-development conditions by land use type or removal of all development. We did not include any human alterations or control structures in the unaltered run. Any onstream waterbodies that were identified within the land cover were simulated as run-of-river structures, where outflow is equal to the inflow less the volume of water loss to evaporation over the surface area of the waterbody. Comparing baseline conditions to altered or future conditions demonstrates the impact of changes in land use, climate, and human alterations on the hydrologic regime.
We used the calibration parameters from 46 stream gages to parameterize the full baseline run. Table 2-2 lists the NHDPlus catchments and total area simulated for each watershed. These catchments represent each instance, where a streamflow time series is available from January 1, 1961, to December 31, 1990. With simulations of the full watersheds, additional analyses can be conducted, including validation of calibrations and advanced assessments of the hydrologic regime.

**Table 2-2. Total Catchments and Area Simulated for Baseline WaterFALL Scenario**

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Subwatershed</th>
<th># Catchments</th>
<th>Area (mi²)</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albemarle-Chowan</td>
<td>—</td>
<td>6,410</td>
<td>4,212</td>
<td>10,908</td>
</tr>
<tr>
<td>Altamaha</td>
<td>—</td>
<td>19,050</td>
<td>13,995</td>
<td>36,247</td>
</tr>
<tr>
<td>Apalachicola</td>
<td>Chattahoochee</td>
<td>6,827</td>
<td>4,616</td>
<td>11,955</td>
</tr>
<tr>
<td></td>
<td>Flint</td>
<td>4,423</td>
<td>2,625</td>
<td>6,800</td>
</tr>
<tr>
<td>Cape Fear</td>
<td>Cape Fear</td>
<td>10,102</td>
<td>5,272</td>
<td>13,654</td>
</tr>
<tr>
<td></td>
<td>Black River</td>
<td>1,945</td>
<td>1,250</td>
<td>3,236</td>
</tr>
<tr>
<td></td>
<td>Northeast Cape Fear</td>
<td>1,210</td>
<td>1,010</td>
<td>2,617</td>
</tr>
<tr>
<td>Edisto</td>
<td>Edisto</td>
<td>3,271</td>
<td>2,760</td>
<td>7,149</td>
</tr>
<tr>
<td></td>
<td>Combahee</td>
<td>1,212</td>
<td>1,200</td>
<td>3,108</td>
</tr>
<tr>
<td>Lower &amp; Upper Pee Dee</td>
<td>Great Pee Dee</td>
<td>20,051</td>
<td>13,936</td>
<td>36,095</td>
</tr>
<tr>
<td></td>
<td>Black River</td>
<td>2,726</td>
<td>1,996</td>
<td>5,170</td>
</tr>
<tr>
<td>Neuse</td>
<td>—</td>
<td>6,865</td>
<td>3,951</td>
<td>10,233</td>
</tr>
</tbody>
</table>

(continued)
Table 2-2. Total Catchments and Area Simulated for Baseline WaterFALL Scenario (continued)

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Subwatershed</th>
<th># Catchments</th>
<th>Area (mi²)</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ogeechee</td>
<td>—</td>
<td>6,181</td>
<td>4,375</td>
<td>11,331</td>
</tr>
<tr>
<td>Pamlico</td>
<td>Tar</td>
<td>4,648</td>
<td>2,686</td>
<td>6,956</td>
</tr>
<tr>
<td>Roanoke</td>
<td>Middle Roanoke</td>
<td>14,678</td>
<td>8,463</td>
<td>21,919</td>
</tr>
<tr>
<td></td>
<td>Lower Roanoke</td>
<td>716</td>
<td>488</td>
<td>1,263</td>
</tr>
<tr>
<td>Santee</td>
<td>Santee</td>
<td>16,349</td>
<td>14,819</td>
<td>38,380</td>
</tr>
<tr>
<td>Savannah</td>
<td>—</td>
<td>12,710</td>
<td>9,848</td>
<td>25,505</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>139,374</td>
<td>97,500</td>
<td>252,524</td>
</tr>
</tbody>
</table>

2.4.1 Model Assumptions and Limitations for Baseline Scenario

The baseline model scenario represents “unaltered” stream conditions to the best extent possible using available data. The unaltered scenario does not represent pre-development conditions, but rather historic conditions where the landscape and stream networks were less altered than under current conditions. The land cover layer used in the baseline model run was created by the USGS by digitizing aerial photographs from the 1970s. This layer does not have the same level of granularity as the 2006 NLCD land cover layer and was not intended for a detailed analysis as it was processed at the 1:100,000 and 1:250,000 scale. Additionally, as with all scenarios, a single land cover was used for the full 30-year (1960–1990) baseline scenario simulation period (i.e., the 1970s coverage). To best assess the model performance using this land cover data set, we chose a calibration period to most closely match the reported land use characterization date, which was the mid-1970s for this area of the country.

Additionally some regulated reservoirs existed, as shown in the land cover layer during this time period. Without a method to differentiate between regulated/operated reservoirs and natural lakes within the land cover layer, we simulated any existing reservoirs using run-of-river methods for the baseline scenario (where outflow is equal to the inflow less the volume of water loss to evaporation over the surface area of the waterbody). This simulation method may affect the estimation of streamflow downstream along the main stem of the rivers with reservoirs; however, including these reservoirs will not affect the upstream or tributary estimates of streamflow in this scenario.

Also, considering the time period of this baseline, it is probable that some human withdrawals and returns existed, but records of those point alterations are not readily available and so they are not included in the baseline run. Although these data limitations highlight some of the uncertainty associated with conducting a historic hydrologic simulation, due to gage selection, it is unlikely the effects of these data limitations are seen in the model performance evaluations. We provide this listing of limitations for informational purposes when assessing baseline scenario estimates in the large rivers downstream of dams and small streams surrounding early urban and industrial areas.

2.4.2 Validation

We selected 60 gages throughout the SALCC region for model calibration and used the parameters from calibration to generate unaltered flow data for each HUC6 watershed in the study area. We used the performance metrics from nearby uncalibrated gages to assess the validity of the model run. The following examples describe the performance metrics used for model validation at two different stream classes in the SALCC region.

The Cub Creek gage near Phenix, VA, is located along a small tributary in northern portion of the Roanoke River Basin (Figure 2-9). This small, perennial stream has a drainage area of just under 100
square miles (mi²) and is less than 15 miles east of the calibrated gage, USGS 02064000 Falling River near Naruna, VA.

The WaterFALL simulated streamflow at the Cub Creek gage is very similar to the USGS observed flow values for the baseline model run (1960–1990). The daily NSE is high (0.40), and the OVE is low (-7.4%), indicating that the model provides a good fit for the observed values at this gage. The FDC (Figure 2-10) demonstrates that the WaterFALL-simulated data are a very good estimation of USGS observed values for high, median, low, and very low flows, but slightly underestimate the magnitude of very high flows (5th percentile).
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

Figure 2-10. Flow duration curve for Validation Gage Cub Creek near Phenix, VA.

The Broad River gage near Boiling Springs, NC, is located along the mainstem of the Broad River in the upper portion of the Santee River Basin (Figure 2-11). This validation gage differs from the previous example due to its large drainage area (875 mi²) and its classification as a stable, high baseflow river (using McManamay et al., 2011). The calibrated gage, USGS 02151000 Second Broad River near Cliffside, NC, is located less than five miles upstream near the confluence of the Second Broad and the Broad Rivers.

Figure 2-11. Location of Validation Gage in the Santee River Watershed.
The WaterFALL modeled data for unaltered conditions (1960–1990) were an excellent match for the USGS observed flow data for the same time period. The low OVE (-4.84%), as well as the very high NSE (0.69), establish the validity of the baseline model run for this gage. The FDC demonstrates that the simulated flow data are a very good representation for observed values across the three orders of magnitude (Figure 2-12).

![Figure 2-12. Flow duration curve for Validation Gage Broad River near Boiling Springs, NC.](image)

### 2.4.3 Examination of Results

Given the amount of data generated, results can be examined in a variety of ways with numerous objectives (more in Section 4). To provide an initial review of the WaterFALL baseline scenario results, we assessed a series of ecoflow metrics in comparison to calculations made using the corresponding USGS gage data. Ecoflow metrics provide a means of summarizing the time series streamflow data using different statistical measures that represent key elements of the hydrologic regime, which relate to biological and ecological needs in the environment.

The SALCC review committee requested four ecoflow metrics for assessment: May low flow, September low flow, March high flow, and January high flow. Low flows were calculated as the 25\(^{th}\) percentile of the flow record, while high flows equate to the 75\(^{th}\) percentile of the flow record. The entire 30-year period was used to compute these metrics. To provide a point of reference for evaluation, we applied a threshold of 30% difference between WaterFALL estimates and the USGS gage. This threshold was used in a USGS study of ecoflow metric estimation by a rainfall-runoff model (Murphy et al., 2012), and so we chose to make some summaries in a similar manner. The following summary describes the overall findings (we added two gages to the original 46 calibration gages to provide additional points of reference for watersheds lacking in number of gages or a particular stream type bringing the total number of comparison points to 48):

- 96% (46/48) of the gages are within the ± 30% boundaries for May low flows (25\(^{th}\) percentile)
- 83% (40/48) of the gages are within the ± 30% boundaries for September low flows (25\(^{th}\) percentile)
- 90% (43/48) of the gages are within the ± 30% boundaries for March high flows (75\(^{th}\) percentile)
- 90% (43/48) of the gages are within the ± 30% boundaries for January high flows (75\(^{th}\) percentile)
Gage data that fell outside of the ± 30% boundaries was found to be influenced by the following factors:

- A few large storm events that may skew the data (September low flows)
- A few years where USGS streamflow values drop near 0 for most of the month (September low flows, May low flows)
- In one instance USGS reports that flow estimates are poor below 200 cubic feet per second (cfs) (Drowning Creek Near Hoffman, NC) (September low flows)
- Possible groundwater or swamp influence (September low flows, March high flows)
- Gages that are highly flashy and difficult to calibrate requires a tradeoff between simulating low/median streamflows and high streamflows where WaterFALL calibration routines were set to defer to achieving better simulation of the lower streamflows (March high flows, January high flows).

Full results for this analysis are provided in Appendix B and include the additional parsing of stream gaging locations among different stream classes as established by McManamay and others (2011). Figure 2-13 presents the results of one of the comparison metrics for small- to medium-sized streams using low flows for the month of May. Of the 48 gages assessed, WaterFALL simulated 96% (46) to have values that are within +/- 30% of the USGS gage observations for this metric. Overall, across the four metrics, we did not see any overarching trends that indicated a general bias within the modeled results. The small and varied differences among simulated and observed metrics indicates that WaterFALL is a valid method to simulate ecoflow metrics across a range of watershed sizes and locations throughout the southeast.

2.5 Select Watersheds for Altered Flow Analysis

This project called for the simulation of altered and future WaterFALL simulations in a selected subset of watersheds. RTI, SALCC, and TNC selected the following six watersheds for modeling of altered/current flows based on available data, results for baseline scenario calibrations within the SALCC, and relevance to other studies within the region:

1. Apalachicola (3 HUC8s within SALCC region only) – important for comparisons with other broader Apalachicola-Chattahoochee-Flint (ACF) studies by USGS and targeted workgroups
2. Altamaha – large basin fully within Georgia
3. Cape Fear – large basin fully within North Carolina; withdrawals/returns data available from the North Carolina Department of Environment and Natural Resources (NC DENR)
4. *Broad (part of the Santee HUC6)* – selection of the Santee with existing OASIS model from North Carolina and important power plant alterations; withdrawals/returns data available for North Carolina portions from NC DENR

5. *Roanoke* – large basin in Virginia/North Carolina; withdrawals/returns data available from the Virginia Department of Environmental Quality (VA DEQ)

6. *Savannah* – highly altered main stem of river with few gages throughout the basin

Additional details on the selection process were outlined in a memo to TNC and SALCC dated December 20, 2012. This memo is included in Appendix C.

### 2.6 Data for Water Withdrawals and Return Flows

Water withdrawal and return data were collected from several state agencies in the SALCC study area. Alteration data within the six watersheds selected for altered scenarios were georeferenced to NHDPlus catchments and loaded into the WaterFALL database. We average monthly data across recent years to represent current conditions and to offset inconsistencies in data collection across political boundaries. All withdrawals and returns are entered by month in units of million gallons per day (MGD).

#### 2.6.1 Data by State

State agencies from Virginia and North Carolina provided withdrawal and return data that were assigned to latitude and longitude coordinate locations. We georeferenced these data to an NHDPlus catchment and loaded them into the WaterFALL database. The Virginia data were not provided with labels or sectors (e.g., industrial, agricultural). The North Carolina data were fully characterized by economic sectors.

South Carolina provided withdrawal data that were aggregated by county. We disaggregated the county-level data to coordinate locations by catchment using watershed maps, listings of surface water intake locations, National Pollutant Discharge Elimination System (NPDES) return data locations, and aerial photos. Specifically, we digitized the point locations included in PDF maps from the 2009 South Carolina State Water Assessment document to determine the coordinate locations for water withdrawals in the state (Wacob et al., 2009). Once we assigned the data to a coordinate location, we georeferenced each alteration to an NHDPlus catchment.

The state of Georgia provided withdrawal and return data georeferenced to NHDPlus catchments (i.e., they did not provide specific coordination locations) for all water uses except irrigation withdrawals. Irrigation withdrawals had previously been aggregated to local watershed nodes (Figure 2-14) as part of the Georgia State-wide Water Management Plan (Georgia Environmental Protection Division [GA EPD], 2010). Many local watersheds had very small agricultural withdrawals (< 5 MGD), in those cases we assigned the location for that withdrawal to the downstream NHDPlus catchment for each local watershed. A few local watersheds had large irrigation withdrawals (> 5 MGD); for those local watersheds, we distributed the total withdrawal equally across the area of cropland defined within the

![Figure 2-14. Local watershed nodes (yellow circles) in the Savannah River Basin (outlined in red) (GA EPD, 2010).](image-url)
NLCD 2006 layer within that watershed. We then summed these distributed withdrawals by NHDPlus catchment, which created a high density of NHDPlus catchments with small agricultural water withdrawals.

2.6.2 Data Compilation

Figure 2-15 illustrates the distribution of alterations across the six watersheds modeled for the current and future condition scenarios. NHDPlus catchments with withdrawal data are highlighted in blue, catchments with return data are highlighted in red, and catchments with both withdrawal and return data are outlined in green. Dense areas of withdrawal in the Apalachicola and Altamaha basins are due to distributed local watershed agricultural withdrawals across cropland areas. The high density of withdrawals is due to the spatial allocation of cropland in each local watershed (see Section 2.6.1). For each highlighted catchment, the WaterFALL database now contains information on each alteration, including whether the alteration represents a return or a withdrawal or both; the source of the data; and a set of monthly values of water either removed from or gained within the catchment due to human use.

Figure 2-15. Overview map of human alterations in the SALCC study area.
2.6.3 Limitations of Human Water Use Data

We collected the best available datasets on human water use from four states in the SALCC study area. In some cases, we collected data collected from multiple agencies within the same state. In order to account for discrepancies across geographic boundaries and/or agencies, we averaged the water use data by month for recent years. In almost every case, we used available data within the range of the years 2000–2012 to represent the current condition. The one exception was the water use data from the Roanoke River Basin, which were provided as an average across the years of 1984 through 2005. The temporal scale provided for each set of water uses also differed between agencies and water use sectors. For instance, NC DENR provided daily water withdrawals for public water supplies for the years 2010 through 2012, while for NPDES discharges, monthly values were provided for sporadic years and months.

The threshold for registering and/or reporting of water withdrawals varies by state and also by water use sector. Water withdrawn for irrigation generally has a higher reporting limit (or in some states, no limit) and many irrigation withdrawals may not be documented. Additionally, there may be differences or overlaps in data reporting across state agencies. In some cases, withdrawal and return data may be monitored by different agencies, which can result in accounting for a withdrawal without accounting for the corresponding return or vice versa. An example of such an occurrence is the inclusion of a discharge permit for an electric power facility without having any record of the withdrawal made for the plant from the local stream. Due to the vast quality of data compiled for this study, individual withdrawal and return data have not been checked for continuity at each data point, and some discrepancies, such as those described, may exist. The detailed review and potential updating of this data constitute a task for further study.
We used several different methods to disaggregate data provided for a larger geographic entity to an NHDPlus catchment. In Georgia, we disaggregated irrigation data from local watersheds to cropland areas within the 2006 NLCD. We assumed that irrigation withdrawals were distributed evenly across cropland areas and that all land classified as cropland used irrigation. In South Carolina, we assigned county-level withdrawal data to latitude and longitude coordinate locations digitized from maps in the South Carolina Water Assessment document. While digitizing a map is not as accurate as specific coordinate locations, it is safe to assume that the level of accuracy falls below the NHDPlus catchment scale. Additionally, although major South Carolina water withdrawals for each use sector were labeled on the maps, minor withdrawals were sometimes listed in text but not documented on a map. We therefore used other datasets, aerial photos, and best professional judgment to determine the location of minor water withdrawals. In a few cases, we placed unassigned minor water withdrawals in a withdrawal location near the outlet of the county.

Finally, interbasin transfers (IBTs) are common throughout the southeast region. In some areas, municipalities source water from multiple river basins. The extent to which these transfers are included within the compiled data is unknown. IBTs are a complex issue because water may be bought and sold between utilities through their daily-used surface water intakes, with an unknown quantity going to service their territory as opposed to being sent via pipeline to another territory outside the basin. Or, as in the case of pump-storage facilities or interlinked reservoirs, there may be specific infrastructure available to move water from one basin to another, or within one basin, on demand. Because most of the identified IBTs in this region work through existing municipal withdrawals, it is expected that some of the withdrawals are accounted for although we lack information on the specific location and amount of the corresponding returns in other basins, which may occur through wastewater treatment plants or other non-consumptive uses (e.g., lawn watering). Further investigation into the extent to which these transfers are accounted for in the existing water use data compilation provides another task for a next stage of this project.

2.7 Approach for Modeling Downstream of Control Points (Dams)

We identified 42 reservoirs within the 6 study watersheds of the Altamaha, Broad, Cape Fear, Roanoke, Savannah, and Upper Apalachicola (Figure 2-16). These reservoirs were identified through the National Inventory of Dams as storage areas with more than 500 acre-feet of normal storage. We verified the locations using geographic information systems (GIS) and aerial photography. After identifying the dams that are likely to have an influence on downstream flows, we selected streamflow gages in each dam’s vicinity to help determine how to best represent control structure flows. Ultimately, we used four different methods to create streamflow estimates from reservoirs: (1) gaged reservoir releases monitored at the outlet of each reservoir; (2) USGS gages below a dam, although not specifically monitoring reservoir releases; (3) downstream USGS gages data altered to remove gains in streamflow between the reservoir and the gage; and (4) representation of reservoirs in a series, or reservoirs that do not have flow records, by a gage downstream of the last reservoir or monitored reservoirs flows at the most downstream reservoir. We describe each method below.
Gaged Reservoirs: The ideal case for historical modeling, including reservoirs, is to have observed flow releases from the dam or a streamflow gage immediately downstream of the dam, where the dam is the only influence. If a stream gage is present in the flow-controlled stream reach, we used the time series gage data to determine the flow to the downstream catchment, which is then routed downstream.

Gage Below a Dam: Several reservoirs had a stream gage located directly below the dam. We used the stream gage flows to replace the simulated outflow at the farthest downstream catchment in the reservoir.

Downstream Gage with Gains Removed: If no flow records were available at the outlet of the reservoir, we used stream gage data from further downstream to simulate outflow from the reservoir. We used a previously created “reach gain” function within WaterFALL to determine the amount of streamflow generated locally between an upstream and a downstream catchment. The summation of the total local flows between the two points can be used to determine the streamflow attributed to the area upstream of the catchment of interest versus the flow that has entered the stream between the two catchments (i.e., the catchment of interest and the downstream catchment that includes a gage). Figure 2-17 illustrates this concept. If there was a dam located at Point #1, but there was a streamflow gage at Point #2 with several tributaries in between, the reach gain function calculated how much flow is generated between the two points, as indicated by the green arrows. Each arrow represents the flow generated within a single catchment. Therefore, when the flow was unknown at Point #1, the summation of the reach gains were subtracted from the flow at Point #2 to estimate the flow at Point #1, regardless of the distance or hydrologic network between the two points.
We used the reach gain method for eight reservoirs within the study area. For a few days within the flow record, the reach gain was larger than the downstream USGS flow records, which resulted in negative outflow values for the reservoir. In these instances, we replaced negative values using linear interpolation between days with positive outflow values so that all reservoir releases were positive (or zero) flow values.

**Reservoirs in Series:** For reservoirs that were in series, there is often little natural flow between the release from one and the tail waters of the next downstream reservoir. Therefore, we used the gage or observed release from the most downstream reservoir within the WaterFALL simulation to represent the flow out of the series of reservoirs. The modeled streamflows for catchments covered by the reservoir areas or for the short segments between the reservoir areas should not be considered in assessments.

### 2.8 Generate Altered Flows for Selected Watersheds

We generated altered flows that represent current conditions for six watersheds in the SALCC basin (Upper Apalachicola, Altamaha, Savannah, Broad, Cape Fear, and Roanoke). The altered model run included a current land cover layer from 2006 (Figure 2-18), known water withdrawals and returns, and the impact of control structures. The altered run spanned a 30-year interval from 1976–2006. Comparing the current condition results to the baseline results illustrates how the flow regime has changed over time. The altered model run can be used to explore the impacts of urbanization or the creation of a new reservoir on a specific stream, as well as how those changes are reflected throughout the entire watershed.

![Figure 2-18. 2006 land cover used for current condition scenarios in six watersheds.](image)
2.8.1 Assumptions and Limitations for Current Condition Scenarios

Altered condition model simulations require the characterization of human interactions with the natural hydrologic regime, typically through withdrawals and returns and the operations of dams. Often, time-varying observational data characterizing these interactions during the simulated time period of interest are not available, and estimates are made of water volumes transferred to and from the stream. As described in Sections 2.6 and 2.7, data on human interactions from withdrawals and returns were obtained from the states of Virginia, North Carolina, South Carolina, and Georgia, and data on reservoir releases were obtained from gages and estimation methods. Because in many cases the information needed to provide a day-by-day human alteration to the system was not available across a long time span or at the spatial or temporal resolution of the simulation, there were uncertainties introduced into the estimation of streamflow on the daily time scale. Although the models are calibrated, care should be given when comparing the reported statistical model performance parameters for daily simulations against typically reported performance in the literature, which often relies on “reference,” or less altered, conditions, where fewer uncertainties are introduced into the model simulations. General guidance on the use of data from this study is provided in Appendix D.

2.8.2 Model Performance and Validation

While on a day-to-day comparison basis between model estimates and observations, there may be uncertainties over the course of a 30-year simulation, the daily model estimates are well-suited to characterizing the daily flow regime. These two points are highlighted through example hydrographs and FDCs from a small watershed with no alterations (Figures 2-19 and 2-20) and from a large watershed with multiple human water uses (Figures 2-21 and 2-22). The small watershed, Falling Creek within the Altamaha Watershed, has a drainage area of 72.2 mi². The large watershed, Dan River within the Roanoke Watershed, has a drainage area of 1,053 mi² and contains several major alterations, including a power plant and reservoirs. Overall, the differences between WaterFALL and USGS gage flows in the daily hydrographs are typically unbiased, with some over- and some under-estimation on a daily basis. However, on average, the daily conditions are represented well as shown in the FDCs where there is typically little divergence along the majority of the curve and hence good representation of the long-term, daily flow regime. High, median, and low flows are typically very well represented. Extreme high flows (< 10th percentile) and extreme low flows (> 90th percentile) tend to be less well correlated. However, it should be noted that USGS flow observations have lower confidence intervals at the extreme high and low ends (Harmel et al., 2006; McMillan et al., 2012). A comprehensive review of observational uncertainties by McMillan and others (2012) resulted in the following estimates of confidence bounds for relative gaged-streamflow error: ±50–100% for low flows, ±10–20% for medium or high (in-bank) flows, and a single estimate of ±40% for out-of-bank flows.

Quantitatively, the daily NSE and OVE were similar between the current conditions and baseline scenarios (~0.3 and -30%, respectively) for Falling Creek. Observed flows during the period of record span nine orders of magnitude, which makes it challenging to model the extreme high and low flows, accounting for the lower daily NSE and larger differences calculated in total volume (i.e., due to differences in estimated extreme high flows). For the Dan River, the quantitative performance metrics show high synchronicity between WaterFALL and the observed flows, with a NSE > 0.5 and a small OVE (~0.3%) for the current conditions scenario.
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

Figure 2-19. Flow duration curve for Falling Creek altered simulation (1977–2006).

Figure 2-20. Segment of the hydrograph (2002–2004) for Falling Creek altered simulation.
Figure 2-21. Flow duration curve for the Dan River altered simulation (1977–2006).

Figure 2-22. Segment of the hydrograph (2002–2004) for the Dan River altered simulation.

Table 2-3 summarizes 30 years of monthly NSE values for 18 sites throughout the 6 simulated watersheds. Monthly metrics are often used in the recent work on developing ecological flows and flow–biology relationships. WaterFALL consistently represents the monthly average flow conditions with a high level of accuracy, as shown by NSE values around or above 0.7, with only a few exceptions in highly regulated and developed areas, as indicated by either reference (Ref) or non-reference (Non-ref) conditions for each gage.
## 2.9 Complete Future Scenarios

We completed a set of future scenarios to provide comparison points on the potential changes to the hydrologic regime across the SALCC. We chose the future scenarios based on available data and the objective to quantify the largest and smallest potential changes. This quantification was accomplished by pursuing downscaled climate results based on the B1 and A1FI emissions scenarios (explained below) formulated for the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report* (see Section 2.9.2). In addition to the two climate time series, the future scenarios included an estimate of land cover in 2050 (see Section 2.9.1) and increased human water use by set county-level percentages (see Section 2.9.3). We simulated two future scenarios for the six watersheds in the SALCC study area. The land use and modified alterations were consistent between scenarios, while the climate inputs differed between the B1 and A1FI scenarios.

### Table 2-3. Monthly NSE Performance Metrics

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<th>Gage ID</th>
<th>STANAME</th>
<th>Drainage (sq. mi)</th>
<th>Type</th>
<th>Monthly Mean Nash-Sutcliffe</th>
<th>Notes</th>
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</table>
2.9.1 Future Land Use

GIS personnel within the SALCC created the 2050 land use coverage (Figure 2-23) using a combination of the 2006 NLCD, Sea Level Affecting Marshes Model (SLAMM) coverage, and a Slope, Land Use, Exclusion, Urban, Transportation, Hillshade (SLEUTH) simulation of urban growth and land use change. The baseline dataset was the 2006 NLCD. Next, the A2 SLAMM 2050 dataset was reclassified to match the NLCD classes, with the exception of the upland developed and undeveloped classes from the SLAMM. Those classes were retained from the 2006 NLCD. The reclassified SLAMM data were then burned into the 2006 NLCD. Next, using the 2050 SLEUTH data, any pixel that had a 50% probability or higher of being urban was burned into the NLCD/SLAMM combination from the previous step. The urban pixels were changed to NLCD class 22 (i.e., developed, low intensity) unless they were classified as 23 or 24 (i.e., medium and high intensity) in 2006; in which case, the pixels were retained as class 23 or 24 (A. Keister, personal communication, 2013).

Figure 2-23. 2050 land use created from the combination of NLCD 2006 and SLEUTH and SLAMM modeling.

2.9.2 Future Climate

We obtained future climate data that were created for the Southeast Regional Assessment Project (SERAP) from Adam Terando at North Carolina State University. The first phase of the SERAP project, led by Katherine Hayhoe of Texas Tech University and funded by USGS, aimed to create future climatic datasets that can be used to project the impacts of climate change on ecosystems in the southeastern United States (Dalton and Jones, 2010). The climate datasets were created by dynamically downscaling existing Global Climate Models (GCMs), including emissions scenarios from the IPCC, and providing a quantifiable uncertainty analysis (Dalton and Jones, 2010). The datasets include daily minimum and maximum temperature and mean precipitation at a 12-kilometer grid scale from 1960 out to 2099.
We selected two future emissions scenarios (B1 and A1FI), provided by the IPCC, for the future model runs in the SALCC study region. The B1 family of scenarios predicts rapid economic growth but with rapid changes toward a service and information economy; population growth that reaches 9 billion in 2050 and then gradually declines; a reduction in material intensity and the introduction of clean and efficient technologies; and an emphasis on global solutions for economic, social, and environmental stability (IPCC, 2007). The B1 emissions projections can be thought of as a “best case” scenario, with lower greenhouse gas emissions due to resource efficient technology. The A1FI scenario is part of the A1 family of emissions projections, which predict rapid economic growth; similar population growth as in B1; the rapid introduction of new technologies; and the convergence of social and cultural interactions worldwide. The subset A1FI scenario predicts that the abundance of new technologies will be fossil intensive (IPCC, 2007). Initially, the A1FI scenario was predicted to be “worst case,” with high greenhouse gas emissions from fossil-intensive technology, although it is currently considered more likely to be “business as usual” with current fossil fuel consumption.

From the 10 different GCMs (PCM, Community Climate System Model version 3 [CCSM3], GFDL 2.0/2.1, HADCM3, GCM2, CGCM3, CNRM, ECHAM5, ECHO) downscaled in the SERAP project, four contained results for both the B1 and A1FI emissions scenarios. From those four GCMs, we used the CCSM3, available from the National Center for Atmospheric Research (NCAR), to provide the climate inputs for the future scenarios because the later version of the CCSM is a subset of NCAR’s current state-of-the-art Community Earth System Model (i.e., CESM). The CCSM is a coupled climate model for simulating the earth's climate system, which is composed of four separate models that simulate the earth's atmosphere, ocean, land surface, and sea-ice (National Center for Atmospheric Research, 2013).

2.9.3 Future Water Use

To estimate water use for the year 2050, we created a county-level multiplier based on the change in water use between 2005 to 2050 for each county in the SALCC study region, as provided in a national study by Roy and others (2010). We applied the county-level multiplier to all human water uses (withdrawals and returns) falling within the NHDPlus catchments of the corresponding county. If an NHDPlus catchment fell within more than one county, we used the multiplier corresponding to the county that contained the majority of the catchment area. Figure 2-24 highlights the changes in county-wide water use from 2005 to 2050 within the SALCC study region.

The county-level multiplier calculated for this study is the ratio of total surface water use in 2050 to total surface water use in 2005. Values for 2005 and 2050 water use were provided by Roy and others (2010). In that study, future water use in 2050 was calculated based on 2005 water use surveys from USGS (Kenny et al., 2009), estimated population projections by the U.S. Census Bureau, and from electricity production projections from the U.S. Department of Energy. They assumed no new advances in water use technology and no growth in the water use sectors of irrigation, livestock, aquaculture, and mining resulting in an estimate of what might happen if water use efficiency remains static in the future (Roy et al., 2010). Municipal water demand was estimated based on 2050 population projections and 2005 per-capita water use. The electricity generation demand was based on a 2030 projection and was estimated for 2050 by linear extrapolation. The total future water use for 2050 was the sum of the projected municipal water use, the projected thermoelectric water use, and the 2005 water use for all other sectors for each county (Roy et al., 2010).
2.9.4 Future Flows in Selected Watersheds

We generated streamflows representing two future climate scenarios for the six selected watersheds (i.e., Upper Apalachicola, Altamaha, Savannah, Broad, Cape Fear, and Roanoke). The future run spanned a 30-year time period from 2030 to 2060 to correspond with the selection of a 2050 land cover data set. The data sources included a land cover layer predicting land use for 2050 and changes in human water use by county. No control structure data were available for the future runs, so we simulated known reservoirs as run-of-river structures. The first future scenario was driven by the B1 climate scenario, which predicts the introduction of clean and resource-efficient technologies. The second future scenario was driven by the A1FI climate scenario, which simulated a future with a rapid introduction of new fossil intensive technologies. Because there were no available comparison data for future events on which to examine model performance, no model statistics were provided. However, we consider the results from the future scenarios in several example assessments in the following section.

3. Example Assessments

Data generated from WaterFALL allows for the evaluation of water allocation and management strategies, ecological flow regimes, and water supply risk assessment, among other objectives, at multiple scales. Depending on the question at hand, assessments may focus on long-term averages, specific timeframes, specific portions of the hydrologic regimes, and relative changes for a specific set of locations between scenarios. Given the numerous ways to use WaterFALL data to make management decisions and answer research questions, we provide two example assessments to illustrate several of
these different focus areas and result formats. The first example looks at the effects of urban sprawl on a tributary stream north of Atlanta and examines the timing and magnitude of extreme flows and monthly mean and median flows due to changing land use. The second example takes a regional look at different long-term ecological flow metrics (based on percentiles of the flow regime) in the Upper Broad River Watershed due to changes in climate, land use, and water use. Further discussion of potential assessments is included in a separate work plan document.

3.1 Urban Sprawl Impacts on Stream

One site-specific example where land use and climate have had an effect on the hydrologic regime over time is in Big Creek near Alpharetta, GA (USGS Gage 02335700). This gage is located just north of the city of Atlanta. Under baseline conditions, its drainage basin contains mostly forested area, with smaller areas of cropland and urban development (Figure 3-1). The 2006 land cover layer shows the northward spread of urban development; developed areas now surround the stream gage and encompass a larger portion of the drainage watershed, replacing areas of forest and cropland (Figure 3-2). By 2050, the projected land cover layer predicts that urban development will continue to intensify and expand upstream into the drainage watershed of Big Creek, creating a drainage basin dominated by urban area (Figure 3-3).

![Figure 3-1. 1970s land use layer centered on USGS 02335700, Big Creek near Alpharetta, GA.](image-url)
The expansion of urban development around the city of Atlanta affected the flow regime at the Big Creek stream gage. Urban development contains more impervious surfaces than undeveloped land; the impervious surfaces allow more runoff to enter the stream network at a faster rate during storm events. Higher rates of flow, followed by a sharp drawdown period, can impact the quality of the aquatic ecosystem, especially if the species have adapted to more gradual changes in flow. Additionally, flashier watersheds can be harmful to populated areas by increasing the risk of flooding and degrading the quality of the streams receiving stormwater runoff. Another consequence of new urban development is the
increased demand for water. The current condition model run contains several human alterations in the drainage watershed, and the demand for water is predicted to increase in the future scenarios by over 50%.

We use WaterFALL-generated flow metrics at daily, monthly, or annual time scales to determine how the flow regime has changed across four model scenarios at the Big Creek stream gage. The FDC displays the changes in the flow regime across an entire period of record; in this case, 30 years. The slope of the baseline scenario (1970 land cover) FDC for this gage is relatively flat between the 5th and the 95th percentile, changing only one order of magnitude, indicating that the flow regime is fairly stable (Figure 3-4). The tails of the curve (< 5% and > 95%) peak sharply upward or downward, signifying that flashy storm events do occur, but they are uncommon. Compared to the baseline results, the slope of the current conditions scenario (2006 land cover) FDC became steeper at both tails (< 15% and > 85%), meaning that extreme high and extreme low flow events became more common over time, which results in a flashier watershed (Figure 3-5).

Figure 3-4. Baseline scenario FDC (1960–1990) for USGS 02335700, Big Creek near Alpharetta, GA (USGS in red; WaterFALL in blue).

Figure 3-5. Current conditions scenario FDC (1976–2006) for USGS 02335700, Big Creek near Alpharetta, GA (USGS in red; WaterFALL in blue).
The hydrograph for the period of 2004 through 2005 demonstrates the increased daily flashiness of the watershed under current conditions (Figure 3-6); while the average daily flow centers around 100 cfs, larger storm peaks that may raise flow by an order of magnitude are followed by correspondingly sharp (quick) declines in flow. The increase in daily flashiness for this watershed is very likely influenced by changes in land use in the drainage watershed, but may also be compounded by changes in climate. Additional analyses can be completed to parse out the direct influences of each of these component drivers on the resulting hydrology in further studies.

Monthly flow metrics provide ecological significance to changes in the flow regime over time. For example, large changes in months in which critical aquatic species spawn may have larger ecological consequences than changes in months not related to critical species milestones. Examination of both the median and mean monthly values provides context on general versus extreme event related changes. The median represents the value directly in the middle of all values experienced during a month, while the mean is the arithmetic average of the values experienced during the month. So if the median and mean are similar, the data are less likely skewed. In hydrology, this means there are fewer extreme storm (or major drought) events in the range of values. If the median and mean are significantly different, then it is likely that extreme storm events are occurring that increase the arithmetic average streamflow. For Big Creek, the median (Figure 3-7) and mean (Figure 3-8) monthly values do not differ significantly in magnitude. Therefore, the influence of extreme storm events with the different scenarios is not likely a major cause of change in this watershed. Additionally, the seasonal changes between the baseline or current scenarios and the future scenarios point to a more sustained change within the watershed caused by human development and, in particular, land use.

The baseline conditions at this gage demonstrate that before the expansion of urban development, this stream was fairly stable with moderate seasonal changes in flow (Figure 3-7). Small and varying changes by month occur with increased development in the current conditions scenario. The B1 (resource efficient) future climate scenario predicts increases in future median monthly flows for all months except October over baseline and current scenarios, with significantly large increases in winter (December–January), early spring (March–April), and late summer (July–August). The A1FI climate scenario (fossil intensive) predicts small increases in winter flows (November–January) and significantly larger increases.
in median summer flows (July–August) and in the months of April and December. Both scenarios predict that this gage will have a smaller second high-flow season in the summer (Figure 3-7).

The shift in low-flow seasonality at this gage could potentially impact ecosystem services at this stream and throughout the region. Future flow predictions generated by WaterFALL could be used as a guideline for watershed management decisions. Zoning restrictions, permit limits on human alterations, and strategic placement of new reservoirs are a few examples of policies that could influence the flow regime at this urban stream and for similar streams in other areas. Other examples where urban streams are more resilient to changes in climate could be used to determine effective management strategies for Big Creek and for the greater Atlanta area.

Figure 3-7. Median monthly flow comparisons across four WaterFALL scenarios for USGS 02335700, Big Creek near Alpharetta, GA.

Figure 3-8. Mean monthly flow comparisons across four WaterFALL scenarios for USGS 02335700, Big Creek near Alpharetta, GA.
3.2 Regional Changes in Ecological Flow Metrics

The Indicators of Hydrologic Alteration (IHA) is a TNC analytical platform that derives 67 ecologically relevant statistical measures of the human impact on hydrology (The Nature Conservancy, 2009). These measures are based on daily streamflow data and characterize the magnitude, duration, timing, frequency, and rate of change of flow over multiple time steps. These metrics have been applied to a range of water resource issues, including ecological flow thresholds, climate change management, and aquatic habitat restoration. By contrasting IHA metrics across different time periods, researchers can gain some understanding of how human activities have impacted flow and, by extension, aquatic ecology.

We created a set of modified IHA variables using WaterFALL data for the North Carolina portion of the Broad River Watershed. These ecoflow metrics were derived for and compared across the four examined scenarios (baseline, current conditions, and two future climate scenarios) to understand how human activity may be impacting aquatic ecology over time. Specifically, the relative percent difference (RPD) in August low flows (25th percentile over 30 years of daily flows) was examined at the outlet of each HUC12 within the watershed. RPD is a measure of change between two values where the size or magnitude of the values being compared is considered, and one of the values is considered the starting point (in this case the baseline scenario). When looking across the hydrologic regime from extreme low to extreme high flows, the RPD allows for better comparisons at different points in the regime than when looking at the absolute differences. August low flow was chosen as an ecoflow metric because, as part of the summer low-flow period, this metric represents a time of high stress for fish communities, especially riffle-run guild members that can be impacted by loss of swift water habitats, heat stress, and food scarcity.

The RPD in August low flow between the baseline and current conditions indicates that most HUC12s within the Broad River watershed have on average seen August low flows decrease in recent years (Figure 3-9). The magnitude of change varies along the different tributaries that make up the watershed. The greatest decreases in flows are seen within the Second Broad River, First Broad River, and Buffalo Creek subbasins (from west to east). The lowest decreases, or least changes in flow, are seen in the southwestern portion of the watershed where the lands remain less developed. Little land use change was initiated in this basin between the 1970s and 2006, and so the reduction in low flows is related to climate and human water use. There are 73 catchments within the watershed that contain human alterations. However, the vast majority of these alterations are less than 5 cfs, and therefore cause little change to the August low flow estimate at the HUC12 level.

![Figure 3-9. RPD comparison of August low flow between 1970s baseline and current conditions for the North Carolina extent of the Broad River basin.](image-url)
Under the future condition scenarios where land use and human water use are estimated at the same 2050 levels between scenarios, August low flows show changes varying in magnitude and direction from baseline conditions under the B1 climate scenario (Figure 3-10) than under the A1FI scenario (Figure 3-11). Under the B1 scenario the majority of the watershed experiences increases in August low flows with the exception of six headwater HUC12s, which show slight decreases in the metric. Under the A1FI scenario changes are more varied throughout the basin, with a greater number of subbasins experiencing decreased August low flows. The Second Broad River, which showed little but mixed changes under the B1 scenario, now consistently shows small decreases in the August low flow except for one headwater HUC12. The First Broad River and Buffalo Creek maintain increases in August low flow but at a smaller magnitude of change. While consistent increases in low flows in the eastern portion of the watershed are likely due to the increase in developed lands surrounding these waterways, the only difference between the future scenarios is the climate driver. The increases from the B1 scenario point to a consistently wetter August across the basin, while the A1FI scenario shows more stress to August low flows, particularly in headwater HUC12s, pointing to more dry and hot Auguts.

Figure 3-10. RPD comparison of August low flow between baseline conditions and future scenario B1 for the North Carolina extent of the Broad River basin.

Figure 3-11. RPD comparison of August low flow between baseline conditions and future scenario A1FI for the North Carolina extent of the Broad River basin.
We examined the 30-year record of future climate conditions for the month of August from both scenarios and found that both temperature and precipitation predictions vary across the watershed between the scenarios. As defined by the IPCC, the A1FI emissions scenarios is characterized by the largest temperature increase of all emissions scenarios with an expected increase of 4 °C by 2099 over 1980s and 1990s average temperatures across the globe. Conversely, the B1 emissions scenario is characterized by the smallest temperature increase of 1.8 °C (IPCC, 2007). These generalized temperature increases were supported within the Broad River Watershed upon summarization of August temperature data for a selected headwater catchment (Figure 3-12), where the temperatures under the B1 scenario are consistently lower than under the A1FI scenario.

![Graph showing temperature comparison between B1 and A1FI scenarios.](image)

**Figure 3-12.** 30-year summary of daily average August temperatures for future scenarios for the headwaters of the Second Broad River (one standard deviation represented by shaded area).

The precipitation changes for each emissions scenario vary based on location and in the timing, frequency, and magnitude of storm events. These variations were also supported through summarization of August daily precipitation values across the flow regime. Within this example watershed, the August low flow metric under the B1 scenario is higher throughout much of the watershed likely due to more storm events and variation in rainfall than under the A1FI scenario. **Figure 3-13** depicts these findings for a selected headwater catchment using the 30-year daily averages and standard deviations in precipitation. The larger spikes in standard deviation of precipitation under the B1 scenario point to larger and more varied storms within August.
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

4. Conclusions

The project demonstrated that WaterFALL can provide a unified, regional hydrologic modeling platform across the southeastern United States that simulates flow regimes at multiple geographic scales. The model was successfully set-up, calibrated, and run to generate 30-year hydrographs for more than 100,000 contiguous NHDPlus catchments within 18 watersheds (HUC6) spread across four states. The model simulated daily surface water flows under past, current, and future climatic, geographic, and demographic conditions. WaterFALL was able to closely replicate the daily time-series flows calculated for 60 USGS stream gages, representing a range of geographic and hydrologic settings. Extensive goodness-of-fit testing demonstrated that there is no consistent bias in the flow estimates generated by WaterFALL. The ability of the model to closely replicate stream gage hydrographs under a variety of different physical conditions and across multiple geographic scales confirms the efficacy of the underlying rainfall-runoff model algorithms and the accuracy of the methods employed by WaterFALL to route the timing and volume of flows throughout highly complex networks of surface water channels. We are not aware of any precedent where a single model has been successfully applied to simulate flow conditions at multiple scales across such a broad landscape.

Anticipated next steps for 2014/2015:
- Model current and future conditions for remaining SALCC basins that are not groundwater dominated (including obtaining and processing water use data)
- Model baseline, current, and future conditions for groundwater-dominated SALCC basins (parameterize WaterFALL and groundwater models including water use data gathering and processing)
- LCC to work with existing data to calculate derivative metrics from time series data based on expert review and guidance for conservation blueprint objectives.
5. References


## Appendix A: Data Sources

In addition to the geospatial, regional, and gage observation data sources defined in the table below, the following document sections provide additional information on sources and methods of processing inputs for the altered and future scenarios:

- Section 2.6: Human water use
- Section 2.7: Representation of water flowing out of control points (e.g., reservoir dams)
- Section 2.9: Land use, climate, and water use for future scenarios

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| Hydrology     | The enhanced National Hydrography Dataset (NHDPlus), Version 1      | NHDPlus is an integrated suite of application-ready geospatial data sets that incorporate many of the best features of the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), and the Watershed Boundary Dataset (WBD). First released in 2006, the NHDPlusV1 consists of 10 components:  
  - 2006 version of the 1:100K NHD  
  - 2004 version of the 30-meter NED  
  - A set of value-added attributes to enhance stream network navigation, analysis, and display  
  - An elevation-based catchment for each flowline in the stream network  
  - Catchment characteristics  
  - Headwater node areas  
  - Cumulative drainage area characteristics  
  - Flow direction and flow accumulation grids  
  - Flowline min/max elevations and slopes  
| Climate data  | 4-kilometer gridded daily temperature and precipitation covering CONUS from 1960 through 2006 | A USDA-funded effort to construct retrospective gridded daily precipitation and temperature datasets for CONUS using two independent and quality-controlled inputs: 1) an enhanced compilation of daily observations derived from the National Climatic Data Center digital archives and 2) the Parameter–Elevation Regressions on Independent Slopes Model (PRISM) maps. | Data for 1960–2001 were provided to us by the USDA directly via the ftp site. Data from 2002–2006 were provided by M. DiLuzio of Texas A&M.  
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| Land Use (Current Conditions)| National Land Cover Database 2006 (NLCD2006)              | A 16-class land cover classification scheme that has been applied consistently across the conterminous United States at a spatial resolution of 30 meters. NLCD2006 is based primarily on the unsupervised classification of Landsat Enhanced Thematic Mapper+ (ETM+) circa 2006 satellite data. | http://www.mrlc.gov/nlcd2006.php
| Land Use (Unaltered, 1970s baseline)| Enhanced Historical Land-Use and Land-Cover Data Sets of the U.S. Geological Survey | - Polygons of land use and land cover were delineated manually from aerial photography and mapped following a two-level hierarchical classification system
- Original digital data sets created by the USGS in the late 1970s and early 1980s later converted by USGS and the USEPA to GIS format in the early 1990s
- Version used now cleaned up for USGS NAWQA program and further modified to create a more accurate, topologically clean, and seamless national data set
- Uses Anderson classification system
- 1:100,000 and 1:250,000 scale | Description: http://pubs.usgs.gov/ds/2006/240/
| Soils                        | Soil Survey Geographic (SSURGO) database                  | Field mapping methods using national standards are used to construct the soil maps in the Soil Survey Geographic (SSURGO) database. Mapping scales generally range from 1:12,000 to 1:63,360; SSURGO is the most detailed level of soil mapping done by the Natural Resources Conservation Service (NRCS). SSURGO digitizing duplicates the original soil survey maps. This level of mapping is designed for use by landowners, townships, and county natural resource planning and management. The U.S. General Soil Map consists of general soil association units. It was developed by the National Cooperative Soil Survey and supersedes the State Soil Geographic (STATSGO) dataset published in 1994. It consists of a broad-based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped. | http://www.soils.usda.gov/survey/geography/ssurg o/description.html
http://soils.usda.gov/survey/geography/statsgo/description.html |
| Subsurface Characterization   | SAC-SMA Parameters from the Soil Survey Geographic Database (SSURGO) | The framework used by Zhang et al. (2011) allowed for estimating 11 soil-related parameters for the Sacramento Soil Moisture Accounting model (a mass balance model) from soil and land cover data. Data is provided on an approximately 4 km x 4km grid.
We adopt 2 of these 11 parameters as a starting point for calibrating the available water capacity of the unsaturated subsurface zone (a volumetric measure in cm/cm) and recession coefficient (a dimensionless rate) within WaterFALL. | Zhang, Y., Zhang, Z., Reed, S., Koren, V., 2011. An enhanced and automated approach for deriving a priori SAC-SMA parameters from the soil survey geographic database. Comput. Geosci. 30 (2), 219–231. |
## Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

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<td>Streamflow</td>
<td>USGS National Water Information System (NWIS) Stream Gages</td>
<td>Daily streamflow data is downloaded for each gage of interest from NWIS. Gages are examined based on characteristics provided for each in the Geospatial Attributes of Gages for Evaluating Streamflow, version II (GAGES II) dataset (Falcone, 2011) and on the daily records.</td>
<td>NWIS: <a href="http://waterdata.usgs.gov/nwis">http://waterdata.usgs.gov/nwis</a> GAGES II: <a href="http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml">http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml</a></td>
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1. Three parameters are calibrated within WaterFALL: the available water capacity (AWC), the recession coefficient, and the seepage parameter. The AWC is a physical parameter that varies by soil type and depth. Therefore, the values obtained in calibration are examined to ensure they fit within realistic boundaries. The recession coefficient and seepage parameter are dimensionless rate constants that equate to a rate of water loss to the stream or deep aquifer, respectively, from the saturated subsurface zone.

2. Streamflow values are not used as model inputs but as data for calibration. In some future model simulations USGS gages may be used as boundary conditions or as representation of control structures/dams in place of model estimations at selected NHDPlus catchments.
Appendix B: SALCC Selected Environmental Flow Metrics Analysis for Baseline Scenario

This appendix provides a series of graphs for the four requested ecoflow metrics: May low flow, September low flow, March high flow, and January high flow. Low flows are calculated as the 25th percentile of the flow record, while high flows equate to the 75th percentile of the flow record. Forty-eight of the 60 calibration gages are displayed in the graphs. Gages from Florida and southern Georgia were not graphed due to the confounding factors of groundwater and swamp flows, as discussed during the November 20th presentation.

Each metric is presented in three ways:

1. General summary
2. Categorized by general McManamay classification (PR – perennial; SB – stable baseflow; IF – intermittent flashy; CSI – coastal/swamp intermittent)
3. Categorized by region (Mountains, Piedmont, Coastal Plain)

Each of the three presentations is shown to its extreme values (top plot on each page) and to a region focused on 300, 500, or 800 cfs and below depending on the metric (bottom plot of each page) in order to “zoom in” on the lower flows clustered near the origins. There are no differences between the two presentations other than the extent of the axes.

To provide a point of reference for evaluation, we use a threshold of 30% difference between WaterFALL estimates and the USGS gage. This threshold was used in a USGS study of ecoflow metric estimation by a rainfall-runoff model (Murphy et al., 2012), and so we chose to make some summaries in a similar manner.

- 96% (46/48) of the gages are within the ± 30% boundaries for May low flows (25th percentile)
- 83% (40/48) of the gages are within the ± 30% boundaries for September low flows (25th percentile)
- 90% (43/48) of the gages are within the ± 30% boundaries for March high flows (75th percentile)
- 90% (43/48) of the gages are within the ± 30% boundaries for January high flows (75th percentile)

Gage data that falls outside of the ± 30% boundaries are influenced by the following factors:

- A few large storm events that may skew the data (September low flows)
- A few years where USGS flow values drop near 0 for most of the month (September low flows, May low flows)
- In one instance, USGS reports that flow estimates are poor below 200 cfs (Drowning Creek near Hoffman, NC) (September low flows)
- Possible groundwater or swamp influence (September low flows, March high flows)
- Gages that are highly flashy and difficult to calibrate tradeoff between low/median flows vs. high flows (March high flows, January high flows)

From analyzing these graphs, there is only one identifiable pattern that emerges. For high flows, WaterFALL estimated high for SBF and low for PR. What we think is going on there can be illustrated with the two sets of graphs below. Perennial streams (top graphs) have a large variation between their high- and low-flow months and have a steeper flow duration curve. When we chose to focus on the average and low flows with our calibrations, we had to trade off the performance at the high end of the
curve. The flow duration curve below is typical where we see some deviation at the highest flows (10% exceedance or less), but the low flows are matched well. For stable baseflows (bottom graphs), we have the opposite issue, where the flow duration curve is extreme on both ends and flows are less variable across the months. The calibrations must focus on pushing low flows to more extreme changes, and so in return, the high flows can be pushed to more extreme changes (i.e., flashiness), resulting in some overestimation. However, it is very important to note that the overestimations of the stable baseflow streams for both months fall within the +/- 30% error bounds for all gages, with the majority falling below +/- 10% error – in essence the ‘noise’ of the flow measurements. The same is true for perennial streams, where the underestimations fall within the +/- 30% error bounds and the majority fall below +/- 20% error – the majority of error is again likely accounted for by noise in the measurements.
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

May Low Flow (25th Percentile)

May Low Flow <500 cfs (25th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

September Low Flows (25th Percentile)

September Low Flows <300 cfs (25th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

September Low Flows (25th Percentile)

September Low Flow <300 cfs (25th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

September Low Flows (25th Percentile)

September Low Flows <300 cfs (25th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

March High Flows (75th Percentile)

March High Flows <500 cfs (75th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

March High Flow (75th Percentile)

March High Flow <500 cfs (75th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

March High Flows (75th Percentile)

March High Flows <500 cfs (75th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

January High Flows (75th Percentile)

January High Flows <800 cfs (75th Percentile)
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales
Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

January High Flows (75th Percentile)

January High Flows <800 cfs (75th Percentile)
Appendix C: Memo on Altered Watershed Selection

Date: December 20, 2012
To: Eloise Kendy, TNC and Rua Mordecai, SALCC
From: M.C. Eddy and R. Dykes
Subject: Selection of 6 watersheds for altered/current conditions streamflow analysis

Current-condition streamflows, i.e., altered conditions, will be modeled in six approximately HUC6 watersheds within the SALCC study boundary. Criteria for selecting these watersheds will include geographic representation, importance of the watershed to other SALCC studies, extent of prior modeling efforts, availability of data on withdrawals and returns, and number and locations of control structures. This memo provides information to help RTI, TNC, and the SALCC-appointed committee agree on the six selected watersheds.

Background

WaterFALL computes two components of surface water flow: 1) runoff generated in the form of excess of infiltration and 2) baseflow that is released from a saturated zone in the subsurface over time. Water moves through the different compartments represented by the model (surface, unsaturated zone, shallow saturated zone, and deep saturated zone) based on physical parameters and rate constants governed by process-based equations and mass balance. Human withdrawals and returns to the system are accounted for in the final streamflow outflows from each catchment based on inflow from the upstream catchments and the locally generated flow from runoff and baseflow. The total streamflow from each catchment is routed through stream networks using the RTI’s lag-routing scheme.

To simulate altered streamflow conditions, WaterFALL accounts for point withdrawals for and returns from human managed systems (e.g., public water supplies, wastewater treatment, industry, and agriculture). Because WaterFALL runs on a daily time step, daily rates are required to include in streamflow calculations. However, daily variations in withdrawal/return rates are not typically tracked in a readily-available format or reported to an overseeing agency. WaterFALL, therefore, has been designed to process alterations on a monthly basis. This means that the same daily flow will be withdrawn or returned every day of the same month. If yearly variations are known for differences in monthly values, they can be input into WaterFALL. Otherwise, the single monthly value for an alteration is used for all occurrences of that month within the simulation.

Alterations are cumulative for a catchment, which means all withdrawals are totaled and returns are totaled and applied at the downstream end of the catchment after considering inflow from any upstream catchment(s). A withdrawal is subtracted from the system before a return is added to the system if both occur within the same catchment. This base assumption in WaterFALL provides that one human alteration can’t be used to satisfy another human alteration in an immediate stream segment/catchment.

Data Requirements

The data requirements for characterizing each of the human alterations simulated within a basin include the following:
- Geographic location of actual hydrological alteration (e.g., location of pipe, not facility) through latitude and longitude coordinates or NHDPlus catchment
- For withdrawals and returns
  - Monthly average (or better resolution) flow value per unique alteration
  - Type of alteration (i.e., withdrawal or return)
  - Defining characteristics of the alteration for documentation and reference
- For control structures (i.e., dams)
  - Daily flow value for full simulation period
  - Defining characteristics of control structure for documentation and reference

Additional details on how control structures may be handled in the absence of monitored time series data will be provided in an additional deliverable.

**Watershed Selection**

At the Southeast Aquatic Resources Partnership (SARP) Ecological Flows Workshop in April 2012, researchers from the region were asked to rank the watersheds most valuable to an assessment of alterations within the southeast. Their suggestions were as follows:

- Altamaha
- Cape Fear
- Roanoke
- Santee
- Savannah
- Suwannee

Based on initial research into available data, results on unaltered watershed calibrations within the SALCC, and interactions with other studies within the region, RTI suggests the following watersheds for altered conditions analyses (italicized watersheds are those that were also suggested at the SARP workshop):

- Apalachicola (3 HUC8s within SALCC region only) – important for comparisons with other broader ACF studies by USGS and targeted workgroups
- Altamaha – large basin fully within Georgia
- Cape Fear – large basin fully within North Carolina; withdrawals/returns data available from NC DENR
- Broad (part of the Santee HUC6) – selection of the Santee with existing OASIS model from North Carolina and important power plant alterations; withdrawals/returns data available for North Carolina portions from NC DENR
- Roanoke – large basin in Virginia/North Carolina; withdrawals/returns data available from VA DEQ
- Savannah – highly altered main stem of river with few gages throughout the basin

Although the full Santee basin was proposed for analysis at the SARP workshop, the highly altered nature of this basin would likely complicate and confound the results of this initial regional study. Given enough time, the data surrounding all of the alterations in this basin could be obtained to the extent possible and modeled with WaterFALL, but for this initial study with model completion set for June we suggest focusing on a single watershed within the Santee. The Saluda, Broad, and Catawba Rivers which make up
the upper portion of the Santee River basin are all highly altered streams with numerous interbasin
transfers between the rivers. However, both the Saluda River and the Catwaba River are additionally
altered by several large reservoirs (i.e., the Catawba has 11 reservoirs in series that are not gaged or
monitored for flow). The Broad River, on the other hand, has fewer large reservoirs or urban areas and
therefore makes a better candidate for identifying, locating, and quantifying human alterations within the
watershed for this initial altered scenarios analysis.

The Suwannee basin originally proposed at the SARP workshop has been shown to be a complex
watershed that is not as well simulated by WaterFALL’s current surface water focus as the other basins
within the region due to its swamp areas and active groundwater-surface water exchange regions. For this
reason, we do not recommend continued modeling of the Suwannee under WaterFALL’s current surface
water configuration and instead propose to look at the upper regions of the Apalachicola-Chattahoochee-
Flint Watershed.
Appendix D: Considerations for Use of Data Generated by WaterFALL for the SALCC

Users of data generated by the SALCC’s WaterFALL model should always bear in mind that although the time step is daily and the spatial discretization is by NHDPlus catchment, the model is calibrated to best fit daily streamflow values that vary over many orders of magnitude across a very large, heterogeneous region. Consequently, it may not perfectly simulate any particular daily flow value but intends to overall capture daily streamflow component or stream reach. As such, suggested uses of the data created for the SALCC under this project include:

- Assessment of relative changes in streamflow patterns across a broad geography resulting from regional stressors such as climate and land-use change.
- Quantitative analysis of monthly, seasonal, and annual streamflow statistics.
- Preliminary assessment of impacts from site-specific (i.e., catchment-level) stressors in order to focus and inform a local study design.

Data is available at the catchment level on a daily time step, and so users may choose to conduct analyses at these levels. However, before using the model for such assessments, it is the user’s responsibility to independently determine how the model’s precision and accuracy will affect the result. The user should consider the following qualifications/checks:

If used at a daily time step:

- Consider use for long-term daily trends and not individual daily predictions
- Note that estimates are not recommended for immediately downstream of dams because most reservoir operations are not explicitly simulated in current and future conditions
- Verify the human water uses included in the simulation
- Examine local calibrations and data
- Recognize the modeled streamflows are calculated as daily averages and therefore may not represent the sub-daily variations in flow associated with quick (< 1 day) storm events and resulting peak flows.

If using at an NHDPlus catchment scale:

- Consider the above referenced checks (e.g., verification of human water uses)
- Note that streamflow is estimated as the cumulative flow at the downstream end of a catchment and may not completely represent changes in flow at sub-reach scales (e.g., flow or depth in a pool versus a riffle).

Finally, the following points summarize the known discrepancies between the SALCC WaterFALL results and observed USGS streamflows, which themselves may include substantial uncertainties:

- Magnitude of extreme high flows [<10th percentile] tend to be underestimated compared to USGS gauge data
- Magnitude of extreme low flows [>90th percentile] tend to be overestimated compared to USGS gauge data
- Timing and frequency of short duration [submonthly] small pulses can differ significantly from USGS gauge data
- Magnitude of extreme flows [high and low] is dampened immediately downstream of dams because most reservoir operations are not explicitly simulated in current and future conditions.