A) Project Summary

1) Organization Title
The Nature Conservancy

2) Project Lead and Co-Participants
Lead: Eloise Kendy, Ph.D., Director, Environmental Flows Program, The Nature Conservancy
Co-Participants: Michele Cutrofello, Research Environmental Engineer, RTI International;
Fekadu Moreda, Ph.D., Senior Hydrological Modeler, RTI International

3) Address, Telephone Number, and E-mail address of Project Lead
415 Monroe Avenue, Helena, MT 59601 (406) 431-9018 ekendy@tnc.org

4) Project Title
Unified Hydrologic Model for Assessing Human and Climate Impacts on Streamflows at Multiple Geographic Scales

5) Focal Issue addressed
Focal Issue #1. The impact of climate change and human population growth on future stream and river flows within the South Atlantic LCC.

6) Project Duration
2 years

7) Project Objectives or a Project Abstract

The objective is to create a hydrologic foundation for detailed assessment of human and climate impacts on stream and river flows, including the impacts of hydrologic alterations on aquatic habitats. A specific application will be to support implementation of ELOHA, the Ecological Limits of Hydrologic Alteration, a scientific framework for determining environmental flow needs for all rivers and streams throughout a very large region. During Year 1, we will model pre-development (unaltered) daily flows for 1960-2006 for every enhanced national hydrography dataset (NHDPLUSPlus) catchment within the SALCC. We will also model current-condition daily flows over the same time period for at least 6 watersheds using available data on current water withdrawals and discharges, and we will assess the feasibility of modeling current conditions for the remaining portions of the SALCC. During Year 2, we will model current and potential future conditions in as much of the SALCC as is feasible, considering data availability and limitations encountered during Year 1. Future conditions will incorporate anticipated climate and land-use change and potential management strategies to address these.
B) Project Description

1) Objectives

The objective is to create a hydrologic foundation within the SALCC that can be employed for multiple purposes. In this project, a specific goal will be to use the hydrologic modeling foundation to implement ELOHA, the Ecological Limits of Hydrologic Alteration, a scientific framework for determining environmental flow needs for all rivers and streams throughout a very large region. During Year 1, we will model pre-development (unaltered) daily flows for 1960-2006 for each of the approximately 250,000 NHDPLUS catchments within the SALCC; we will model current-condition daily flows over the same time period for 6 watersheds; and we will assess the feasibility of modeling current conditions for the remaining portions of the SALCC. During Year 2, we will model current and future conditions in as much of the SALCC as is feasible, considering data availability and limitations encountered during Year 1.

2) Narrative

The Watershed Flow and ALLocation (WaterFALL™) system is a new watershed modeling tool and decision-support platform developed by the Research Triangle Institute (RTI) to enable interactive quantitative investigation of water availability and allocation at multiple geographic scales. The WaterFALL™ system employs a well-established hydrologic rainfall-runoff model, the Generalized Water Loading Function (GWLF), which has been modified to run on EPA’s enhanced National Hydrography Dataset (NHDPLUS) hydrologic network. GWLF is a well-known rainfall-runoff model that calculates stream flows using a daily time-step. All of the data required to parameterize the model are indexed to each NHDPLUS catchment. The GWLF model is then run for each individual catchment. NHDPLUS Routing routines are embedded to allow the cumulative water resource impacts across any number of user-selected catchments to be quantified. Advantages of this distributed model architecture include:

- **Scalability.** The model, which is based on a physically delineated network of catchments, can be run on a single catchment or any hydrologic unit upstream of a user-selected catchment up to entire watersheds.
- **Portability.** The model can be run anywhere on the NHDPLUS network (i.e. the contiguous U.S.) with minimal model set up, calibration, or additional data inputs.
- **Accessibility.** The model is built on an advanced Oracle web-server delivery platform and can be accessed from almost any internet-connected computer.
- **Usability.** The model employs simple graphical interfaces for spatial navigation and a variety of other tools to facilitate “what if?” analyses in real time.

Year 1

A key feature of WaterFALL™ is that all of the input data for the model is indexed onto the NHDPLUS catchments. RTI has currently indexed complete climate and land use data sets for the 17 watersheds that cross North Carolina. As an initial Task under this project, RTI will index
all the data need to parameterize the model to the ~250,000 NHDPLUS catchments within the SALCC. This setup effort will not require project funding. Once the base data layers have been indexed to the catchments, RTI will use WaterFALL™ to generate unaltered daily hydrographs throughout the SALCC. The product will be tabular and graphical daily unaltered flow data for every NHDPLUS catchment within the SALCC. The time-series data can be exported and used to support other analyses, such as comparison to current conditions as indicated by gauged data.

WaterFALL™ includes the capability to account for water withdrawals and return flows in each NHDPLUS catchment. In most cases, however, reliable water consumption data are not available at the geographic scale of an individual NHDPLUS catchment or as a daily (or even monthly) time-step. For some sectors, such as electric utilities, relatively good information on water withdrawal rates can be obtained and indexed to NHDPLUS catchments. For other sectors, particularly agriculture, little or no accurate data exists. The only nationwide database on water withdrawals is maintained by the USGS. However, these data are aggregated by counties and cannot easily be disaggregated to individual NHDPLUS catchments. Accordingly, during Year 1, RTI will assess the applicability of existing data for water withdrawals, return flows, and land cover for simulating current-condition hydrographs. RTI will attempt to use available data to simulate current-condition hydrographs in at least 1 watershed in each of the LCC states (AL, FL, GA, NC, SC, VA). This may involve linking to existing USGS stream gauge data or other data sources from sub-areas within the SALCC. The Nature Conservancy (TNC) will oversee the modeling and ensure that it meets the needs of ecologists who will use the synthesized flow data to analyze flow-ecology relationships. TNC also will assist in acquiring data, and will serve as liaison between RTI and the SALCC Water Resource Information Coordinator (Mary Davis).

Year 1 will conclude with a report assessing the feasibility of modeling current conditions, considering the availability and limitations of water-use data, for each state. The feasibility analysis will propose a process or processes for disaggregating available water-use data to the spatial and temporal scales of the model. As a parallel effort, TNC plans to use WaterFALL™ to compare unaltered, current and future flows in 4 watersheds within North Carolina. As part of that work, we will also investigate data sources and approaches for incorporating the impact of water withdrawals and return flows on unaltered flows and develop recommendations for including those in the modeling platform. Based on those recommendations, the SALCC, RTI, and TNC will agree on a practical scope for Year-2 modeling.

Year 2

During Year 2, RTI will model current and future conditions in selected watersheds. The extent of this effort will depend on outcomes of the Year 1 feasibility analysis. TNC will work with SALCC and stakeholders to define at least 2 future scenarios to model, which incorporate anticipated climate changes and potential management strategies to address them.
3) Relationship to LCC niche

**Geographic scale:** Although discrete hydrologic models and water management decision-support systems exist throughout much of the SALCC, no single model spans the entire geography. The proposed WaterFALL model would cover the entire SALCC at a uniform temporal and spatial scale, allowing for integrated, cross-jurisdictional scientific assessment and water management.

**Taxonomic scope:** The WaterFALL model will incorporate the hydrologic impacts of water withdrawals and consumption (as feasible); discharges or return flows; land use changes such as urbanization, deforestation, or agricultural practices; and climate change. These changes can be input and analyzed at discrete sites within the modeled area. This phase of the modeling will not explicitly address ecological impacts; however, it provides the hydrologic foundation for analyzing the relationship between flow alteration and ecological response, which may be determined for any taxonomic or habitat variable for which data are available. Once determined, these relationships will inform the stakeholder-driven decisions of environmental flow needs throughout the SALCC.

**Decision focused:** Tracking those environmental flow needs within the WaterFALL™ model will transform the model into a decision support system that tells water managers where and when water is available for withdrawal without impairing ecological health. The model can also be used to analyze various land-use scenarios to support a growing population as the climate changes. These analyses may be conducted at any scale within the model, from small watershed to the entire SALCC. Therefore, the model can supplement the more detailed analyses that watershed-specific models allow, thereby integrating water management decisions across the entire SALCC.

**Forward looking:** WaterFALL™ output depends on climate and land cover input. Therefore, the model can readily be run with predicted changes in climate replacing historical climate as model input, or be used to examine impacts of land use changes. Possible changes in temperature can be examined independently, or in combination, with expected changes in rainfall amounts or patterns. Users can adjust management options such as water withdrawals and land use to assess various strategies for maintaining ecological health while providing for a growing human population in the future. Because the model is spatially discrete, it can be used to prioritize not just actions, but also their specific locations, within the SALCC.

**Adaptive:** Inputs to the model consist of data layers that are apportioned and then indexed to each NHDPLUS catchment. As new or alternative data sets become available, they can also be indexed to NHDPLUS as either an alternative set of inputs or to replace the prior set of inputs. For example, the model currently uses daily PRISM rainfall data across a 4 km grid for the years 1960 to 2006. As data for more recent years are made available, the data layers will be updated. In addition, down-scaled predictions of future climate condition can also be indexed onto NHDPLUS, providing the user with optional data sets to employ, depending on the nature of the analysis. Similarly, when updated land-use data sets are published they can replace
older, obsolete data. In this manner, the modeling platform is highly adaptive and undergoes continuous improvement. These improvements are implemented by RTI, and do not require any action on the part of model users.

**Making connections and filling gaps** between existing partnerships, states, organizations and LCC’s: As explained above, the WaterFALL™ model will supplement existing models of subareas within the SALCC. As an umbrella hydrologic model for the entire region, it can provide a consistent platform for discussions, analyses, and decision-making among the many partners, states, and organizations within the SALCC. Equally importantly, WaterFALL™ is being developed for the entire conterminous United States. In the long term, it can provide a consistent platform between all the LCCs. Therefore, this project represents a pilot test of national significance.

The outcomes listed above pertain to the ultimate intended product. However, we should be clear that modeling current and future conditions presents significant challenges in terms of acquiring, disaggregating, and indexing water use data to daily time steps at the NHDPLUS reach scale. Therefore, the extent to which each of these outcomes can be accomplished within this proposed project depends on the availability and state of water use data, including withdrawals and return flows. It is our intent to model as much as is feasible within the time and budget constraints of this project, and to conclude this project with a detailed plan for fully accomplishing all of these outcomes.

### 4) Project Timeline

<table>
<thead>
<tr>
<th>Date</th>
<th>Deliverable</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 31, 2011</td>
<td>Detailed work plan.</td>
</tr>
<tr>
<td>Aug 31, 2011</td>
<td>Base model parameters indexed to all NHDPLUS catchments in the SALCC</td>
</tr>
<tr>
<td>Dec 31, 2011</td>
<td>WaterFALL™ model simulation of unaltered daily flows throughout the SALCC at NHDPLUS reach scale. Output will be time-series hydrographs at the outlet of each catchment and exported data sets that can be used for additional, off-line analysis.</td>
</tr>
<tr>
<td>June 10, 2012</td>
<td>Feasibility analysis report proposing a process or processes for simulating current-condition hydrographs throughout the SALCC.</td>
</tr>
<tr>
<td>June 30, 2012</td>
<td>Demonstration and provision of WaterFALL™ model simulation of current-condition flows, incorporating current water uses based on best available data, return flows, , and land use for at least one HUC-6 (size of North Carolina’s 17 watersheds) watershed in each SALCC state.</td>
</tr>
<tr>
<td>June 30, 2012</td>
<td>Meeting between SALCC, TNC, RTI, and stakeholders invited by SALCC to agree upon scope of Year 2 modeling, including future-condition scenarios.</td>
</tr>
<tr>
<td>Dec 31, 2012</td>
<td>Progress report</td>
</tr>
<tr>
<td>June 30, 2013</td>
<td>Final report and presentation or webinar on modeling results and future applications for improving water resources management within the SALCC. Detailed work plan for completing current and future-condition models for the entire SALCC.</td>
</tr>
</tbody>
</table>
RTI has built a new watershed modeling tool and decision-support platform to enable interactive quantitative investigation of water availability and allocation at multiple geographic scales. The Watershed Flow and ALLocation (WaterFALL™) system employs a well-established hydrologic model, the Generalized Water Loading Function (GWLF) that has been modified to run on EPA’s enhanced National Hydrography Dataset (NHDPlus) hydrologic network. RTI has indexed extensive data layers onto each individual NHDPlus catchment to provide all of the input data needed to parameterize and run the GWLF model within a catchment. Routing routines are embedded to allow the cumulative water resource impacts across any number of user-selected catchments to be quantified. Advantages of this distributed model architecture include:

- **Scalability.** The model, which is based on physically delineated network of catchments, can be run on a single catchment or any hydrologic unit upstream of a user-selected catchment up to entire watersheds.
- **Portability.** The model can be run anywhere on the NHDPlus network (i.e. the contiguous U.S.) with minimal model set up, calibration, or additional data inputs.
- **Accessibility.** The model is built on an advanced Oracle web-server delivery platform and can be accessed from almost any internet connected computer.
- **Usability.** The model employs simple graphical interfaces for spatial navigation and a variety of other tools to facilitate “what if?” analyses in real time.

**Intended Uses**

WaterFALL™ has been developed to address 4 primary needs:

1. **Climate Change Adaptation.** WaterFALL™ employs GWLF to calculate runoff based on precipitation rate, ambient temperature, and ground cover/use. Down-scaled climate modeling of future changes in precipitation and/or temperature, as well as possible changes in land cover such as deforestation, can be easily accommodate by the model and employed to determine how predicted climate changes may shift the availability of water at any user-designated geographic location. The effectiveness of actions to adapt to climate change, including such things as increased conservation levels, expansion of reservoirs or other storage systems, changes in agricultural production or other land cover modifications, can be quantified using WaterFALL™.
2. **Water Allocation and Management.** WaterFALL™ will enable water resource planners and managers to systematically evaluate the impacts of proposed water allocation strategies on water availability throughout an entire watershed. State and regional water resources managers will be able to employ the model to quantify the carrying capacity (i.e. “available daily yield”) of local watersheds, and to better understand how calculated yields would likely be altered as a consequence of either temporary or permanent changes in rainfall amounts (i.e. drought conditions), changes in average air temperatures, changes in water withdrawal or consumptive use rates, depletion of inter-connected groundwater supplies, or changes in land use patterns.

3. **Ecological Flow Development.** WaterFALL™ provides enormous flexibility as a tool for establishing ecological flow regimes. When applied to a watershed, or user-defined sub-basin, the model produces a complete hydrograph for each NHDPlus catchment included in the basin. As a result, flows are profiled for very small stream reaches, often 100 meters or less in length. The model performs completely independently of stream gage data, eliminating the need for extensive statistical extrapolation of historical flow data. WaterFALL™ is particularly well suited for implementation of the Ecological Limits of Hydrologic Alteration (ELOHA) framework developed under the auspices of The Nature Conservancy. It can easily model unaltered flow conditions, and can also be set up to reflect past land cover and land use characteristics. Relevant model output includes stream velocity and depth in addition to total flow.

4. **Water Supply Risk and Impact Assessment.** WaterFALL™ is an efficient, easy to use tool for large consumers of water to: a) assess site-specific vulnerability of water supplies; b) support plant siting studies; c) better target water conservation investments; or d) satisfy sustainability measurement and reporting requirements such as those included within the Global Reporting Initiative (GRI) framework. Many States are also in the process of developing and implementing new regulations that will require large water users, typically those withdrawing in excess of 100,000 gallons/day, to apply for water use permits. Under these rules, applications for a water use permit may need to include modeling data on the impacts of the proposed withdrawals on downstream users and on “hydrologically interconnected” water resources. WaterFALL™ is well suited for rapidly quantifying withdrawal impacts, at any user-define scale.

WaterFALL™ is envisioned to ultimately incorporate other elements relevant to integrated watershed planning and management such as ecosystems services valuation. For example, it will allow a user to determine the impacts of upstream forest loss on downstream sediment levels, and then also calculate the economic cost associated with increasing sedimentation such as reductions in storage capacity, de-rating of hydro-electric installations, impairment of fisheries or other possible ecosystem damages. Future versions of WaterFALL™ will also include capability for calculating nutrient runoff from soils and for linking to existing water quality models such as QUAL2K or other similar models.
System Architecture

WaterFALL™ is configured to overlay on the NHDPlus. The NHDPlus network provides high resolution topographic representation of more than 2 million catchments (average size 2.5 km² nationwide) that can be combined by the user to form hydrologic units of varying size ranging from individual streams or stream reaches to entire multi-state river basins. This feature enables the model to be fully portable to any user-defined region within the conterminous United States and to be scaled to any user-defined hydrologic boundaries.

GWLF, first described by Haith and Shoemaker (1987), encompasses all major components of the hydrologic cycle and is in widespread use. The main inputs to the model are daily precipitation and temperature. Evapotranspiration rates are calculated based on temperature and land use parameters. The lack of reliance on past historical data for purposes of calculating streamflows, along with the ability to calculate evapotranspiration losses under alternative climatic conditions, combine to make the model well suited for purposes of evaluating hydrologic impacts associated with climate change.

GWLF

GWLF uses the Universal Soil Loss Equation (USLE) and SCS Curve Number methods for runoff and sediment calculations. The NHDPlus catchment scale provides a reasonable watershed size on which to develop individual, but networked GWLF applications. The intermediate level data requirements of the model are met with geo-referenced national datasets (SSURGO, NLCD, etc.) and regional datasets (evapotranspiration cover factors, etc.).

A variety of climate datasets are available to satisfy the precipitation and temperature inputs to the model. One such source is the network of COOP weather stations available from the National Climatic Data Center (NCDC). A second source is gridded historical climate records derived from NCDC digital archives and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Di Luzio et al., 2008). Both sets of data have been tested within WaterFALL™ and options to choose between datasets are provided where available. Future climate scenarios can be met by indexing compiled climate model output, such as that available from ClimateWizard (climatewizard.org), to the NHDPlus catchments.

The streamflow gages indexed to the NHDPlus in the USGS National Water Information System are accessed through the data structure to provide the actual flow measurements for calibration and validation of the model. Calibration against field monitoring data for streamflow has been performed to verify model performance in flow volume and timing within a series of test watersheds within North Carolina. Calibration of other areas will be completed as testing and validation continues.

Additional hydrologic parameters have been included from gridded datasets compiled by the National Weather Service (NWS) at the 4 km scale. These datasets were originally compiled to parameterize the Sacramento Soil Moisture Accounting (SAC-SMA) model. While some of the parameters match between GWLF and SAC-SMA model requirements, others have been slightly modified for our use. These parameters serve as a base of calibration for WaterFALL™.

**Web Interface**

The web-based interface to the model begins with a map view of the contiguous U.S. Users can select from among several different views within the map and navigate like any typical internet map interface. The WaterFALL™ interface includes a variety of functions for navigating the map and viewing and modifying the default model data. The model is run from this interface and simple result summaries are also presented with the option to export the data. The following screens provide a view of the editing and display screens contained within the interface.
WaterFALL™’s mapping interface uses ArcGIS server and displays maps from Microsoft’s Bing interface. Users can navigate the mapping interface much in the way they navigate current internet mapping sites like Bing and Google. The user has the ability to pan in any direction, zoom in or out, and switch between Street, Topographic, and Satellite background map views. NHDPlus is displayed over the map background for easy identification and navigation of the stream network. Controls along the left side of the interface allow the user to define their watershed of interest once a catchment on the map is clicked or a latitude and longitude is entered. These functions are controlled through the “Get Catchment List” and “Define Watershed” buttons. If the watershed highlighted on the map (as shown in the figure above) is not the intended watershed, the user can use the “Clear” button to start over. The controls along the left also allow the user to select run dates (using the calendar icons) and run the model once the watershed is defined. The user may also download the list of NHDPlus catchments (shown in the list on the bottom left of the screen) within their selected watershed for external use.
Future enhancements to WaterFALL™ will allow users to add human withdrawals and returns to the selected NHDPlus catchment to account for infrastructure such as drinking water intakes and wastewater treatment plant or industrial discharges. On this screen users will also be able to select to use monitored streamflow data in place of model generated data for this catchment. This option is envisioned to be used below control structures where gaged data is more representative of reality than estimated releases from the structure. The user may also select to add a time series of releases from a control structure in place of model generated flow for the catchment on this screen. Finally, the flow generated by the underlying hydrologic model within the catchment, including effects of user-entered withdrawals or returns is displayed in graph form on this display for reference.
The hydrologic parameters displayed on this screen were culled from a variety of sources including SSURGO, regional regressions, NWS datasets, and general look up tables. Therefore, a user with more detailed knowledge of the local system may wish to modify the default parameters to better represent the stream and watershed characteristics. In the future, users will be able to modify model parameters by selecting the “Modify” box and entering a new value, which will be checked for reasonableness before being accepted into the model. After making modifications the user can also choose to go back to the default values within the database by selecting the “Restore to Defaults” button.
We are currently exploring several different meteorological datasets to include in the default database for WaterFALL™ and therefore, this screen will likely be modified in the future to let users select from the different datasets provided. The functions available on the screen will not change, however. Displayed on the left side of the screen are summary statistics of the selected dataset. On the right side is a graphic summary of the data. A simple representation of a “what if” scenario is allowed through this screen where users can globally (meaning the entire time series) modify the climate dataset by an absolute degree value for temperature or a relative percent precipitation using slider bars. The user can also select to modify the data just for the local catchment or for the entire watershed area under analysis. Finally, the user may choose to use their own time series of temperature and precipitation data rather than relying on any of the default datasets contained in the database. Required format for the data will be provided.
The land uses included in WaterFALL™ are listed in the menu along the left side of screen. Clicking on each of the land uses listed will bring up the screen shown here specific to the land use category. The area of the land use within the currently selected catchment is displayed along with the parameters corresponding to the land use. The user may keep the default values or modify the values as with the previous screens. Likewise, the user can return to using default values after making modifications using the “Return to Defaults” button at the bottom. Also on this screen (although not currently shown) the user has the option to chose to modify the area of each land use within the catchment. These modifications are made on the AREAS screen selected at the bottom left of the screen and described below.
Database Interface: Land Use – Areas Form

The AREAS selection at the bottom of the left side of the screen brings up a tab where each of the land uses selected for area modification will appear with their current area in the catchment. The user then enters a new area for each land use until the total change in area displayed at the bottom equals zero. A user will not be allowed to navigate off this screen until that total equals zero. This feature allows a user to simulate land use changes within the catchment for a wide range of scenarios ranging from a return to natural conditions to a fully developed urban area.
The outputs displayed on this screen are currently simple summaries of the streamflows and related data (e.g. velocity, channel depth) for the entire simulation run. A graph on the right side of the screen allows the user to display the inflow to the catchment and the outflow at the outlet in a range of time steps or the annual flow duration curves for each year of the simulation. The user may also export the graph picture or a text file of the model results from this screen. Finally, an additional summary of the annual average streamflows (mean annual, maximum annual, and minimum annual) for this catchment are displayed to reflect the range of streamflow conditions expected for the catchment. This data will also be exported with the text file.
The various performance measures presented in the screen are a work in progress and will likely be modified in future versions. Current there are three sections to evaluate streamflows: (1) Comparison to streamflows from an external file uploaded by the user; (2) Comparison to minimum and maximum flow values entered on the screen by the user; and (3) Parameterization of the streamflows in the Water Use Regime framework described by Weiskel and others (2007). Future enhancements/changes to this screen will likely incorporate flow duration curves and percentiles.