HydroFlows App Methods Document

Created by RTI International (contact mceddy@rti.org)

January 2016

Overview

RTI applied the Watershed Flow and Allocation model (WaterFALL®) to perform catchment-scale flow modeling for the rivers and streams in the 15 major watersheds within Louisiana and Mississippi in support of The Nature Conservancy's (TNC's) Freshwater Assessment. The daily streamflows calculated with the model for each catchment of the enhanced National Hydrography Dataset (NHDPlus) within these watersheds were summarized through graphical means and as a set of predetermined hydrologic metrics at the 12-digit hydrologic unit (HUC12). A baseline scenario was created which simulates the current, altered state of the watersheds. A set of three potential future scenarios were also simulated which consider increased water uses, climate change, and a combination of the two impacts.

WaterFALL Description

WaterFALL is a rainfall–runoff model based on an updated version of the Generalized Water Loading Function (Haith and Shoemaker, 1987) and modified to run on the NHDPlus by RTI. Simulating flows at a daily timestep, 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 represents land–surface hydrology using the curve number method for computing runoff and a first-order depiction of infiltration and loss to deep aquifer storage. Each NHDPlus catchment is parameterized with climate, topographic, land use, and soil properties based on geospatial data, allowing each catchment to be treated as its own watershed simulation. Enhancements to the simulation of rainfall–runoff processes 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 catchments based on water velocities through the NHDPlus stream network. The routing mechanism links together each individual catchment into the larger overall watershed, while allowing for the tracking of local streamflow contributions to each stream segment, as well as cumulative streamflows downstream through the network. This framework is suitable for simulating streamflows in any watershed up to the head of tide (**Figure 1**).

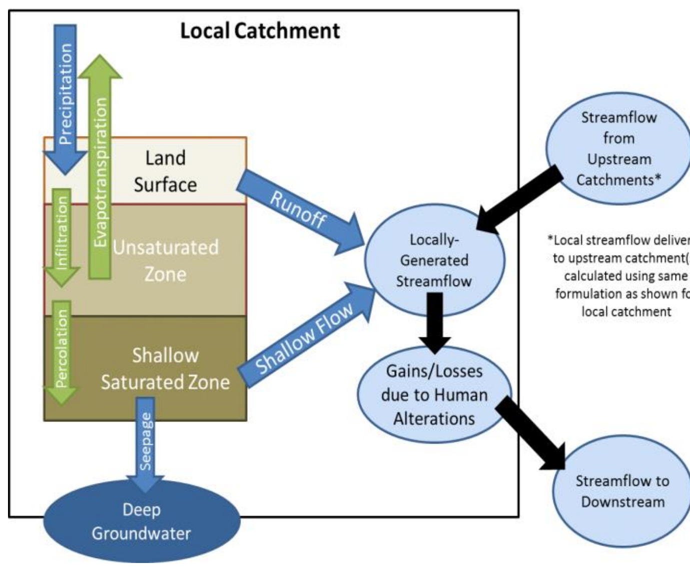

Figure 1. Schematic of the local and watershed processes within WaterFALL

Each of the catchments are characterized in terms of the parameters listed in **Table 1**. When the model is run input parameters are automatically extracted from the WaterFALL database for each catchment. This feature provides two main benefits. First, it enables flow simulations to reflect small-scale variations in soils, land cover, and climate conditions. This granularity contributes to model accuracy. Second, it provides extensive scalability; a watershed may be comprised of a few dozen catchments or of several thousand catchments. Model inputs are georeferenced to each catchment and only need to be changed when evaluating a scenario based on a presumed change in existing conditions. Any point withdrawal or discharge to a stream is tracked within the model by the catchment in which it falls and through a monthly flow rate. **Tables 2 and 3** provides the specific data sources used to parameterize the model within Louisiana and Mississippi.

Table 1. WaterFALL Model Parameters and Definition Methods

Model Parameter	WaterFALL Determination	Applied to
Temperature/ precipitation	Georeferenced from grid to catchments using area weighting	Catchment by day
Land use categories	Georeferenced from geospatial layer	Catchment
Slope	Derived in AHD dataset from national Digital Elevation Model	Catchment; stream segment
Curve number	Look-up table based on land use and soil hydrologic group	Land use category
Cover coefficient	Look-up table based on land use category and growing season	Land use category
Soil hydrologic group	Georeferenced to each land use category within a catchment	Land use category
Available water capacity (AWC)	Georeferenced by land use type and soil hydrologic group; calibrated	Catchment
Recession coefficient (Rcoeff)	Georeferenced by land use type and soil hydrologic group; calibrated	Catchment
Seepage rate	Calibrated (starting value based on best professional judgment using watershed geophysical conditions)	Catchment
Start and end dates of growing season	Georeferenced from national geospatial layer of first and last freeze dates	Catchment
Number of daylight hours	Calculated based on latitude of catchment centroid and day of the year	Catchment by day

A full description of the standard WaterFALL model technical components and performance across the state of North Carolina can be found in Eddy et al. (under revision for JAWRA). Within Louisiana and Mississippi modifications were made to account for further retention of water within the flatter and wetter topography of the bayou systems within the region. These areas were accounted for via parameterization of additional water channels for retaining water within NHDPlus catchments based on uninitialized flowlines in the dataset. A second modification for this application consisted of making corrections on baseflows in certain major stream reaches that showed clear influences of groundwater discharge based on gaged hydrograph separation techniques. These corrections were made in place of a linked groundwater model accounting for the deeper aquifer systems. The rivers on which these corrections were made include: Amite River, Tangipahoa River, Tickfaw River, and Homochitto River.

Table 2. Data Sources used within WaterFALL for Application within Louisiana and Mississippi

Element	Name	Description	Source/Citation
Hydrologic Network	The enhanced National Hydrography Dataset (NHDPlus), Version 2	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).	http://www.horizon-systems.com/nhdplus/
Climate data (Current Conditions)	The Parameter–Elevation Regressions on Independent Slopes Model (PRISM)	PRISM datasets provide estimates of precipitation (ppt), minimum temperature (tmin), and maximum temperature (tmax) for daily time series data since January 1981. The spatial scale for this data set is a 30 second (approximately 4-kilometer) grid covering CONUS. Data is available from January 1981 through 2012 (at time of modeling).	http://www.prism.oregonstate.edu/recent/ DiLuzio, M., G.L. Johnson, C. Daly, J.K. Eischeid, and J.G. Arnold. 2008. Constructing retrospective gridded daily precipitation and temperature datasets for the conterminous United States. *Journal of Applied Meteorology and Climatology*, 47: 475-497
Land Use	National Land Cover Database 2011 (NLCD2011)	A 16-class land cover classification scheme that has been applied consistently across the conterminous United States at a spatial resolution of 30 meters. NLCD 2011 is based primarily on a decision-tree classification of circa 2011 Landsat satellite data.	http://www.mrlc.gov/nlcd2011.php Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354
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's 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.	http://www.soils.usda.gov/survey/geography/ssurgo/description.html http://soils.usda.gov/survey/geography/statsgo/description.html

Element	Name	Description	Source/Citation
Subsurface Characteri-zation	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 are provided on an approximately 4 km x 4km grid. Two of these 11 parameters are adopted as a starting point for calibrating the **available water capacity** (AWC) of the unsaturated subsurface zone (a volumetric measure in cm/cm) and **recession coefficient** (a dimensionless rate) within WaterFALL.[1]	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.
Streamflow[2]	USGS National Water Information System (NWIS) Stream Gages	Daily streamflow data are 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.	NWIS: http://waterdata.usgs.gov/nwis GAGES II: http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml
Water Use (Current Conditions)	Withdrawals: see Table 3 Discharges: National Pollutant Discharge Elimination System (NPDES) permits	A number of different resources by state were used to calculate monthly average withdrawal rates by water sector and catchment. For discharges, facilities (i.e., outfalls) listed within the NPDES database were indexed to individual catchments. For any data for which only annual or permit limits were specified, monthly disaggregations were made using the proportions specified within the Water Supply Stress Index (WaSSI) modeling effort. *See following section for calculation of future alterations	EPA PCS-ICIS search for NPDES permits: https://www3.epa.gov/enviro/facts/pcs-icis/search.html WaSSI: http://www.wassiweb.sgcp.ncsu.edu/

Element	Name	Description	Source/Citation
Climate data (Future Conditions)	Coupled Model Intercomparison Project 5 (CMIP5)	Future projected daily climate data were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" repository. The most extreme emissions scenario (RCP 8.5) from the CMIP5 was chosen to demonstrate a more extreme estimate of the potential climate changes (Taylor et al., 2012) in an attempt to better highlight the more vulnerable areas. The Coupled Physical Model GFDL CM3 run by the NOAA Geophysical Fluid Dynamics Laboratory provided daily data for the selected time period at a 1/8 degree spatial resolution (~12 km by 12 km) across the states (Bureau of Reclamation, 2013).	CMIP5 data by model and emission scenario: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ Bureau of Reclamation. 2013. Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs. 47 pp. Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center. Taylor, K.E., R.J. Stouffer, and G.A. Meehl. 2012. An Overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93: 485-498. doi:10.1175/BAMS-D-11-00094.1

[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 that 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 model simulations, USGS gages are used as boundary conditions or as representation of control structures/dams in place of model estimations at selected NHDPlus catchments.

Table 3. Data Sources for Withdrawal Estimates

State	Sector	Data Source	Location Source
LA	Agriculture	USGS National Data (2005); CropScape land cover with water use rate by crop type (see next section)	Agricultural land use classifications
	Industrial	Louisiana USGS Data (2004-2012)	Louisiana USGS Data (2004-2012)
	Public Supply	Louisiana USGS Data (2004-2012)	Louisiana USGS Data (2004-2012)
	Power Generation	Louisiana USGS Data (2004-2012)	Louisiana USGS Data (2004-2012)
TX	Agriculture	USGS National Data (2005); CropScape land cover with water use rate by crop type (see next section)	Agricultural land use classifications
	Industrial	USGS National Data (2005)	NPDES permit (2009-2012) or EIA Database (2005)
	Public Supply	Texas Water Right Database (2000-2011); USGS National Data (2005)	TX Surface Water Intake (updated 2012)
	Power Generation	Texas Water Right Database (2000-2011); Energy Information Administration (EIA) Database (2005)	EIA Database (2005)
AR	Agriculture	Arkansas USGS Data (2010)	Arkansas USGS Data (2005)
	Industrial	Arkansas USGS Data (2010)	Arkansas USGS Data (2005)
	Public Supply	No surface water public water supplies in the study area	
	Power Generation	EIA Database (2005)	EIA Database (2005)
MS	Agriculture	USGS National Data (2005); CropScape land cover with water use rate by crop type (see next section)	Agricultural land use classifications
	Industrial	USGS National Data (2005)	NPDES permit (2009-2012) or EIA Database (2005)
	Public Supply	Mississippi Department of Health	Descriptive information by facility
	Power Generation	EIA Database (2005)	EIA Database (2005)

Future Water Uses

To make projections of future water use for this initial simulation of future conditions, TNC and RTI developed two different approaches based on current water use estimates for agriculture and for the public water supply, industrial, and mining water use sectors.

Agricultural Water Use: The mix of crops (based on CropScape land cover data) within each catchment was recalculated by assuming an exchange of one crop type for another using the rate of change seen between the 2000 and 2014 CropScape data layers. For example, assume 10% of all corn crops were retired and planted with rice instead. Water use rates were then recalculated for this crop acreage with the original withdrawal rates.

To recalculate the crop mix, RTI utilized the comparison tool available for the USDA's CropScapes data looking at the trends between the years 2010 and 2014 and the four major crops within the region (cotton, soybeans, corn, and rice). **Tables 4 and 5** present the changes in area by crop type and between crop types in Louisiana. (The same method and calculation was used in Mississippi.)

Table 4. Overall percent change in area for the four major crops in Louisiana between 2010 and 2014

Crop	% Change 2010 to 2014
Corn	-21
Cotton	-36
Rice	-23
Soybeans	33

Table 5. Percent change between crop types

Crop	% Lost to Corn	% Lost to Cotton	% Lost to Rice	% Lost to Soybeans	Other % Change
Corn	-	0	0	-22	-1
Cotton	-3	-	0	-24	-8
Rice	-1	0	-	-14	-7
Soybeans	0	0	0	-	10

To calculate projected water use for irrigation, the percent changes between acres of crop types were applied to the existing acres of croplands in 2014 in each catchment. Then the additional changes for other land areas were applied.

Once the new acres of each crop type were calculated for each catchment, the average irrigation rate by crop type was applied. For current water use estimates the 8-year average rate had been applied (**Table 6**). For the future projection assessment, the maximum rate measured with in the Yazoo was applied instead of the average to provide a conservative (i.e., higher) estimate of future water use. The highest rates occurred during 2006 for all crop types.

Table 6. Annual average irrigation by crop from the Yazoo River Basin (Acre-ft per acre)

Crop	2002	2003	2004	2005	2006	2007	2008	2009	8 year average
Cotton	0.5	0.5	0.3	0.5	0.8	0.5	0.6	0.3	**0.5**
Beans	0.7	0.6	0.4	0.6	1.0	0.8	1.0	0.6	**0.7**
Corn	0.9	0.6	0.4	1.0	1.2	0.8	1.2	0.8	**0.9**
Rice	3.2	2.8	2.5	3.0	3.4	3.0	3.1	2.8	**3.0**

Public Water Supply/Industrial/Mining: For this initial future water use scenario a straight percentage increase on water withdrawals and returns was applied, leaving consumption at current rates. According to recent summaries of water use in Louisiana by USGS and LA DOT ("Water Use in Louisiana, 2010"), uses for water supply and industry have actually decreased between 2005 and 2010. To again make a conservative approach, a 10% increase in existing public water supply, industrial, and mining water uses was applied given the absence of other data.

Model Application

Figure 2 displays the area covered by the WaterFALL simulations of streamflow within Louisiana and Mississippi. In total there were 23 separate watersheds simulated by selecting the most downstream pour point of the major watersheds (typically a 6-digit hydrologic unit [HUC6]) within the states. In some instances, due to the size of the watersheds, boundary conditions were set upstream from the state boundary using gaged flows (Ouachita, Red, Sabine, and Tombigbee) and for the Atchafalaya the simulated flows from the outlets of the Ouachita and Red and gaged flows from the Mississippi River were used as upstream boundary conditions. Boundary conditions based on gaged flows were held constant for future scenarios.

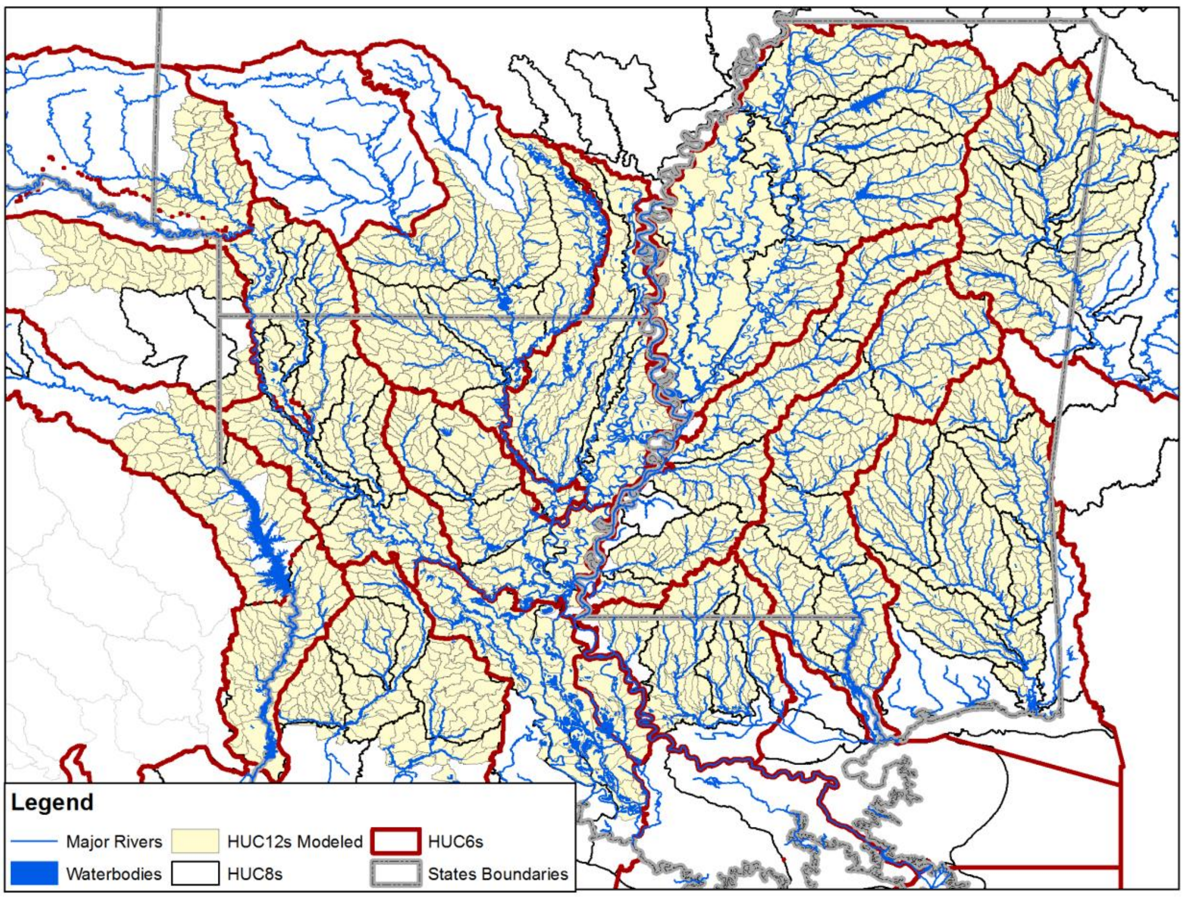

Figure 2. Modeled Watersheds within Louisiana and Mississippi using WaterFALL

Within Louisiana a total of 15 watersheds and subwatersheds (including the Pearl Watershed which originates in Mississippi) were modeled, which includes 15,011 HUC12s and 58,053 individual NHDPlus catchments. Within Mississippi a total of 8 watersheds and subwatersheds were modeled, which includes 888 HUC12s and 54,701 individual NHDPlus catchments.

Four scenarios were modeled:

- **Current conditions:** 1981 through 2012 climate, 2011 land use, and current estimates of water use
- **Projected water use change:** Climate and land use same as current conditions; Water uses projected to future levels
- **Projected climate change:** Land use and water use same as current conditions; Climate time series from 2013 to 2043
- **Combined water use and climate change:** Land use the same as current conditions; Climate time series from 2013 to 2043; Water uses projected to future levels

30 year time series of daily streamflows were produced for each catchment for each of the four scenarios.

Model Performance

WaterFALL was calibrated to a selection of USGS streamflow gages within each of the simulated watersheds. Calibration metrics are available for each gage. Additional gages were used to validate the model parameters determined through calibration and applied to the remaining areas of the watershed. An example of the model performance for the Ouachita Watershed is provided in **Figures 3 and 4** and **Table 7**. Calibration was conducted using both quantitative (Nash-Sutcliffe Efficiency [NSE], percent bias [%Bias], and coefficient of determination [R^2]) and qualitative (flow-duration curve and hydrograph) comparisons with gaged flows.

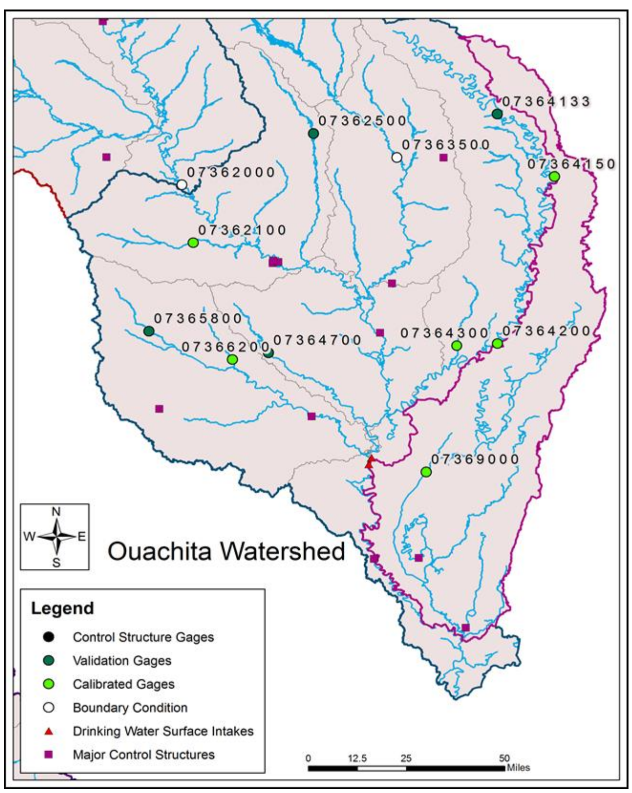

Figure 3. Locations of Calibration, Validation, and Boundary Condition Gages within the Ouachita Watershed as used in WaterFALL

Table 7. Performance Metrics for the Ouachita Watershed Calibration Gages

Gage ID	Site Name	Drainage Area (mi^2)	NSE	%BIAS	R^2
07366200	Little Corney Bayou near Lillie, LA	208	0.73	-5	0.74
07369000	Bayou Lafourche near Crew Lake, LA	361	0.84	-5	0.86
07364133	Bayou Bartholomew at Garrett Bridge, AR	380	0.70	9	0.71
07364150	Bayou Bartholomew at McGehee, AR	576	0.67	19	0.71
07364200	Bayou Bartholomew near Jones, LA	1,187	0.49	36	0.66
07362100	Smackover Creek near Smackover, AR	385	0.65	6	0.66

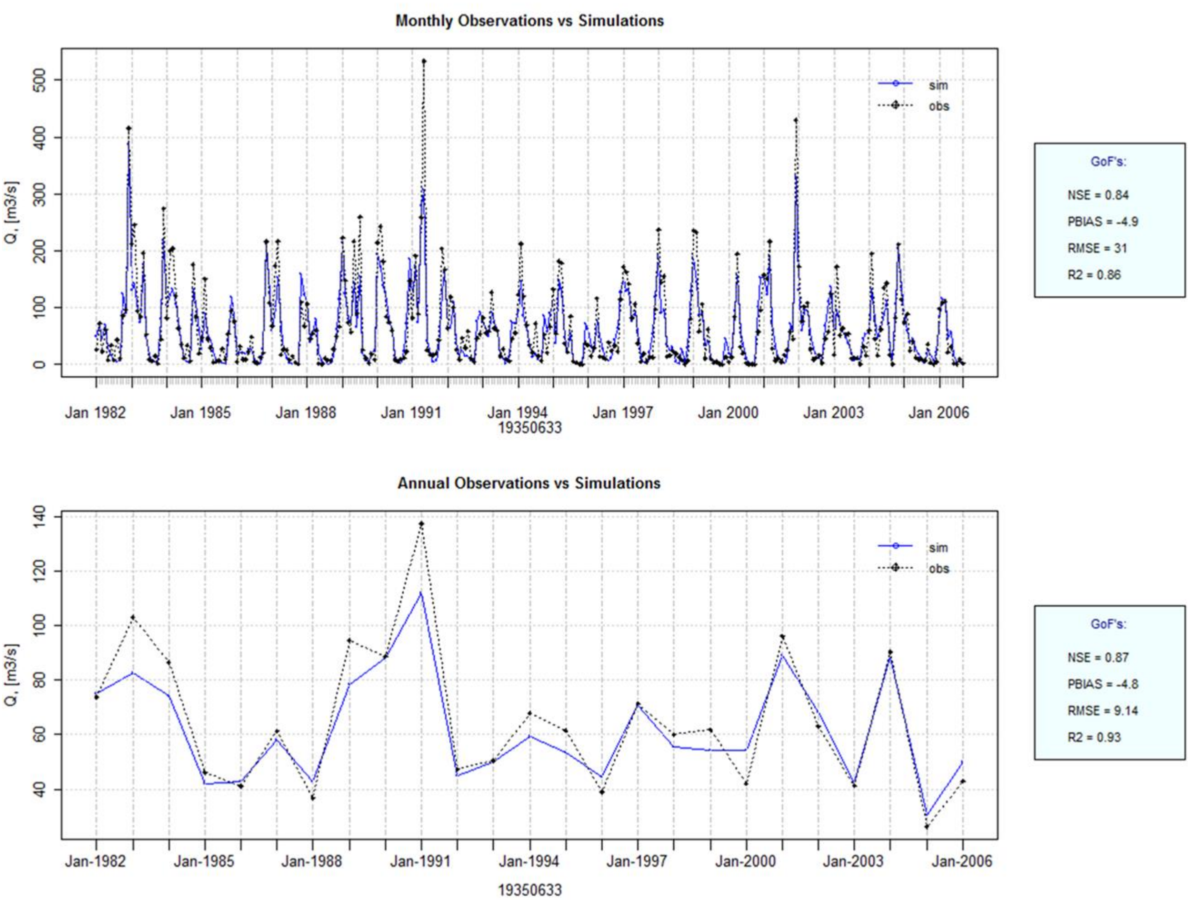

Figure 4. Monthly and Annual Hydrographs of Modeled and Gaged Data at USGS 07369000 Bayou Lafourche near Crew Lake, LA

Hydrologic Metrics

TNC and RTI determined a set of hydrologic metrics (**Table 8**) to calculate at both the HUC12 and catchment level within all study watersheds to facilitate the use and display of the modeled data within the Freshwater Network. The metric selection was based on the determination of Richter et al., 1996 that certain hydrologic metrics are biologically relevant. These metrics have been preprocessed using the EflowStats package in R developed by USGS (Thompson and Archfield, 2015) for each scenario run (e.g., current and three future scenarios) and can be accessed through various methods within the HydroFlows App of the Freshwater Network.

Table 8. Hydrologic Metrics Calculated from the Daily Catchment and HUC12 Modeled Time Series

Name	Description	Unit	Note
Monthly median	Monthly median flow	cfs	Mean over period of record (POR); value per month
Monthly mean	Monthly mean flow	cfs	Mean over POR; value per month
1-Day Min	Annual minima, 1-day mean	cfs	Mean over POR
1-Day Max	Annual maxima, 1-day mean	cfs	Mean over POR
3-Day Min	Annual minima, 3-day mean	cfs	Mean over POR
3-Day Max	Annual maxima, 3-day mean	cfs	Mean over POR
7-Day Min	Annual minima, 7-day mean	cfs	Mean over POR
7-Day Max	Annual maxima, 7-day mean	cfs	Mean over POR
30-Day Min	Annual minima, 30-day mean	cfs	Mean over POR
30-Day Max	Annual maxima, 30-day mean	cfs	Mean over POR
90-Day Min	Annual minima, 90-day mean	cfs	Mean over POR
90-Day Max	Annual maxima 90-day mean	cfs	Mean over POR
Zero flow days	Number of zero flow days	count	Mean over POR
Baseflow index	Base flow index: 7-day minimum flow/mean flow for year	unitless	Mean over POR
Date of Min	Julian date of each annual 1-day minimum	unitless	Mean over POR
Date of Max	Julian date of each annual 1-day maximum	unitless	Mean over POR
Low pulse count	Number of low pulses within each water year	count	Mean over POR; the pulse thresholds are the 25th and 75th percentiles of the distribution of flows.
High pulse count	Number of high pulses within each water year	count	Mean over POR; the pulse thresholds are the 25th and 75th percentiles of the distribution of flows.
Low pulse duration	Mean duration of low pulses	days	Mean over POR; the pulse thresholds are the 25th and 75th percentiles of the distribution of flows.
High pulse duration	Mean duration of high pulses	days	Mean over POR; the pulse thresholds are the 25th and 75th percentiles of the distribution of flows.

In addition to the hydrologic metrics calculated from individual time series, a set of "Ecochange" metrics were calculated by comparing each future scenario to the current condition scenario using methods defined by Vogel et al. (2007). By calculating the difference between the flow duration curves of the current and potential future scenarios the values of Ecosurplus and Ecodeficit can be determined. Ecosurplus is defined as the fraction of water now available in excess of the baseline condition (i.e., current streamflow conditions). Ecodeficit is the fraction of water lost from the baseline condition. Illustrations of these concepts are shown in **Figure 5**. Further explanation of these concepts is provided within the HydroFlows App when viewing these metrics at the HUC12 level.

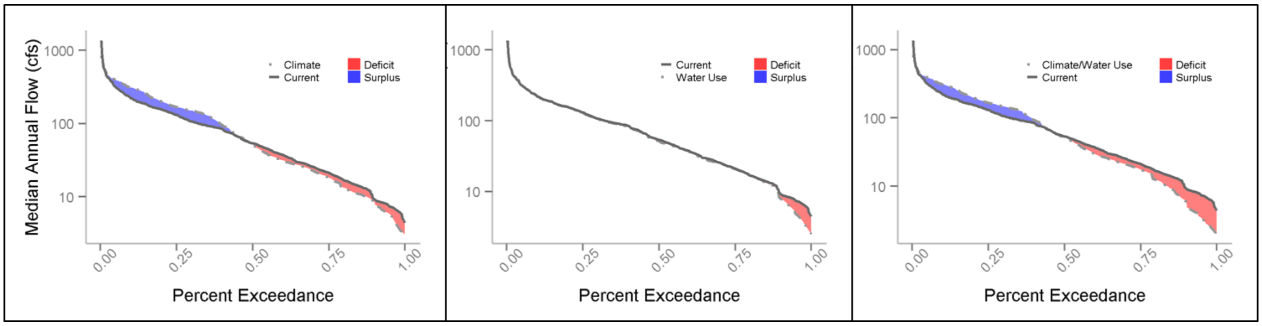

Figure 5. Examples of Ecodeficit and Ecosurplus across Future Scenarios

References

Eddy, M.C., F.G. Moreda, R.M. Dykes, B. Bergenroth, A. Parks, and J. Rineer. (Accepted; Under revision). The Watershed Flow and Allocation Model: A Spatially Explicit NHDPlus-Based Watershed Modeling Approach for Multiple Scales and Conditions. *Journal of the American Water Resources Association (JAWRA).*

Haith, D.A., and L.L. Shoemaker. 1987. Generalized Watershed Loading Functions for Stream Flow Nutrients. *Journal of the American Water Resources Association (JAWRA)* 23(3):471-478.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun, 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology* 10(4):1163-1174.

Thompson, J. and S. Archfield. 2015. The EflowStats R Package. U.S. Geological Survey. Available at: https://github.com/USGS-R/EflowStats.

Vogel, R.M., J. Sieber, S.A. Archfield, M.P. Smith, C.D. Apse, and A. Huber-Lee. 2007. Relations among storage, yield, and instream flow. *Water Resources Research* 43, W05403, doi:10.1029/2006WR005226.