FINAL REPORT

Demonstration and Validation of BASINS Watershed Modeling System Enhanced for Military Installations – Fort Benning

ESTCP Project RC-201307

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ACRONYMS AND ABBREVIATIONS

ACF	Apalachicola-Chattahoochee-Flint River Basin
BASINS	Better Assessment Science Integrating point and Non-point Sources
BASINS.MIL	Military Enhanced BASINS Modeling System
BMP	Best Management Practice
BRAC	Base Realignment and Closure
CAT	Climate Assessment Tool
CBP5	Chesapeake Bay Program HSPF Phase 5.3 Model
CEQ	Council on Environmental Quality
CWA	Clean Water Act
DC	District of Columbia
DMPRC	Digital Multi-Purpose Range Complex
DoD	Department of Defense
DUSD(I&E)	Deputy Under Secretary of Defense (Installations and Environment)
EBM	Enhanced Baseline Fort Benning Model
EFDC	Environmental Fluid Dynamics Code
EISA	Energy Independence and Security Act
EO	Executive Order
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FAPH	Fort AP Hill
FAPH Model	Fort AP Hill BASINS.MIL model
FB	Fort Benning
FB Model	Fort Benning BASINS.MIL model
FTABLE	HSPF Model Hydraulic Function Table
GA	State of Georgia
GAB Roads	Graded Aggregate Base roads
GHMTA	Good Hope Mechanized Training Area
GIS	Geographic Information System
HSPF	Hydrological Simulation Program FORTRAN
IMPLND	HSPF Model Impervious Land Segment Used for Landscape Simulation
LIDAR	Light Detection and Ranging
LID	Low Impact Development
MCOE	Fort Benning Maneuver Center of Excellence
MD	State of Maryland

NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NLCD	National Land Cover Data
NSE	Nash-Sutcliffe Efficiency
NSM	Nutrient Simulation Module
OV	Observed Value
PERLND	HSPF Model Pervious Land Segment Used for Landscape Simulation
PI	Principal Investigator
PO	Performance Objective
QA	Quality Assurance
R	Correlation coefficient
R2	Coefficient of Determination
RCHRES	HSPF Model Stream or Reservoir Reach Used for Channel Simulation
RVSM	Runoff Volume Simulation Model
SEDZLJ	Sediment transport algorithm for EFDC
SERDP	Strategic Environmental Research and Development Program
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TR-20	Technical Report 20
TR-55	Technical Report 55
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
USFS	United State Forest Service
USGS	United State Geologic Survey
VA	State of Virginia
VDCR	Virginia Department of Conservation and Recreation
VADEQ	Virginia Department of Environmental Quality
WEPP	Water Erosion Prediction Project
WEPP:Road	WEPP Interface for Predicting Forest Road Runoff, Erosion and Sediment Delivery
WIP	Watershed Implementation Plan
WDM	Watershed Data Management

1.0 INTRODUCTION

The BASINS Modeling System is a GIS-based system and features a well-developed interface for different dynamic watershed models, and numerous pre- and post-processing tools that are shared by the models. Two types of enhancements, using the Hydrological Simulation Program – FORTRAN (HSPF) as the primary modeling code, were developed for the BASINS modeling system for military-specific applications: (1) data and methodologies that address key military land stressors (i.e., urban encroachment, prescribed burning, timber harvesting, military training, and unpaved roads), and (2) software refinements related to model linkages and algorithms.

BASINS.MIL was used to build a continuous computer simulation model of hydrology and water quality for the watersheds on and surrounding Fort Benning, Georgia (GA). This model is referred to as the FB Model (or FB Enhanced Baseline Model). Preliminary model applications of the FB Model were performed to provide proof-of-principle demonstration of the modeling system and the model enhancements to support watershed management decisions on the Installation.

The demonstration/validation of BASINS.MIL is the next step to fully demonstrate the validity of the technology to meet DoD's need for tools to evaluate watershed hydrology and water quality for system-level assessments. As illustrated in Figure 1.1, the technology transfer of BASINS.MIL demonstration/validation leverages the watershed model developed on Fort Benning (FB) by conducting further modeling applications on FB, and by developing a watershed model for another installation that will be used to further demonstrate the technology. Fort AP Hill (FAPH), Virginia was selected as the second site since it provides a unique opportunity to (a) demonstrate the transferability of the BASINS.MIL modeling framework to a new installation and (b) demonstrate the ability of BASINS.MIL to address TMDL issues.

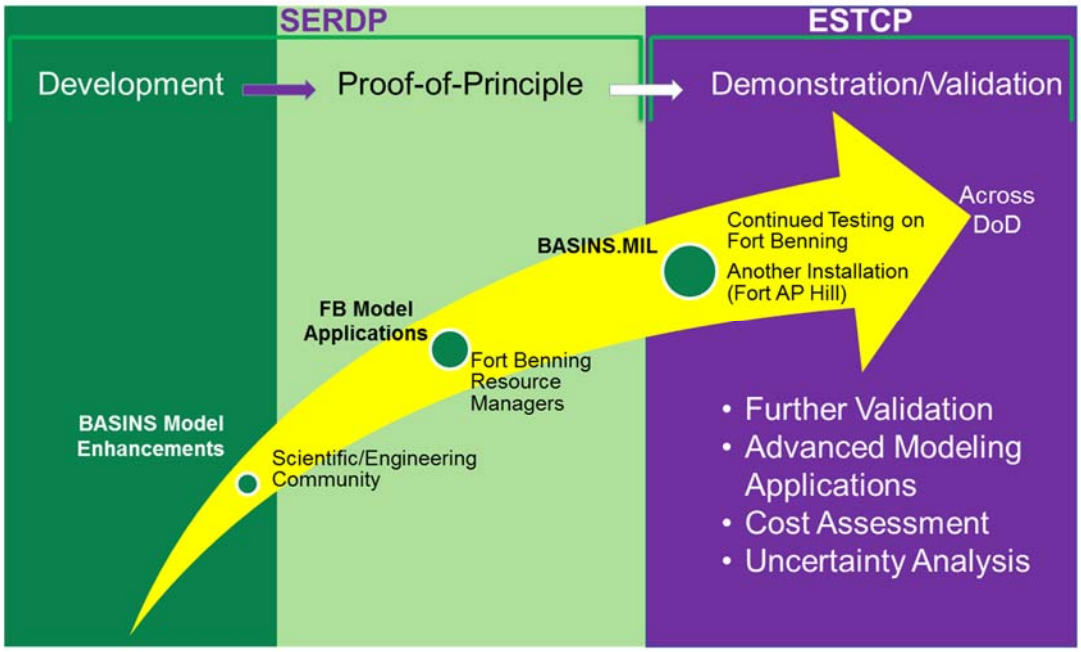


Figure 1.1. Technology Transfer Process for BASINS.MIL.

1.1 BACKGROUND

The DoD uses, and in many cases directly manages approximately 30 million acres of land to accomplish its testing and training missions. Often such use results in direct and indirect physical impacts to soil, vegetation, and water resources. Impacts that result in soil erosion and runoff (whether from rain or snowmelt) with subsequent changes in water flows and loading of sediment, nutrients, and pollutants to receiving water bodies can result in compliance, sustainability, and stewardship problems. In accordance with the guidelines and goals established in the Unified Federal Policy for a Watershed Approach to Federal Land and Resource Management, the DoD Instruction 4715.03 calls for a watershed-based approach to manage operations, activities, and lands to avoid or minimize impacts to wetlands, groundwater, and surface waters on or adjacent to installations. Watershed modeling systems are a critical component of efforts to support this mandate, and maintain military readiness and sustainability of DoD testing and training lands.

In a formal solicitation, ESTCP sought demonstration projects that support the advancement of land and water resources management within a watershed context on DoD installations. The focus was on models and decision support tools associated with watershed hydrology, erosion, and impacts to receiving water bodies and their aquatic receptors. Specifically, ESTCP sought proposals that demonstrate innovative but technically mature technologies, along with associated methodological approaches, that are relevant to a military land use and management context, with the expectation that application of such models/tools would facilitate the ability of DoD installations to sustain their training and testing missions while meeting compliance and stewardship responsibilities.

Use of continuous simulation computer techniques (such as BASINS.MIL) for evaluation of watershed hydrology and water quality offers much promise as a system-level assessment tool. However, this technology has been slow to be embraced by DoD installations due in part to a variety of perceived and real shortcomings such as: 1) uncertainty about costs related to site-specific data needs, 2) expertise needed to apply the modeling system, 3) disparity between the scale of the assessment need and the scale of the model's resolution, and 4) a lack of knowledge regarding the versatility and relevance of the technology to address compliance-specific management issues on installations.[1]

1.2 OBJECTIVE OF THE DEMONSTRATION

The overarching objective of this project was to further demonstrate BASINS.MIL which was developed by the SERDP-funded Project RC-1547 as a tool for watershed-based decision making on military installations.

The specific objectives of the BASINS.MIL demonstration/validation are related to modeling capabilities, model performance, and cost assessment/comparisons of the technology. The combined host sites offer an opportunity to meet the objectives in each of the three categories. Table 1.1 lists the components of the BASINS.MIL demonstration/validation associated with each host site. Components of the demonstration/validation will be performed on FB and FAPH.

[1] This general perception of reluctance by DoD users to apply continuous simulation computer techniques is most likely related to a set of compounding issues, including budget pressures, regulatory foci, and DoD policies.

The FB portion of the demonstration/validation is focused on demonstration of the BASINS.MIL capabilities and performance, whereas the objective for the FAPH components is focused on cost assessments related to the transferability of the BASINS.MIL modeling framework to a new installation, and to demonstrate the ability of BASINS.MIL to address small-scale assessments and TMDL issues.

Table 1.1. Components of BASINS.MIL Demonstration/Validation Associated with Each Host Site

Objectives	Components of Demonstration/Validation	Host Installation: Fort AP Hill	Host Installation: Fort Benning
Modeling Capabilities	Unpaved road design and maintenance		✓
	Climate non-stationarity		✓
	Small-scale modeling assessment	✓	
Model Performance	Validation of WEPP modeling results		✓
	Data Richness versus Model Performance		✓
	Uncertainty of modeling results	✓	✓
Cost Assessment & Advantages	Cost assessment of BASINS.MIL application at a new location	✓	
	Comparison with other modeling approaches	✓	
	TMDL assessment application	✓	

1.3 REPORT OBJECTIVE AND CONTENTS

Given the large number and broad variety of demonstrations that were established and performed for this project, during the development of the schedule and deliverables for the Demonstration Plan (Donigian et al., 2013), ESTCP requested that separate reports be developed that describe the collection of demonstrations that were performed at each of the two demonstration sites in addition to the traditional Project Final Report. Accordingly, this report provides a full account of the demonstrations that were performed at Fort Benning; it will be followed by a parallel report that provides like material for Fort AP Hill.

This report is comprised of a main body that contains a synopsis and conclusions/ recommendations for each of the four Fort Benning tasks (unpaved road investigations are considered jointly). For each task, the full documents that were submitted to, and approved by ESTCP are included in their entirety as appendices.

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2.0 OVERVIEW OF BASINS.MIL DEMONSTRATIONS AT FORT BENNING

The demonstrations and validations that were performed at Fort Benning are the following:

Task 5: Data Richness Versus Model Performance

This component of the FB Demonstration implemented an approach to quantify the change in model performance relative to the richness of data that are available for model set up. Specifically, the objective was to quantify the change in performance of a BASINS.MIL hydrology model as a function of the number of observed flow data sites (gages) available for calibration within the watershed. Several important restrictions embedded in this objective are worth noting. The objective applies to hydrology only and to the existing FB Model because of the installation and data collection (since 2008) of new flow gages within the model domain. This understanding then allows inference to how model performance relates to amount of flow information needed to make different types of watershed management decisions relevant to installations across DoD.

Task 6: Unpaved Road Sediment Erosion Modeling Application

The first objective of this task was to collect and use data for unpaved road erosion at Fort Benning to validate the WEPP model. The strategy for selecting data collection sites was established by the WEPP:Road model developer, Dr. William Elliot of the US Forest Service. The primary consideration was characterizing extremes in potential sediment erosion at the Installation, and demonstrating the model's ability to reproduce the full range of observed sediment erosion phenomena. The second objective of the task was to evaluate the usefulness of the data gathered in support of the WEPP:Road as a potential resource for determining justifiable adjustments to the unpaved road land use category in the FB Watershed Model.

Task 7: Model Demonstration for Climate Non-Stationarity and Land Use Change Impact Analysis

The objective of a climate non-stationarity assessment was to demonstrate the usefulness of a BASINS.MIL model (i.e., FB Model) results to characterize changes in hydrology and sediment associated with potential climate scenarios and land uses. This objective is consistent with an overarching goal to demonstrate the capability of applying BASINS.MIL in operational mode to assess alternative conditions and practices by defining and evaluating advanced management scenarios.

Task 9: Demonstration of Sensitivity and Uncertainty Analysis

The objective of this task was to demonstrate that sensitivity and uncertainty analyses conducted with a BASINS.MIL model can be used to first provide understanding of the relative sensitivities of simulation results to adjustments made in various model input parameters, and second quantify uncertainties in model results/predictions related to relevant regulatory standards and/or indicators.

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3.0 FORT BENNING TASK 5: DATA RICHNESS VERSUS MODEL PERFORMANCE

3.1 TASK SYNOPSIS

An important consideration for the transferability of BASINS.MIL is the cost associated with data requirements for model setup and application for the Installation and the incremental benefit that collecting additional data has in addressing management-relevant questions. The DoD needs to better understand the costs and benefits associated with data richness and model performance. Especially in relatively data-poor settings, installations are unclear about how much to invest in monitoring to meet a specific level of model performance. General guidance based on quantitative results, which is the objective of Task 5, is essential.

Objective of Task 5

This component of the FB dem/val develops and implements an approach to quantify the change in model performance of the Fort Benning Enhanced Baseline Model (AQUA TERRA Consultants, 2013) relative to the quantity and quality of available data for model setup and application. This objective has site specificity related to FB as well as a broader application of the results/conclusions that are achieved to military installations with similar rainfall-runoff and landscape features. The approach in this report is designed to consider a full range of data availability issues, from little or no data for model setup and calibration to multiple gage sites with multiple years of observations and varying levels of model application experience. The goal is to provide installations with information on potential tradeoffs in model performance compared to the needs of additional data collection to instill higher confidence in model results across various spatial scales.

HSPF is the main watershed modeling code in BASINS and is a comprehensive, process-based mathematical model used to simulate hydrologic and water quality processes in natural and man-made water systems (Bicknell et al., 2005). The model uses input information such as the time history of rainfall, temperature, evaporation, and parameters related to land-use patterns, soil characteristics, and land-management practices to simulate the processes that occur in a watershed. The initial result of an HSPF simulation is a time history of the quantity and quality of water transported over the land surface and through various soil zones down to the groundwater aquifers. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations that result from the Installation's unique weather and land conditions can be predicted. The model then uses these land-derived loading results and stream channel information to simulate instream processes. From these simulations, HSPF produces a time history of water quantity and quality at any point in the watershed.

The extensive amount of watershed-related data collected at FB makes it well-suited for conducting a set of conditional data scenarios that compare the data used for model set-up and application and the resulting model performance. At the onset of the SERDP project, the major limitation with respect to hydrologic modeling on the FB watersheds was that only a single flow gage was available for calibration, even though it was well-located at the center of the watershed. In response to this limitation, SERDP agreed to fund additional flow data collection, which included five stream gages that were installed by the US Geological Survey (USGS) on the Installation in 2008.

Figure 3.1 shows the Fort Benning Watershed and the locations of the USGS gages. The gaging stations provide additional flow data and rating curves beyond the original simulation period (1999–2008) of the FB Model, which was based solely on the McBride Bridge gage site on Upatoi Creek. Strategically located to assist in and support future model calibrations, the new USGS gaging stations (**RED** stars in Figure 3.1) were installed and data were collected through 2012 to support modeling efforts at each of the sites. The new USGS sites are listed below:

- Pine Knot Creek Near Eelbeck, Georgia (Station No. 02341725)
- Upatoi Creek Below Baker Creek Near Upatoi, Georgia (Station No. 02341665)
- Ochillee Creek at Ochillee, Georgia (Station No. 02341910)
- Randall Creek Near Upatoi, Georgia (Station No. 02341750)
- Upatoi Creek at GA357 at Fort Benning, Georgia (Station No. 02342070).

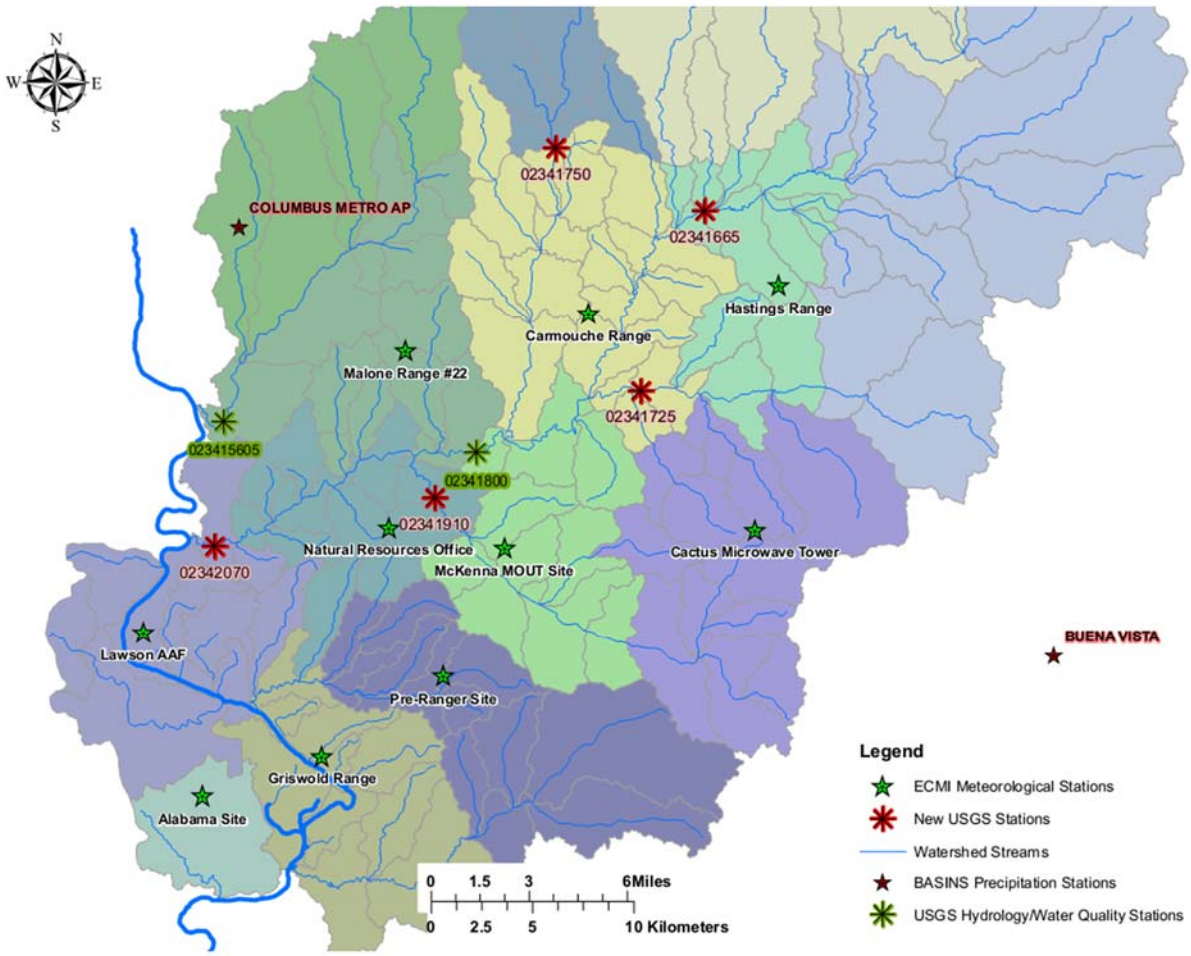


Figure 3.1. Location of US Geological Survey Gage Sites Within the Upatoi Creek Watershed Near Fort Benning.

Modeling Approach and Conditional Data Scenarios

The technical approach to this task consists of a set of conditional data scenarios that reflect alternative levels of data quantity and/or quality available to support the model setup and calibration. The challenge of this task was to design these conditional data scenarios so that model performance can be quantified as a function of the data made available for each scenario. These scenarios, associated data requirements, and availability are summarized in Table 3-1 below.

Table 3.1. Data Requirements and Availability for Each Conditional Data Scenario

Conditional Data Scenario	Data Requirement	Data/Knowledge Availability
Blind Validation	Additional time-series data to extend modeling simulation	New flow data not used in calibration
Incremental Recalibration	Hydrologic flow data from five new gages	Adding data from the new gages one at a time and recalibrating
Applying Non-Calibrated Parameters by a New or Inexperienced Model User	Regional maps, soils data, cross-sectional data and other parameter guidance available from public sources	No data from new stream gages; modeler has no calibration experience nor knowledge of previous model calibrations
Data Quality	USGS Gage Rating System	USGS ratings for the new FB gages

Blind Validation

This data scenario involves comparing simulated flow variables from the FB Enhanced Baseline Model, which was developed in RC-1547, with the hydrologic (flow) data observed at the new USGS gages for their extended period of record from 2008 to 2012. This analysis is essentially a blind validation (i.e., it is a validation performed after the calibration has been completed and before the new flow data was being collected and was available). This analysis is intended to demonstrate how well the calibrated model predicts the flows measured but not used in the calibration. The analysis addresses how well the model performs, not only at the McBride Bridge site where it was calibrated but also at other watershed sites where no data for calibration existed. While this analysis does not yet answer how the calibration and model performance would change and improve as additional data were made available, it sets the stage for that analysis in the next conditional data scenario (i.e., the incremental calibration).

The model results for the blind validation demonstrate a relatively successful simulation and imply that a single gage may be adequate for representing the entire watershed, but the simulation is less successful at the smaller tributary sites. The results suggest that the McBride Bridge calibration parameters provide a fair-to-good overall simulation for the extended period for most of the other sites, but they do not work very well for the Pine Knot Creek Subwatershed. This implies that using a single flow gage for a relatively large watershed, such as the Upatoi Creek, at 300–500 square miles, may provide a reasonable simulation for *some* smaller tributary subwatersheds, but the same level of accuracy cannot be guaranteed for *all* subwatersheds.

Incremental Recalibration

Incremental recalibration involves comparing the simulated flow variables from the FB Model at each of the new USGS stream gages with parameter sets that have been recalibrated in a sequential step-wise fashion using one gage at a time, so that incremental improvements (and changes) in model performance metrics can be evaluated as applied to the drainage area above the stations. Thus, the percent of the upstream watershed that is now gaged becomes an important factor in the analyses because it identifies how much of the upstream drainage area has now been calibrated.

This analysis was a key focal point of this investigation because it addresses the key issue of how the model metrics will improve by incrementally using additional data for successive calibration efforts. The analyses at all of the impacted gages were performed at each step to assess how the metrics are changed with each additional calibration effort. With improvements in upstream gages, subsequent parameter refinements may be needed in the downstream gage sites (i.e., the previous calibration may have included offsetting, or compensating, errors that could only be identified with the additional data at multiple sites). In fact, this situation did occur.

The model results from the recalibration effort make it clear that the additional data provided by the new USGS gage sites allow a much more spatially accurate model for the various subwatersheds of Upatoi Creek. This accuracy also supports using the model for assessments closer to the scale of typical disturbances, construction, and other activities that may be the focus of future modeling and assessment/evaluation efforts. From the results presented in Chapter 3.0 of the Final Task 5 Report (AQUA TERRA Consultants, 2018), the flow-duration curves, and the hydrographs in Appendix A, the following conclusions were developed:

a. For monthly flows, the correlation metrics are primarily in the good-to-very good range (from the corresponding scale in Figure 3.2), except for the Pine Knot Creek and Randall Creek gages, which extend to the fair range.

b. For daily flows, the same correlation metrics are mostly in the fair-to-good range ($R > 0.8$ and $R^2 > 0.64$ respectively), with the Baker Creek gage as an exception.

c. For Moriasi et al.'s (2007) thresholds (MFE > 0.5, RSR < 0.7, PBIAS < 25 percent [monthly] to 35 percent [daily]), the monthly simulation results satisfy all of these metrics at all of the sites. For daily flows, the same holds true except for the Baker Creek site (i.e., RSR = 0.74 and MFE = 0.46), and both of these very nearly satisfy the metrics.

d. The very good-to-excellent agreement of the flow-duration curves provides a visual confirmation of the accuracy of the recalibrated model throughout the full range of flows observed at the gages. Only Randall Creek and the low-flow region for the Ochillee Creek gage indicate some deviation from the observed flow-duration curve.

The results obtained from the incremental calibration demonstrate that each of the gages provide additional information that helps to improve the spatial representation of the watershed and provides insight into how and which model parameters need to be changed to represent the spatial variability of the watershed.

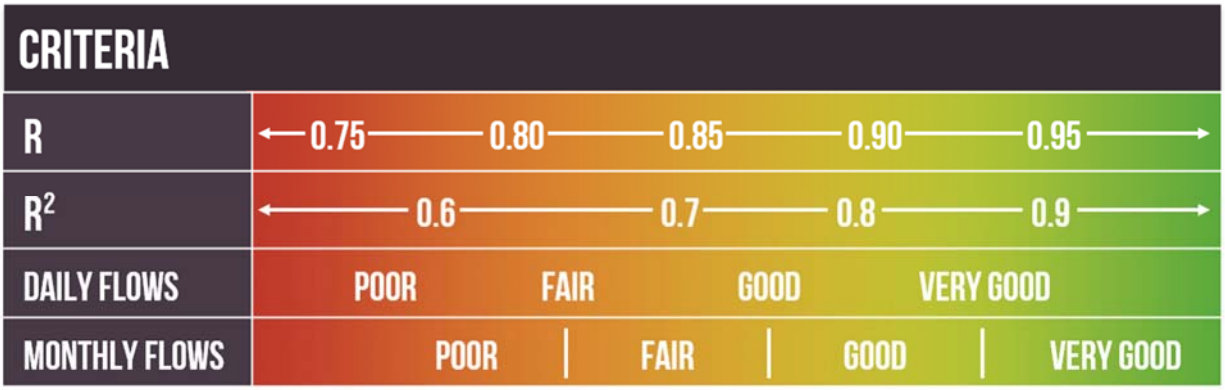


Figure 3.2. R and R^2 Value Ranges for Model Performance (Donigian, 2002).

Application of Non-Calibrated Parameters by a New Model User

This effort involved comparing the FB Model simulated flow variables at the long-term, historical USGS gage at McBride Bridge, with simulated flow variables derived from a non-calibrated parameter set that was estimated from regional maps, soils data, and other parameter guidance available from public sources. The subsequent calibration was performed by an engineer with experience in HSPF operations but no previous calibration experience. This analysis shows the level of model performance that can be expected from installation staff with a water resources background but no previous HSPF experience, which is likely to occur at many installations. This analysis also provides a resource manager with some sense of the value of modeling experience and the ability of installation staff to calibrate and effectively use watershed models.

Before initiating this effort, the calibrated model parameters were selectively perturbed, so that the starting model was no longer calibrated. A high-level comparison of the differences between the calibrated perturbed model and the Enhanced Baseline Model may indicate that the calibrated perturbed model achieved a slightly higher level of accuracy for some metrics. The calibrated perturbed model achieved an annual, average flow error of 2.2 percent and met all of the annual average flow statistical criteria compared to an average annual flow error of 7.5 percent and achievement of 13 out of 15 of the annual average flow statistical criteria for the Enhanced Baseline Model. After a more in-depth review, however, the overall model-period annual averages do not represent the actual level of accuracy because of more extreme high- and low-error volumes seen in the annual and monthly flow volumes, which cancel out in the calibrated perturbed model. This assessment is also supported by observing the flow-duration curve, which indicates overall similar accuracy for a large portion of the flows, but very large discrepancies in the high-percentage, flow-exceedance range for the calibrated perturbed model. Although the calibrated perturbed model produces better high-level summary statistics, the Enhanced Baseline Model better simulates the hydrology at Upatoi Creek at McBride Bridge for the entire modeling period of 2000–2008.

To achieve better model results in the calibrated perturbed model, the individual who is calibrating should have more experience with previous hydrology calibrations. A deeper understanding of how the various parameters influence the overall hydrology would increase the accuracy and efficiency of the calibration process for a relatively novice user. For someone with little calibration experience, additional effort would allow for further adjustments to be made and additional lessons learned, along with a better understanding of the parameters' influence in the calibration process.

However, the bottom line of this experiment is that a relatively inexperienced model user can attain a reasonably accurate simulation when provided guidance and consultation during the calibration effort.

As part of this task, we were also asked to evaluate the impact of using Light Detection and Radar (LiDAR) data to generate the Final Function Tables (FTABLEs) (i.e., stage-discharge relations used in the hydraulic routing) used in the model and assess the differences that result from this improved data. Because both actual cross-section measurements and stream channel LiDAR data were used in developing the FTABLES in the Enhanced Baseline Model, we decided to reverse the assessment. We generated FTABLES using the default options in BASINS, which are based on geomorphic relations of channel dimensions (i.e., top width, depth, bottom width) as a function of regional characteristics and drainage area. We compared the results using these default FTABLES to the Enhanced Baseline Model results. In general, the results show very small differences caused by the additional data that were used to develop improved FTABLES. The statistical measures of calibration confirm that the differences caused by FTABLE adjustment in this model are quite small. Because the model was calibrated with the improved FTABLES, we expected that reverting to using the original BASINS FTABLEs would cause the statistics to be somewhat worse. The results of our demonstration confirm that most model results are not especially sensitive to improvements in the FTABLES, as long as the FTABLES demonstrate reasonable flow-discharge relations. Note that this conclusion is specific to the HSPF channel hydraulic representation and is not likely to apply where multi-dimensional issues are of concern (e.g., point source discharges and mixing zones) where higher resolution approaches may be needed.

Data Quality

We consider both quantity and quality of collected data to be considerations in a full evaluation of data richness as related to model performance. This discussion is directed toward ultimately comparing the relative modeling uncertainty that is attributable to data-collection error to the modeling uncertainty that is attributable to errors in model parameterization. Accordingly, the focus here is associated with those conditional data scenarios that include using observed flow data from one or more of the FB USGS gage stations.

Following standard USGS practice, the metadata provided with the FB USGS flow datasets (and essentially all of the USGS flow data) assigns an accuracy rating of excellent, good, fair, or poor to the daily data for each gage site. The accuracy rating scale is provided in Table 3-2.

Table 3.2. Expected Tolerance

Tolerance*	Percent (%)
Excellent	5
Good	10
Fair	15
Poor	> 15

* 95 percent of values are within this tolerance of the true value.

An excellent rating indicates that approximately 95 percent of the values are within 5 percent of the true value, and the tolerance is similar for the other ratings. For the FB gages, the long-term McBride Bridge gage, and the five other new gages, the USGS has assigned an accuracy rating of fair to poor uniformly across all of the gages, with a few exceptions of a good rating for selected years. This rating indicates that the USGS expects that errors up to 15 percent or greater can be expected for all of the data that were collected at the gages.

As described in our Final Demonstration Plan (AQUA TERRA Consultants, 2014), Performance Objective #8 of the project addresses and estimates uncertainty that is introduced into the modeling because of uncertainty in selecting values for the most sensitive model input and parameters. Model uncertainty runs with Monte Carlo analyses were performed to determine the 90 percent confidence interval range representing the simulated values between the 5th and 95th percentiles, and these results were then used to calculate the percent uncertainty as the mean deviation from the calibrated model results. The results of these analyses showed uncertainty levels of about 30% for mean flow and 40% to 70% for high and low flows, respectively. Uncertainties for sediment/TSS were comparable, but are generally expected to have higher uncertainty due to the extreme variability of sediment dynamics.

We have performed similar uncertainty analyses (UA) for a few other HSPF-modeled watersheds and their results provide some basis for comparison. These watersheds include the Housatonic River Watershed (256 square miles [sq mi]) in western Massachusetts (Donigian and Love, 2007) and the Illinois River Watershed (1,500 sq mi) in eastern Arkansas and western Oklahoma (Mishra and Donigian, 2015). These UA efforts have produced similar results and indicate model uncertainties caused by parameter value uncertainties that range from 10 percent to 15 percent for mean annual streamflow and runoff, uncertainties that range from 15 percent to 25 percent for high flows, and uncertainties that range from 25 percent to 45 percent for low flows. Our experience with watershed modeling, and specifically with HSPF applications, supports these ranges as being reasonable approximations of the expected uncertainty levels for the FB/Upatoi Watershed model.

Although this analysis is not precise, the level of uncertainty in the flow data observations (i.e., 15 percent or greater) is generally at a much lower level than the expected uncertainty in the model predictions (i.e., 10–45 percent). Unless there are site-specific issues (e.g., a highly unstable bed, gage mechanical problems, backwater effects), data quality is not expected to be a significant issue for uncertainty in the observed flow data when compared to the potential uncertainty in the model predictions. However, the same cannot be said for sediment and water quality data, which are likely to have higher levels of uncertainty than noted here.

3.2 CONCLUSIONS AND RECOMMENDATIONS

Throughout this investigation, several lessons were learned regarding watershed modeling in general and to specific conditions evident for the FB and Upatoi Creek watershed conditions. Elucidating some of those lessons here may be beneficial both for watershed modelers and installation managers who may need to decide on data collection and modeling efforts on their lands and installations.

a. The highest priority for new data needs to be directed to precipitation monitoring. Without adequate coverage of precipitation gages, watershed modeling efforts will be severely inhibited. If tradeoffs need to be considered between additional precipitation gages or flow gages, a greater density of precipitation gages will likely provide a better foundation for the modeling, as long as an adequate number of flow gages are included. A reasonable rule-of-thumb would be to have **two to three times** as many precipitation gages as flow gages.

b. All efforts should be made to calibrate watershed models at a scale as close as possible to the scale at which decisions are or need to be made. This recommendation obviously presumes that data will also be collected at close to that same scale.

c. Calibration to a single flow gage on a mid-size watershed (i.e., greater than 100–300 sq mi), with the gage located at the midpoint or outlet of the watershed, may provide reasonable simulations for any and all tributaries, but the same or similar agreement with flow in tributaries is not guaranteed. Even though the land-surface features (e.g., land use, vegetation, slope, and soils) may be similar, the subsurface may demonstrate significantly different behavior and hydrologic response. This difference was evident in the Pine Knot Creek Subwatershed of Upatoi Creek, which is situated in the Coastal Plain physiographic province versus the Piedmont province for most of the rest of the Upatoi watershed. While Hortonian-type runoff models are appropriate for the Piedmont areas, non-Hortonian runoff mechanics are evident in the Coastal Plain where the shallow groundwater levels inhibit infiltration and drive the runoff process.

d. The expected uncertainty in flow measurements is expected to be significantly less than model uncertainty, but this same relationship may not apply to sediment and water quality measurements.

e. Novice model users with a water resources background can be expected to perform a credible job for model calibration if provided with expert guidance and consultation during the calibration effort.

f. Model results may not be highly sensitive to exact channel representation (e.g., cross sections and slopes) as long as they provide a reasonable approximation to the overall channel configuration. However, some water quality variables may be sensitive at extremely high or low flows, especially low flows, when approximations within the models may influence the model results produced. This sensitivity can occur at extreme low flows in the range of water depths of a few inches or less. Refinements, or adjustments, to the FTABLES (stage-discharge relationships) for low flows in HSPF may help to resolve issues for these conditions. Note that this conclusion is specific to the HSPF channel hydraulic representation and is not likely to apply where multi-dimensional issues are of concern (e.g., point source discharges and mixing zones) where higher resolution approaches may be needed.

4.0 FORT BENNING TASK 6: UNPAVED ROAD EROSION MODELING APPLICATION

4.1 TASK SYNOPSIS

It is a repeated message throughout forestry literature that road erosion is commonly the largest contributor to sediment production within forest watersheds, such as those that comprise Fort Benning and numerous other DoD lands. Since 2007 AQUA TERRA/RESPEC, in collaboration with the USFS's Rocky Mountain Research Station, has been investigating sediment erosion from unpaved roads at Fort Benning (FB). For SERDP Project RC-1547 we developed a watershed-scale hydrology and sediment model that represented 24 different land use types, one of which was unpaved roads. With forewarning that unpaved roads were likely a major contributor of eroded soils, we developed a hybrid model application in which we used EPA's watershed scale Hydrological Simulation Program Fortran (HSPF) (Bicknell et al., 2005) for modeling catchment-scale phenomena in combination with USFS's hillslope-scale Watershed Erosion Prediction Project (WEPP:Road) Model (Elliot et al., 1999). Using this hybrid modeling capability, the smaller-scale model used more detailed process formulations to estimate road-specific erosion quantities in the form of time series loadings that were subsequently represented as point loadings to the watershed-scale model's detailed stream reach network. Results from the baseline FB Model estimated that 28 percent of the total sediment erosion for the Installation's watershed was attributable to the less than 3 percent of land that comprises the unpaved road network (AQUA TERRA Consultants, 2010).

The hybrid model application that was performed for the SERDP project relied on literature values of sediment loss since monitoring data of actual sediment loss from unpaved roads on Fort Benning were not available. As a component of AQUA TERRA/RESPEC's current ESTCP project RC-201307, the issue of unpaved road erosion at Fort Benning has been re-visited. In 2014/2015 USFS collected runoff and erosion data resulting from storm events at two different unpaved road sites within Fort Benning: one site was unimproved, i.e., constructed of native soils, and the other had been re-engineered by rebuilding it in compacted layers of aggregate to improve trafficability and reduce erosion. Such improved roads are designated as "graded aggregate base" or GAB roads.

Prior to this ESTCP monitoring program at Fort Benning, watershed managers did not know the amount of sediment being lost from the original road management, nor the effects of the GAB road design. Monitoring-based estimates for mean annual sediment erosion from GAB roads are comparable to those estimated by the original FB model that was developed for SERDP under RC-1547, while those for the unimproved site were significantly greater. Site-specific WEPP:Road model applications at FB have been calibrated and validated as a component of the ESTCP project (Elliot et al., 2017).

This task addressed the final component of the ESTCP unpaved road task, which was to evaluate the implications of the site-specific monitoring data and WEPP:Road validations to the overall representation of unpaved road erosion in the watershed-scale (and installation-scale) FB HSPF Model. The evaluation requires a look back at the original hybrid modeling approach and results that were developed under SERDP project RC-1547; re-visiting the results of the ESTCP monitoring and WEPP:Road modeling effort; and finally, providing a critical analysis and

conclusions regarding the relevance and extensibility of the small-scale results to modeling watershed–scale erosion from Fort Benning's extensive unpaved road network. Increased understanding of site-specific unpaved road erosion at Fort Benning offers an opportunity to assess the issue of sediment loss from these unpaved roads, and subsequent delivery to stream channels, which is a classic problem for watershed-scale sediment modeling efforts.

Fort Benning's Hybrid Unpaved Road Modeling

To make available a more robust set of formulations for simulating sediment washoff, USDA's Watershed Erosion Prediction Project (WEPP) Model (Flanagan and Steele, 1995) was used as a modeling 'partner' for HSPF. The WEPP application utilized modeling assumptions and data that are specific to unpaved roads and are components of the WEPP:Road interface developed by the U.S. Forest Service (Elliot et al., 1999). It should be noted that the most significant benefit that we perceived to introducing WEPP:Road into the Fort Benning modeling framework was not expectation of more accurate estimates of sediment washoff for unpaved roads. Rather, the most attractive aspect of the model was its greater level of detail in characterizing a variety of road types, and therefore its potential utility in supporting the representation and evaluation of sediment washoff from a variety of alternative road types and management practices.

WEPP-Road Application to Fort Benning Under SERDP RC-1547

Figure 4.1 provides a flowchart of the application components and sequencing that were required for the Fort Benning WEPP:Road demonstration application as part of SERDP project RC-1547. The approach featured the following requirements and/or assumptions:

1. In a parallel manner to the watershed-scale HSPF simulation scheme for unpaved roads (and other land use types), a 'representative' road segment was selected for each of the 14 different weather segments into which the FB watershed model is divided. Net unit area erosion delivered to the stream system by travel across the flow path (road surface, fill slope, forest buffer) for each of the representative road segments was simulated.
2. For the purpose of mapping WEPP:Road results to the previous HSPF results, the unpaved road area estimates for each of the 14 sub-areas were assumed to include both the road surface and fill slope overland flow elements (OFEs) represented in the WEPP:Road modeling scheme. Thus, the forest buffer OFE associated with each road segment <u>was not</u> considered to be a component of the road area for purposes of computing unit area sediment delivery to the stream system. Instead, the same delivery ratio utilized for other HSPF land use types was also applied to the sediment washoff from road surface and fillslope.
3. The WEPP:Road interface typically utilizes regionalized *daily* weather data, whereas the FB Watershed Model utilizes 14 much more localized *hourly* observed weather datasets to represent the sub-areas of the Installation. In the context of the Fort Benning hybrid modeling exercise the localized weather data were reformatted (using a "wrapper") into a breakpoint file, which enabled a 'stand-alone' version of the WEPP Model (i.e., not the model version integrated into WEPP:Road) to perform its simulations using the same hourly data that drives the HSPF model and was used to simulate sediment washoff from all the other land use areas.

4. After de-coupling the weather data that are typically provided by the WEPP:Road Interface to the WEPP Model, it was still necessary to provide to WEPP:Road input parameter values that define the road characteristics and physical settings for each of the 14 representative road segments so that the Interface could translate and generate the contents of three input files (Soils, Slope, Vegetation) that provide parameter values for all the rest of the input required by the WEPP Model. Our approach was to maintain as much consistency between the physical meaning implied/imposed by parameters/values that were originally used for modeling unpaved roads using HSPF and the parameters/values subsequently required for modeling the same unpaved roads using WEPP:Road.

5. The input provided to WEPP:Road for all representative road segments at Fort Benning characterized the roads as outsloped; comprised of native materials; lacking addition of gravel or rock; and subject to heavy traffic.

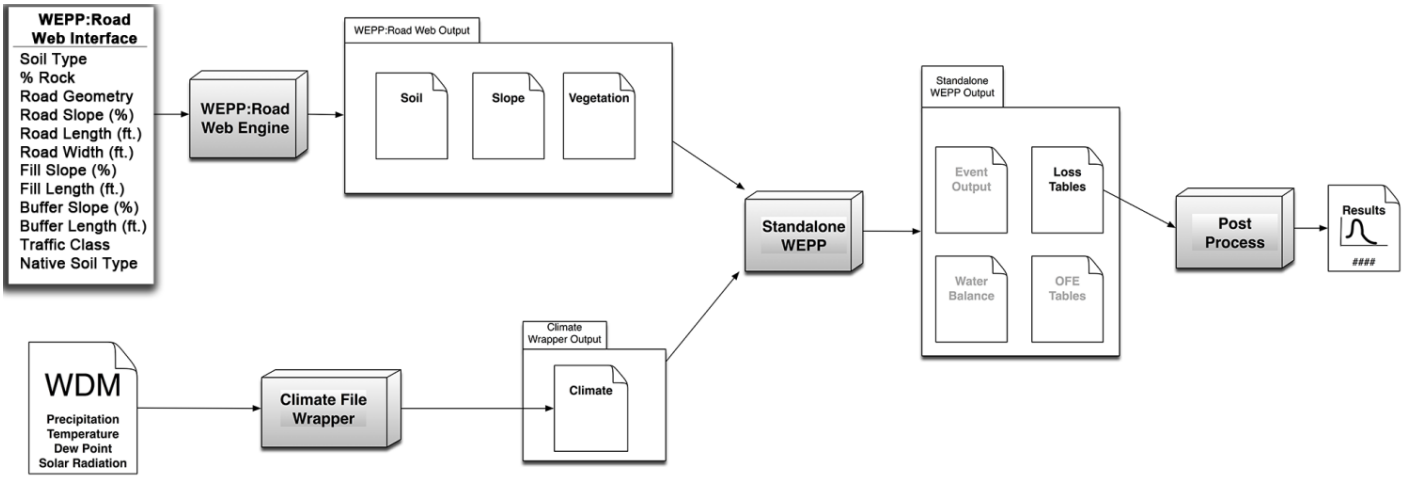


Figure 4.1. Flowchart for Application of WEPP:Road to Estimate Sediment Loadings From Fort Benning's Unpaved Roads Under SERDP RC-1547.

Calibration of WEPP:Road to Fort Benning's Unpaved Roads

Refinements of the HSPF sediment washoff calibration for all land use types progressed to a point where confidence was gained in the estimates that the model generated for unit area sediment washoff. When this had been accomplished, it was justifiable to use the HSPF annual unit area sediment washoff results (expressed as tons/acre/year) that were estimated for unpaved roads using HSPF as calibration targets for the parallel WEPP:Road simulations. (Recall that the primary objective of introducing WEPP:Road into the Fort Benning modeling framework was not expectation of more accurate estimates of sediment washoff for unpaved roads, but rather having available its greater level of detail in characterizing a variety of road types, and therefore its potential utility in supporting the representation and evaluation of a variety of alternative road management practices.)

Integrating WEPP Results Into HSPF to Achieve Hybrid Modeling

Figure 4.2 depicts the logistical linkage that was established for demonstrating a hybrid modeling methodology using the WEPP model to provide unit area sediment washoff data for the HSPF watershed model. Sediment washoff loadings that the HSPF model had previously estimated were replaced with sediment washoff loadings that were generated by the WEPP Model. Both loading estimates relied on the simulated HSPF flow values. The mechanics of this process were as follows:

- Output from 14 WEPP simulations was processed to get daily loads (kg/m^2) at the edge of the fill slope overland flow element (OLE).
- Daily loads were imported to the watershed data management (WDM) file and units were converted from kg/m^2 to tons/acre.
- Daily loads were distributed to hourly intervals according to the hourly input precipitation pattern, with an initial set aside of 0.2 inch to accommodate for depression storage.
- Hourly unit area loads were multiplied by unpaved area acreages and used as input to each HSPF stream reach.

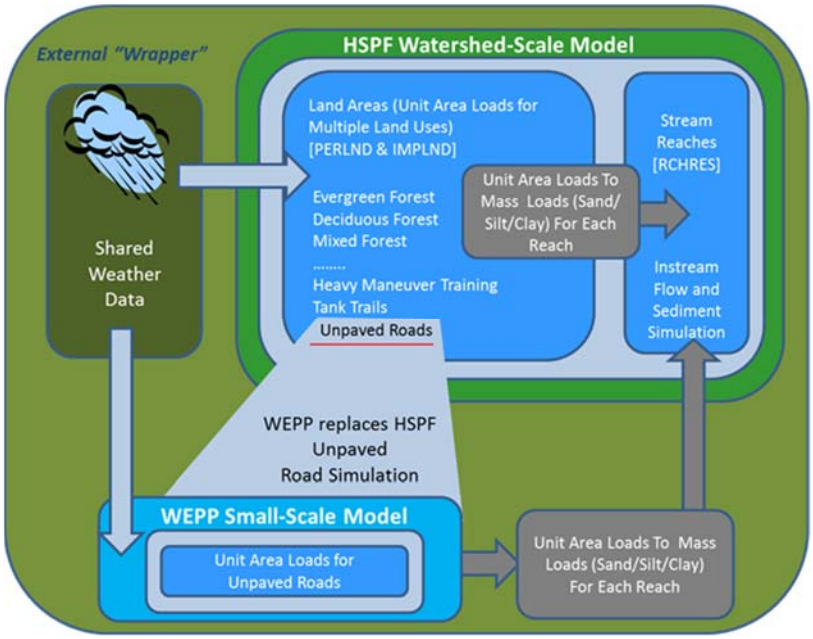


Figure 4.2. HSPF/WEPP Linkage for Performing Hybrid Modeling Under SERDP RC-1547

Hybrid Modeling Results

Simulated unit area edge-of road sediment washoff for the 14 meteorological segments for WEPP road segments (road plus fillslope) ranged from **1.3 to 2.9 tons/acre/year**. These results fall on the lower end of the expected range of values for unpaved road erosion. In an extensive literature search performed for RC-1547, Imhoff and others (2010) derived a possible range of **2 to 20 tons/acre/year** for unit area erosion from unpaved roads (see Figure 4.3).

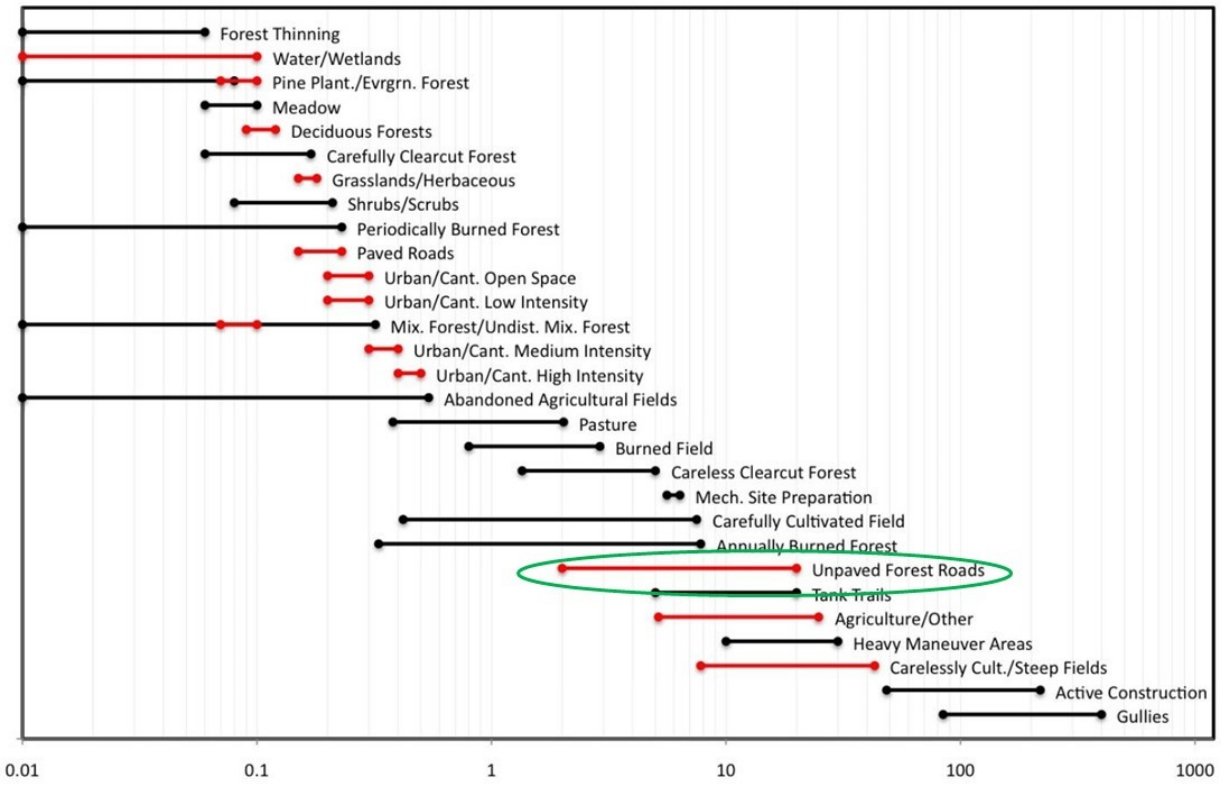


Figure 4.3. Unit Area Erosion Values (ton/ac/yr) for Different Land Use Types or Activities (Imhoff et al., 2010).

RC-201307 Sediment Erosion Monitoring and WEPP Analysis

Data to define road topography (i.e., slope, length and width of road segments) and runoff/erosion for two road types and levels of traffic intensity were collected at the sampling sites selected by the USFS. The two types of roads sampled were those with a natural road base and those with a graded aggregate base (GAB). GAB roads are designed to accommodate tank travel and training exercises. Both road types experience maintenance activities, with the natural base roads receiving gravel applications as needed after intense rainfall/erosion events, and the GAB roads typically being repaired after military training events. A GAB test site was selected that has relatively low vehicular traffic, and a natural base road was selected that experiences heavy traffic. Data that were collected and incorporated in the calibration and validation of WEPP include: soil water content, rainfall, total runoff, sediment delivered to sediment boxes, and suspended sediment concentration and yield.

Data collection took place in the months of March, June, and July of both 2014 and 2015. As described fully by Elliot and others (2015, 2017) a combination of manual grab samples and automatic mechanical sampling was employed to collect data that could in turn be used to estimate storm runoff and erosion volumes. Edge-of-road sediment washoff estimates from the unimproved road were achieved for 25 storms, and 27 estimates were achieved for the GAB roads.

Calibration of the WEPP model for runoff and erosion was implemented, randomly assigning approximately half of the storm events at each site to "calibration", and half to "validation." From the recording rain gages, single storm "breakpoint" precipitation files for the WEPP model calibration were built for each storm and each gage.

Finally, in order to capture the range of precipitation variability that is necessary to estimate expected mean annual runoff and sediment washoff values, the calibrated parameter values resulting from the 2014/2015 sampling program were used in conjunction with a longer (100 years), stochastic precipitation record that had been previously developed for a nearby precipitation station.

Sampling and Modeling Results

Edge-of-road sediment washoff from the unimproved road ranged from zero to **8 tons/acre** (18 t ha^{-1}) for individual storms. The unimproved road site had less runoff, but still generated nearly ten times as much sediment per mm runoff compared to the improved road design at a rainfall storm volume of 20 mm. Edge-of-road sediment washoff from GAB roads ranged from zero to **3.3 tons/acre** (7.4 t ha^{-1}) from individual storms.

Table 4.1 summarizes the WEPP soil erodibility properties that resulted from calibration/validation of WEPP:Road at the two sample sites. For comparison the far-right column provides values that have been previously established for the soil/condition that is considered the most highly erodible.

Table 4.1. WEPP Soil Erodibility Values for GAB (at DMPRC) and Natural Material (at Hourglass Road) Sampling Sites

Erodibility Parameter	Unimproved (Hourglass)	Improved (GAB on DMPRC)	WEPP Road for Sandy Loam High Traffic
Hydraulic Conductivity (mm h^{-1})	3.0	1.3	10.2
Interrill Erodibility (kg s m^{-4})	1,000,000	1,000,000	2,000,000
Rill Erodibility (s m^{-1})	0.09	0.0008	0.0004
Critical Shear (Pa)	0.0001	1.5	2

Using the parameter values that are reported in Table 4-1, WEPP was run using a stochastic precipitation record 100 years in length that had been developed for the nearby Talbotton, Georgia meteorological station. Simulations were performed for six scenarios that are considered relevant to the Fort Benning setting. The estimated average annual edge-of-road erosion rates are presented in Table 4-2. Overall, Elliot (2016) concluded that the unimproved road site generated more than 3.5 times as much sediment as the improved GAB site.

Table 4.2. Average Annual Erosion Rates for Different Management Methods on Three Different Road Length and Steepness Combinations.

Model parameterization is based on ESTCP monitoring data for the 2015/2016 sampling period.

Road Topography		Edge-of-Road Sediment Washoff (tons/acre/year)	
Segment Length (ft)	**Segment Gradient (%)**	**Unimproved**	**GAB**
300	1	25	10
200	2	70	10
120	3	120	11

The results shown in Table 4-2 suggest that the estimated edge-of-road sediment washoff from GAB roads was generally about **10 tons/acre/year**, regardless of topography. The unimproved road tended to be much more affected by the terrain, with edge-of-road sediment washoff ranging from **25 tons/acre/year** for the lowest gradient to **120 tons/acre/year** for the 3 percent gradient. Elliot (2016) suggests that viewed as a whole, a reasonable estimate of annual edge-of-road erosion for Fort Benning roads would be **10 tons/acre/year** at the GAB road site and **70 tons/acre/year** on the unimproved road site.

4.2 CONCLUSIONS AND RECOMMENDATIONS

Recall that Imhoff and others (2010) derived a possible range of **2 to 20 tons/acre/year** for unit area edge-of-road sediment washoff from unpaved roads (refer back to Figure 4.3). Elliot's estimation of **10 tons/acre/year** for edge-of-road erosion from Fort Benning's GAB roads fits comfortably into the middle of this range. However, we believe that the **70 tons/acre/year** estimate that Elliot derived using the monitoring data (and generated rainfall) from the unimproved road site more closely approximates a worst case scenario: the road section that Fort Benning and USFS staff selected as the monitoring site was steeper than most roads in Fort Benning's unpaved road network, and it experienced heavier traffic than most roads, including tank traffic. As a result, rutting was prevalent, and erosion was extreme.

The current FB Watershed Model utilizes a uniform sediment calibration target for all the Installation's unpaved roads; at the time of the model development, the only available unpaved road coverage for the Installation watersheds did not identify/distinguish alternative categories of unpaved roads (i.e., differences in construction practices, traffic intensity, etc.). Estimated erosion is, however, subject to model segment-specific differences in overland flow length and slope. At the time the model was developed, information was not readily available that would allow us to define the areal coverage and geographical distribution of *more than one type* of unpaved road, either in terms of traffic, maintenance, road surface erodibility and/or other physical or geometrical characteristics. Modeling roads at the current level of detail requires approximation of a *single* unit area edge-of-road erosion rate for each model segment. Since the edge-of-road value derived from monitoring the GAB site essentially falls in the middle of the range of literature values that we originally collected and used in conjunction with professional judgment to establish sediment loading rates for the FB Watershed Model's 14 meteorological segments, we believe that there is no justification for adjusting the current model's representation of the unpaved road component of sediment delivery to Fort Benning's stream network.

In addition, based on our experience with the watershed model and sediment calibration, we feel it would be difficult, if not impossible, to calibrate the model predictions to observed instream sediment concentrations with unpaved road sediment loading rates **higher by more than an order-of-magnitude,** as defined by the results of the WEPP:Road and USFS data collected. The key missing element with the WEPP:Road unpaved road loading rates is the fraction of those rates that are actually **delivered** to the stream. As noted earlier, this has been somewhat of a 'holy grail' for sediment modeling at the watershed scale. Below we cite a study that may provide a template to investigate sediment delivery.

In light of the WEPP:Road study results and the analysis above, we offer the following recommendations:

1. We recommend that Fort Benning road engineers take full advantage of the validated WEPP:Road Model as a tool for road design to support site-specific design and construction decisions.
2. We recommend that both Fort Benning engineering staff and SERDP/ESTCP consider the unpaved road erosion estimates derived by the final version of the watershed model that was developed for SERDP RC-1547 as reasonable at a watershed scale.
3. Fort Benning has continued to improve and discretize its coverages for unpaved roads during the years that have followed the completion of the SERDP project in 2011. It is our understanding that a basis may now exist for characterizing and modeling up to three different categories of unpaved roads, each with significantly different erosion potential. To the extent that Fort Benning has interest in fine-tuning the resolution of unpaved road erosion to a more discrete scale, an update of the FB HSPF Watershed model (road surface areas; spatial distribution of the different road types; road surface erodibility characterization for multiple road types) to take advantage of new and better data, we see the opportunity for model refinement that can provide an improved tool for FB staff.
4. Recent studies have adapted the technique of 'radiometric fingerprinting' to estimate sediment apportionment for agricultural watersheds, helping to define how much of instream sediments are derived from field and non-field sources (Whiting et al., 2005; Schottler et al., 2010). The technique is based on measurements of radioisotopes, 210Pb and 137Cs, in both surface soils and instream sediment (TSS) samples, and using the differences in the signatures to define where the instream sediment originated, i.e., from surface erosion (field sources) or streambanks, ravines, channel bluffs, etc. (non-field sources). Performing these analyses on nested, or successive sites along a channel or river system could help to assess and quantify sediment delivery processes that are often problematic in watershed scale sediment modeling efforts. SERDP and/or ESTCP might consider funding such an effort at FB which could help improve the representation of unpaved road contributions in the FB model, and provide a significant contribution to the issue of sediment modeling on many military installations.

5.0 FORT BENNING TASK 7: MODEL DEMONSTRATION FOR CLIMATE NON-STATIONARY AND LAND USE CHANGE IMPACT ASSESSMENT

5.1 TASK SYNOPSIS

The effects of future climate change and future residential (or cantonment) and training area development all have important management implications for military installations. BASINS.MIL provides the necessary tools and methods to help watershed managers understand and manage the potential impacts (combined or separately) of climate change and land use change on water resources at the watershed scale. Moreover, because climate and residential development can result in similar types of impacts, e.g. higher peaks and lower low flow conditions, the management of land use impacts is a potentially important adaptive strategy for increasing resilience to climate change (Pyke et al., 2011).

An assumption that long-term climate is 'stationary' has traditionally been a guiding principle and foundation of water management and policy. Stationarity implies the following (Milly et al. 2008):

1. Over the timescales relevant to water resource management (e.g., 20-50 years), natural systems fluctuate within unchanging boundaries.
2. The probability of any event (e.g. a 100-year flood peak flow, or a drought of a given magnitude) does not change over these timescales.
3. Probabilities can be reasonably estimated from observation.

Global temperature increases serve as a forcing function to disrupt historical climate patterns, resulting in increased 'non-stationarity'. These climatic changes introduce the potential to further widen the range between extremes of streamflow and water quality conditions, and by doing so, the changes tend to amplify the limitations of utilizing observational records and traditional water resources analysis techniques. Practically speaking, introduction of more frequent or greater magnitude events (e.g., droughts, floods) can exacerbate existing problems (e.g. aging infrastructure, user conflicts, endangered/exotic species).

The objective of this climate non-stationarity assessment is to demonstrate the usefulness of BASINS.MIL model methodologies and results in enabling military planners to characterize changes in hydrology and sediment that may result from changed climate and future land use as they are represented in plausible change scenarios. The climate change scenario and modeling ensemble that are utilized for this demonstration originate from widely-respected climate scientists and modelers. A plausible future land use scenario for Fort Benning's largest watershed was formulated with guidance from ESTCP.

The exercise that is central to the ESTCP demonstration of a BASINS.MIL HSPF application to evaluate the impacts of climate non-stationarity is a one-to-one comparison and evaluation of two alternative sets of modeling results for the Upatoi Creek Watershed (UCW) (453 mi^2), the major watershed containing Fort Benning: one set of results generated by EPA's previous coarser (i.e., larger scale) application (USEPA, 2013a) of HSPF to the entire Apalachicola-Chattahoochee-Flint (ACF) River Basin (19,869 mi^2), and corresponding results generated by the current effort for a second finer-scale Fort Benning application in which the UCW comprises the majority of the

Fort Benning HSPF Watershed Model. The Upatoi Creek Watershed comprises approximately *two percent* of the ACF Watershed, demonstrating vastly different scales for the two applications.

Results and climate change deltas (i.e., changes in magnitude, intensity and timing of precipitation plus changes in air temperature from a 'baseline' climate condition) for the USEPA's regional HSPF climate change study of the ACF Basin, which includes the FB Model domain, were used to develop a comparable climate change scenario that was evaluated using the Upatoi Creek Watershed (UCW) within the FB Model. The climate change scenario that is depicted is the Weather Research and Forecasting (WRFP) scenario for the Year 2050 as described in USEPA (2013b).

Mean annual stream flow, flood frequency, and mean annual sediment loss are the quantitative metrics that are used to establish reasonableness and consistency of simulation results. Flood frequencies for 100-, 50- and 25-year events are determined through a Log Pearson III analysis of the annual peak flows. Mean annual sediment loss is measured by total suspended solids (TSS). Comparison of observed and simulated flow duration and continuous time series of daily flow are used as qualitative measures of success. Visual comparison of flow, flow duration and linear regression results that are generated for the Year 2050 climate change scenario by the ACF Model to those generated by the FB model provides an additional set of *qualitative* metrics. That is to say, visual similarity of results from the two models suggests 'success' in achieving our demonstration/ validation objective.

It is a reasonable expectation that the impacts on flow and sediment loadings that are estimated by the two HSPF models will be reasonably consistent in terms of the direction, magnitude and frequency of change from their baseline simulations. Satisfying this qualitative definition of 'success' is the basis for assessing whether the task's success criteria is met. The success criteria for performance objectives for annual stream flow and flood frequencies simulated by the FB Model are expected to be in the same direction and within 15-20% of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed. Mean annual sediment loss is expected to be in the same direction and within 20-35% of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed. Qualitatively, the graphical comparisons of the FB Model's simulated values for the baseline condition and climate scenario for flow, flow duration, and linear regression denote success if they demonstrate similar patterns (i.e., shape, magnitude) and the same direction of change as the ACF climate scenario results for the Upatoi Creek Watershed. The demonstration satisfied all these performance objectives.

To develop and simulate *land use change* scenarios (and their potential impacts) that most effectively demonstrate the utility of BASINS.MIL for land use analysis/management called for a somewhat different approach. Since the intent of EPA's ACF study was to assess the general sensitivity of underlying watershed processes to changes in climate and urban development and not to develop detailed, location-based models that represent management and operational activities in full detail, potential future changes in management and operational activities were not considered or represented in EPA's future scenario (Year 2050) for the Upatoi Creek Watershed. In lieu of comparing results for FB and ACF land use change scenarios, the land use change modeling demonstration that is presented in this report focuses on comparing consistency and credibility of the impacts of two very different, but plausible land use change trajectories for Fort Benning.

The UCW land use change demonstration first required an update of current land conditions to reflect our best understanding of land use conditions in Year 2013, a point in time where the manifestations of the 2005 Base Realignment and Closure (BRAC) on Fort Benning had stabilized. Two alternative Year 2050 scenarios were defined by representing additional changes to the Year 2013 post-BRAC baseline: Scenario 1 estimated installation land use change (with a focus on cantonment and training areas) consistent with a "limited-aggression world", and Scenario 2 estimated installation land use change consistent with a "heightened-aggression world". The difference in the scenarios was a world political condition of "heightened-aggression" requiring increased cantonment areas reflecting increased Installation population and training demands. The objective of the land use change assessment demonstration was achieving reasonable results, and we believe that this objective was also achieved.

This ESTCP task is the first demonstration of utilizing the HSPF model to assess potential military-centric environmental impacts resulting from climate non-stationarity. The central need that was demonstrated was the marriage of a site-appropriate high-end climate change scenario with a highly detailed characterization of an installation-scale watershed. As a result, a more tangible assessment of the impact of changed climate on specific military land use types and activities can be achieved. In performing this demonstration, we found nothing unique about military settings, or the necessary customization of model development and assessment procedures, that imposes significant limitations on the utility of the modeling technology in a military setting. Rather, we find ample opportunity and utility for such model assessments.

Using simulated mean annual streamflow as a performance metric, the UCW simulation using the FB Model successfully captures the effects of the WRFP climate change scenario shown in the ACF Model. The ACF model shows a decrease of 19.5 percent in mean annual streamflow at the upper Upatoi pour point, and a decrease of 20.0 percent at the lower Upatoi point. The FB Model shows a nearly identical change, from 19.8 percent at the upper pour point to 19.7 percent at the lower pour point. At the upper Upatoi pour point, the ACF model predicts slight increases in flood event peak magnitudes while the FB Model shows slight decreases. In contrast, at the pour point from the entire Upatoi, both the ACF and Fort Benning model simulations predict slight increases in flood event peak magnitudes. The fact that the models show slightly different results at the upper pour point can be attributed to a difference in spatial resolution between the two models, where the ACF model consists of only one subbasin and stream reach at the pour point, while the FB Model consists of 17 for each. The effect of the difference in spatial resolution is less pronounced further downstream, which is consistent with expectations of the peak flows being attenuated with additional travel time. Graphical comparisons between FB simulated values and observed data for flow duration, daily flow timeseries, and flow linear regression are similar to ACF climate scenario results for the Upatoi Creek Watershed. Each set of plots shows a similar trend when comparing the effects of the climate change scenario on the ACF and Fort Benning model results. The climate scenario shows higher peak flows for some storm events, but most often shows reduced flows overall.

The ACF Model shows lower erosion amounts than the FB Model, while the FB Model shows lower sediment transport/loss than the ACF Model. However, the percent changes are relatively similar, with the Fort Benning model within 18.2 percent of the ACF model change at the upper pour point, and a much closer 6.7 percent difference at the lower pour point.

The fact that the models show significant difference in the amount of sediment transport/loss can be attributed to the apparent assumption in the ACF Model that the stream channels are stable and are neither scouring nor depositing. In the FB Model, the sediment (silt and clay) scour and deposition parameters were calibrated to available TSS/sediment data, and the results demonstrated more dynamic changes to the channel through both scour and deposition.

The difference in scale and resolution between the ACF and FB models also provides important insight in the use of models for smaller scale assessments, such as might be needed for EISA 438 issues, hydromodification, local flooding, etc. It is clear from the model comparisons that when models are used for watershed planning and management, the scale of the modeling assessment (or decision to be made) should be as close as possible to the scale of the watershed change or BMP being evaluated, so that scale differences will not unduly impact the evaluation. Thus the FB model would be a much better choice for assessments on FB than the ACF model as its smaller scale and higher resolution provides a better and finer representation of the watershed and drainage processes that need to be accurately depicted.

Both land use change scenarios that were simulated resulted in less than one percent change in both mean annual streamflow and mean annual sediment transport. This small increase is expected, since the actual increase in urbanized area (an increase of approximately 15 percent

more urbanized acreage for the 'Heightened Aggression' scenario) is relatively small on a watershed-wide basis, from 7.8 percent of the watershed in the post-BRAC baseline to 9.0 percent of the watershed in the 'Heightened Aggression' scenario; a difference of only 1.2% of the watershed. Experience with prior modeling studies that assessed the impact of urbanization have shown significant, and sometimes dramatic, increases in peak flows, sediment loss/transport, and channel alterations, but these types of changes are usually observed when changes in the effective impervious area (i.e. EIA, or directly-connected impervious area) begin to exceed 10% or more of the watershed (Booth and Jackson, 1994). Impacts continue to mount and accelerate as that percentage increases further. The changes in EIA for our scenarios are considerably less, in the range of 1 to 2%, so the minimal impacts in our simulations are expected.

With DoD's institutional commitment to further reducing stormwater by means of implementing green infrastructure practices, it is likely that the major focus of concern with impacting streamflow and sediment phenomena by land use change will focus on the training lands.

As is often the case in watershed modeling perhaps the biggest challenge we faced in performing this demonstration centered on <u>defining justifiable and insightful</u> change scenarios. For example,

at the planning stage of our land use change assessment demonstration, we anticipated representing and assessing a major increase in Heavy Maneuver Areas (HMAs) in the Upatoi Creek Watershed (UCW) during the course of development from pre-BRAC to Year 2050. Instead we discovered that the development and use of HMAs in the UCW that had been planned as a component of BRAC 2006 had never really been implemented due to unresolved issues related to potential impact on the Red Cockaded Woodpecker population, an endangered species. Further, Fort Benning had resolved to permanently re-locate (by summer 2016) the majority of the tank training activities that had been planned for the UCW to the Good Hope Area outside of the watershed that we had selected for our demonstration. As a result, we were unable to justify and demonstrate a Year 2050 land use alternative in the UCW that addressed both the simultaneous impacts of cantonment/urban growth **and** the potential impacts of a high level of vehicular training at a military installation.

In many, if not most watersheds the process of developing land use change scenarios is focused on estimating (1) where and how quickly non-urban land use areas will be converted to urban land use areas and (2) where and how quickly urban land use areas will increase in population density and imperviousness. The land use change trajectories for military installations do not typically follow this paradigm. Instead they often focus on transition of non-urban (undisturbed) land use types into training areas with specialized landscape alterations. Increases in the size or imperviousness of cantonment areas may accompany changes in training areas, but are rarely the most influential impact on hydrology. Further, land use changes typically occur in response to distinct realignment decisions for military training locations/methods, and these decisions/actions cannot be readily anticipated in the more distant future (e.g., in the year 2050). Offsite increases in the built environment to accommodate increased troop levels are an additional factor that must be considered. Hence, an additional necessary element of developing future land use change scenarios for watersheds that contain both military and non-military lands is approximating a correlation between cantonment growth within the installation area and expected urban development in the adjacent non-military areas. To respond to such a complex and volatile planning and management environment, a general need (i.e., not just for climate change applications) exists at installations to develop and apply watershed-based models as an active component of their planning process.

Study results have several implications for future planning and management of the water resources within the FB installation. In interpreting the results of the future climate scenario, it is important to be mindful that the WRFP scenario that was depicted is the hottest and driest scenario of all those that were produced by EPA's GCM/RCM model ensemble. As such, the scenario results arguably offer a 'worst case' depiction of low flow conditions in the Upatoi Creek Watershed. While beyond the scope of this demonstration project, a broadening of the investigation to include consideration of the impacts of reduced streamflow on dissolved oxygen and/or threatened species could provide the installation with a means of evaluating potential climate change impacts on additional management concerns (e.g., aquatic habitats).

Another streamflow-related result that has potential implications to the installation is the FB Model's predictions of slight increases in flood event peak magnitudes despite the fact that the

WRFP scenario depicts an average annual reduction in precipitation of approximately 10 percent. Simulated flood peaks are clearly increased by the scenario's representation of storm precipitation intensification. Since results from all the other GCM/RCM models that EPA used to simulate this region predict greater streamflow than the WRFP scenario, it is justifiable for Fort Benning planners to be concerned that flood peak magnitudes at various locations within the installation may, indeed, increase in future years as a result of climatic change. Local storm peaks in cantonment areas that are not explicitly addressed in this demonstration could be problematic.

The results of the land use change demonstration suggest that cantonment/urban growth at Fort Benning and in nearby non-military lands is not likely to have comparable impacts on streamflow and erosion as would development of additional training facilities. With DoD's institutional commitment to further reducing stormwater by means of implementing green infrastructure practices, it is likely that the major focus of concern with impacting streamflow and sediment phenomena by land use change at Fort Benning will continue to focus on the training lands.

5.2 CONCLUSIONS AND RECOMMENDATIONS

With respect to utilizing BASINS.MIL to investigate the potential impacts of climate change and land use change on streamflow and/or sediment erosion/transport, this demonstration suggested that technical implementation issues are minimal. As is often the case in watershed modeling perhaps the biggest challenge lies in defining useful and plausible change scenarios.

In the case of climate change, it was noted earlier in this report that common practice (due to model uncertainty) is to use weather changes projected by multiple RCM's to generate a suite of possible impacts on endpoints of concern in a regional watershed model (or, after further downscaling, to a smaller watershed model).

In the case of land use change, a different issue comes into play in defining changes that can be deemed reasonable. Changes in land use on military installations tend to be much more unpredictable than those to public land or private land. Management decisions related to training or cantonment development that are previously predicated on mitigating physical environmental impacts (streamflow, erosion) can be superseded by issues that are ancillary to water resources, such as mitigating impacts on endangered species. Decisions regarding base realignment and closure can effectively move major environmental disturbance from one installation to another. National budgetary decisions, as influenced by our nation's perspective on the need for military build-ups or reductions, can reverse the trajectory of change within short or sustained periods of time. This uncertainty again argues a need for defining and assessing a variety of possible futures and sustaining an operable model for this and other planning/design issues that encompasses the entire spatial extent of an installation.

Another issue related to defining reasonable land use scenarios that is somewhat unique to installations is the concurrent impact that a change in mission has on multiple land use categories. When a change in level or type of military training occurs at a base, changes to cantonment and training areas are interrelated and change scenarios must foresee and represent the interrelationships in a rationale manner.

Expressing change scenarios requires adjustment of information expressed in a baseline representation of the installation. For experienced or properly coached model users the mechanics of doing this are relatively straightforward. However, it is important to remember that typical change scenarios are expressed by applying adjustment factors (i.e. multipliers) to the land use distribution and spatial segmentation scheme that has been developed for the baseline condition. The land use categories that are the focus of a change scenario are adjusted uniformly within the model-defined subregions in which change is assumed to occur, and a scheme is used to make proportional increases or decreases to a collection of land use categories that can reasonably be assumed to be affected by conversion. The spatial resolution that can be achieved in defining a change scenario cannot achieve a finer resolution than that represented in the baseline model segmentation scheme. However, when it is deemed advantageous, BASINS.MIL model segmentation schemes can be refined selectively for subregions that require finer resolution.

Viewing the central objective of this demonstration (i.e., providing a means of assessing change alternatives) from the broader ESTCP perspective of "implementing a technology", it is also warranted to consider possible *implementation issues* as they pertain to using this technology to assess possible environmental impacts and make adaptive planning decisions.

The use of the core watershed model in BASINS.MIL (HSPF) for assessing potential environmental impacts of land use change has been common practice in various non-military settings for decades. Military-centric land use change analysis has previously been successfully demonstrated as a component of the SERDP Project (RC-1547) that resulted in development of BASINS.MIL. The unique aspect of this ESTCP demonstration was development, assessment, and *comparison* of parallel climate and land use scenarios for a shared point in time, Year 2050. This objective was successfully met. Neither the SERDP nor the ESTCP land use change assessment demonstrations revealed any issues that suggest that model applications to a military-centric watershed would be expected to provide a less effective planning tool than has been commonly used to guide management practices in other mixed-use watersheds world-wide.

The use of the HSPF for assessing potential environmental impacts of climate change has evolved over the past decade. This ESTCP task is the first demonstration of utilizing the model to assess potential military-centric environmental impacts. The central need that was demonstrated was the marriage of a site-appropriate high-end climate change scenario with a highly detailed characterization of an installation-scale watershed. As a result, a more tangible assessment of the impact of changed climate on specific military land use types and activities can be achieved. In performing this demonstration, we found nothing unique about military settings, or the necessary customization of model development and assessment procedures, that imposes significant limitations on the utility of the modeling technology in a military setting. Rather, we find ample opportunity and utility for such model assessments.

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6.0 FORT BENNING TASK 9: DEMONSTRATION OF SENSITIVITY AND UNCERTAINTY ANALYSIS

6.1 TASK SYNOPSIS

When a natural system (e.g., a watershed) is modeled mathematically or physically, some degree of uncertainty is always present (Morgan and Henrion, 1990). The primary reason for this uncertainty is that the models represent only an approximation of reality; i.e., the real watershed systems that exist in nature. The USEPA (1999) noted that the model predictions cannot be any better than the accuracy of the observed data and the calibration and validation results and, therefore, will always have some uncertainty associated with the output. Uncertainty analysis is a procedure used to determine the confidence limits or reliability of model predictions with respect to the errors associated with observations and a model. Quantifying the uncertainty in modeling results is important to stakeholders and decision makers so that they may have additional information on the probability of achieving watershed management objectives. Stakeholders and decision makers can use the information about uncertainty in establishing a more accurate Margin of Safety (MOS) for the practices and procedures needed to achieve the watershed management objectives (Mishra, 2011).

Estimating uncertainty requires assessing the model parameters and inputs to which the model is sensitive to identify the primary parameters/inputs of concern, because of their critical impacts on watershed response and behavior. A sensitivity analysis is typically conducted to better understand how adjustments to the model parameters affect results. Sensitivity runs provide useful information regarding the physical, chemical, and biological processes represented in a model and identify the most influential parameters and inputs for improving model accuracy. This type of analysis provides insight into forcing factors in models and how adjustments made will affect results, both for historical conditions and potential management scenarios. A sensitivity analysis is usually conducted independent of uncertainty analysis, but often as a precursor as noted above.

A sensitivity analysis measures the variability of model outputs caused by perturbations in model parameter values and input data; i.e., how sensitive is the model to changes in the input forcing functions (e.g., precipitation) and parameters that describe its characteristics. Informal sensitivity analyses (iterative parameter adjustments) are generally performed during model calibration to ensure that reasonable values for model parameters will be obtained, thereby resulting in acceptable model results. The degree of allowable adjustment of any parameter is usually directly proportional to the uncertainty of its value and is limited to its expected range of realistic values. Knowledge about the model sensitivity to the model parameters and inputs can help direct model parameter selection for additional investigation, support data collection planning efforts, aid in model calibration, and ultimately serve as a precursor for the uncertainty analysis.

This section presents and summarizes the procedures used in the sensitivity and uncertainty analyses performed for the Upatoi Creek Watershed (UCW) model at Fort Benning, Georgia, along with the analyses results; complete results for this task are provided in Mishra and Donigian (2017) and Appendix F. For the sensitivity analyses, a sensitivity factor was calculated as the ratio of the percent change in model output to the percent change in input/parameter value (expressed as a percentage). These sensitivity factors allowed the input and parameters to be ranked in terms of the highest to lowest impacts on model outputs. This ranking method provided the means for selecting the most sensitive inputs and parameters for the subsequent uncertainty analyses.

The uncertainty analyses were conducted with a Monte Carlo procedure whereby the most sensitive parameters were assigned probability distributions, random values were drawn from these distributions, the model was run for each parameter selection combination, 1,000 model runs were performed, and the model results were analyzed to produce the outputs with 90 percent confidence bounds to reflect and quantify the model uncertainty for each output variable of interest.

Sensitivity Analysis

For the UCW sensitivity analysis effort, a methodology that was adapted from Donigian and Love (2007) was used to conduct a sensitivity analysis (SA) followed by uncertainty analysis (UA). These steps were performed following the completion of the calibration and validation of the UCW model using BASINS.mil (based on the EPA HSPF model) so that the SA results were focused on model performance when it is providing a reasonable representation of the watershed behavior and response. The steps involved in the SA were performed with the HSPEXP+ software (HSPEXP+1.40beta) (Mishra et al., 2017). The specific steps for a SA are as follows:

1. Critical model inputs and parameters were identified based on previous experience, literature review, and the specific calibration experience for the UCW model. Table 6-1 lists the selected model inputs and parameters, their definitions, and relevant values from the calibration and SA perturbations.
2. Reasonable percent perturbations of model parameters and inputs from the calibrated values in both positive and negative directions were established based on the same experience/sources as noted above in step 1.
3. Critical model output values of concern, at two sites within the UCW, were identified to provide the targets (or metrics) for the SA. These analysis sites were limited to the Upatoi Creek at McBride Bridge (Reach 46) and the UCW model outlet (Reach 74). For both hydrology and sediment, the metrics were selected from those assessed as part of the "weight-of-evidence" approach to model calibration and included annual runoff volume, highest 10 percent flows, lowest 25 percent flows, annual and daily sediment (total suspended sediments [TSS]) loads and concentrations (see Table 6-2 for a list of the model outputs analyzed).
4. Model simulations for a 13-year period (October 1, 1999–September 30, 2012) were performed as a baseline run for the SA.
5. To conduct an SA, HSPEXP+ 1.40 beta (Mishra et al., 2017) was modified to read a specification file that contained information about the parameters to be varied, magnitude of variation, and the outputs to be analyzed. HSPEXP+ then used the values from the specification file to alter the parameter values, run the model, extract relevant output, save it in a text file, and repeat the process for the next simulation. A sample specification file for a SA is provided in Figure 6.1.
6. Following the completion of all of the simulations (i.e., 15 simulations, including 1 for baseline and 14 for input/parameter changes), the sensitivity factor was calculated as the ratio of percent change in model output to the percent change in input/parameter value (expressed as a percentage), as follows:

$$SF = \frac{\Delta y}{\Delta x} \times 100 \quad (1)$$

where:

Δy = percent change in output

Δx = percent change in input.

7. Model input and parameters were ranked according to the value of the sensitivity factor, as shown in Table 6-3.

Table 6.1. List of HSPF Parameters That Were Adjusted to Assess Model Sensitivity for the Upatoi Creek Watershed Model at Fort Benning

Category	Model Input Parameter	Input/ Parameter Definition	Calibration Value			Percent Change to the Calibrated Value		Parameter Value Range	
			Weighted Mean	Minimum	Maximum	Decrease	Increase	Decrease	Increase
Meterologic Time Series	Mean Precipitation (in/yr*)	Mean Annual Precipitation				15	15		
Hydrology	LZSN (in)	Lower Zone Nominal Soil Moisture Storage	9.00	3.5	15.2	50	50	1.75	22.8
	INFILT (in/hr**)	Index to Infiltration Capacity of the Soil	0.17	0.013	0.631	50	50	0.007	0.947
	INTFW	Interflow Inflow Parameter	4.49	0.4	7	30	30	0.28	9.1
	LZETP	Lower Zone Evapotranspiration	0.31	0.075	0.6	25	25	0.0563	0.75
	DEEPFR	Fraction of Groundwater Inflow to Deep Losses	0.20	0.1	0.4	50	50	0.05	0.6
	UZSN (in)	Upper Zone Nominal Soil Moisture Storage	1.15	0.16	3.38	50	150	0.08	8.45

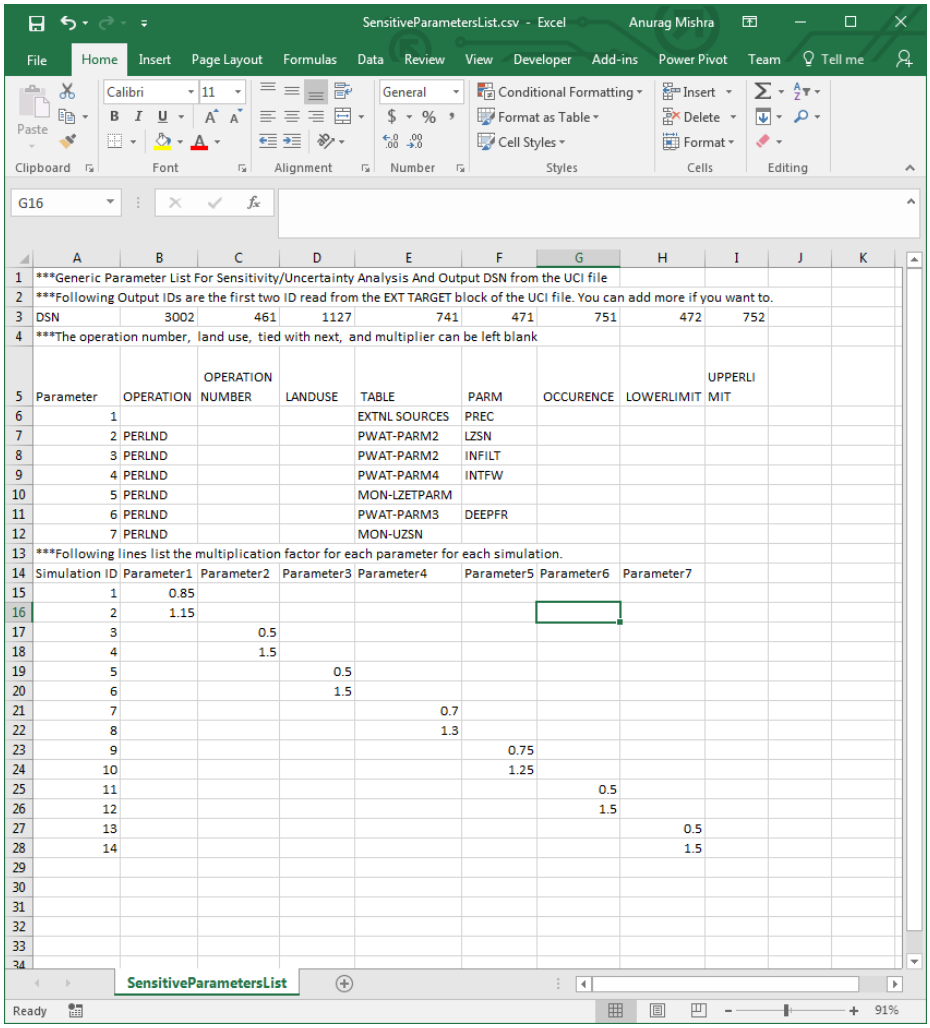
*in/yr = inches per year.
**in/hr = inches per hour.

Table 6.2. List of Outputs of Interest at Reach 46 (McBride Bridge) and Reach 74 (Upatoi Creek Outlet) in the Upatoi Creek Watershed Model at Fort Benning

Hydrology	Water Quality
Mean Annual Flow (cfs*)	Mean Daily TSS Load (tons per day)
Annual Peak Daily Flow (cfs)	Mean TSS Conc. (mg/L**)
Mean Annual Runoff (in)	
10% High Runoff Volume (in)	
25% High Runoff Volume (in)	
50% High Runoff Volume (in)	
50% Low Runoff Volume (in)	
25% Low Runoff Volume (in)	
10% Low Runoff Volume (in)	

*cfs = cubic feet per second.

**mg/L = milligrams per liter.



	A	B	C	D	E	F	G	H	I	J	K
1	***Generic Parameter List For Sensitivity/Uncertainty Analysis And Output DSN from the UCI file										
2	***Following Output IDs are the first two ID read from the EXT TARGET block of the UCI file. You can add more if you want to.										
3	DSN	3002	461	1127	741	471	751	472	752		
4	***The operation number, land use, tied with next, and multiplier can be left blank										
5	Parameter	OPERATION	OPERATION NUMBER	LANDUSE	TABLE	PARM	OCCURENCE	LOWERLIMIT	UPPERLIMIT		
6	1				EXTNL SOURCES	PREC					
7	2	PERLND			PWAT-PARM2	LZSN					
8	3	PERLND			PWAT-PARM2	INFILT					
9	4	PERLND			PWAT-PARM4	INTFW					
10	5	PERLND			MON-LZETPARM						
11	6	PERLND			PWAT-PARM3	DEEPFR					
12	7	PERLND			MON-UZSN						
13	***Following lines list the multiplication factor for each parameter for each simulation.										
14	Simulation ID	Parameter1	Parameter2	Parameter3	Parameter4	Parameter5	Parameter6	Parameter7			
15	1	0.85									
16	2	1.15									
17	3		0.5								
18	4		1.5								
19	5			0.5							
20	6			1.5							
21	7				0.7						
22	8				1.3						
23	9					0.75					
24	10					1.25					
25	11						0.5				
26	12						1.5				
27	13							0.5			
28	14							1.5			
29											
30											
31											
32											
33											
34											

Figure 6.1. Example Specification File for Sensitivity Analysis With HSPESP+1.40beta.

A sensitivity factor of 100 percent indicates that the model output changes in direct proportion; i.e., one to one, to the change of the parameter value; whereas, a value of 200 percent indicates a 2:1 response, and a 10 percent indicates a relatively insensitive 0.1:1 response (i.e., a 10 percent change produces only a 1 percent change in model output). The results are graphically depicted in a "tornado diagram" for each model output (e.g., Figures 6.3 and 6.4) for display and ease of interpretation. The tornado diagrams show the change in output for a certain change in the input parameter using a blue band. Percent change in the input is shown as a legend in both sides of the band. When the signs of change in the input and the change in output are both on the same side, the sensitivity is positive and vice versa. For example, in Figure 6.2, sensitivity of average annual runoff volume is positive for PREC (precipitation), and negative for LZETP (Lower Zone Evapotranspiration); i.e., increasing PREC increases average annual runoff volume and vice versa; whereas, increasing LZETP decreases annual average runoff volume and vice versa.

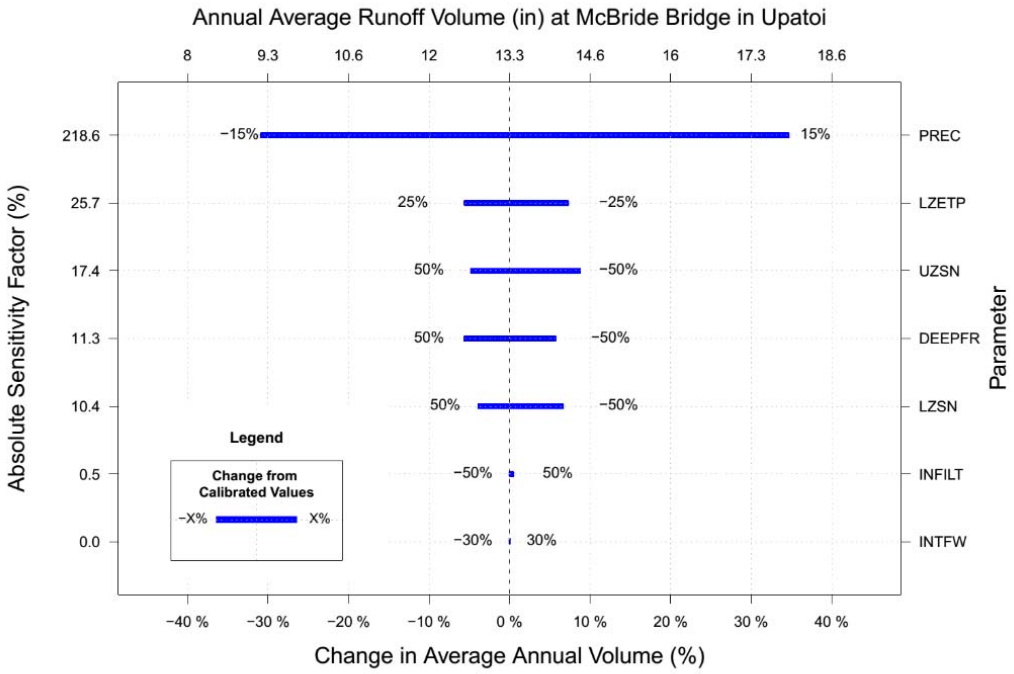


Figure 6.2. Tornado Diagram of Parameter Sensitivity for Annual Average Runoff Volume at Reach 46 in Upatoi Creek Watershed at Fort Benning (*y*-axis is not to scale).

The blue bands show the change in output for the labeled change in input.

Table 6.3 lists the sensitivity factors for different outputs of interest at McBride Bridge (Reach 46) and the Upatoi Creek outlet (Reach 74) to different inputs/parameters. The sensitivity factors at Reach 74 were very close to the sensitivity factors at Reach 46. Tables list only the results where the sensitivity was greater than 20 percent. A complete set of tornado diagrams is provided for Reach 46 in Appendix F and in the original Project Report (Mishra and Donigian, 2017).

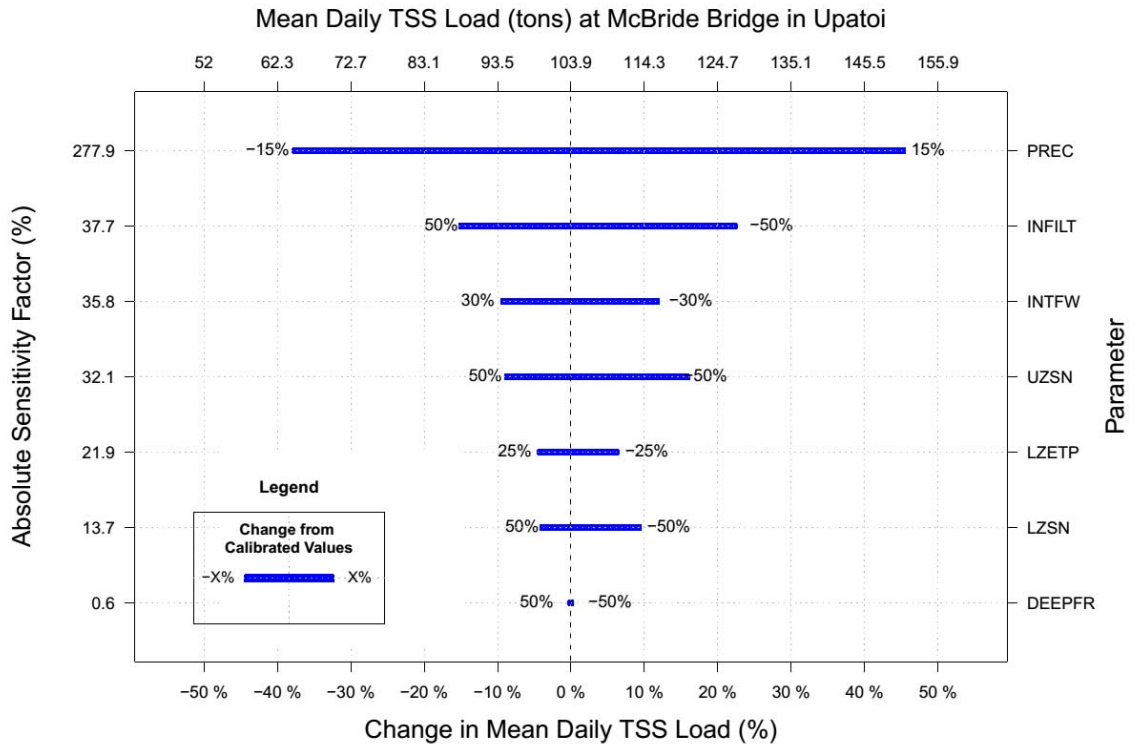


Figure 6.3. Tornado Diagram of Parameter Sensitivity for Daily Total Suspended Solids Loading at Reach 46 in Upatoi Creek Watershed at Fort Benning (*y*-axis is not to scale).

Table 6.3. Sensitivity Factors for Hydrology and Water Quality Outputs of Interest at Reach 46 (McBride Bridge) for Selected Parameters (Only Factors Greater Than ±20 Percent Are Shown)

	Hydrology Outputs									Water Quality Outputs	
Parameter/ Input	**Mean Annual Runoff**	**Annual Peak Flow**	**Mean Annual Flow Rate**	**10% High**	**25% High**	**50% High**	**50% Low**	**25% Low**	**10% Low**	**Mean TSS Concentration**	**Mean Daily TSS Load**
PREC	218.6	177.9	218.6	238.7	228.6	222.0	202.0	206.3	210.2	20.0	277.9
DEEPFR								–20.7	–20.8		
INFILT		–33.6		–21.7			24.1	25.9	28.2	–33.0	–37.7
INTFW		–27.5								–31.2	–35.8
LZETP	–25.7		–25.7	–20.2	–21.3	–22.8	–39.7	–48.3	–54.5		–21.9
LZSN											
UZSN		–23.4		–24.1	–21.9						–32.1

Uncertainty Analysis

The parameters and inputs that demonstrate the greatest sensitivity were then selected for further investigation in the UA. The sensitivity factor for precipitation was the highest for almost all the outputs of interest. Including precipitation in the SA demonstrated its importance in model performance. However, precipitation was not selected for UA because it is an input climate forcing time series, and its impact was included in the UA through the 10-year simulations using actual precipitation data. Additionally, including precipitation directly in the UA would have masked the model uncertainty for most all of the other parameters.

The UA involved Monte Carlo simulation of the UCW model with parameters randomly drawn from their respective statistical distributions. The parameters that resulted in greater than 30 percent sensitivity factors in all the outputs of interest were selected for the UA. Although LZSN was not as sensitive as other parameters, it was included in the UA because it is a major calibration parameter.

Each selected parameter was assigned a probability distribution. The distribution of parameters represents a modeler's expectations of the range, variability, and distribution of the parameter value in nature. For UAs conducted with watershed models such as HSPF, bounded probability distributions (both normal and lognormal) are frequently used (Donigian and Love, 2007; Mishra, 2011), so that the parameters are confined to physically realistic values and remain within the computational limits of the HSPF model. Some model parameters may be correlated and their correlation may be provided while sampling the parameters from their respective distributions. Correlations may be considered explicitly using a covariance matrix (Donigian and Love, 2007) or the distribution can be derived in such a way that correlation among parameters is implicit, using any of the Bayesian techniques (Mishra, 2011). With the limited number and range of parameter values in the HSPF model, selected for the UA, the correlation among parameters was assumed to be not significant and therefore ignored in this UA. The steps for a UA are as follows:

1. The model parameters that result in sensitivity factors greater than 30 percent were selected. Additionally, LZSN was also selected for uncertainty analysis as noted above (see Table 6.4).
2. A probability distribution and value range limits were assigned to each model parameter. Assigning the probability distribution to the model parameters is based on the specific knowledge of the parameters, processes, and algorithms used in the HSPF model; calibration experience with the UCW model; and followed practices used by Donigian and Love (2007). The correlation among the parameters was assumed to be insignificant for this application. The parameters that are a function of soil and/or climate were assigned a lognormal (LN) distribution and the parameters that are a function of vegetation were assigned a normal (NO) distribution.

   For the uncertainty analysis, the calibrated parameter range provided the basis for the range in which approximately 90 percent of these parameter values are expected. Based on this 90 percent range, standard deviation of these parameters was calculated as the range/3.3 (i.e., ± 1.65 standard deviation from the mean of the normal distributions).

Table 6.4. List of Parameters That Were Varied for the Uncertainty Analysis

Parameter Details					Calibrated Values					Distribution Parameters		
Category	**Name**	**Definition**	**Type**	**Distribution Type**	**Minimum**	**Maximum**	**Mean**	**90% Range**	**Std. Dev. (90% Range/ 3.3)**	**Lower and Upper Limits**	**Std. Dev. For Underlying Normal Distribution**	**Mean for Underlying Normal Distribution**
Hydrology	INFILT (in/hr)	Index to Infiltration Capacity of the Soil	Soil/ Climate	LN	0.01	0.63	0.17	0.01 – 0.63	0.19	0.005 – 0.7	1.18	–2.41
	INTFW	Interflow Inflow Parameter	Soil/ Climate	LN	0.40	7.00	4.50	0.40 – 7.00	2.00	0.3 – 7	0.87	0.51
	UZSN (in)	Upper Zone Nominal Soil Moisture Storage	Soil	LN	0.16	3.38	1.15	0.16 – 3.38	0.97	0.1 – 4	0.92	–0.31
	LZSN	Lower Zone Nominal Storage	Soil/ Climate	LN	3.50	15.20	9.00	3.50 – 15.2	3.55	2.5 – 6.0	0.45	1.98
	LZETP	Lower Zone Evapotranspiration	Vegetation	NO	0.16	0.38	0.31	0.16 – 0.38	0.07	0.05 – 0.9	N/A	N/A

For the LN distributions, standard deviation and mean of the underlying normal distributions were calculated based on the range, as follows:

$$\text{std. dev} = \ln\left(\text{upper bound}/\text{lower bound}\right)\Big/3.3$$

$$\text{mean} = \ln\left(\text{lower bound}\right) + 1.645 \times \text{std. dev}$$

To get the resulting LN distributions, the values from the normal distribution obtained with mean and standard deviation calculated above were individually exponentiated (i.e., assigned as exponent with base e). All of the distributions calculated above were truncated at their lower and upper limits (see Table 6.4) to avoid breaching physically realistic values and associated computational limits of HSPF. As examples, Figures 6.4 and 6.5 show the resulting NO and LN distributions of two parameters, LZETP and INTFW.

3. Random model parameter values were drawn based on their respective distributions and range limits, using the "pse" package (Chalom and Prado, 2017) in R (Venables et al., 2017). The "pse" package provides the flexibility to draw samples from a distribution using a Latin Hypercube Sampling (LHS) scheme, which ensures that the entire parameter space is sampled efficiently.

4. In Monte Carlo simulations, the number of parameter draws should be enough to converge on an estimate of the probability distribution of the output variables (Gardner and O'Neill, 1983). This number is generally achieved by trial and error and increases with the number of parameters and their variability. Mishra (2011) conducted Monte Carlo simulation with about 26 parameters and the number of simulations were 12,000. Donigian and Love (2007) performed a series of tests with the number of runs ranging from 150 to 1,500 and found that a stable output distribution could be obtained with about 500–600 runs; their subsequent uncertainty analyses for about 30 parameters/inputs was based on 600 runs.

   To ensure an adequate number of simulations, RESPEC started with a set of 1,000 parameter draws and calculated various output metrics (mean, standard deviation, 5 percentile, 95 percentile, and probability density function) after the end of 50, 100, 200, 500, and 1,000 simulations. The output metrics showed no significant difference after 500 and 1,000 simulations for all the outputs of interest, which indicated that a sufficient number of simulations had been conducted (see Figure 6.6).

5. In the UCW model, the parameters vary spatially and, therefore, a single value cannot be assigned to each individual parameter. The parameter sets generated in the previous steps were normalized by dividing them with their respective mean values to generate a multiplication factor for each parameter. For each HSPF simulation, the existing parameters were multiplied by these multiplication factors.

6. Using HSPEXP+, the User Control Input (UCI) file for each HSPF simulation of the UCW model was regenerated by using the multiplication factors for each parameter from the previous step, a model simulation was conducted, and the relevant output was saved in a text file for later processing.

7. Various statistics for the outputs of interest were calculated from all of the runs, including different percentiles, uncertainty, and probability density functions (see Tables 6.5 and 6.6).

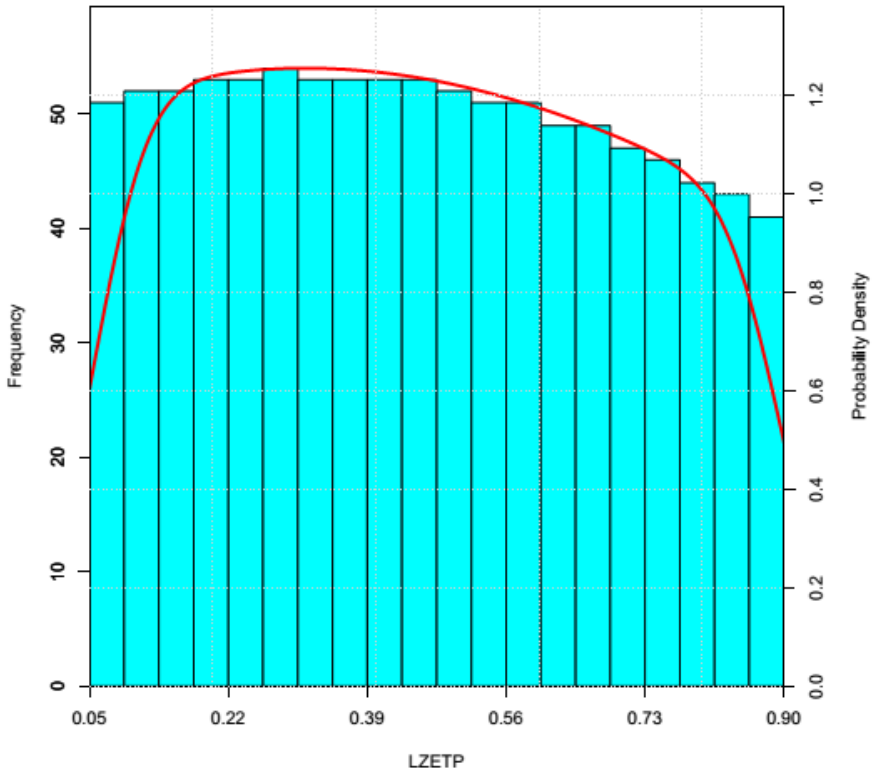


Figure 6.4. Histogram and Probability Density Function of Bounded and Normally Distributed Parameter, LZETP.

Tables 6.5 and 6.6 show the primary UA results. The results are shown at both the Reach 46 (McBride Bridge) and Reach 74 (Upatoi Creek outlet). For each output metric, the table includes the mean value, the 5th and 95th percentile values, and the overall "Percent Uncertainty" which is calculated as the average deviation from the mean value; i.e., the sum of the 5th percentile minus the mean, and the 95th percentile minus the mean divided by 2. Percent uncertainty represents the average deviation from the mean value for the 90 percent confidence range.

Thus, the overall uncertainty in hydrology outputs varied from 28 percent to 77 percent over the full range of flows, while mean flows showed uncertainties of about 28 to 30%. The uncertainty in the mean TSS concentration was observed to be between 28 and 32%; however, the uncertainty in mean TSS loading at the two locations was 40.9 and 42.3 percent. These ranges reflect the relative difficulties in calibrating the TSS loading compared to average flow rate and average TSS concentration.

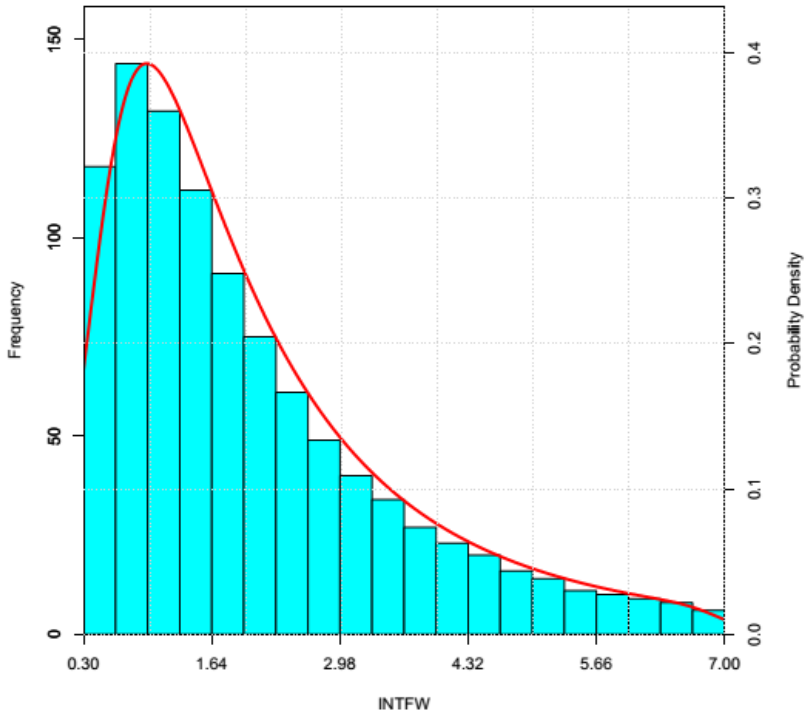


Figure 6.5. Histogram and Probability Density Function of Bounded and Log Normally Distributed Parameter, INTFW.

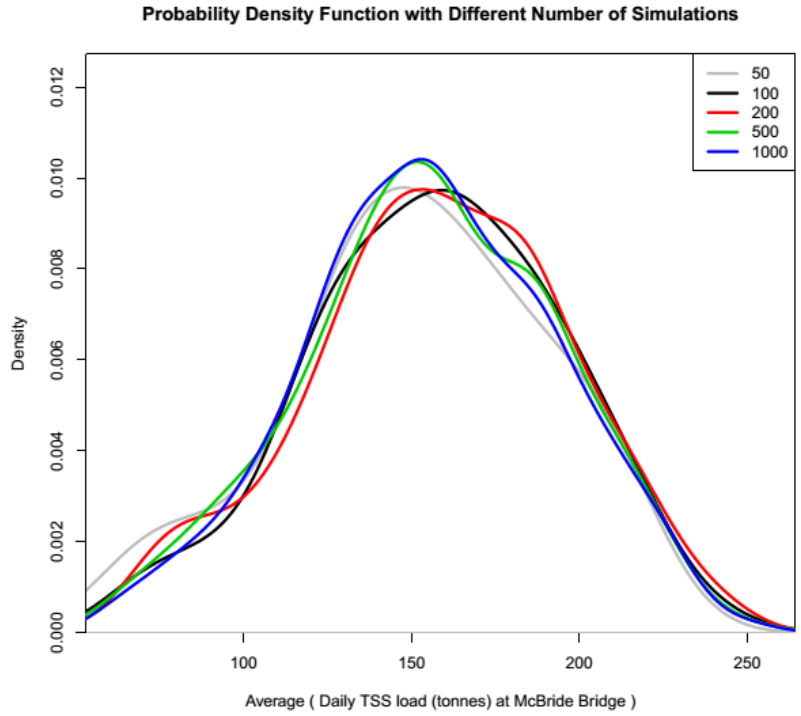


Figure 6.6. Probability Density Function of Mean Daily Total Suspended Solids (Tons/Day) in Reach 46 Generated With Different Number of Monte Carlo Simulations.

Table 6.5. Mean, 5th and 95th Percentiles and Uncertainty of Hydrology Outputs of Interest at Reach 46, and Reach 74 in the Upatoi Creek Watershed Model at Fort Benning

	Mean Daily Flow Rate (cfs)	Annual Peak Flow (cfs)	Mean Annual Runoff (in)	10% High (in)	25% High (in)	50% High (in)	50% Low (in)	25% Low (in)	10% Low (in)	5% Low (in)
Reach 46 (McBride Bridge)										
5th Percentile	259.5	4,822.8	10.4	4.9	7.0	8.9	1.0	0.3	0.1	0.03
Mean	349.6	8,797.4	14.0	8.2	10.2	12.2	1.8	0.6	0.2	0.07
95th Percentile	457.7	12,330.0	18.3	11.9	13.8	15.9	3.1	1.2	0.4	0.14
% Uncertainty	28.3	42.70	28.3	43.0	33.2	28.5	59.5	68.0	74.1	77.2
Reach 74 (Upatoi Creek Outlet)										
5th Percentile	320.7	5,506.4	9.6	4.6	6.5	8.3	1.0	0.3	0.1	0.03
Mean	439.8	10,430.2	13.2	7.6	9.6	11.5	1.7	0.6	0.2	0.07
95th Percentile	583.4	14,998.7	17.5	11.1	13.1	15.1	3.0	1.1	0.3	0.14
% Uncertainty	29.9	45.5	29.9	43.0	34.5	29.7	58.6	67.3	73.0	76.3

Table 6.6. Mean, 5th and 95th Percentiles, and Uncertainty of Water Quality Outputs of Interest at Reach 46, and Reach 74 in the Upatoi Creek Watershed Model at Fort Benning

	Mean TSS Concentrations (mg/l)	Mean Daily TSS Load (tons/day)
Reach 46 (McBride Bridge)		
5th Percentile	25.9	90.7
Mean	39.9	155.2
95th Percentile	51.7	217.8
% Uncertainty	32.3	40.9
Reach 74 (Upatoi Creek Outlet)		
5th Percentile	33.6	109.0
Mean	49.6	190.7
95th Percentile	64.0	270.5
% Uncertainty	30.7	42.3

Frequency duration curves of flow were also plotted to illustrate the uncertainty in flow simulation for the entire range of flows (see Figure 6.7). The curves are plotted with 5th and 95th percentile curves as shown in Figure 6.7; the uncertainty increases for low flow conditions and high flow events, with the lowest uncertainty for the moderate flow ranges. The frequency duration curve of TSS concentration (Figure 6.8) illustrates the uncertainty in TSS concentration for entire range of TSS concentration. The relative uncertainty in TSS concentration is lower at higher concentrations and increases for lower values.

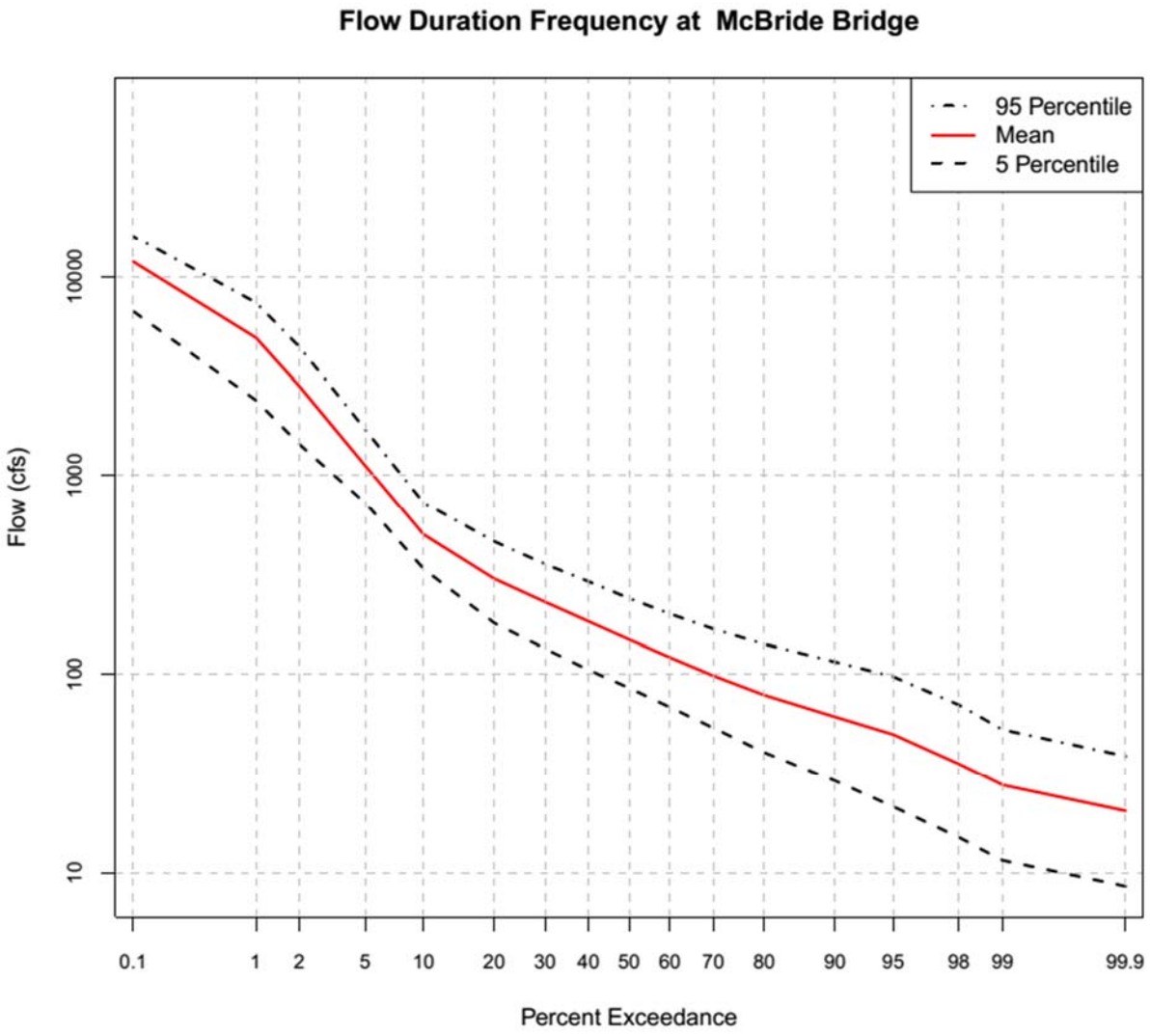


Figure 6.7. Flow Frequency Duration Curves at Reach 46 (McBride Bridge) With 5 and 95 Percentile Curves to Illustrate the Model Uncertainty

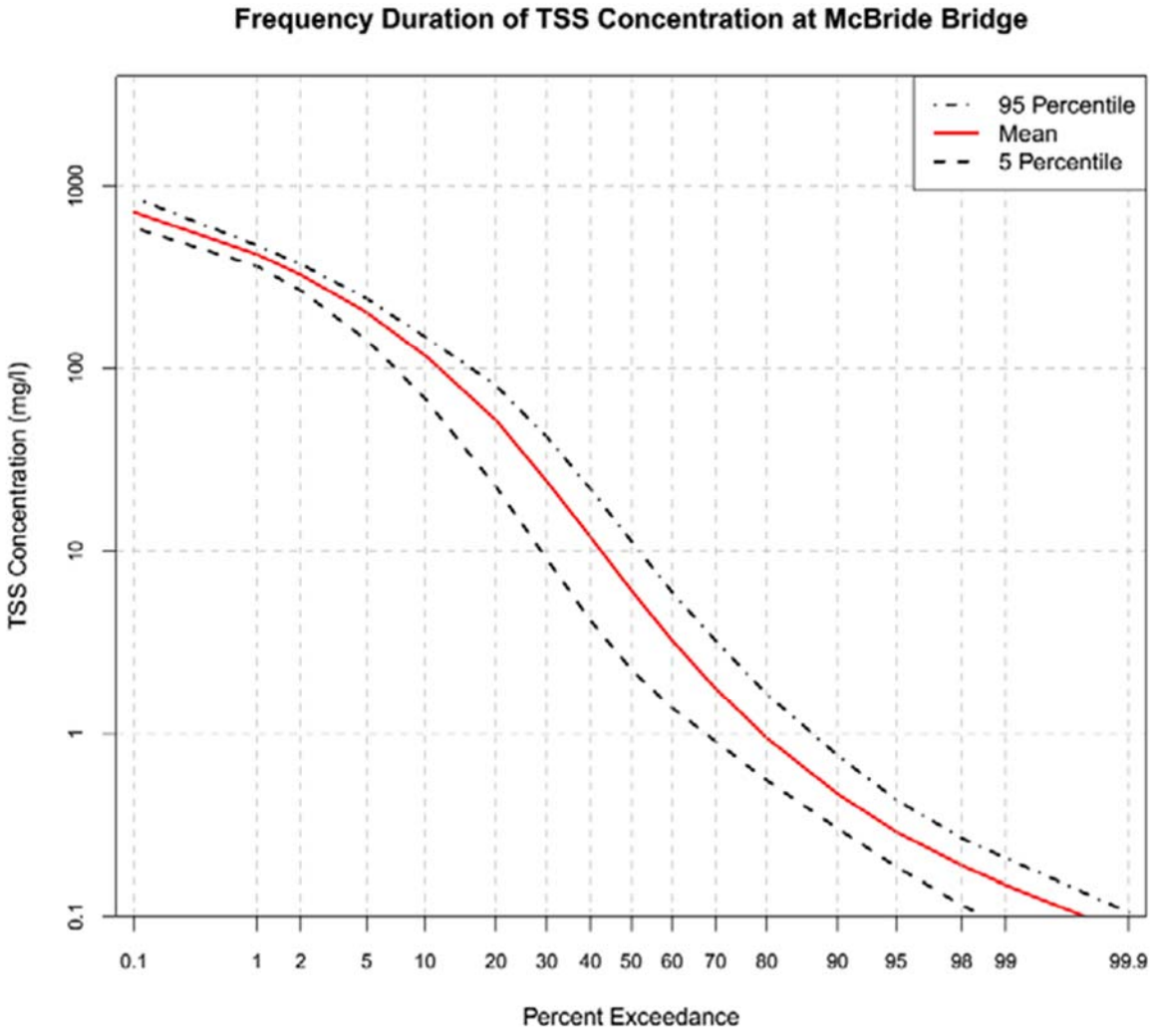


Figure 6.8. Total Suspended Solids Frequency Duration Curves at Reach 46 (McBride Bridge) With 5 and 95 Percentile Curves to Illustrate the Model Uncertainty.

6.2 CONCLUSIONS AND RECOMMENDATIONS

Sensitivity Analysis

Review of the SA results summarized in Table 6.3, along with the tornado diagrams provided herein, and in Appendix F, support the following conclusions:

1. As expected, the precipitation clearly dominates the SA results shown in Table 6.3 and the attachment to Appendix F, compared to all of the other inputs and parameters included in the SA, with Sensitivity Factors mostly in the range of 150 percent to over 250 percent for hydrology model outputs. The only cases when the precipitation sensitivity factor is less than 100 percent is for sediment concentration outputs, and this occurs because the precipitation impacts both the load (i.e., numerator) and the flow (i.e., denominator) of the concentration calculation—in the same direction.

2. Other than precipitation, the mean annual runoff volume was sensitive to LZETP because of its impact on the evapotranspiration component of the water balance; this is especially true during low flow conditions; e.g., 50 percent low, 25 percent low, and 10 percent low.
3. Peak flow rates are sensitive to more parameters, as shown in Table 6.3, with the greatest sensitivity after precipitation being INFILT (the infiltration index) in the model. The increase in INFILT causes reduction in peak flow and the direct surface runoff, but increases low flow. A decrease in INFILT causes increases in peak flow and the direct surface runoff and decreases low flow.
4. The hydrology parameters that impact the flow regime the most; e.g., precipitation, INFILT, INTFW, UZSN, and LZETP, also affected the sediment load.
5. An increase in INFILT and INTFW reduces the surface runoff without affecting total runoff (< 20 percent sensitivity factor); therefore, their reduction also reduces the sediment load and concentration.

The results of the SA for the UCW model are consistent with our experience in other watersheds, and they provide a sound basis for selecting parameters for the UA.

Uncertainty Analysis

From the UA results shown in Tables 6.5 and 6.6, the following conclusions are derived:

1. Model uncertainty increases from median flow rate to both high flow rates and low flow rates (i.e., extremes)
2. Model uncertainty increases from median flow volume to high and low flow volumes.
3. Model uncertainty in mean TSS concentration are similar to the uncertainty in mean flow (around 30 percent); however, the uncertainty in daily TSS load is greater (about 40 percent).
4. Uncertainty estimates at Reach 46 (McBride Bridge) and Reach 74 (Upatoi Creek Outlet) are essentially the same; the differences in the Percent Uncertainty between these two sites is considered insignificant.

Based on the past experiences with UA in HSPF models in other watersheds, the results of this investigation are reasonable and realistic.

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APPENDIX A

TASK 5 FINAL REPORT

DATA RICHNESS VERSUS MODEL PERFORMANCE



TECHNICAL REPORT

TASK 5: DATA RICHNESS VERSUS MODEL PERFORMANCE

Demonstration and Validation (Dem/Val) of BASINS Watershed Modeling System Enhanced for Military Installations (BASINS.MIL) on Fort Benning

RC-201307
23013

February 2018
Version 1

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EXECUTIVE SUMMARY

The Military Enhanced Better Assessment Science Integrating Point and Non-Point Sources Modeling System (BASINS.MIL) was developed in the Strategic Environmental Research and Development Program- (SERDP-) funded Project RC-1547 as a tool for watershed-based decision making on military installations. Two types of enhancements that use the Hydrological Simulation Program–FORTRAN (HSPF) as the primary rainfall-runoff modeling code were developed for the Better Assessment Science Integrating Point and Non-Point Sources (BASINS) Modeling System for military-specific applications: (1) data and methodologies that address key military land and water stressors and (2) software refinements related to model linkages and science algorithms. Preliminary model applications were performed on Fort Benning (FB), Georgia, to provide a proof-of-principle demonstration of the modeling system and the enhancements to support the evaluation of watershed-management issues on the installation.

The Environmental Security Technology Certification Program (ESTCP) Demonstration and Validation Program (dem/val) of BASINS.MIL, under ESTCP Project RC-201307, is the next step to fully test the validity of the technology to ensure that it meets the Department of Defense's (DoD's) need for tools to evaluate watershed hydrology and water quality for system-level assessments. The overall objectives of the BASINS.MIL dem/val on FB are related to modeling capabilities and model performance of the technology.

An important consideration for the transferability of BASINS.MIL is the cost associated with data requirements for model setup and application for the Installation and the incremental benefit that collecting additional data has in addressing management-relevant questions. The DoD needs to better understand the costs and benefits associated with data richness and model performance. Especially in relatively data-poor settings, installations are unclear about how much to invest in monitoring to meet a specific level of model performance. General guidance based on quantitative results, which is the objective of Task 5, is essential.

OBJECTIVE OF TASK 5

This component of the FB dem/val develops and implements an approach to quantify the change in model performance of the Fort Benning Enhanced Baseline Model [AQUA TERRA Consultants, 2013] relative to the quantity and quality of available data for model setup and application. This objective has site specificity related to FB as well as a broader application of the results/conclusions that are achieved to military installations with similar rainfall-runoff and landscape features. The approach in this report is designed to consider a full range of data availability issues, from little or no data for model setup and calibration to multiple gage sites with multiple years of observations and varying levels of model application experience. The goal is to provide installations with information on potential tradeoffs in model performance compared to the needs of additional data collection to instill higher confidence in model results across various spatial scales.

HSPF is the main watershed modeling code in BASINS and is a comprehensive, process-based mathematical model used to simulate hydrologic and water quality processes in natural and man-made water systems [Bicknell et al., 2005]. The model uses input information such as the time history of rainfall, temperature, evaporation, and parameters related to land-use patterns, soil characteristics, and land-management practices to simulate the processes that occur in a watershed. The initial result of an HSPF simulation is a time history of the quantity and quality of water transported over the land surface and through various soil zones down to the groundwater

aquifers. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations that result from the Installation's unique weather and land conditions can be predicted. The model then uses these land-derived loading results and stream channel information to simulate instream processes. From these simulations, HSPF produces a time history of water quantity and quality at any point in the watershed.

The extensive amount of watershed-related data collected at FB makes it well-suited for conducting a set of conditional data scenarios that compare the data used for model set up and application and the resulting model performance. At the onset of the SERDP project, the major limitation with respect to hydrologic modeling on the FB watersheds was that only a single flow gage was available for calibration, even though it was well-located at the center of the watershed. In response to this limitation, SERDP agreed to fund additional flow data collection, which included five stream gages that were installed by the US Geological Survey (USGS) on the Installation in 2008. The gaging stations provide additional flow data and rating curves beyond the original simulation period (1999–2008) of the FB Model, based on the McBride Bridge gage site on Upatoi Creek. Strategically located to assist in and support future model calibrations, the new USGS gaging stations were installed and data were collected through 2012 to support modeling efforts at each of the sites. The new USGS sites are listed below:

- Pine Knot Creek Near Eelbeck, Georgia (Station No. 02341725)
- Upatoi Creek Below Baker Creek Near Upatoi, Georgia (Station No. 02341665)
- Ochillee Creek at Ochillee, Georgia (Station No. 02341910)
- Randall Creek Near Upatoi, Georgia (Station No. 02341750)
- Upatoi Creek at GA357 at Fort Benning, Georgia (Station No. 02342070).

MODELING APPROACH AND CONDITIONAL DATA SCENARIOS

The technical approach to this task consists of a set of conditional data scenarios that reflect alternative levels of data quantity and/or quality available to support the model setup and calibration. The challenge of this task was to design these conditional data scenarios so that model performance can be quantified as a function of the data made available for each scenario. These scenarios and associated data requirements and availability are summarized in the following table:

Table ES-1. Data Requirements and Availability for Each Conditional Data Scenario

Conditional Data Scenario	Data Requirement	Data/Knowledge Availability
Blind Validation	Additional time-series data to extend modeling simulation	New flow data not used in calibration
Incremental Recalibration	Hydrologic flow data from five new gages	Adding data from the new gages one at a time and recalibrating
Applying Non-Calibrated Parameters By a New or Inexperienced Model User	Regional maps, soils data, cross-sectional data and other parameter guidance available from public sources	No data from new stream gages; modeler has no calibration experience nor knowledge of previous model calibrations
Data Quality	USGS Gage Rating System	USGS ratings for the new FB gages

BLIND VALIDATION

This data scenario involves comparing simulated flow variables from the FB Enhanced Baseline Model, which was developed in RC-1547, with the hydrologic (flow) data observed at the new USGS gages for their extended period of record from 2008 to 2012. This analysis is essentially a blind validation (i.e., it is a validation performed after the calibration has been completed and before the new flow data was being collected and was available). This analysis is intended to demonstrate how well the calibrated model predicts the flows measured but not used in the calibration. The analysis addresses how well the model performs, not only at the McBride Bridge site where it was calibrated but also at other watershed sites where there no data for calibration existed. While this analysis does not yet answer how the calibration and model performance would change and improve as additional data were made available, it sets the stage for that analysis in the next conditional data scenario (i.e., the incremental calibration).

The model results for the blind validation demonstrate a relatively successful simulation and imply that a single gage may be adequate for representing the entire watershed, but the simulation is less successful at the smaller tributary sites. The results suggest that the McBride Bridge calibration parameters provide a fair-to-good overall simulation for the extended period for most of the other sites, but they do not work very well for the Pine Knot Creek Subwatershed. This implies that using a single flow gage for a relatively large watershed, such as the Upatoi Creek, at 300–500 square miles, may provide a reasonable simulation for *some* smaller tributary subwatersheds, but the same level of accuracy cannot be guaranteed for *all* subwatersheds.

INCREMENTAL RECALIBRATION

Incremental recalibration involves comparing the simulated flow variables from the FB Model at each of the new USGS stream gages with parameter sets that have been recalibrated in a sequential step-wise fashion using one gage at a time, so that incremental improvements (and changes) in model performance metrics can be evaluated as applied to the drainage area above the stations. Thus, the percent of the upstream watershed that is now gaged becomes an important factor in the analyses because it identifies how much of the upstream drainage area has now been calibrated.

This analysis was a key focal point of this investigation because it addresses the key issue of how the model metrics will improve by incrementally using additional data for successive calibration efforts. The analyses at all of the impacted gages were performed at each step to assess how the metrics are changed with each calibration effort. With improvements in upstream gages, subsequent parameter refinements may be needed in the downstream gage sites (i.e., the previous calibration may have included offsetting, or compensating, errors that could only be identified with the additional data at multiple sites). In fact, this situation did occur.

The model results from the recalibration effort make it clear that the additional data provided by the new USGS gage sites allow a much more spatially accurate model for the various subwatersheds of Upatoi Creek. This accuracy also supports using the model for assessments closer to the scale of typical disturbances, construction, and other activities that may be the focus of future modeling efforts. From the results presented in Chapter 3.0, the flow-duration curves, and the hydrographs in Appendix A, the following conclusions were made:

a. For monthly flows, the correlation metrics are primarily in the good-to-very good range (from the corresponding scale in Figure ES-1), except for the Pine Knot Creek and Randall Creek gages, which extend to the fair range.

b. For daily flows, the same correlation metrics are mostly in the fair-to-good range ($R > 0.8$ and $R^2 > 0.64$ respectively), with the Baker Creek gage as an exception.

c. For Moriasi et al.'s (2007) thresholds (MFE > 0.5, RSR < 0.7, PBIAS < 25 percent [monthly] to 35 percent [daily]), the monthly simulation results satisfy all of these metrics at all of the sites. For daily flows, the same holds true except for the Baker Creek site (i.e., RSR = 0.74 and MFE = 0.46), and both of these very nearly satisfy the metrics.

d. The very good-to-excellent agreement of the flow-duration curves provides a visual confirmation of the accuracy of the recalibrated model throughout the full range of flows observed at the gages. Only Randall Creek and the low-flow region for the Ochillee Creek gage indicate some deviation from the observed flow-duration curve.

The results obtained from the incremental calibration demonstrate that each of the gages provide additional information that helps to improve the spatial representation of the watershed and provides insight into how and which model parameters need to be changed to represent the spatial variability of the watershed.



Figure ES-1. R and R^2 Value Ranges for Model Performance [Donigian, 2002]

APPLICATION OF NON-CALIBRATED PARAMETERS BY A NEW MODEL USER

This effort involved comparing the FB Model simulated flow variables at the long-term, historical USGS gage at McBride Bridge, with simulated flow variables derived from a non-calibrated parameter set that was estimated from regional maps, soils data, and other parameter guidance available from public sources. The subsequent calibration was performed by an engineer with experience in HSPF operations but no previous calibration experience. This analysis shows the level of model performance that can be expected from installation staff with a water resources background but no previous HSPF experience, which is likely to occur at many installations. This analysis also provides a resource manager with some sense of the value of modeling experience and the ability of installation staff to calibrate and effectively use watershed models.

Before initiating this effort, the calibrated model parameters were selectively perturbed, so that the starting model was no longer calibrated. A high-level comparison of the differences between the calibrated perturbed model and the Enhanced Baseline Model may indicate that the calibrated perturbed model achieved a slightly higher level of accuracy for some metrics. The calibrated perturbed model achieved an annual, average flow error of 2.2 percent and met all of the annual average flow statistical criteria compared to an average annual flow error of 7.5 percent and

achievement of 13 out of 15 of the annual average flow statistical criteria for the Enhanced Baseline Model. After a more in-depth review, however, the overall model-period annual averages do not represent the actual level of accuracy because of more extreme high- and low-error volumes seen in the annual and monthly flow volumes, which cancel out in the calibrated perturbed model. This assessment is also supported by observing the flow-duration curve, which indicates overall similar accuracy for a large portion of the flows, but very large discrepancies in the high-percentage, flow-exceedance range for the calibrated perturbed model. Although the calibrated perturbed model produces better high-level summary statistics, the Enhanced Baseline Model better simulates the hydrology at Upatoi Creek at McBride Bridge for the entire modeling period of 2000–2008.

To achieve better model results in the calibrated perturbed model, the individual who is calibrating should have more experience with previous hydrology calibrations. A deeper understanding of how the various parameters influence the overall hydrology would increase the accuracy and efficiency of the calibration process for a relatively novice user. For someone with little calibration experience, additional effort would allow for further adjustments to be made and additional lessons learned, along with a better understanding of the parameters' influence in the calibration process. However, the bottom line of this experiment is that a relatively inexperienced model user can attain a reasonably accurate simulation when provided guidance and consultation during the calibration effort.

As part of this task, we were asked to evaluate the impact of using Light Detection and Radar (LiDAR) data to generate the Final Function Tables (FTABLEs) (i.e., stage-discharge relations used in the hydraulic routing) used in the model and assess the differences that result from this improved data. Because both actual cross-section measurements and stream channel LiDAR data were used in developing the FTABLES in the Enhanced Baseline Model, we decided to reverse the assessment. We generated FTABLES using the default options in BASINS, which are based on geomorphic relations of channel dimensions (i.e., top width, depth, bottom width) as a function of regional characteristics and drainage area. We compared the results using these default FTABLES to the Enhanced Baseline Model results. In general, the results show very small differences caused by the additional data that were used to develop improved FTABLES. The statistical measures of calibration confirm that the differences caused by FTABLE adjustment in this model are quite small. Because the model was calibrated with the improved FTABLES, we expected that reverting to using the original BASINS FTABLEs would cause the statistics to be somewhat worse. The results of our demonstration confirm that most model results are not especially sensitive to improvements in the FTABLES, as long as the FTABLES demonstrate reasonable flow-discharge relations. Note that this conclusion is specific to the HSPF channel hydraulic representation and is not likely to apply where multi-dimensional issues are of concern (e.g., point source discharges and mixing zones) where higher resolution approaches may be needed.

DATA QUALITY

We consider both quantity and quality of collected data to be considerations in a full evaluation of data richness as related to model performance. This discussion is directed toward ultimately comparing the relative modeling uncertainty that is attributable to data-collection error to the modeling uncertainty that is attributable to errors in model parameterization. Accordingly, the focus here is associated with those conditional data scenarios that include using observed flow data from one or more of the FB USGS gage stations.

Following standard USGS practice, the metadata provided with the FB USGS flow datasets (and essentially all of the USGS flow data) assigns an accuracy rating of excellent, good, fair, or poor to the daily data for each gage site. The accuracy rating scale is provided in Table ES-2.

Table ES-2. Expected Tolerance

Tolerance	Percent (%)
Excellent	5
Good	10
Fair	15
Poor	> 15

95 percent of values are within this tolerance of the true value.

An excellent rating indicates that approximately 95 percent of the values are within 5 percent of the true value, and the tolerance is similar for the other ratings. For the FB gages, the long-term McBride Bridge gage, and the five other new gages, the USGS has assigned an accuracy rating of fair to poor uniformly across all of the gages, with a few exceptions of a good rating for selected years. This rating indicates that the USGS expects that errors up to 15 percent or greater can be expected for all of the data that were collected at the gages.

As described in our Final Demonstration Plan [AQUA TERRA Consultants, 2014], Performance Objective #8 of the project addresses and estimates uncertainty that is introduced into the modeling because of uncertainty in selecting values for the most sensitive model input and parameters. Model uncertainty runs with Monte Carlo analyses were performed to determine the 90 percent confidence interval range representing the simulated values between the 5th and 95th percentiles, and these results were then used to calculate the percent uncertainty as the mean deviation from the calibrated model results. The results of these analyses showed uncertainty levels of about 30% for mean flow and 40% to 70% for high and low flows, respectively. Uncertainties for sediment/TSS were comparable, but are generally expected to have higher uncertainty due to the extreme variability of sediment dynamics.

We have performed similar uncertainty analyses (UA) for a few other HSPF-modeled watersheds and their results provide some basis for comparison. These watersheds include the Housatonic River Watershed (256 square miles [sq mi]) in western Massachusetts [Donigian and Love, 2007] and the Illinois River Watershed (1,500 sq mi) in eastern Arkansas and western Oklahoma [Mishra and Donigian, 2015]. These UA efforts have produced similar results and indicate model uncertainties caused by parameter value uncertainties that range from 10 percent to 15 percent for mean annual streamflow and runoff, uncertainties that range from 15 percent to 25 percent for high flows, and uncertainties that range from 25 percent to 45 percent for low flows. Our experience with watershed modeling, and specifically with HSPF applications, supports these ranges as being reasonable approximations of the expected uncertainty levels for the FB/Upatoi Watershed model.

Although this analysis is not precise, the level of uncertainty in the flow data observations (i.e., 15 percent or greater) is generally at a much lower level than the expected uncertainty in the model predictions (i.e., 10–45 percent). Unless there are site-specific issues (e.g., a highly unstable bed,

gage mechanical problems, backwater effects), data quality is not expected to be a significant issue for uncertainty in the observed flow data when compared to the potential uncertainty in the model predictions. However, the same cannot be said for sediment and water quality data, which are likely to have higher levels of uncertainty than noted here.

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ACRONYMS

BASINS	Better Assessment Science Integrating Point & Non-Point Sources
BASINS.MIL	Military Enhanced BASINS Modeling System
BMP	Best Management Practice
CERL	Construction Engineering Research Laboratory
DEM/VAL	ESTCP Demonstration and Validation Program
DoD	Department of Defense
EPA	Environmental Protection Agency
ERDC	Environmental Research and Development Center
ESTCP	Environmental Security Technology Certification Program
ET	Evapotranspiration
FB	Fort Benning
FTABLE	Function Table for HSPF
GA	Georgia
GIS	Geographic Information System
HSPF	Hydrological Simulation Program–FORTRAN
INFILT	Infiltration Parameter for HSPF
MSL	Mean Sea Level
NCDC	National Climatic Data Center
PET	Potential Evapotranspiration
PI	Principal Investigator
RC	Resource Conservation
RCHRES	Reach Segment in HSPF
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
USACE	US Army Corps of Engineers
USGS	US Geological Survey
WDM	Watershed Data Management
WY	Water Year

1.0 INTRODUCTION AND PROJECT TIMELINE

1.1 PROJECT BACKGROUND AND OBJECTIVES

The Military Enhanced Better Assessment Science Integrating Point and Non-Point Sources Modeling System (BASINS.MIL) was developed in the Strategic Environmental Research and Development Program- (SERDP-) funded Project RC-1547 as a tool for watershed-based decision making on military installations [AQUA TERRA Consultants, 2013]. Two types of enhancements, which use the Hydrological Simulation Program – FORTRAN (HSPF) as the primary rainfall-runoff modeling code, were developed for the Better Assessment Science Integrating Point and Non-Point Sources (BASINS) Modeling System for military-specific applications: (1) data and methodologies that address key military land and water stressors and (2) software refinements related to model linkages and science algorithms. Preliminary model applications were performed on Fort Benning (FB), Georgia, to provide proof-of-principle demonstration of the modeling system and the enhancements to support evaluation of watershed-management issues on the installation.

The Environmental Security Technology Certification Program (ESTCP) Demonstration and Validation Program (dem/val) of BASINS.MIL is the next step to fully test the validity of the technology to meet the Department of Defense's (DoD's) need for tools to evaluate watershed hydrology and water quality for system-level assessments. The overall objectives of the BASINS.MIL dem/val on FB are related to modeling capabilities and model performance of the technology. Table 1-1 lists the various components of the BASINS.MIL dem/val on FB; Task 5, the focus of this report, is highlighted as part of the model performance assessment.

Table 1-1. Components of the BASINS.MIL Demonstration and Validation on Fort Benning

Components of Dem/Val	
Modeling Capabilities	Unpaved road design and maintenance
	Climate non-stationarity
	Small-scale modeling assessment
Model Performance	Validation of WEPP modeling results
	Data richness versus model performance
	Uncertainty of modeling results

1.2 THE DEPARTMENT OF DEFENSE'S NEED

An important consideration for the transferability of BASINS.MIL is the cost associated with data requirements for model setup and application for the Installation and the incremental benefit that collecting additional data has on addressing management-relevant questions. The DoD needs a quantitative basis to better understand the costs and benefits associated with data richness and model performance. Especially in relatively data-poor settings, installations are unclear about how

much to invest in monitoring to meet a specific level of model performance. General guidance based on quantitative results is essential, which is the objective of Task 5.

1.3 OBJECTIVE OF TASK 5

This component of the FB dem/val develops and implements an approach to quantify the change in model performance of the FB Enhanced Baseline Model (or FB Model) [AQUA TERRA Consultants, 2013] relative to the quantity and quality of available data for model setup and application. This objective has site specificity related to FB as well as a broader application of the results/conclusions that are achieved to military installations with similar rainfall-runoff and landscape features. The approach in this report is designed to consider a full range of data availability issues, from little or no data for model setup and calibration to multiple gage sites with multiple years of observations and varying levels of model application experience. The goal is to provide installations with information on potential tradeoffs in model performance and the costs of additional data collection to instill higher confidence in model results across various spatial scales.

1.4 TECHNOLOGY DESCRIPTION

BASINS.MIL is a technology/methodology that has the opportunity for widespread application across the DoD. Using HSPF as the core modeling code, the BASINS.MIL enables immediate access to accepted modeling science for agriculture, forestry, urban, and other land uses; national-scope databases that fuel model applications; and expedient methods for setting up the HSPF model using the available data. BASINS.MIL thereby provides an equivalent modeling capability for all land-use types that may be present within a military-impacted watershed. In this way, both the military land areas and non-military areas are subject to a uniform-level watershed modeling technology with reasonably equivalent accuracy and reliability. See Chapter 2.0 of the Demo Plan [AQUA TERRA Consultants, 2014] for further discussion.

1.4.1 BASINS

BASINS is a Geographic Information System- (GIS-) based system and features a well-developed interface for different dynamic watershed models, and numerous pre- and post-processing tools that are shared by the models. Comprehensive documentation of BASINS is available at: *http://www.epa.gov/waterscience/basins/*

1.4.2 HSPF

HSPF [Bicknell et al., 2005] is the main watershed modeling code in BASINS and is a comprehensive, process-based mathematical model used to simulate hydrologic and water quality processes in natural and man-made water systems. The model uses input information such as the time history of rainfall, temperature, evaporation, and parameters related to land-use patterns, soil characteristics, and land-management practices to simulate the processes that occur in a watershed. The initial result of an HSPF simulation is a time history of the quantity and quality of water transported over the land surface and through various soil zones down to the groundwater aquifers. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations that result from the Installation's unique weather and land conditions can be predicted. The model then uses these land-derived loading results and stream channel information to simulate instream processes. From these simulations, HSPF produces a time history of water quantity and quality at any point in the watershed.

HSPF simulates for extended periods of time the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams. The model uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs [Bicknell et al., 2005]. HSPF simulates interception, soil-moisture storage, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, groundwater recharge, dissolved oxygen, biochemical oxygen demand, temperature, pesticides, conservatives (i.e., non-reactive and non-depositional material), fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton. The program can simulate one or many pervious or impervious unit areas that discharge to one or many river reaches or reservoirs. A frequency-duration analysis can be performed for any time series. HSPF allows almost any time step, in minutes, that results in a whole, integer number of equal time steps in 1 day. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or non-point source treatment alternatives, and flow diversions. Open-source (free) programs (including BASINS), which are available separately, support data pre-processing and postprocessing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file.

1.4.3 Pervious Land Segments

A land segment is a subdivision of the simulated watershed. The boundaries are established according to the user's needs, but generally, a segment is defined as an area with similar hydrologic and water quality characteristics. For modeling purposes, water, sediment, and water quality constituents that leave the watershed move laterally to a downslope segment or to a reach/reservoir. A segment of land with the capacity to allow enough infiltration to influence the water budget is considered pervious. In HSPF, PERLND is the module that simulates the water quality and quantity processes that occur on a pervious land segment.

The primary module sections in PERLND simulate snow accumulation and melt, the water budget, sediment produced by land-surface erosion, and water quality constituents by various methods. Other sections perform the auxiliary functions of correcting air temperature for use in snowmelt and soil temperature calculations; producing soil temperatures to estimate the outflow temperatures and influence reaction rates in the agri-chemical sections; and determining outflow temperatures, which influence the solubility of oxygen and carbon dioxide.

1.4.4 Impervious Land Segments

In an impervious land segment, little or no infiltration occurs; however, land-surface processes do occur. Snow may accumulate and melt, and water may be stored or may evaporate. Various water quality constituents accumulate and are removed. Water, solids, and various pollutants flow from the segments by moving laterally to a downslope segment or to a reach/reservoir.

The HSPF IMPLND module simulates various processes with many of them similar to the corresponding sections in the PERLND module. In fact, because the sections snow and air temperature components perform functions that can be applied to pervious or impervious segments, they are shared by both modules.

1.4.5 Streams and Reservoirs

This module simulates the processes that occur in a single reach of an open or closed channel or a completely mixed lake. For convenience, such a processing unit is referred to as an RCHRES. In keeping with the assumption of complete mixing, the RCHRES consists of a single zone situated between two nodes, which are the extremities of the RCHRES.

Flow through a RCHRES is assumed to be unidirectional. Water and other constituents that arrive from other RCHRES's and local sources enter the RCHRES through a single gate. Outflows may leave the RCHRES through one of several gates or exits. A RCHRES can have up to five outflow exits. Precipitation, evaporation, and other fluxes also influence the processes that occur in the RCHRES, as part of the overall mass balance in an RCHRES.

1.4.6 BASINS.MIL

BASINS.MIL is the technology/methodology that resulted from the SERDP-funded Project RC-1547 which was conducted on FB. The project involved substantial efforts to understand and represent military impacts, as well as improve the state of science for watershed modeling. The outcome was a military enhancement of the BASINS modeling system and its proof-of-principle applications. Based on domain knowledge of the military mission, specifically with respect to military readiness activities and environmental compliance and resource protection, datasets were identified and methodologies designed to support watershed impact assessments related to the leading stressors on military installations (i.e., military training, prescribed burning, urban encroachment, timber harvesting, and unpaved road erosion). Software refinements were developed to (1) improve HSPF representation of processes specific to military activities (e.g., canopy changes caused by prescribed burning, and compaction/erosion caused by armored tank training), (2) include complex channel modeling beyond what is available in HSPF (i.e., Engineering Fluid Dynamics Code [EFDC] / Sediment Transport Algorithm for EFDC [SEDZLJ]), and (3) allow for linkages to other models (i.e., AQUATOX, Water Erosion Prediction Project [WEPP], and WEPP:Road) [AQUA TERRA Consultants, 2013]. The products of the FB project, in essence, provide the BASINS/HSPF user with options for building a military enhanced HSPF model as shown conceptually in Figure 1-1. With regard to the complex channel modeling, the extensive data, expertise, and computational requirements presented significant obstacles to effective use by most installations. However, the comparison with HSPF model results did demonstrate the suitability of HSPF for many sediment-related modeling purposes.

1.4.7 Fort Benning Model

Using BASINS.MIL's components, a watershed model was developed for the watersheds on and surrounding FB (i.e., the FB Model). The FB Model was developed to simulate hydrology and water quality from 1999 to 2008. See the Final Report of SERDP RC-1547 [AQUA TERRA Consultants, 2013] for a complete description and application of the FB Model.

1.5 REPORT CONTENT

This report presents the results of our Task 5 effort to assess how data richness impacts model performance, so that the benefit of additional data collection can be evaluated to attain a preferred level of model accuracy. Following this overview of background and objectives of the work effort, Chapter 2.0 presents our overall approach to each of the project tasks, and Chapter 3.0 provides results and discussion of the effort. Chapter 4.0 is a summary of the lessons learned from this effort.

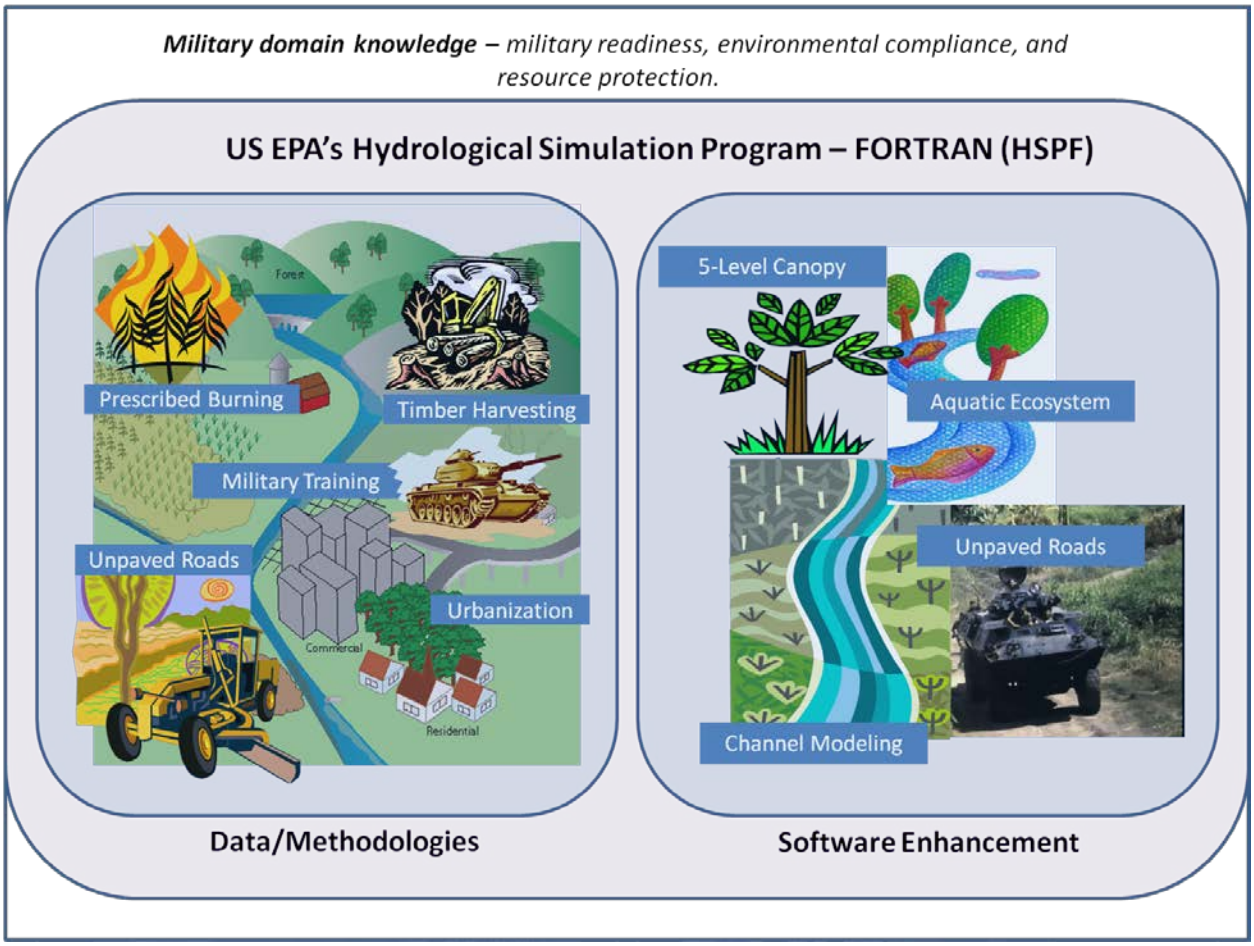


Figure 1-1. Conceptual Illustration of BASINS.MIL.

2.0 TASK 5 APPROACH

The extensive amount of watershed-related data collected at FB makes it well-suited for conducting a set of conditional data scenarios that compare the data used for model setup and application and the resulting model performance. At the onset of the SERDP project, the major limitation with respect to hydrologic modeling on the FB watersheds was that only a single flow gage was available for calibration, even though it was well-located at the center of the watershed, which is shown in Figure 2-1. In response to this limitation, SERDP agreed to fund additional flow data collection, which included five stream gages that were installed by the US Geological Survey (USGS) on the Installation in 2008. The gaging stations provide additional flow data and rating curves beyond the original simulation period (1999–2008) of the FB Model. Strategically located to assist in and support future model calibrations, the USGS gaging stations are listed below and their locations are shown in Figure 2-1; the new USGS sites are the red flower symbols, while the historic gage on Upatoi Creek at McBride Bridge is the green flower symbol:

- Pine Knot Creek Near Eelbeck, Georgia (Station No. 02341725)
- Upatoi Creek Below Baker Creek Near Upatoi, Georgia (Station No. 02341665)
- Ochillee Creek at Ochillee, Georgia (Station No. 02341910)
- Randall Creek Near Upatoi, Georgia (Station No. 02341750)
- Upatoi Creek at GA357 at Fort Benning, Georgia (Station No. 02342070).

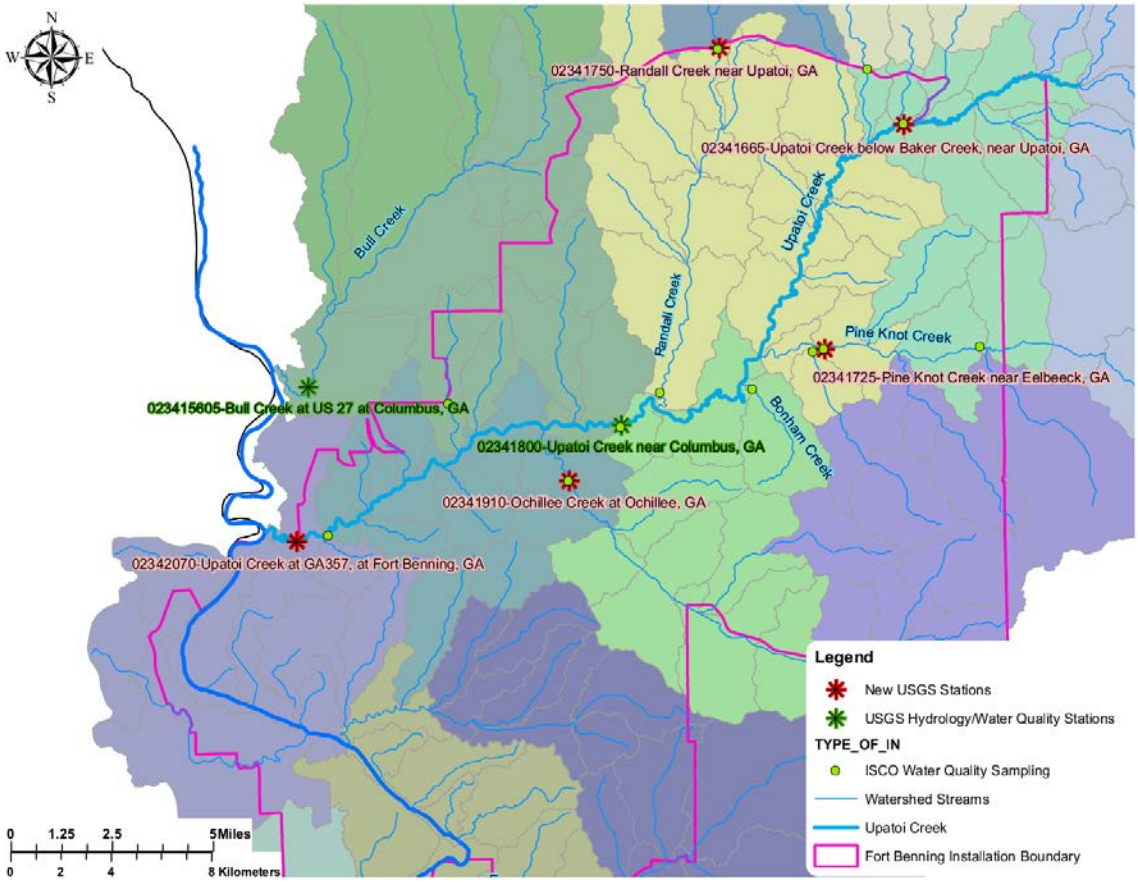


Figure 2-1. Five Supplemental US Geological Survey Monitoring Sites at Fort Benning.

The USGS monitoring program was implemented for approximately 3 years from October 2008 through September 2011 for all five sites, and another year was added for the Pine Knot Creek gage (USGS 02341725) as part of another SERDP project. Each site included a continuous stage recorder, with tie-ins to local benchmark (elevation) monuments. In addition, many events at each site (e.g., 4–25 separate storms) were monitored for flow measurements to develop paired stage-discharge values for use in developing rating curves. By the end of the 3-year program, rating curves were developed and available for all five of the USGS monitoring sites. The final rating curves for the five sites are shown in Figure 2-2 along with the original FB HSPF Model Function Table (FTABLE) curves for comparison.

The FTABLE for each reach is essentially a rating curve (i.e., stage-discharge paired values) in addition to reach volume and surface area, which is used to perform the hydraulic routing in HSPF RCHRES of inflows from upstream and local drainage areas. With the additional measured rating curves for the new USGS sites, the original FTABLES for those sites in the FB Model and adjacent stream reaches (upstream and downstream) were revised to more closely match the newly observed stage-discharge relationships derived with the new USGS flow data. In Figure 2-2, the separation between the new rating curve (red line) and the old rating curve (blue line) indicates the degree of difference between the curves at each stage value (i.e., x-axis). As the separation increases with stage, the differences are magnified, especially at high-flow rates. Note that for three sites, the new (red) curve is higher than the old (blue) curve, which indicates that the original FB Model underestimated flow rates for storm peaks; whereas, for the other two sites, where the old (blue) curve is higher, the original model overestimated the peak storm flows. The adjustments that extended to the adjacent stream reaches (upstream and downstream) assumed the same stage-discharge as for reaches where the new USGS gages were located. These FTABLE revisions were part of the effort that produced the FB Model [AQUA TERRA Consultants, 2013].

2.1 MODELING APPROACH AND CONDITIONAL DATA SCENARIOS

The technical approach to this task consists of a set of conditional data scenarios that reflect alternative levels of data quantity and/or quality available to support the model setup and calibration. The challenge of this task is to design these conditional data scenarios so that model performance can be quantified as a function of the data made available for each scenario. These scenarios and associated data requirements and availability are summarized in Table 2-1 and described in the following subsections.

Also, two additional issues should be addressed to establish a consistent framework for comparisons of the results of each scenario. First, a baseline model or condition is needed to which the results from each scenario will be compared to assess a change or difference in model performance. The logical baseline is the Enhanced Baseline Model for FB, which resulted from SERDP RC-1547, and the model performance metrics that were produced as a result of that effort. Those results are summarized in Chapter 3.0. Because only the McBride Bridge gage was available for calibrating the FB Model, all the model results of the scenarios are compared to the FB Model performance at the McBride Bridge gage.

The second issue is the relative spatial locations of the USGS gages and their available length of record, which will influence the type of model-data comparisons that can be made. The locations of the gages are shown in Figure 2-1. the drainage area at each gage and the percent of watershed at McBride Bridge and at the Upatoi Outlet are shown in Table 2-2. This latter metric indicates how much area of each watershed is monitored by upstream gages, which is a key metric in designing a monitoring plan. The impact of the gage location on the assessment procedures is discussed below under the incremental calibration task (Section 2.4).

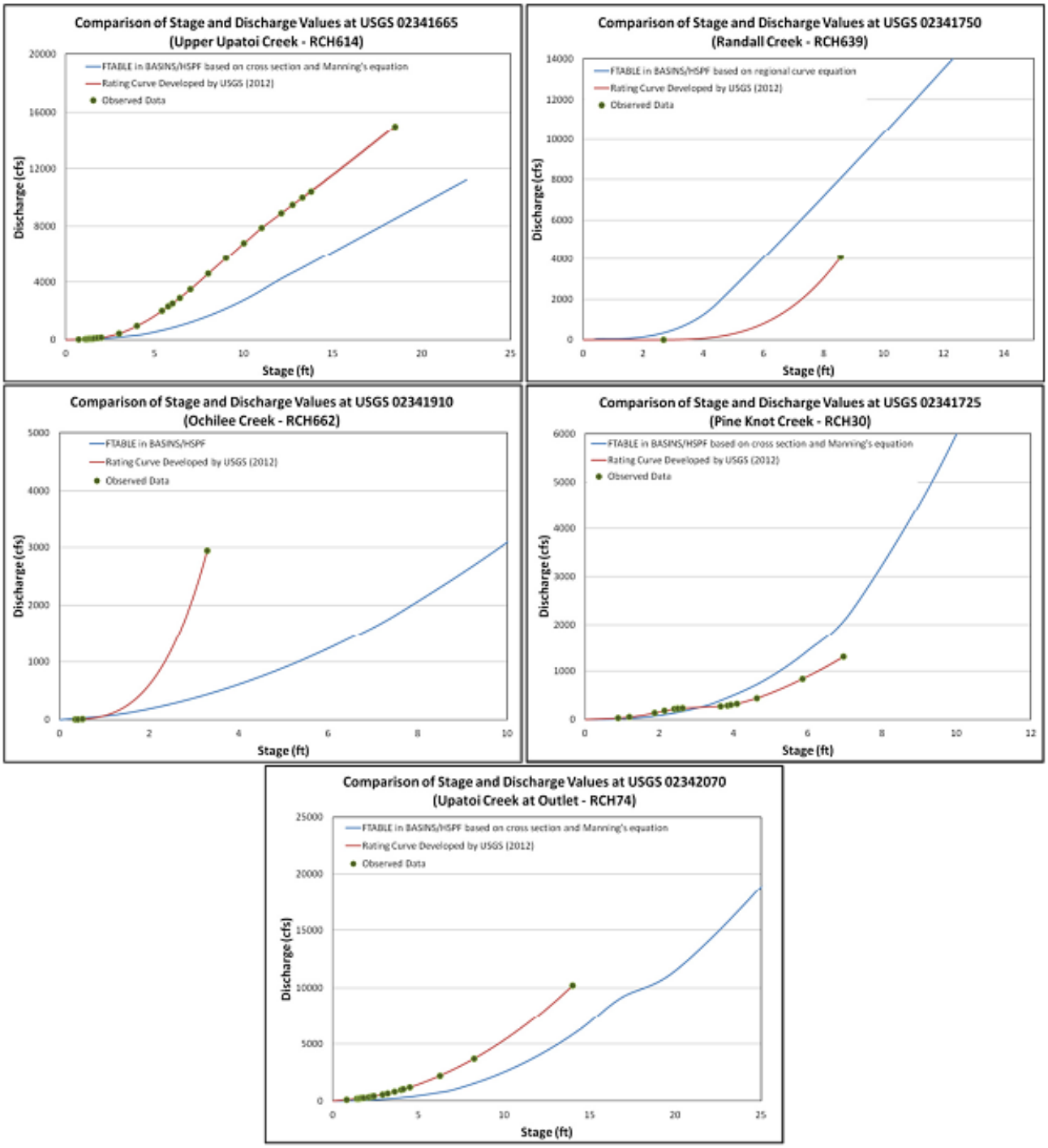


Figure 2-2. Rating Curves for US Geological Survey Gage Sites at Fort Benning.

Table 2-1. Data Requirements for Each Conditional Data Scenario

Conditional Data Scenario	Data Requirement	Data/Knowledge Availability
Blind Validation	Additional time-series data to extend modeling simulation	New flow data not used in calibration
Incremental Recalibration	Hydrologic flow data from five new gages	Adding data from the new gages one at a time and recalibrating
Application of Non-Calibrated Parameters by a New or Inexperienced Model User	Regional maps, soils data, cross-sectional data and other parameter guidance available from public sources	No data from new stream gages; modeler has no calibration experience nor knowledge of previous model calibrations
Data Quality	USGS Gage Rating System	USGS ratings for the new FB gages

Table 2-2. US Geological Survey Fort Benning Gages, Drainage Areas, and Watershed Percentages

USGS Gage	Model Reach Num	Description	Area of Watershed (sq mi)	Percent of Watershed at McBride (%)	Percent of Watershed at Outlet (%)
02341665	614	Upatoi Creek below Baker Creek, near Upatoi, GA	155.2	46	34
02341725	30	Pine Knot Creek near Eelbeck, GA	65.9	19	15
02341750	639	Randall Creek near Upatoi, GA	18.6	5	4
02341800	46	Upatoi Creek Near Columbus, GA (McBride Bridge)	339.7	100	75
02341910	662	Ochillee Creek at Ochillee, GA	63.9	N/A	14
02342070	74	Upatoi Creek at GA357, at Fort Benning, GA (Outlet)	452.0	N/A	100

sq mi = square mile.

Table 2-3 shows the period of record for each gage, including the long-term McBride Bridge gage and the five recent USGS gages whose installation was funded by SERDP. Note that the period of record varies for some of the recent gages because of initial access and installation issues; these current records vary from 3.6 years for Randall Creek to almost 4 years for Pine Knot Creek.

To implement a consistent basis for model-data comparisons, the same period of record for all of the new gages. To attain that consistency, we use regression analyses between each of the new gages and the longer McBride Bridge gage record and then use the resulting regression relationships to fill in (for any missing data) and extend the records so that a full, 4-year record (i.e., 2008–2012) is available for the model-data comparisons at the new gages. Tests were performed between the original and filled/extended data to confirm the validity of the data fill-in procedures.

Table 2-3. Daily Discharge Data for US Geological Survey Fort Benning Gages With Record Lengths

USGS Station	Station Name	Start Date	End Date	Length of Record (years)
02341665	Upatoi Creek Below Baker Creek, near Upatoi, GA[a]	10/23/2008	12/31/2011	3.2
02341725	Pine Knot Creek near Eelbeck, GA[b]	10/22/2008	09/30/2012	4.0
02341750	Randall Creek near Upatoi, GA	10/23/2008	05/16/2012	3.6
02341800	Upatoi Creek at McBride Bridge[c]	04/01/1968	07/16/2014	46.2
02341910	Ochillee Creek at Ochillee, GA	10/23/2008	05/15/2012	3.6
02342070	Upatoi Creek at GA357, at Fort Benning, GA	10/23/2008	01/31/2012	3.3

(a) Last 3 months' data are provisional.
(b) Last 8 months' data are provisional.
(c) Last 10 months' data are provisional.

2.2 DATA EXTENSION

The baseline FB Model was originally developed to simulate hydrology, sediment, and water quality from October 1, 1999, to September 30, 2006. After developing a baseline model, an enhanced model application strategy was developed that included a hybrid modeling approach and incorporated varying interception, forest cover, and infiltration by prescribing burning practices [AQUA TERRA Consultants, 2013]. To demonstrate these enhanced model application strategies, the baseline model was extended until September 30, 2008.

Under the SERDP work effort, the hydrologic simulation period for the FB Model was extended by 4 additional years (i.e., until September 30, 2012) to provide the database foundation needed for this effort. This model-period extension required extending the meteorological time series to allow for the full simulation of the FB Model to continue through 2012. Other time series that also required extension were the canopy cover of the three layers and infiltration parameter changes caused by the prescribed burning activities on the watershed.

2.2.1 Precipitation

The baseline FB Model was developed with precipitation data from 11 sources. Ten of these sources were the Ecosystem Characterization and Monitoring Initiative (ECMI) precipitation stations within the watershed, and one of them was Columbus Metro Airport (BASINS Station) with long-term data (Figure 2-3 and Table 2-4). The dataset at Columbus Metro Airport was complete and at a 1-hour interval. The ECMI stations had precipitation data at 30-minute intervals from 1999 through 2006 with some missing data. These missing data were filled by the nearest station with available data.

To demonstrate the enhanced modeling application strategy, the original FB Model was extended until September 30, 2008. The hourly precipitation data at Columbus Metro Airport and daily precipitation data at the Buena Vista station were available for the extended period.

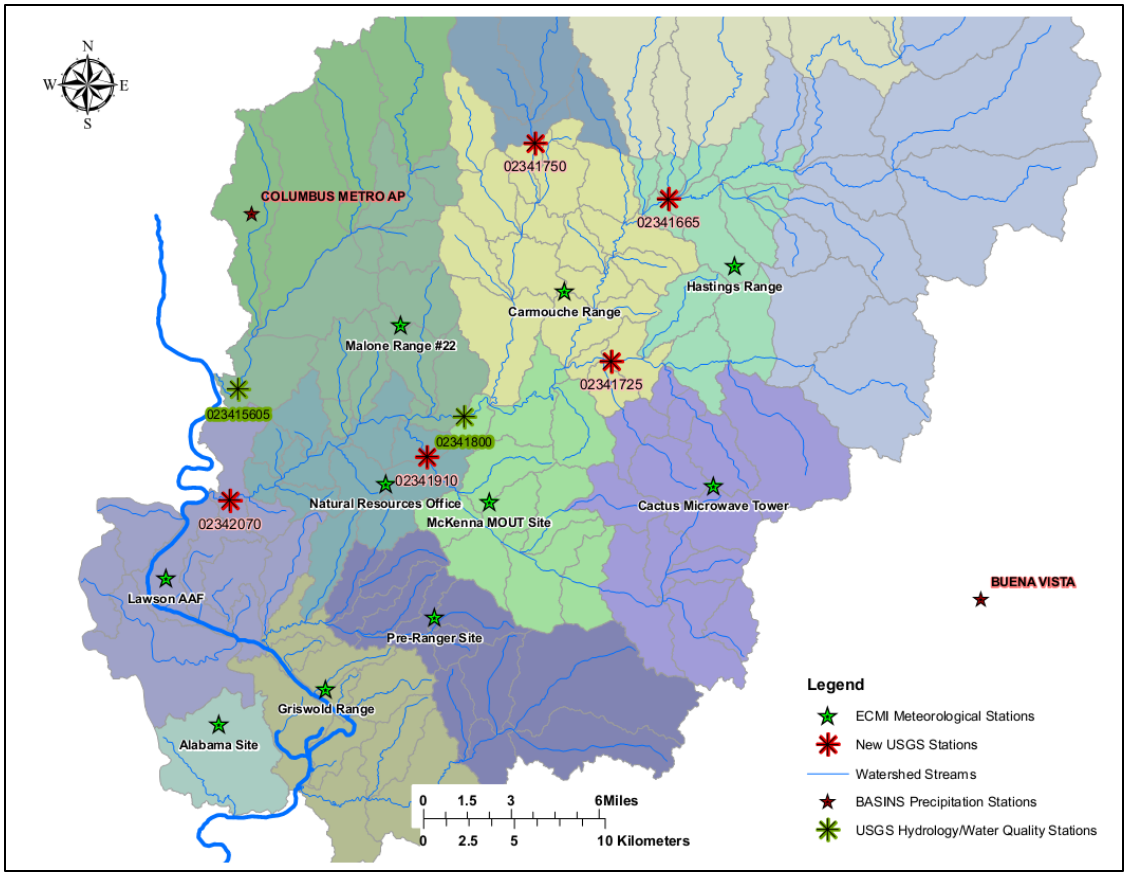


Figure 2-3. Location of Ecosystems Characterization and Monitoring Initiative, US Geological Survey, and BASINS Precipitation Stations in and Near Fort Benning.

Table 2-4. Precipitation Stations In and Near the Fort Benning Study Area [AQUA TERRA Consultants, 2007]

Site Name	Source	Start	End[a]	Average Annual (inches)	Percent Missing (%)
Natural Resources Office	ECMI	3/15/2000	12/31/2006	42.50	4.9
Griswold Range	ECMI	8/13/1999	12/31/2006	41.02	5.6
Pre-Ranger Site	ECMI	8/15/1999	6/25/2006	39.57	16.9
McKenna MOUT Site	ECMI	8/13/1999	12/31/2006	33.57	2.2
Cactus Microwave Tower	ECMI	8/16/1999	12/31/2006	41.74	6.7
Hastings Range	ECMI	2/1/2002	4/6/2006	47.58	10.2
Carmouche Range	ECMI	8/13/1999	12/31/2006	37.59	4.5
Malone Range #22	ECMI	8/14/19999	12/31/2006	41.98	3.4
Alabama Site	ECMI	8/15/1999	12/31/2006	32.50	5.6
Lawson AAF	ECMI	5/1/2003	12/31/2006	36.71	2.2
Columbus Metro Airport	BASINS Hourly	5/31/1948	3/31/2006	48.50	Complete[b]
Buena Vista	BASINS Daily	12/31/1975	12/31/2006	49.89	Complete[b]

(a) At the time of retrieval.
(b) Missing data in these records were filled as part of the BASINS development effort.

However, the quality of precipitation data at the ECMI stations was spotty for this period; approximately 60 percent of the precipitation data were missing at the stations.

To fill this missing data, the precipitation data at each of the ECMI stations from October 1, 1999, to September 30, 2006, were compared with Columbus Metro Airport and Buena Vista data (depending on proximity). Based on this comparison (and experience with the validation run for 1989–1999), a multiplication factor was developed for each ECMI station (Table 2-5). This multiplication factor was used to generate the precipitation record for when the precipitation record was missing for the ECMI stations.

Table 2-5. Ecosystem Characterization and Monitoring Initiative Precipitation Station and the Multiplier Used With Long-Term Stations to Fill and Extend the Data

ECMI Station	Multiplication Factor	Long-Term Precipitation Station
Natural	0.98	Columbus Metro Airport
Griswold	1.067	Columbus Metro Airport
Pre Ranger	1.078	Columbus Metro Airport
McKenna	0.858	Columbus Metro Airport
Cactus	0.952	Buena Vista
Hastings	0.952	Buena Vista
Carmouch	0.99	Columbus Metro Airport
Malone	1.045	Columbus Metro Airport
Alabama	0.858	Columbus Metro Airport
Lawson AAF	0.891	Columbus Metro Airport

Sources of precipitation data for the 4-year extension period (i.e., Water Year [WY] 2008 through WY 2012) include the two long-term stations, (Columbus Metro Airport and Buena Vista), and four on-site, temporary USGS stations (Table 2-6 and Figure 2-3). The precipitation data at the USGS stations, Columbus Airport, and Buena Vista were mapped to the ECMI stations (Table 2-7), based on proximity (Figure 2-3). This priority list was used to generate precipitation records at all of the ECMI stations.

2.2.2 Potential Evapotranspiration

Consistent with the approach used for the original simulation period [AQUA TERRA Consultants, 2007], daily maximum and minimum temperature data from the Columbus Metro Airport station were used to calculate PET using the Hamon method. All of the data records were available for the 4-year extension period.

2.2.3 Canopy Cover and Infiltration Time Series

In the enhanced FB Model, the canopy cover time series for the understory of forest areas were developed using the prescribed burning data [AQUA TERRA Consultants, 2013]. These time series followed a 3-year pattern, depending upon the burn schedule. This pattern was extended through September 30, 2012. The overstory for the three forest types was not affected by

Table 2-6. US Geological Survey Stations With Precipitation Data

Station	Station Location	Start Date	End Date	Percent Missing (%)
GA092166	Columbus Metro Airport	5/31/1948	2/25/2013	
GA091372	Buena Vista	12/31/1975	2/25/2013	
02341725	Pine Knot Creek near Eelback, Georgia	10/21/2008	7/22/2013	0.4
02341910	Ochillee Creek at Ochillee, Georgia	10/23/2008	5/13/2012	1.8
02342070	Upatoi Creek at GA357, at Fort Benning, Georgia	10/23/2008	5/14/2012	7.8
02341800	Upatoi Creek Near Columbus, Georgia	9/30/2007	1/14/2014	12.1

Table 2-7. ECMI Stations and Priority List for Filling Missing Precipitation Data. Columbus Metro Airport and Buena Vista use the same multiplication factor shown in Table 2.5

ECMI Station	1st priority	2nd Priority	3rd Priority	4th Priority	5th Priority
Natural Resources Office	02341910	02341800	02341725	0232070	CM AP[(a)] (0.98)
Griswold	02342070	02341910	02341800	02371725	CM AP (1.067)
Pre Ranger	02341910	02341800	02342070	02341725	CM AP (1.078)
McKenna MOUT	02341910	02341800	02341725	02342070	CM AP (0.85)
Cactus Microwave	02341725	02341800	02341910	BV[(b)] (0.952)	
Hastings	02341725	02341800	02341910	BV (0.952)	
Carmouch	02341725	02341800	02341910	CM AP (0.99)	
Malone	02341810	02341910	CM AP (1.045)		
Alabama	02342070	02341910	02341800	02341725	CM AP (1.067)
Lawson AAF	02342070	02341910	02341810	CM AP (0.891)	

(a) Columbus Metro Airport.
(b) Buena Vista.

the prescribed burning and it followed a yearly pattern. The same pattern was extended through September 30, 2012. The forest floor was assumed to be unchanged in the original model and it was kept that way for the extended period. The prescribed burning reduces the infiltration rates of forested land categories. The infiltration capacity was assumed to be reduced by 30 percent after the prescribed burning and would recover in the next 3 years [AQUA TERRA Consultants, 2013]. A similar pattern was extended through September 30, 2012.

2.2.4 Discharge

The USGS gage at McBride Bridge (02341800) was the primary calibration site for the baseline and extended model. The discharge data at this station was available through November 13, 2013, at the time of retrieval. The discharge data for the complete simulation period was downloaded and added to the WDM file. The USGS started additional monitoring at five USGS stations in FB in 2008 and collected 15-minute discharge data (Table 2-8). The data at these USGS stations were added to the WDM file and used for hydrology calibration in the incremental calibration task.

Table 2-8. Discharge Data at the US Geological Survey Gages in Fort Benning

USGS Station	Station Name	Start Date	End Date	Percent Missing (%)
02341800	Upatoi Creek at McBride Bridge	3/31/1968	11/13/2013	0.0
02341725	Pine Knot Creek near Eelback, Georgia	10/22/2008	9/29/2012	1.4
02341750	Randall Creek near Upatoi, Georgia	10/22/2008	5/15/2012	11
02341910	Ochillee Creek at Ochillee, Georgia	10/23/2008	5/14/2012	11
02342070	Upatoi Creek at GA357, at Fort Benning, Georgia	10/23/2008	01/31/2012	18
02341665	Upatoi Creek Below Baker Creek, near Upatoi, Georgia	10/23/2008	12/31/2011	22

The missing periods in the daily time series of these five new gages were filled by using regression based on the McBride Bridge daily data. This fill-in resulted in datasets that covered the 2009-2012 water years. The missing periods were primarily the first 20 days of the 4-year timespan and a period at the end that ranged from 5 months to 9 months.

2.2.5 Resegmentation Needed to Facilitate Incremental Calibration

The existing Upatoi model required some resegmentation to facilitate calibration of each of the four small creeks. The original model's meteorological segments, each of which consists of a complete set of the PERLND and IMPLND types (i.e., land use/land cover), did not coincide with the watersheds of the small creeks. Therefore, if parameter changes were made to the PERLNDs in a met segment (MS) to calibrate one of the creek watersheds, the calibration of another creek would be affected. By resegmenting and adding new MSs that coincide with the creek watersheds, calibration could be carried out on each watershed independently without affecting the simulation of the other small watersheds.

This resegmentation was performed by subdividing several of the MSs. An MS is subdivided by creating a new set of PERLNDs and IMPLNDs that have the same (initial) parameters and meteorological inputs and changing the entries in the schematic block that create the creek watershed so that they use the new MS PERLNDs and IMPLNDs.

For this task, unique ID numbers were assigned to the MSs in the model for the original model segmentation as shown in Figure 2-4. These ID numbers were generally based on the first digit of the PERLND numbers; for example, MS #1 has PERLNDs numbered 101–124. MS #10, however, has PERLNDs numbered 951–974. Only Randall Creek receives runoff from MS #5; therefore, no new MSs were needed for Randall Creek.

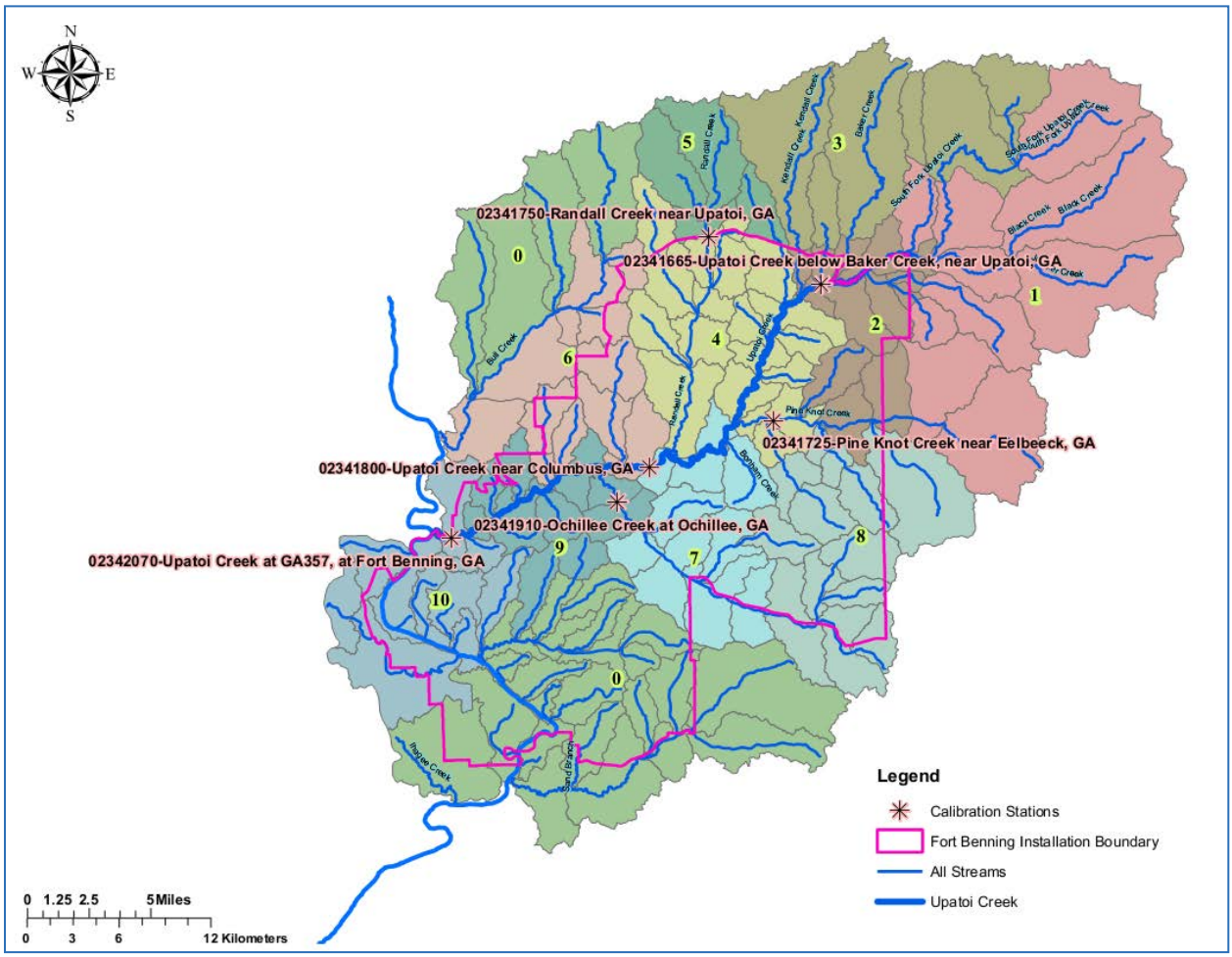


Figure 2-4. Original Meteorologic Segmentation.

Ochillee Creek receives runoff from MS #7, MS #8, and MS #9. MS #7 and MS #9 are not used by any other of the small creeks; however, MS #8 contributes to Pine Knot Creek. Therefore, MS #8 was subdivided, and the new MS #8A is used for Pine Knot Creek. The original MS #8 is used for only Ochillee Creek, along with MS #7 and #9. The PERLND numbers for MS #8A are 851–874.

Upatoi Creek below Baker Creek receives runoff from MS #1, MS #2, and MS #3, and Pine Knot Creek receives runoff from MS #1, MS #2, MS #4, and MS #8A. Therefore, MS #1 and MS #2

were duplicated, and the new MS #1A and MS #2A are used for Pine Knot Creek. The original MS #1 and MS #2 are used for Upatoi Creek below Baker Creek, along with MS # 3. The new MS #1A and MS #2A have PERLNDs numbered 151–174 and 251–274, respectively. Pine Knot Creek (as noted above) uses the original MS #4 and new MS #1A, MS #2A, and MS #8A.

MW #7 was also subdivided, since a portion of it drains directly to the McBride Bridge gage, and it was decided to isolate the incremental calibration changes on Ochillee Creek from the McBride Bridge results. The new MS #7A (PERLNDs 751–774) is used for the McBride Bridge watershed, and the original MS #7 is used for Ochillee Creek.

In summary, four new MSs were created that use (i.e., before incremental calibration) the same hydrologic parameters as the current MS #1, MS #2, MS #7, and MS #8. Figure 2-5 shows this modified segmentation.

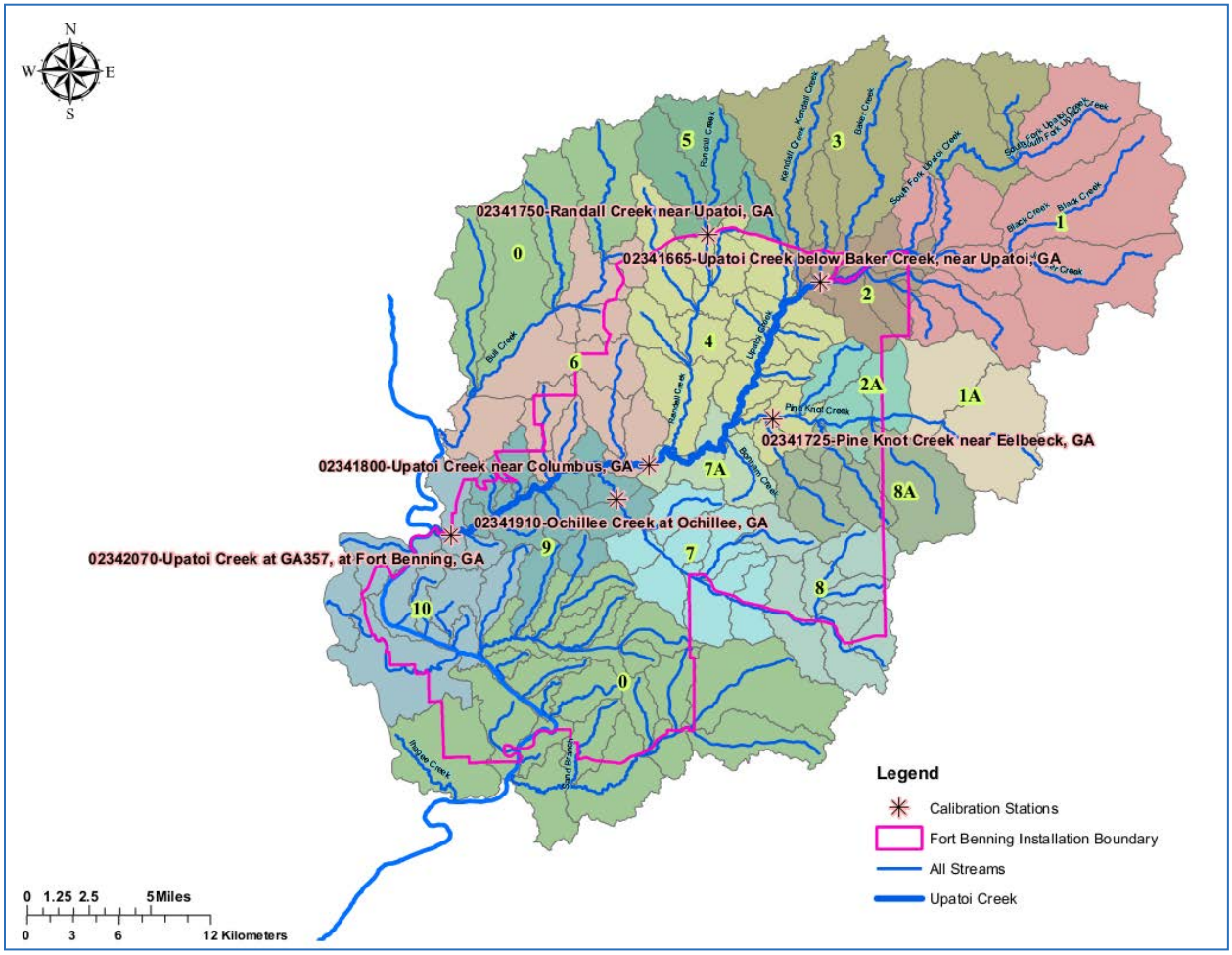


Figure 2-5. Modified Meteorologic Segmentation for Incremental Calibration.

2.3 BLIND VALIDATION

This data scenario involves comparing simulated flow variables from the FB Enhanced Baseline Model (FB Model as developed in RC-1547) with the hydrologic (flow) data observed at the new USGS gages for their extended period of record from 2008 to 2012. This analysis is essentially a blind validation (i.e., a validation is performed after the calibration has been completed and before

the new flow data being collected are available). This model is intended to demonstrate how well the calibrated model predicts the flows measured but not used in the calibration. The analysis addresses how well the model performs, not only at the McBride Bridge site where it was calibrated but also at other watershed sites where no data for calibration existed. While this analysis does not yet answer the question of how the calibration and model performance would change and improve as additional data were made available, it sets the stage for that analysis in the next conditional data scenario (i.e., the incremental calibration). As part of this analysis, the simulation period for the FB Model has been extended from 2008 through 2012, as discussed above, to allow simulation through the end of the USGS data-collection effort.

2.4 INCREMENTAL RECALIBRATION

Incremental recalibration involves comparing the simulated flow variables from the FB Model at each of the recent USGS stream gages with parameter sets that have been recalibrated in a sequential step-wise fashion, one gage at a time so that incremental improvements (and changes) in model performance metrics can be evaluated when applied to the drainage area above the stations. Thus, the percent of the upstream watershed that is now gaged becomes an important factor in the analyses.

This analysis is the focal point of this investigation and addresses the key issue of how the model metrics will improve by incrementally using additional data for successive calibration efforts. The analyses at all of the impacted gages were performed at each step to assess how the metrics are changed with each calibration effort. With improvements in upstream gages, subsequent parameter refinements may be needed in the downstream gage sites (i.e., the previous calibration may have included offsetting, or compensating, errors that could only be identified with the additional data at multiple sites).

As noted above, the relative spatial locations of the recent gages are a determining factor for which gages were calibrated and in which order. Consequently, we performed the following sequence of calibration efforts and model performance assessments:

a. Calibrated on the Upper Upatoi gage (2341665) near Upatoi, Georgia, and assessed at McBride Bridge (2341800)
b. Calibrated on the Pine Knot Creek gage (2341725) and assessed at McBride Bridge (2341800)
c. Calibrated on the Randall Creek gage (2341750) and assessed at McBride Bridge (2341800)
d. Calibrated on the Ochillee Creek gage (2341910) and assessed at Upatoi Creek outlet (2342070) GA357 at Fort Benning, Georgia
e. Calibrated at the Upatoi Creek outlet, which was a final calibration focused on only those parameters for the incremental area between the Ochillee-Upatoi Creek confluence and the outlet.

These procedures start at the upstream end of the Upatoi Watershed with the Baker gage, which drains the largest single subwatershed to the McBride Bridge gage at 46 percent (shown in Table 2-2). Pine Knot Creek is the next largest, followed by Randall Creek, which is the smallest, in terms of drainage area to McBride Bridge. The rest of the watershed, which is downstream of McBride Bridge, represents only 25 percent of the entire watershed, and 14 percent is from Ochillee Creek, which was calibrated next; its impact was assessed at the Upatoi Creek outlet. That assessment was limited to the 4 years of extended data for that outlet gage. The final step was to assess whether any adjustments might be useful for the incremental area upstream of the

outlet to improve the local calibration of that area because this represents only approximately 11 percent of the total Upatoi Creek Watershed. Because the entire model executes in a single run, the incremental calibration steps a, b, and c (above) were performed simultaneously with parameter adjustments made for all three watersheds in each calibration run. The model results were assessed after each run; subsequent adjustments were made as part of the overall calibration process.

2.5 APPLICATION OF NON-CALIBRATED PARAMETERS BY A NEW MODEL USER

This effort involved comparing the FB Model simulated flow variables at the long-term, historical USGS gage at McBride Bridge, with simulated flow variables derived from a non-calibrated parameter set estimated from regional maps, soils data, and other parameter guidance available from public sources. The subsequent calibration was performed by an engineer with experience in HSPF operations but no previous calibration experience. This analysis shows the level of model performance that can be expected from installation staff who have a water resources background but no previous HSPF experience, which is likely to occur at many installations. This analysis should provide a resource manager with some sense of the value of modeling experience and the ability of installation staff to calibrate and effectively use watershed models.

One variation of the basic analysis described above was performed, at the request of the ESTCP Project Manager, by replacing all of the existing FTABLES in the FB Model with comparable default ones derived from the BASINS procedures (based on geomorphic relationships of channel width and depth to drainage area). This process more closely reflects conditions without cross-section data.

This analysis was designed in an attempt to emulate a situation where the staff performing the parameter estimation would not be biased by any previous HSPF calibration experience and have no knowledge of the FB Model and previous calibration efforts on the Upatoi Watershed.

2.6 DATA QUALITY

We consider both quantity and quality of collected data to be considerations in a full evaluation of “data richness” as related to model performance. This discussion is directed toward ultimately comparing the relative modeling uncertainty that is attributable to data-collection error to the modeling uncertainty that is attributable to errors in model input and parameterization. Accordingly, the focus here is associated with those conditional data scenarios that include using observed flow data from one or more of the FB USGS gage stations.

Following standard USGS practice, the metadata provided with the FB USGS flow datasets assigns a rating of excellent, good, or fair for the data for each gage site. An excellent rating indicates that about 95 percent of the values are within 5 percent of the true value. Similarly, a good rating is within 10 percent and fair rating is within 15 percent; anything greater than 15 percent is considered poor. This rating system provides the basis for developing error bounds on the flow-duration curve (as well as the annual flow volumes) developed from observed data. In developing error bounds, we investigated the rating that USGS has assigned to each of the gage records at FB because the McBride Bridge record is likely to have a higher rating than the other gages.

Performance Objective #8 of the project has addressed uncertainty that is introduced into the modeling by selecting values for the most sensitive model parameters. The results of the model uncertainty runs in the Monte Carlo analyses were analyzed to determine the 90 percent

confidence interval range that represents the simulated values between the 5th and 95th percentiles. Data quality is further discussed in Section 3.6, where the uncertainty analysis results are presented.

3.0 RESULTS AND DISCUSSION

3.1 MODEL PERFORMANCE ASSESSMENT

Standard model performance metrics were applied to compare statistical results for each of the conditional data scenarios described earlier. Table 3-1 lists general calibration/validation tolerances or targets that have been used by modelers and presented in BASINS/HSPF workshops over the past 20 years [Donigian, 2002; Duda et al., 2012]. The values in the table attempt to provide some general guidance in terms of the percent-mean errors or differences between simulated and observed values, so that users can gage what level of agreement or accuracy (i.e., very good, good, fair) may be expected from the model application. The hydrology/flow targets are highlighted because they are the primary focus of this effort. The caveats at the bottom of the table indicate that the tolerance ranges should be applied to mean values and that individual events or observations may show larger differences, and still be acceptable. In addition, the level of agreement to be expected depends on many site and application-specific conditions, including the data quality, purpose of the study, available resources, and available alternative assessment procedures that could meet the study objectives.

Table 3-1. General Calibration/Validation Targets or Tolerances for HSPF Applications [Donigian, 2002; Duda et al., 2012]

Percent Difference Between Simulated and Recorded Values			
	Very Good	Good	Fair
Hydrology/Flow	< 10	10–15	15–25
Sediment	< 20	20–30	30–45
Water Temperature	< 7	8–12	13–18
Water Quality/Nutrients	< 15	15–25	25–35
Pesticides/Toxics	<20	20–30	30–40

Caveats:

Relevant to monthly and annual values; storm peaks may differ more
Quality and detail of input and calibration data
Purpose of model application
Availability of alternative assessment procedures
Resource availability (i.e., time, money, personnel)

Figure 3-1 provides value ranges for both correlation coefficients (R) and the coefficient of determination (R^2) for assessing model performance for both daily and monthly flows. Figure 3-1 shows the range of values that may be appropriate for judging how well the model is performing based on the daily and monthly simulation results. The ranges for daily values are lower to reflect the difficulties in exactly duplicating the timing of flows, given the uncertainties in the timing of model inputs (mainly precipitation).

Given the uncertain state-of-the-art, in-model performance criteria, the inherent errors in input and observed data, and the approximate nature of model formulations, absolute criteria for watershed model acceptance or rejection are not generally considered appropriate by most modeling professionals. However, most decision makers want definitive answers to the question: *How accurate is the model?*



Figure 3-1. R and R^2 Value Ranges for Model Performance [Donigian, 2002].

For any watershed modeling effort, the level of expected agreement is tempered by the complexities of the hydrologic system, the quality of the available precipitation and flow data, and the available information to help characterize the watershed and quantify the human impacts on water-related activities. These tolerances were applied to comparisons of simulated and observed mean flows, annual runoff volumes, mean monthly and seasonal runoff volumes, and daily flow-duration curves. Larger deviations would be expected for individual storm events and flood peaks in both space and time. The values shown above have been derived primarily from HSPF experience and selected past efforts on model performance criteria; however, they reflect common tolerances accepted by many modeling professionals.

The model results from the individual scenarios are shown as time series (and time averages) and as cumulative frequency curves (i.e., flow-duration curves), and all of the same model performance metrics are calculated that were used in the calibration process. Where possible, results are also shown for cases where the stream gages are nested in terms of contributing areas. Model results are compared relative to the established criteria for model performance (i.e., very good, good, fair, and poor).

Success of this exercise is measured by the ability of the set of conditional data scenarios to delineate the change in model performance per category of data quantity and quality. The performance tests and comparisons developed in these scenarios are specific to the data and datasets available on FB and based on supplementing selected types of data and/or knowledge for the calibration process.

In comparing the model performance for each of the conditional data scenarios described above, we tabulated the results from the model runs for the various graphical displays and model performance metrics described below for the FB Baseline Model; the comparisons provided in this section are examples of the components of our weight-of-evidence approach to model performance assessment as applied in this effort. These comparisons of observed and simulated values include the following:

- Annual and monthly flows
- Daily flows
- Daily flow-duration (cumulative frequency) curves
- Flow correlation and error statistics
- Storm hydrographs.

Table 3-2 provides monthly and daily targets for selected correlation and error statistics for monthly and daily flow comparisons, which represent an overall good calibration and which relates to our performance objective. Section 3.2 contains tables and figures that represent these comparisons. This weight-of-evidence approach to model performance testing produces an aggregate assessment based on all of these graphical results and comparison metrics to evaluate the model performance changes that are associated with each conditional data scenario for model application and calibration.

Table 3-2. Monthly and Daily Statistics Targets for a Good Calibration of Flow Volume

Statistics	Monthly	Daily
Correlation Coefficient	> 0.87	> 0.84
Coefficient of Determination	> 0.70	> 0.70
Mean Error (%)	< 15%	< 20%
Model Fit Efficiency	> 0.60	> 0.50

The target values in Table 3-2 are generally consistent with those presented by Moriasi et al. [2007], which is a common reference on model evaluation guidelines published by the American Society of Agricultural and Biological Engineers (ASABE).

3.2 FORT BENNING ENHANCED BASELINE MODEL RESULTS

This section is extracted from Appendix C of the RC-1547 Final Report [AQUA TERRA Consultants, 2013] and summarizes the final hydrology model results for the FB Enhanced Baseline Model. This summary is presented here because it is the baseline to which the model performance assessments in this task are compared to evaluate the degree of change in model results for each of the scenarios that were previously discussed.

The FB watershed was simulated for WYs 2000–2006 (October 1999–September 2006) in the original Baseline Model simulation [AQUA TERRA Consultants, 2010], and for the Enhanced Baseline FB Model, the simulation period was extended for an additional 2 years, through WY 2008 (i.e., September 2008). For this Task 5 investigation, the simulation is extended through WY 2012.

As discussed in previous reports, the calibration process involves multiple model-data comparisons of observed and simulated flow that usually start with a daily flow comparison (Figure 3-2) and the daily flow-duration curves (Figure 3-3). In the Upatoi Watershed, the daily simulated flow matched well with observed daily flow. In addition, the seasonal patterns are well-represented and the dynamic nature of the daily flow simulation clearly represents the observed values. The flow-duration comparison in Figure 3-3 illustrates a good-to-very good calibration, with only slight deviations at mid-range and high flows.

To further evaluate the model performance, we calculated the annual average statistics of the model (Table 3-3) and different error terms (Table 3-4). The average annual statistics show that the model simulates the flow close to observed flow, and total volume has an error of 7.5 percent, which is less than the criterion for total flow. Most of the errors are within the acceptable limits, except 50 percent low flow and seasonal volume error. The seasonal volume error could be improved with a denser network of precipitation gages, because the summer storms in the southeastern US are very localized.

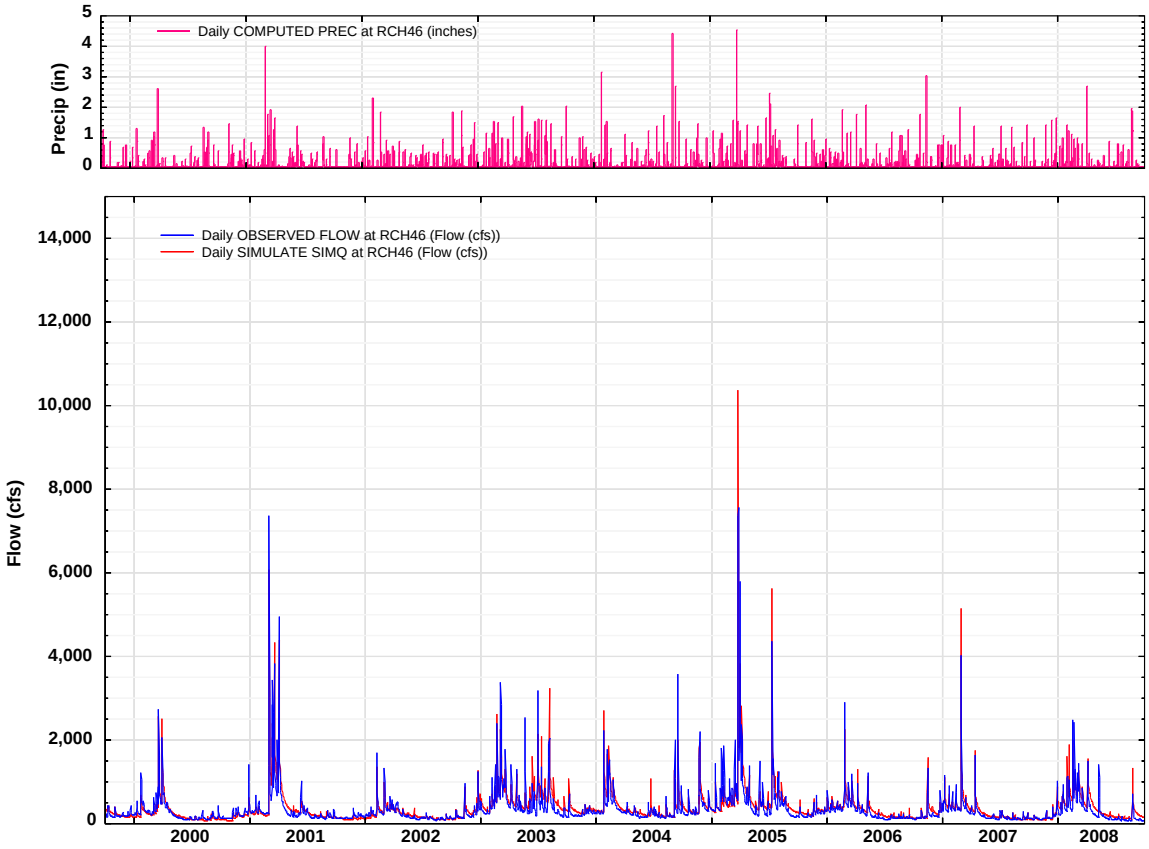


Figure 3-2. Comparison of Observed and Simulated Flow in Upatoi Creek at McBride Bridge for the Complete Calibration Period.

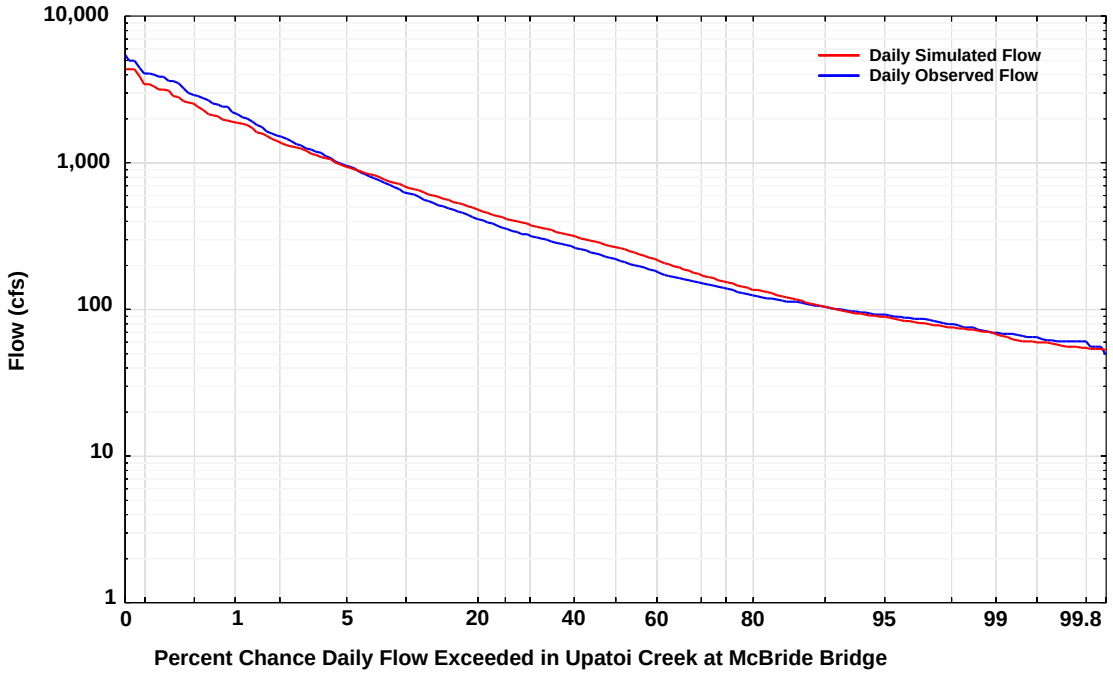


Figure 3-3. Frequency-Duration Curve of Flow in Upatoi Creek at McBride Bridge.

Table 3-3. Annual Average Statistics of Flow in Upatoi Creek at McBride Bridge for the Calibration Period

	Observed Total Runoff	Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow
Total (in)	13.4	14.4	2.3	4.6
10 Percent High (in)	5.1	4.8		
25 Percent High (in)	7.8	8.0		
50 Percent High (in)	10.6	11.3		
50 Percent High (in)	2.8	3.2		
25 Percent Low (in)	1.1	1.1		
10 Percent Low (in)	0.4	0.3		
Storm Volume (in)	3.0	2.9	1.0	1.3
Average Storm Peak (cfs)	1,381	1,293	954.6	483.1
Baseflow Recession Rate (dimensionless)	1.0	1.0		
Summer Volume (in)	2.4	2.9		
Winter Volume (in)	3.8	3.7		
Summer Storms (in)	0.6	0.6	0.2	0.2
Winter Storms (in)	0.7	0.6	0.3	0.3

in = inches.
cfs = cubic feet per second.

Table 3-4. Error Terms and Criteria for the Annual Average Flow Statistics

Errors	Current	Criteria	Meets Criteria?
Total Volume (%)	7.5	10	OK
10 Percent Highest Flows (%)	–5.2	15	OK
25 Percent Highest Flows (%)	1.6	10	OK
50 Percent Highest Flows (%)	6.1	10	OK
50 Percent Lowest Flows (%)	12.9	10	Fails
25 Percent Lowest Flows (%)	4.3	10	OK
10 Percent Lowest Flows (%)	–2.8	10	OK
Low-Flow Recession	–0.01	0.03	OK
Storm Volumes (%)	–5.6	15	OK
Seasonal Volume Error (%)	22.7	20	Fails
Average Storm Peak (%)	–6.3	15	OK
Summer Volume Error (%)	20.0	20	OK
Winter Volume Error (%)	–2.8	15	OK
Summer Storm Volume Error (%)	–3.8	15	OK
Winter Storm Volume Error (%)	–9.3	15	OK

Comparing annual flow volumes for each year during the calibration period shows that simulated flow volumes are generally greater than observed flow volume (Table 3.5). The variation in the volume and distribution of rainfall during the calibration period is responsible for this distribution. In 5 years out of 9 years, the simulated runoff was greater than observed by more than 10 percent, but conversely, 4 years out of 9 years are less than 10 percent different. Note that the biggest difference was in the extended period of 2008 and that large difference likely biased the volume error term in the positive direction. The years 2007 and 2008 also required missing data to be filled in, which can often lead to volume errors in the model comparison. Those differences in the 2007–2008 period likely had a bigger impact on the error terms than the model enhancements.

Table 3-5. Simulated and Observed Yearly Flow Volume (Inches) for Calibration Period

Year	Precipitation	Simulated	Observed	Residual	Percent Error (%)
2000	31.3	9.1	10.0	–0.8	–8.2
2001	41.1	15.2	15.3	–0.0	–0.2
2002	32.5	7.4	7.9	–0.5	–6.7
2003	58.1	21.4	19.0	2.4	12.4
2004	44.1	14.9	12.9	2.0	15.6
2005	53.5	24.4	23.8	0.6	2.4
2006	37.4	12.6	10.8	1.8	16.3
2007	37.3	11.5	10.1	1.4	14.2
2008	38.8	13.3	11.0	2.3	20.9
Mean	**41.6**	**14.4**	**13.4**	**1.0**	**7.5**

The monthly flow volumes were also compared (Table 3-6 and Figure 3-4). The percent error in monthly flow volume was as high as 27 percent for June and as low as –7 percent for February. In general, the flow was over-simulated in warmer months compared to colder months. Separate statistics were calculated to compare monthly and daily flow volumes (Table 3-7). The statistics improved from daily to monthly volumes, which underscores that calibrating daily flow volumes is very difficult. According to the model performance criteria specified in the Baseline Report, the model performance is good for daily flows and very good for monthly flows.

3.3 BLIND VALIDATION

Selected statistical model results of the blind validation period (WY 2009–2012) are shown below (Table 3-8 and Table 3-9) for the six locations. Within these two tables, the statistical performance metrics are ordered upstream to downstream from left to right in the tables, and definitions and formulas for the metrics are provided in Appendix C. The top part of Table 3-8 contains monthly values and the bottom part contains daily values. Note that this blind validation is essentially a validation performed after the calibration has been completed and before the new flow data were collected and available.

Table 3-6. Comparison of Simulated and Observed Average Monthly Flow Volume (Inches)

Month	Simulated	Observed	Residual	Percent Error (%)
October	0.66	0.56	0.10	18.2
November	0.77	0.75	0.02	2.4
December	0.92	0.90	0.02	2.0
January	1.20	1.20	0.00	–0.4
February	1.60	1.72	–0.12	–6.7
March	2.66	2.65	0.00	0.2
April	1.95	1.69	0.27	15.7
May	1.00	0.85	0.15	18.0
June	0.91	0.72	0.20	27.4
July	1.08	0.93	0.16	16.8
August	0.92	0.79	0.13	16.9
September	0.75	0.67	0.08	12.7
Total	**14.42**	**13.42**	**1.01**	**7.5**

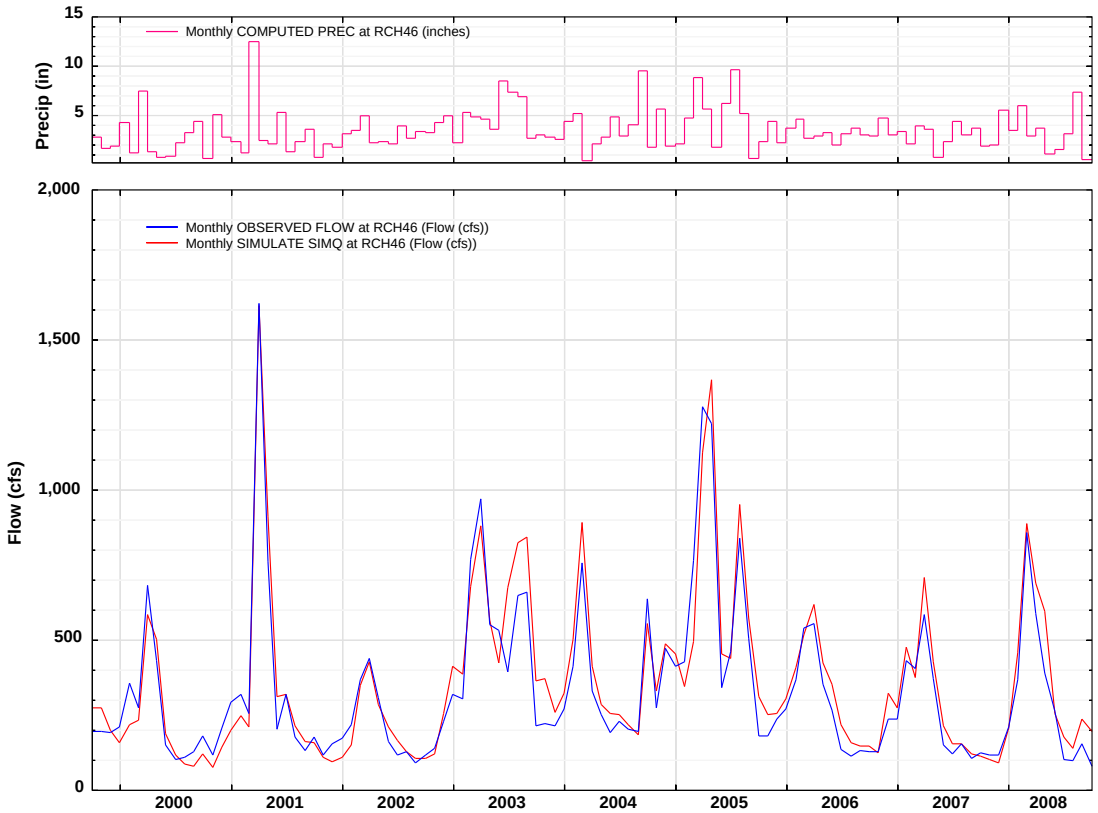


Figure 3-4. Monthly Flow Volume for the Calibration Period.

Table 3-7. Monthly and Daily Statistics of Flow Volume for Water Years 2000–2008

Statistics	Monthly	Daily
Correlation Coefficient	0.96	0.89
Coefficient of Determination	0.92	0.79
Mean Error (cfs)	24.9	25.2
Mean Absolute Error (cfs)	64.0	105.4
RMS Error (cfs)	83.5	211.8
Model Fit Efficiency	0.90	0.78

Table 3-8. Monthly and Daily Statistics of Flow for Extended Period (Water Years 2009–2012) – Blind Validation

Statistic Performance Metrics	Monthly					
	Upatoi Creek Below Baker Creek	Pine Knot Creek	Randall Creek	Upatoi Creek McBride Bridge	Ochillee Creek	Upatoi Creek at GA357 (outlet)
Correlation Coefficient	0.944	0.885	0.832	0.966	0.951	0.956
Coefficient of Determination	0.892	0.782	0.692	0.933	0.904	0.915
Mean Error (cfs)	–6.8	3.3	6.1	104.5	17.1	154.6
PBIAS–Mean Percent Error (%)	–2.8	3.6	30.	26	24	29
Mean Absolute Error (cfs)	79.1	47.0	12.0	121.3	22.8	168.4
RMS Error (cfs)	146.3	67.5	19.1	175.0	35.1	261.2
RSR - RMSE-Observations Standard Deviation Ratio	0.43	2.0	0.58	0.40	0.49	0.45
Model Fit Efficiency	0.816	–3.038	0.656	0.835	0.759	0.793
Daily						
Correlation Coefficient	0.772	0.704	0.77	0.832	0.819	0.82
Coefficient of Determination	0.596	0.496	0.593	0.692	0.672	0.673
Mean Error (cfs)	–7.5	3.1	6.0	103.3	16.8	153.1
PBIAS - Mean Percent Error (%)	–3.1	3.4	30.	26.	24.	29.
Mean Absolute Error (cfs)	131.3	52.0	16.5	175.6	38.3	246.6
RMS Error (cfs)	438.8	106.3	52.3	428.8	81.1	578.5
RSR–RMSE-Observations Standard Deviation Ratio	0.68	1.8	0.70	0.60	0.60	0.64
Model Fit Efficiency	0.539	–2.261	0.512	0.644	0.639	0.578

Table 3-9. Error Terms for Extended Period (Water Years 2009–2012)–Blind Validation

Error Terms	Upatoi Creek Below Baker Creek	Pine Knot Creek	Randall Creek	Upatoi Creek McBride Bridge	Ochillee Creek		Upatoi Creek at GA357
Error in Total Volume (%)	–3.1	3.4	30.0	25.8	23.6		29.1
Error in Average Storm Peak (%)	–41.5	67.4	–10.7	21.5	–6.0		

This validation is intended to demonstrate how well the calibrated model predicts the measured flows that were not used in the calibration. The analysis addresses how well the model performs, not only at the McBride Bridge site where it was calibrated for the earlier historic period but also at the other watershed sites where no data for calibration existed. Data were subsequently collected by the USGS as part of this effort.

The validation at the Upatoi Creek McBride Bridge gage shows that several metrics are lower statistically than for the calibration period at the same gage. However, with the exception of the total volume error, which is borderline high at 26 percent, the extended period statistics are still within or very close to the targets that are considered a good and acceptable simulation. The same can be stated for the Upatoi Creek Watershed outlet gage at GA357.

For the other small gages, the statistics are generally in the fair-to-good categories with the exception of total flow at Randall and Ochillee Creeks and the overall flow simulation and daily statistics at Pine Knot Creek. The flow-duration curves for all six gages are shown in Figures 3-5 through 3-10. Pine Knot Creek demonstrates a flow regime that is quite different from the other watersheds as is indicated by the flow-duration curve in Figure 3-6. This watershed is in the coastal plain and demonstrates a more constant groundwater contribution and relatively low storm peaks, compared to the other gage sites; the minimum observed flow is 50 cubic feet per second (cfs), and the range of observed flows is low (only 50–600 cfs). By comparison, the flow-duration curve for Ochillee Creek (Figure 3-9), which is the same size watershed and adjacent to Pine Knot, ranges from 5 cfs to 1,500 cfs over the same time period, which is more than three orders of magnitude. The Ochillee Creek simulation statistics are very similar to the McBride Bridge statistics, and the hydrology parameter set that works well at the McBride Bridge gage and Ochillee Creek is unlikely to adequately represent the Pine Knot Creek watershed. This conclusion is borne out from the corresponding flow-duration curves (i.e., Figure 3-6 for Pine Knot Creek versus Figures 3-8 and 3-9 for McBride Bridge and Ochillee Creek, respectively).

Tables 3-8 and 3-9 show performance metrics data; these metrics are defined in Appendix C. Given the number of different gage sites, comprehending the general assessment of the blind validation is challenging without some thresholds or targets for guidance. Moriasi et al. [2007] suggests that an acceptable model performance can be established with an MFE (also NSE) greater than 0.50, an RSR (RMSE-observations standard deviation ratio) less than 0.70, and a PBIAS less than 25 percent for monthly values or 35 percent for daily values. Using these suggested guidelines and analyzing the metrics, we can state the following:

1. Based on the MFE, all of the sites show acceptable simulations, except Pine Knot Creek, which is the only site with an MFE less than 0.50
2. Based on PBIAS, all of the sites, including Pine Knot Creek, show values less than 25 percent to 35 percent, but several sites (e.g., Randall and Upatoi Creek at GA357) are borderline and near the upper end of that range.

3. Based on the RSR, all sites except Pine Knot Creek show values less than or equal to 0.70, but again, Randall is borderline.
4. Based on the correlation metrics (i.e., correlation coefficient, coefficient of determination), as compared to the Figure 3-1 performance range, the values are essentially all greater than 0.50, with Pine Knot being borderline at 0.496.
5. This analysis has further reinforced the need for the weight-of-evidence approach to model performance, which demonstrates that relying on any single performance metric can lead to inaccurate assessments of model capabilities and utility. Graphical comparisons, such as the flow-duration curves and time-series plots, further supplement the model assessment procedures to provide visual confirmation of the model's ability to represent observed data. This is especially relevant to Pine Knot Creek, which shows poor agreement for both the flow-duration curve (Figure 3-6) and daily flow time-series plots (Appendix A). This analysis of the values in Tables 3-8 and 3-9 demonstrates the fallacy of using only one or two metrics to assess model performance.

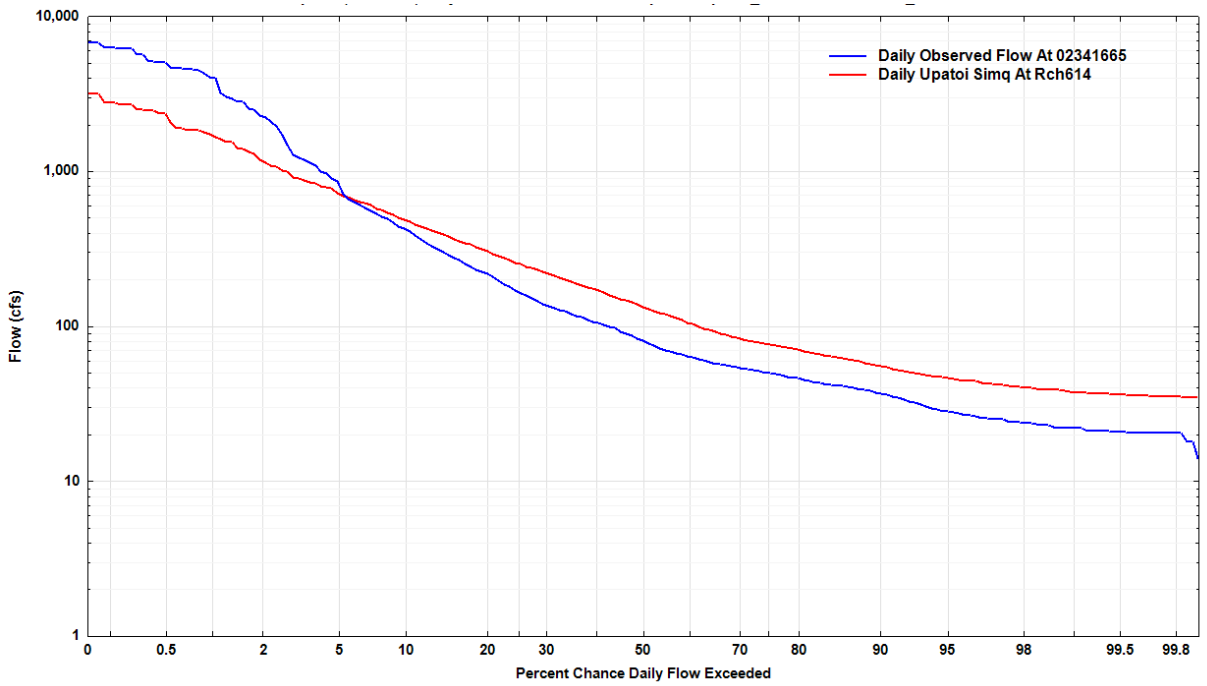


Figure 3-5. Flow-Duration Graph for Upatoi Creek Below Baker Creek–Extended Period (Blind Validation).

In summary, the blind validation appears to be relatively successful and implies that a single gage may be adequate for representing the entire watershed, but the simulation is less successful at the smaller tributary sites. This exercise suggests that the McBride Bridge calibration parameters provide a fair-to-good overall simulation for the extended period for most of the other sites, but they do not work very well for the Pine Knot Creek Subwatershed. The total flow volume error is also a concern, and PBIAS/Mean Error at four of the larger gages is greater than 23 percent over the 4-year extended period and generally higher than Moriasi's thresholds for a satisfactory simulation [Moriasi et al., 2007]. This data implies that using a single flow gage for a relatively large watershed like Upatoi Creek at 300–500 square miles (sq mi), may provide a reasonable simulation for *some* smaller tributary subwatersheds. The same level of accuracy cannot be expected or guaranteed for *all* of the subwatersheds.

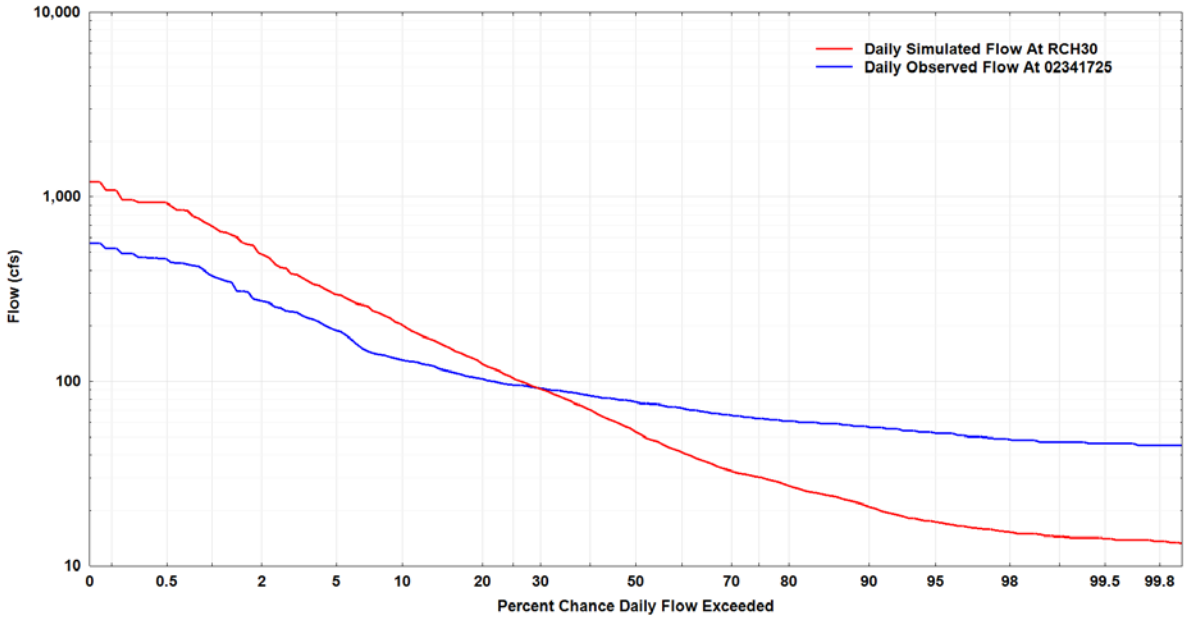


Figure 3-6. Flow-Duration Graph for Pine Knot Creek–Extended Period (Blind Validation)

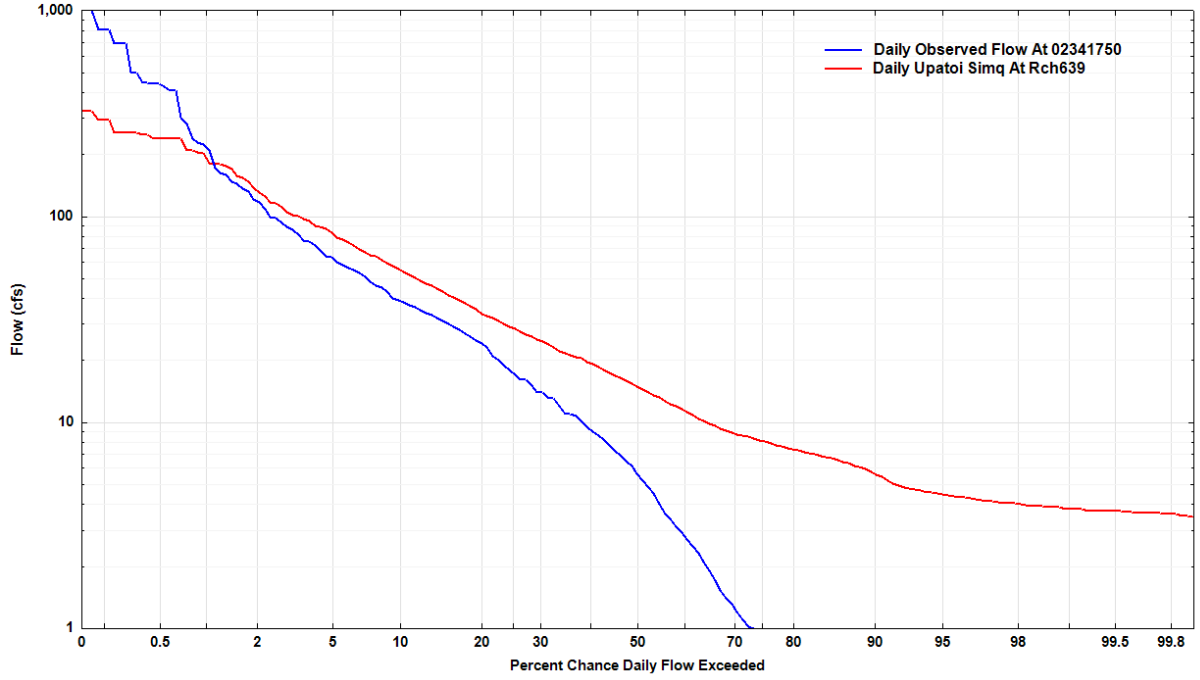


Figure 3-7. Flow-Duration Graph for Randall Creek–Extended Period (Blind Validation).

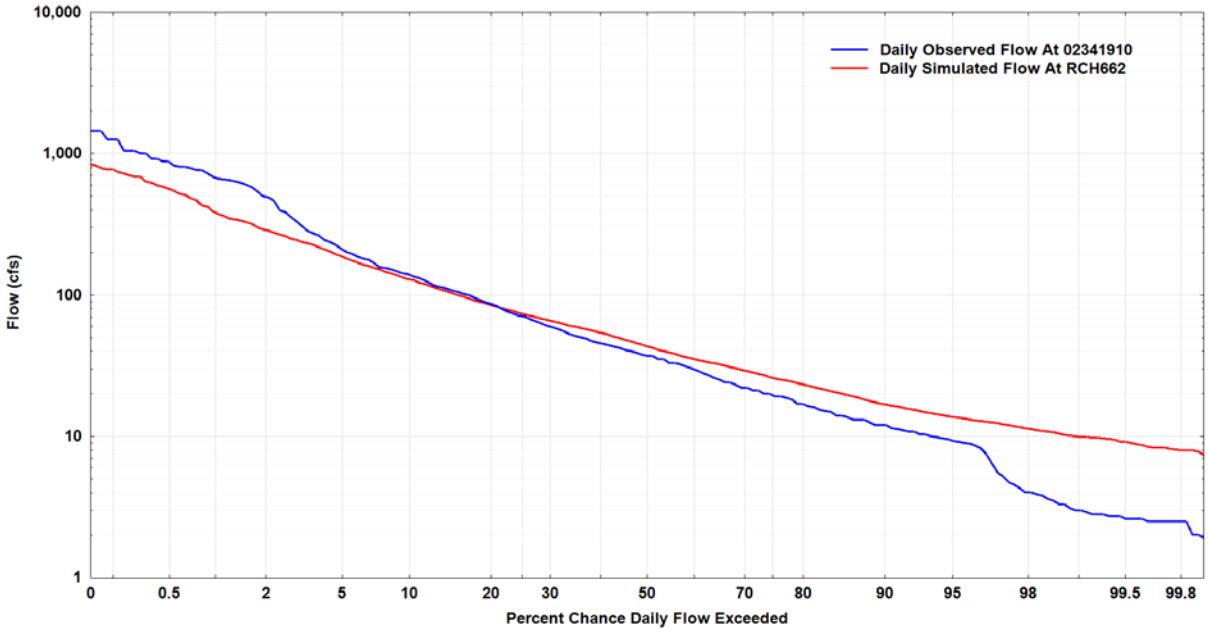


Figure 3-8. Flow-Duration Graph for Ochillee Creek–Extended Period (Blind Validation).

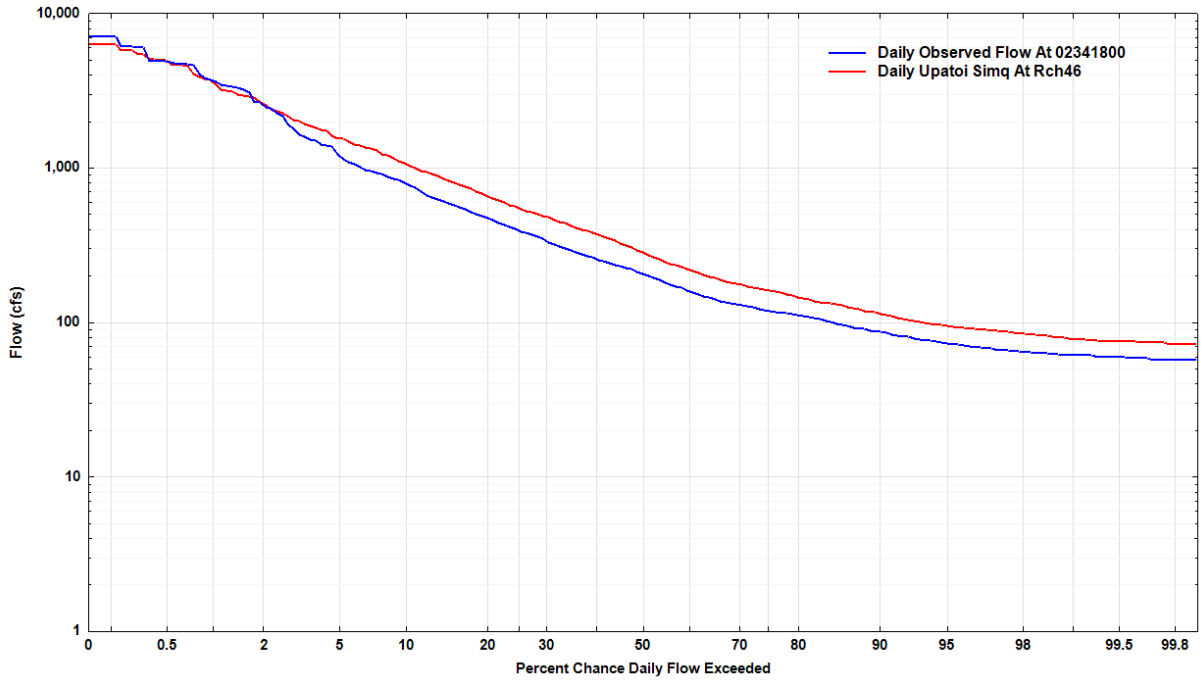


Figure 3-9. Flow-Duration Graph for Upatoi Creek at McBride Bridge–Extended Period (Blind Validation).

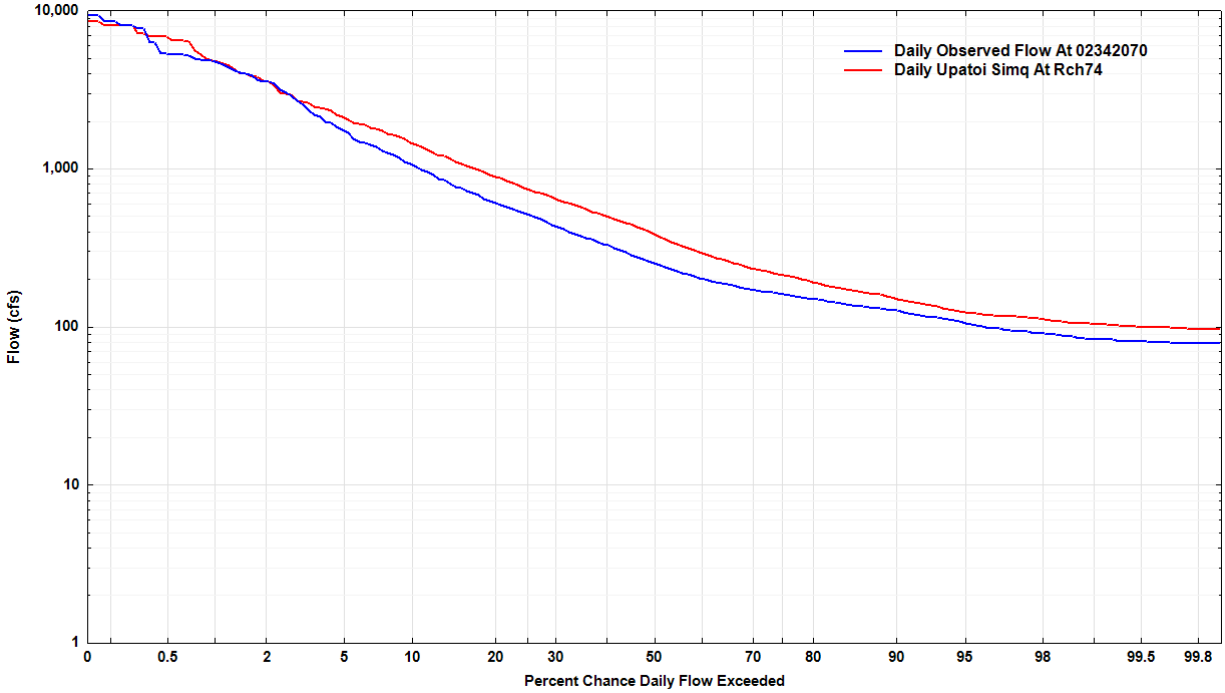


Figure 3-10. Flow-Duration Graph for Upatoi Creek at GA357–Extended Period (Blind Validation).

3.4 INCREMENTAL CALIBRATION

The approach to incremental calibration was outlined in Section 2.1 These steps involved the following:

a. Calibrating on the Upper Upatoi gage (2341665) near Upatoi, Georgia, and assessing at McBride Bridge (2341800)

b. Calibrating on the Pine Knot Creek gage (2341725) and assessing at McBride Bridge (2341800)

c. Calibrating on the Randall Creek gage (2341750) and assessing at McBride Bridge (2341800)

d. Calibrating on the Ochillee Creek gage (2341910) and assessing at Upatoi Creek outlet (2342070) GA357 at Fort Benning, Georgia

e. Calibrating at the Upatoi Creek outlet, which was a final calibration that focused on only those parameters for the incremental area between the Ochillee-Upatoi Creek confluence and the outlet.

The incremental calibration steps *a*, *b*, and *c* were performed simultaneously with parameter adjustments made for all three of the watersheds in each calibration run, followed by calibration runs for the remaining two sites. The following subsections discuss the incremental calibration effort for each gage site.

3.4.1 Upatoi Creek Below Baker Creek

This watershed represents 45 percent of the area of the calibrated watershed at the McBride Bridge gage, so the blind validation results were expected to be fairly good. Furthermore, this

watershed is dominated by the upland portion of the watershed, which is also a large fraction of the area that drains to the McBride Bridge gage. The total simulated flow was only 3 percent low, and the statistics were very good (monthly Nash Sutcliffe efficiency and correlation coefficient equals 0.816 and 0.944, respectively). The high flows were under-simulated, and the low flows were over-simulated. As a result, our initial calibration focused on reducing infiltration on the PERLNDs; we also investigated increasing the rainfall slightly along with increases to the loss to deep groundwater. The final values of infiltration are reduced by 75 percent from the original calibrated values. The precipitation factor is increased by 1.02, and the deep groundwater fraction remains at 0.1. The resulting comparison is 1 percent under-simulated in total flow, and the monthly statistics mentioned above improved to 0.883 and 0.954. The high-flow/low-flow distribution is good; however, some errors were found in seasonal volumes and storm statistics. The statistics are shown in Tables 3-10 and 3-11 for comparison to the blind validation results. The flow-frequency graph for the Upatoi Creek below Baker Creek is shown in Figure 3-5. Hydrographs (arithmetic and log scales) are provided in Appendix A.

Table 3-10. Monthly and Daily Statistics of Flow for Incremental Recalibration (Extended Period Water Years 2009–2012)

Statistic	Monthly					
	Upatoi Creek Below Baker Creek	Pine Knot Creek	Randall Creek	Upatoi Creek McBride Bridge	Ochillee Creek	Upatoi Creek at GA357
Correlation Coefficient	0.954	0.924	0.901	0.970	0.948	0.959
Coefficient of Determination	0.909	0.855	0.811	0.941	0.899	0.919
Mean Error (cfs)	–1.2	–4.2	1.3	28.0	0.6	30.8
PBIAS–Mean Percent Error (%)	–0.49	–4.6	6.4	7.0	0.81	5.9
Mean Absolute Error (cfs)	69.4	14.7	8.2	70.9	17.1	112.0
RMS Error (cfs)	116.0	18.3	14.4	108.0	24.9	166.0
RSR–RMSE-Observations Standard Deviation Ratio	0.34	0.54	0.44	0.25	0.34	0.29
Model Fit Efficiency	0.883	0.703	0.804	0.937	0.879	0.916
	Daily					
Correlation Coefficient	0.704	0.782	0.832	0.832	0.810	0.823
Coefficient of Determination	0.496	0.611	0.693	0.692	0.657	0.678
Mean Error (cfs)	–2.0	–4.3	1.2	27.2	0.4	29.9
PBIAS–Mean Percent Error	–0.83	–4.7	6.2	6.8	0.57	5.7
Mean Absolute Error (cfs)	131.0	19.9	12.8	139.6	31.1	185.0
RMS Error (cfs)	477.0	40.3	41.8	433.0	81.0	546.0
RSR–RMSE-Observations Standard Deviation Ratio	0.74	0.68	0.56	0.60	0.60	0.61
Model Fit Efficiency	0.455	0.531	0.689	0.637	0.639	0.623

3.4.2 Pine Knot Creek

The Pine Knot Creek blind validation results indicated that the gage is likely to be dominated more by groundwater than at the other gage sites, because the recorded flows range only between 50 and 600 cfs, as shown by the very flat flow-duration curve (Figure 3-6). The overall volume error

was small at 3.5 percent; however, high flows were too high and low flows were too low. The recalibration efforts focused on increasing infiltration and nominal upper zone soil-moisture storage (UZSN) to decrease the high flows and increases to lower zone nominal soil-moisture storage (LZSN) to increase the baseflow and also to evaporate some of the excess water added to the subsurface by the infiltration increases. Loss to deep groundwater was reduced and the baseflow evapotranspiration (ET) parameter was reduced to 0 to increase the baseflow in interim runs, but the final baseflow deep loss factor was set to 0.2, which is an increase from the original value of 0.04.

Table 3-11. Error Terms for Incremental Recalibration (Extended Period Water Year 2009–2012)

Error Term	Upatoi Creek Below Baker Creek	Pine Knot Creek	Randall Creek	Upatoi Creek McBride Bridge	Ochillee Creek	Upatoi Creek at GA357
Total Volume (%)	–0.8	–4.6	6.2	6.8	0.6	5.7
Average Storm Peak (%)	14.7	–10.4	–10.8	25.9	–2.0	10.8

Several runs were made with increased rainfall inputs to investigate whether possible uncertainty in the rainfall could be combined with parameter adjustments to increase the baseflow and ET by increases in infiltration. These runs were not initially productive.

Several series of runs were made to investigate the effect of varying the nonlinear groundwater recession parameter (KVARY) along with the groundwater recession coefficient (AGWRC). The best agreement was obtained with a very high value of AGWRC 0.997–0.999) and a relatively small non-zero value of KVARY (0.3). Note that these were the adjustments that were the most effective in calibrating this watershed. During the extensive sets of calibration runs on Pine Knot Creek, adjustments were also made to the interflow parameters INTFW and IRC. In the final parameter set, INTFW was reduced to a range of 0.8–2.0 from the original value of 7.0. IRC was initially increased to try to slow the interflow recession but was later decreased to a range of 0.2–0.3.

Once the groundwater recession parameter adjustments were made, the flow comparison was improved, another set of runs was adjusted for the rainfall factor, and the deep groundwater loss factor were made to improve parameter consistency with nearby watersheds. In the final runs, the rainfall factor was increased by 5 percent and the groundwater loss factor was increased to 0.2. These adjustments resulted in a total volume error to –5 percent and greatly improved the high-flow low-flow distribution. The Nash Sutcliffe and correlation coefficient statistics improved from –3.0 and 0.885 to 0.702 and 0.925, respectively (Tables 3-10 and 3-11). Virtually all of the calibration statistics satisfy our criteria. The recalibrated flow-frequency graph for Pine Knot Creek is shown in Figure 3-6, and the agreement is now much more consistent with the other sites. Hydrographs (arithmetic and log scales) are provided in Appendix A.

3.4.3 Randall Creek

The Randall Creek Watershed is relatively small (18 sq mi), and the blind validation results were under-simulated at high flows and greatly over-simulated at low flows, which resulted in 30 percent over-simulation in total volume. The monthly statistics were fair (MFE = 0.656 and Correlation Coefficient = 0.832). Calibration focused primarily on reducing infiltration and increasing the LZSN to increase the high flows and reduce the low flows and, therefore, the total

volume. The final infiltration index (INFILT) was reduced by 75 percent of the original value, and the LZSN was increased to approximately twice its original value. The low flows were difficult to reduce entirely with LZSN, so the precipitation factor was reduced to 0.97, the loss to deep groundwater was increased to 0.4, and the baseflow ET parameter was increased to 0.09 to improve the comparison at low flow levels. Final adjustments to baseflow ET (0.06) and LZSN (20 percent increase) were made to improve parameter consistency with the nearby watersheds. The UZSN parameter was also decreased slightly to improve the high-flow agreement. The interflow and groundwater recession parameters were also adjusted slightly. These adjustments improved the total volume error to 4 percent high and greatly improved the high-flow/low-flow distribution. The Nash Sutcliffe and correlation coefficient statistics improved to 0.804 and 0.901, respectively (Tables 3-10 and 3-11). The average storm peaks are still too low by 11 percent and the low flows are still slightly too high. However, the observed low flows that the model has difficulty representing are consistently below 1 cfs. The flow-frequency graph for Randall Creek is shown in Figure 3.7. Hydrographs (arithmetic and log scales) are provided in Appendix A.

3.4.4 Ochillee Creek

The Ochillee Creek blind validation results were fair with a 24 percent over-simulation in total flows, primarily caused by the low flows, which was similar to Randall Creek. The high flows were fairly good, and the statistics represented that. The monthly Nash Sutcliffe and correlation coefficient statistics were 0.759 and 0.951, respectively. The recalibration focused on reducing the total volumes primarily with increases to the LZSN, the loss to deep groundwater, and the baseflow ET parameter. The LZSN was increased a total of approximately 200 percent, and the deep groundwater and baseflow ET parameters increased to 025 and 0.05, respectively. The UZSN parameter was also reduced by 40 percent to increase the high flows. These changes improved the total flow error to 0.6 percent and improved the Nash Sutcliffe statistic to 0.879; the correlation coefficient slightly decreased to 0.948. Most other statistical measures of the calibration are very good (Tables 3-10 and 3-11). The flow-frequency graph for the Ochillee Creek is shown in Figure 3-8. Hydrographs (arithmetic and log scales) are provided in Appendix A. Note that the apparent discontinuity in the curve at approximately 10 cfs, where the model results show a smooth linear decrease. This increase is not uncommon, and we have seen this in several watersheds that we have modeled. We have attributed this increase primarily to channel geomorphology, changes in cross sections along the stream channel, and variable groundwater levels/conditions throughout the channel reach. The relatively long reaches used in HSPF cannot accurately represent these types of variability and where overbank flows may occur at relatively low depths at points along the channel reach. In addition, flow measurements at these low depths are difficult to gage accurately and may have considerable uncertainty.

3.4.5 Upatoi Creek at McBride Bridge and Upatoi Creek at GA357 (Outlet)

Once the four small creeks were calibrated, the status of the flow comparison at the two primary Upatoi Creek gages downstream of the smaller creeks was reviewed, and efforts were made to improve the calibration at these two gages. Before any adjustments (i.e., compared to the Blind Validation), the two gages were over-simulated by approximately 25 percent. Note that the sum of the observed flow at the three small creek gages that are upstream of the McBride Bridge gage is almost 90 percent of the observed flow at McBride Bridge (for the 4-year calibration period), while the drainage area of the three creeks is 70 percent of the total area at the McBride gage. Several periods show that the sum of the flow at the three creeks is larger than the flow at McBride Bridge, which implies some intermediate channel losses. This fact makes the calibration task fairly difficult if one assumes that hydrologic conditions are similar over the watershed. The flow-

frequency graphs for the extended period for the Upatoi Creek at McBride Bridge and Upatoi Creek at GA357 are shown in Figures 3-9 and 3-10, respectively.

The attempts to improve agreement at the McBride Bridge and GA357 gages used two primary adjustment techniques: (1) adjusting hydrology parameters in the intermediate (incremental) area, (i.e., the area downstream of the three small creeks and upstream of the McBride Bridge and/or the GA357 gage); and (2) assuming that significant flow losses are occurring from the Upatoi Creek main channel downstream of the three creeks and before the McBride Bridge gage. The initial runs involved increasing the deep groundwater loss factor to remove flow at the lower flow rates, along with increasing infiltration to reduce the high flows and a slight increase in the LZSN to evaporate more water. These adjustments were sufficient to bring the overall water balance within or close to the 10 percent criterion at the two main gages.

The second method of reducing the flows (i.e., losses of water directly from the main channel) was also implemented to see how this method would work. Instead of the extreme values of deep groundwater loss, channel losses were added to seven mainstem reaches beginning with the reach downstream from the Upatoi/Baker gage and ending with the reach that is downstream of the McBride Bridge gage. After several adjustments to the loss rates, the statistics were definitely improved and were mostly within the criteria for both gages. The monthly Nash Sutcliffe and correlation coefficient statistics are 0.937 and 0.970 at the McBride Bridge gage and 0.916 and 0.959 at the GA357 gage (Tables 3-10 and 3-11). The average storm peak error is fairly high at the McBride Bridge gage, but is good at the GA357 gage. The flow-frequency graphs are shown in Figures 3-11 and 3-12. Hydrographs (arithmetic and log scales) are provided in Appendix A.

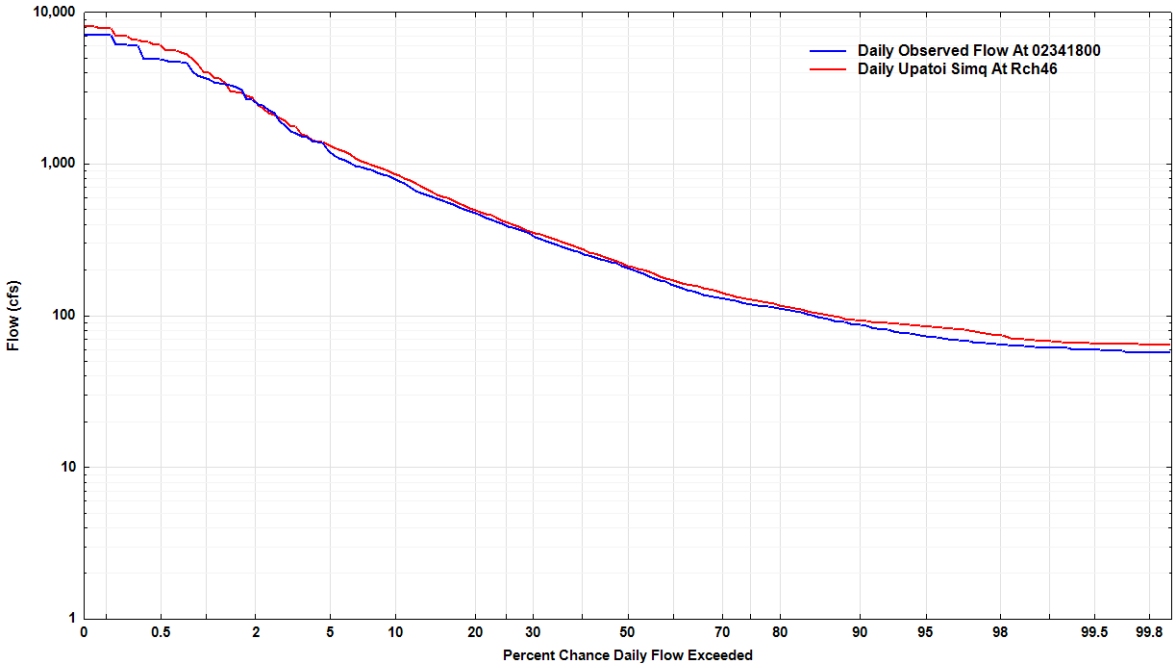


Figure 3-11. Flow-Duration Graph for Upatoi Creek at McBride Bridge–Recalibration.

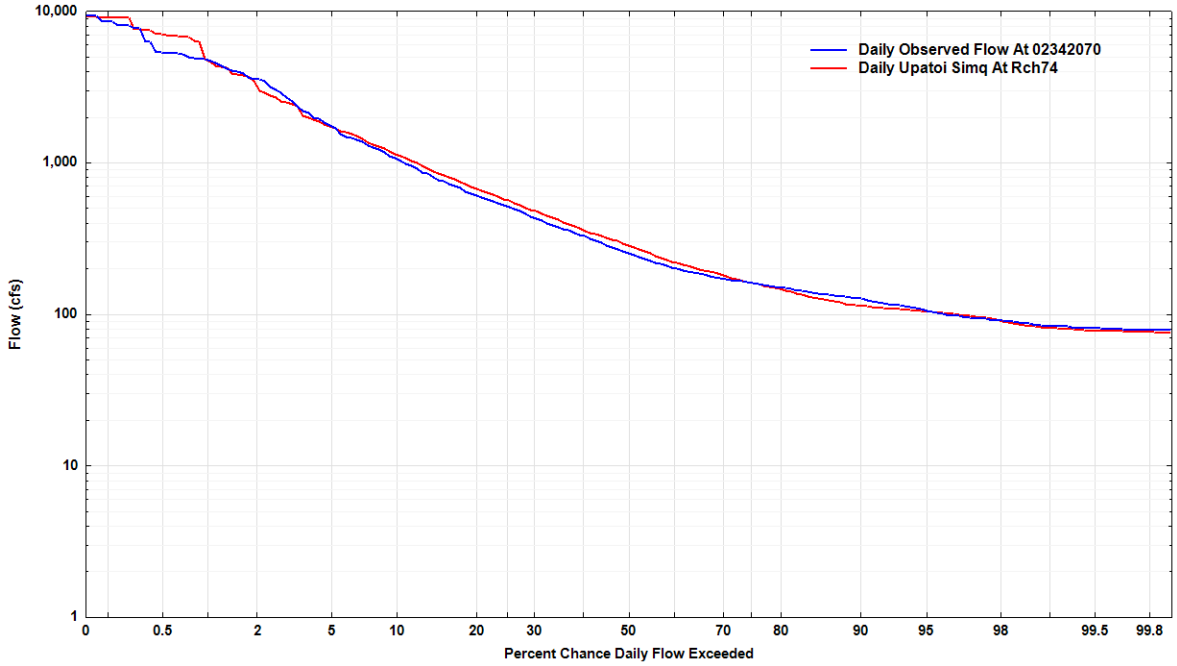


Figure 3-12. Flow-Duration Graph for Upatoi Creek at GA357–Recalibration.

3.4.6 Conclusions from Recalibration Effort

The model results from the recalibration effort make it clear that the additional data provided by the new USGS gage sites allow a much more spatially accurate model for the various subwatersheds of Upatoi Creek. This accuracy also supports using the model for assessments closer to the scale of typical disturbances, construction, and other activities that may be the focus of future modeling efforts. From the results presented in Tables 3-10 and 3-11, the flow-duration curves, and the hydrographs in Appendix A, the following conclusions were made:

a. For monthly flows, the correlation metrics are primarily in the good-to-very good range (using the corresponding scale in Figure 3-1), except for Pine Knot Creek and Randall Creek, which were in the fair range.

b. For daily flows, the same correlation metrics are mostly in the fair-to-good range ($R > 0.8$ and $R^2 > 0.64$, respectively), with the Baker gage as an exception.

c. For Moriasi et al.'s (2007) thresholds (MFE > 0.5, RSR < 0.7, PBIAS < 25 percent [monthly] to 35 percent [daily]), the monthly simulation results satisfy all these metrics at all sites [Moriasi et al., 2007]. For daily flows, the same holds true except for the Baker site, i.e., RSR = 0.74 and MFE = 0.46, and both of these very nearly satisfy the metrics.

d. The very good-to-excellent agreement of the flow-duration curves shown above provides a visual confirmation of the accuracy of the recalibrated model throughout the full range of flows observed at the gages. Only Randall Creek and the low-flow region for the Ochillee gage indicate some deviation from the observed.

e. One anomaly, which is shown in Table 3-11, is that the metric Error in Average Storm Peak actually increased in the incremental calibration, to 25.9 percent, from its value in the blind validation, at 21.5 percent. In addition, the same metric was only –6.3 percent for the original Enhanced Baseline Model (Table 3-4) for the metrics during the original calibration period of 2000–2008. That metric has offsetting differences, whereby under-

simulation of the peak flows occurred at Baker, Pine Knot, and Randall creeks, but the corresponding peak flows at McBride Bridge are well-simulated, as shown in the flow-duration curves. As discussed for McBride Bridge, evidence suggests that channel losses were occurring between the upper gages and McBride Bridge, which apparently has a significant impact on the peak storm flows. The FTABLES (stage-discharge curves) are overestimating the storm peaks when overbank flows occur at the high-flow depths, which would tend to attenuate the storm peaks. This phenomenon should be further examined in any future efforts on Upatoi Creek.

3.5 APPLICATION OF NON-CALIBRATED PARAMETERS BY A NEW USER

Two methods were selected to test the effects of non-calibrated parameters and data quality. First, an engineer with little experience with using HSPF was tasked with attempting to calibrate a version of the model that had been perturbed by selectively changing some hydrology calibration parameters so that the model was no longer calibrated. This analysis was designed in an attempt to emulate the condition where the staff performing the parameter estimation and calibration are not biased by any previous knowledge of the FB Model and previous calibration efforts on the Upatoi Watershed. As discussed in Chapter 2.0, the second method involved replacing all of the existing FTABLES in the FB Model with comparable default ones derived from the BASINS procedures (based on geomorphic relationships of channel width and depth to drainage area), which would more closely reflect conditions without cross-section data.

3.5.1 User Background

Mr. Paul Marston of RESPEC conducted the hydrologic calibration of the Perturbed FB HSPF Model. A majority of Mr. Marston's work pertaining to HSPF has involved using and analyzing HSPF model outputs. Further details from Paul's professional background can be seen in Figure 3-13. His previous experience includes high-level understanding of the User Control Input (UCI) file structure and model outputs, generating preferred model outputs for total maximum daily load (TMDL) work, and quality assurance/quality control (QA/QC) analysis using water balance and water quality outputs. Mr. Marston had very little experience with calibrating any HSPF models before working on this project. His experience included adjusting phosphorus concentrations that came from specific land uses to correct lake concentration issues. This work was completed with heavy guidance from an experienced HSPF user.

3.5.2 Calibration Resources

Resources that were used by Mr. Marston during the calibration process includes the US Environmental Protection Agency (EPA) BASINS "Technical Note 6" and "Watershed Model Calibration and Validation: The HSPF Experience" provided by Tony Donigian [Donigian, 2000]. These documents helped guide Mr. Marston on which parameters to focus on during the calibration process, how these parameters affected the model's hydrology, and what acceptable ranges of values were acceptable for these parameters. The program HSPEXP+ was used to run the model and generate the necessary flow statistics and flow graphs for model accuracy analysis along with providing specific criterion for various annual flow statistics. Along with guidance from these documents and HSPEXP+, Mr. Marston was provided assistance and consultation from both Mr. Anurag Mishra and Mr. Tony Donigian during the calibration process. The advice received from Mr. Mishra and Mr. Donigian was general and meant to guide Mr. Marston in the right direction; they did not directly aid in any of the calibration steps by providing specific parameter values to correct simulated versus observed data inaccuracies. Issues discussed between Mr. Marston, Mr. Mishra, and Mr. Donigian included baseflow reduction after reducing peak flows, mid-range flow reductions, and better accuracy in storm event flows and baseflows.

3.5.3 Results

The FB watershed perturbed model simulated water years (WY) 2000–2008 and followed the same time period as the Enhanced Baseline Model. All of the precipitation and other meteorological data that were used for the perturbed model are the same as what was used in the Enhanced Baseline Model.



RESPEC

Paul Marston

WATERSHED SCIENTIST I, WATER & NATURAL RESOURCES BUSINESS UNIT

Technical Expertise

- ✓ *Biological Stressor Identification*
- ✓ *HSPF Modeling*
- ✓ *Water Quality Monitoring*
- ✓ *Technical Writing*

Education

BS in Environmental Science, University of Iowa, Iowa City, IA (2013)

Work History

RESPEC (2015–Present)

Minnesota Pollution Control Agency (2013–2015)

Minnesota Department of Natural Resources (2012)

Stutsman, Inc. (2010)

OVERVIEW

Mr. Marston is a watershed scientist in RESPEC's Water & Natural Resources business unit. His primary areas of expertise include hydrology, stream biology assessment, and Hydrological Simulation Program—FORTRAN (HSPF) modeling and data assessment.

Before joining RESPEC, Mr. Marston spent over 2 years working for the Minnesota Pollution Control Agency (MPCA). He focused on aiding staff in developing biological stressor identification reports, was the lead author for a biological stressor identification report, conducted extensive water quality monitoring, and aided in developing HSPF model output Quality Assurance/ Quality Control (QA/QC).

TECHNICAL EXPERIENCE

Biological Stressor Identification. Mr. Marston was the lead author of the *Little Sioux River Watershed Biotic Stressor Identification Report* for the MPCA. Along with writing the report, he conducted water quality monitoring in a variety of watersheds across Minnesota to collect the necessary data to support the development of the biological stressor identification reports. He coupled this data with analysis of local fish and macroinvertebrate data to determine which streams were impaired.

HSPF Modeling. Mr. Marston used the US Environmental Protection Agency-(EPA-) supported HSPF model applications to extract model outputs and conducted calculations for total maximum daily load (TMDL) development. He analyzed model outputs and aided in model recalibrations. He developed excel spreadsheets for the MPCA to expedite the QA/QC process of HSPF model results, which allowed for better evaluation of models received.

Water Quality Monitoring. Mr. Marston has developed and conducted extensive water quality monitoring, which provided the necessary data for biological stressor identification reports. Water monitoring included using point sondes to collect basic water chemistry; conducting habitat assessment; sampling macroinvertebrates in streams; collecting water samples for metals, nutrients, and chlorophyll-*a*; and deploying sondes for continuous basic water chemistry data to detect diurnal trends in streams of concern.

Technical Writing. Mr. Marston has experience in technical writing from being lead author of the Little Sioux River Watershed Biotic Stressor Identification Report. He used various sources of data to summarize the status of various streams in the Little Sioux River Watershed and determine whether the streams were impaired or not for the local biology.

SELECTED PUBLICATIONS & PRESENTATIONS

Marston, P., 2015. *Little Sioux River Watershed Biotic Stressor Identification Report,* wq-ws5-10230003a, prepared by the Minnesota Pollution Control Agency, St. Paul, MN.

Figure 3-13. Résumé for Mr. Paul Marston**.**

As discussed in Chapter 2.0, a “no gage” data scenario was to be derived to compare the results of the Enhanced Baseline Model to one calibrated by an individual with minimal calibrating experience and no prior knowledge of the FB Model. The remainder of this section discusses the qualitative and quantitative comparison of the model results with the observed data and Enhanced Baseline Model. In this particular comparison, model reach 46 (Upatoi Creek at McBride Bridge) is used to present the results and analysis.

The calibration process involved various model-data comparisons of observed and simulated flow for the perturbed model starting with daily flow comparison and daily flow-duration curves. Results of the initial analysis indicated that the perturbed model simulated peak flows that were too high and baseflows that were too low when compared to the observed data. These errors in the simulated flows were corrected after a series of calibrations and resulted in a model that more accurately captured the peak flows and baseflows. Calibration was conducted to correct values for the infiltration rate (INFILT), LZSN, KVARY, AGWRC, fraction of infiltrating water lost to groundwater storage (DEEPFR), ET by riparian vegetation as active groundwater enters the streambed (BASETP), direct evaporation of groundwater storage (AGWETP), UZSN, INTFW, and lower zone ET (LZETP). A brief summary of parameter adjustments for forest land uses is shown in Table 3-12. Forest land use dominates the landscape in the FB Model area, which makes the adjustments to these parameters the most impactful. For a complete list of the parameter adjustments for all land uses, see Appendix B. The forest land uses are split into evergreen, deciduous, and mixed forests; all three have one unburnt and three burn cycle classes. As seen in Table 3-12, all of the parameters outside of INFILT and AGWRC use the same values for all of the forest land uses.

The flow-duration curve represents flows in the 0–95 percent exceedance rate for the calibrated perturbed model when compared to that of the Enhanced Baseline Model, but significantly less accurate in the 95–100 percent exceedance rate range (Figures 3-14 and 3-15). Comparing the calibrated perturbed model to the Enhanced Baseline Model, the peak daily flows are greater in the calibrated perturbed model (Figures 3-16 and 3-17).

An additional evaluation was conducted throughout the calibration process by looking at the calculated annual average statistics (Table 3-13) from the model and different error terms (Table 3-14). The annual average statistics show that the calibrated perturbed model simulates the flow close to observed flow with a total volume error of 1.2 percent compared to 7.5 percent for the Enhanced Baseline Model. All of the error terms for the calibrated perturbed model meet the criterion, whereas the Enhanced Baseline Model meets all but 50 percent low flow and the seasonal volume error. Note that the seasonal volume error for the calibrated perturbed model just met the criterion at 19.8. Supporting the visual comparison of the two models from the daily flow statistics, the calibrated perturbed model is slightly more accurate in the mid-range flows, whereas the Enhanced Baseline Model more accurately represents the peak flows and baseflows.

Comparing annual flow volumes for each year during the calibration period shows that simulated flow volumes are greater than observed flow volume for a majority of the years for both the calibrated perturbed model and the Enhanced Baseline Model (Table 3-15). Another trend that is shared by the two models is overall lower simulated flows in the first few years compared to observed flows, followed by higher simulated flows from 2003 through 2008 (with the exception of 2005 for the calibrated perturbed model). Note the degree to which the flows differ from simulated to observed. Although the calibrated perturbed model results in a lower mean annual error, the results show individual years of larger errors than the Enhanced Baseline Model, which end up canceling each other out for the overall lower mean annual error.

Table 3-12. Summary of Parameter Adjustments for Calibration

Parameter	Land Use	Original Values	Calibrated Values
LZSN	Forest	4.0–5.5	8–9
	U/C		
	Shrub, Grass, Ag/Other		
	Shrub		
	Grass		
	Ag/Other		
INFILT	Ev Forest	0.105	0.315
	D Forest	0.105	0.315
	M Forest	0.105	0.315
	Shrub		
	Grass	0.095	0.200
	Ag/Other		
KVARY	All Forest		0.2
AGWRC	Forest	0.960–0.972	0.995
	U/C	0.960	0.930
	Shrub, Grass, Ag/Other	0.950	0.960
DEEPFR	Wetland	0.008	0.200
BASETP	All Forest		
	Shrub	0.01	0.05
	Ag/Other		
	Wetland	0.01	0.03
AGWETP	Wetland	0.10	0.30
UZSN	U/C		
	Paved Roads		
	Tank Trails		
	Heavy Maneuver Unpaved Roads		
	Water/Wetlands		
	Ag/Other		
	Shrub		
	Grass		
	All Forest		
INTFW	U/C		
	Paved Roads		
	Tank Trails		
	Heavy Maneuver Unpaved Roads		
	Shrub		
	Grass		
	Ag/Other		
	Water/Wetlands		
LZETP	All Forest	0.1	0.2

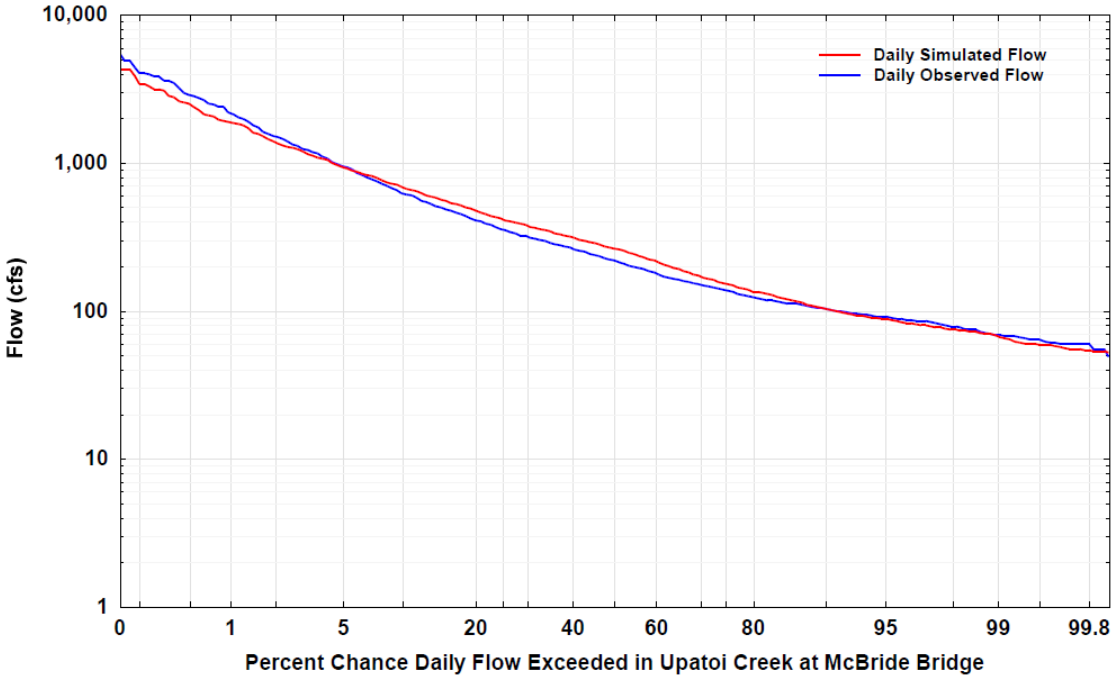


Figure 3-14. Frequency-Duration Curve of Flow in Upatoi Creek at McBride Bridge for the Enhanced Baseline Model.

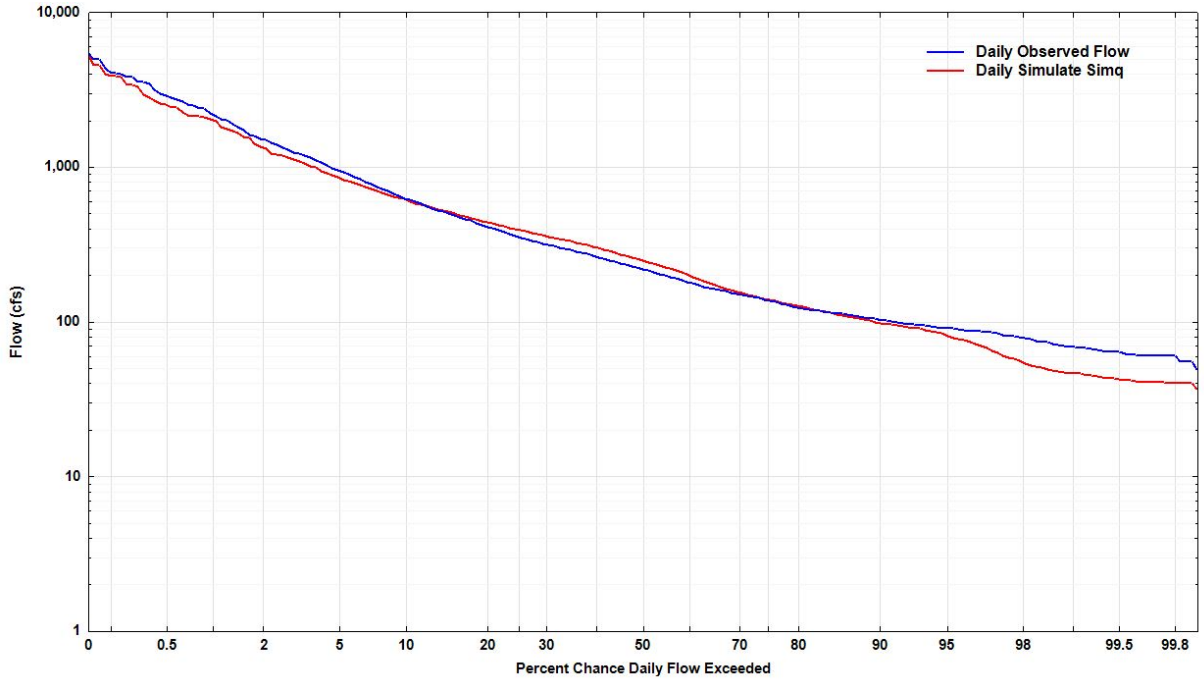


Figure 3-15. Frequency-Duration Curve of Flow in Upatoi Creek at McBride Bridge for the Calibrated Perturbed Model.

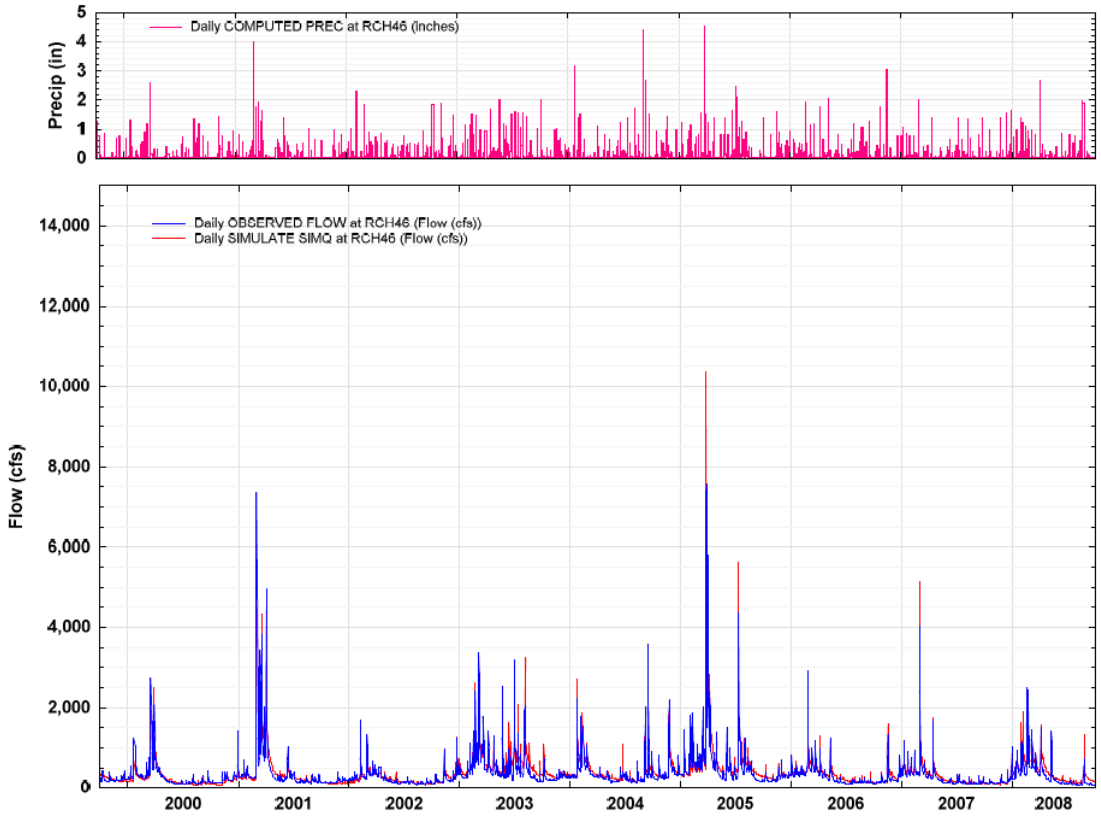


Figure 3-16. Comparison of Observed and Simulated Flow in Upatoi Creek at McBride Bridge for the Complete Enhanced Baseline Model Calibration Period

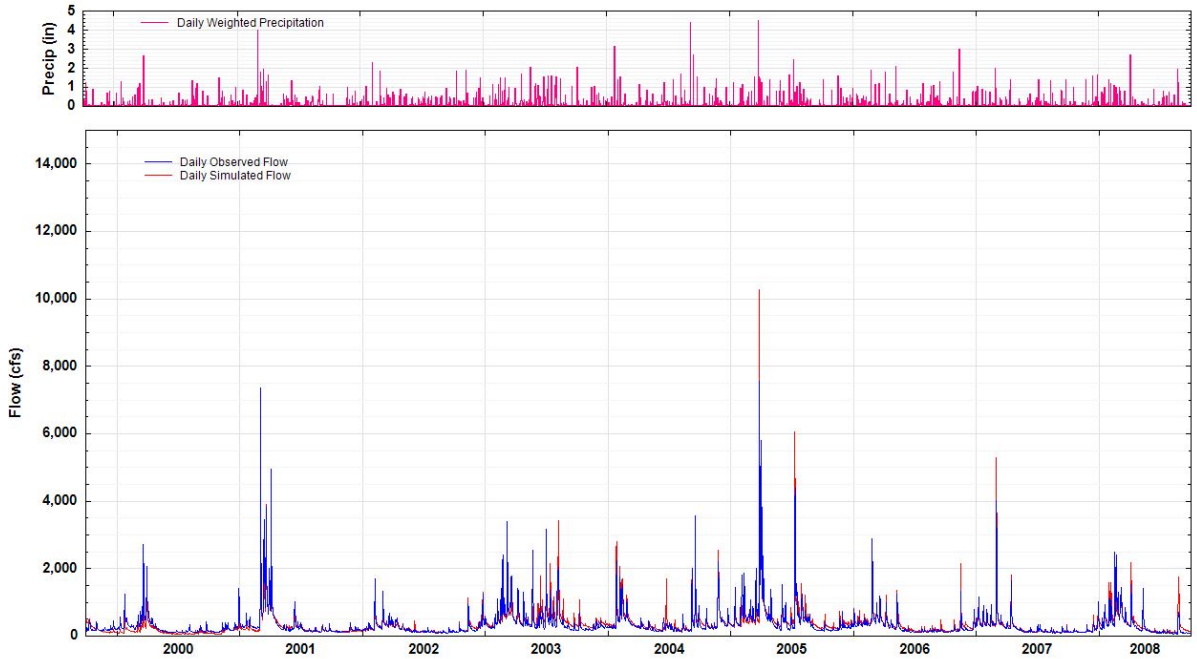


Figure 3-17. Comparison of Observed and Simulated Flow in Upatoi Creek at McBride Bridge for the Complete Perturbed Model Calibration Period.

Table 3-13. Annual Average Statistics of Flow in Upatoi Creek at McBride Bridge for the Calibration Period for Both the Calibrated Model and the Enhanced Baseline Model

	Observed Total Runoff	Calibrated Perturbed Model			Enhanced Baseline Model		
		Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow	Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow
Total (in)	13.4	13.6	2.0	2.5	14.4	2.3	4.6
10 Percent High (in)	5.1	4.6			4.8		
25 Percent High (in)	7.8	7.5			8.0		
50 Percent High (in)	10.6	10.7			11.3		
50 Percent Low (in)	2.8	2.9			3.2		
25 Percent Low (in)	1.1	1.0			1.1		
10 Percent Low (in)	0.4	0.3			0.3		
Storm Volume (in)	3.0	2.9	0.8	1.2	2.9	1.0	1.3
Average Storm Peak (cfs)	1,380.9	1,342.0	748.3	747.2	1,293.0	954.6	483.1
Baseflow Recession Rate(dimensionless)	1.0	1.0			1.0		
Summer Volume (in)	2.4	2.8			2.9		
Winter Volume (in)	3.8	3.6			3.7		
Summer Storms (in)	0.6	0.6	0.2	0.2	0.6	0.2	0.2
Winter Storms (in)	0.9	0.8	0.2	0.3	0.6	0.3	0.3

For the calibrated perturbed model, 5 years of 9 years exceed a 10 percent error, and 1 year of 9 years exceeds 20 percent, which is the same as the enhanced model. The calibrated perturbed model, however, has 2 years that are just below 20 percent in 2004 and 2006 and 1 year with a 35 percent error, which is significantly higher than the highest error of 20.9 percent for the Enhanced Baseline Model. The WY 2006 daily flow hydrograph for the Enhanced Baseline Model is depicted in Figure 3-18. To illustrate the higher simulated flow volumes compared to observed flows for the calibrated perturbed model, the WY 2006 daily flow hydrograph is shown in Figure 3-19.

The monthly flow volumes were also used for model comparison (Table 3-16, Figure 3-20, and Figure 3-21). The monthly percent error for the calibrated perturbed model was as high as 28 percent and low as –13 percent for the Enhanced Baseline Model, the monthly percent error was as high as 27 percent and low as –7 percent. This supports the trend from analyzing annual flow errors that show that both high and low extremes are greater for the calibrated perturbed model even with a lower total error. Both models represent a trend of overestimating flows in warm months and underestimating flows in colder months. Separate statistics were calculated to compare monthly and daily flow volumes (Table 3-17). The statistics improved for both models from daily to monthly volumes, which supports that calibrating to daily flow volumes is difficult. According to the model performance criteria specified in the Baseline Report, the performance of both models is very good for monthly flows and the calibrated perturbed model is very good for daily flows, while the Enhanced Baseline Model is good for daily flows.

Table 3-14. Error Terms and Criteria for the Annual Average Flow Statistics for Both the Calibrated Perturbed Model and the Enhanced Baseline Model

Errors	Criteria	Current (Calibrated Perturbed Model)	Meets Criteria?	Current (Enhanced Baseline Model)	Meets Criteria?
Total Volume (%)	10	1.2	OK	7.5	OK
10 Percent Highest Flows (%)	15	–8.6	OK	–5.2	OK
25 Percent Highest Flows (%)	10	–4.2	OK	1.6	OK
50 Percent Highest Flows (%)	10	0.5	OK	6.1	OK
50 Percent Lowest Flows (%)	10	3.8	OK	12.9	Fails
25 Percent Lowest Flows (%)	15	–4.3	OK	4.3	OK
10 Percent Lowest Flows (%)	20	–13.4	OK	–2.8	OK
Low-Flow Recession (dimensionless)	0.03	0.0	OK	0.0	OK
Storm Volumes (%)	15	–5.5	OK	–5.6	OK
Seasonal Volume (%)	20	19.8	OK	22.7	Fails
Average Storm Peak (%)	15	–2.8	OK	–6.3	OK
Summer Volume (%)	20	14.6	OK	20.0	OK
Winter Volume (%)	15	–5.2	OK	–2.8	OK
Summer Storm Volume (%)	15	3.1	OK	–3.8	OK
Winter Storm Volume (%)	15	–5.3	OK	–9.3	OK

Table 3-15. Simulated and Observed Yearly Flow Volume (Inches) for Calibration Period for Both Calibrated Perturbed Model and Enhanced Baseline Model

			Calibrated Perturbed Model			Enhanced Baseline Model		
Year	Precipitation	Observed	Simulated	Residual	Percent Error (%)	Simulated	Residual	Percent Error (%)
2000	31.4	10.0	6.5	–3.5	–35.1	9.1	–0.8	–8.2
2001	41.1	15.3	13.0	–2.2	–14.6	15.2	0.0	–0.2
2002	32.5	7.9	7.3	–0.6	–7.6	7.4	–0.5	–6.7
2003	58.1	19.0	20.1	1.1	5.6	21.4	2.4	12.4
2004	44.1	12.9	15.4	2.5	19.1	14.9	2.0	15.6
2005	53.5	23.8	23.7	–0.1	–0.3	24.4	0.6	2.4
2006	37.4	10.8	12.9	2.1	19.3	12.6	1.8	16.3
2007	37.3	10.1	11.0	0.9	9.2	11.5	1.4	14.2
2008	38.8	11.0	12.3	1.3	11.6	13.3	2.3	20.9
Mean	41.6	13.4	13.6	0.2	1.2	14.4	1.0	7.5

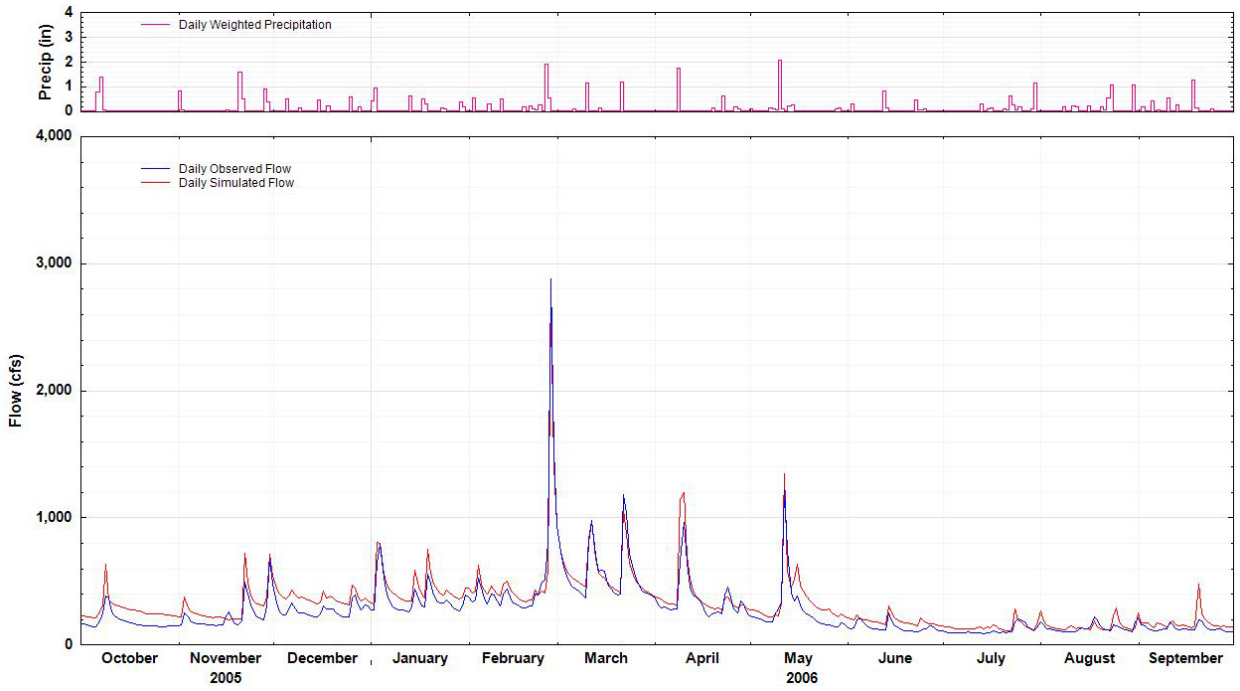


Figure 3-18. Flow in Upatoi Creek at McBride Bridge for Water Year 2006 for the Enhanced Baseline Model.

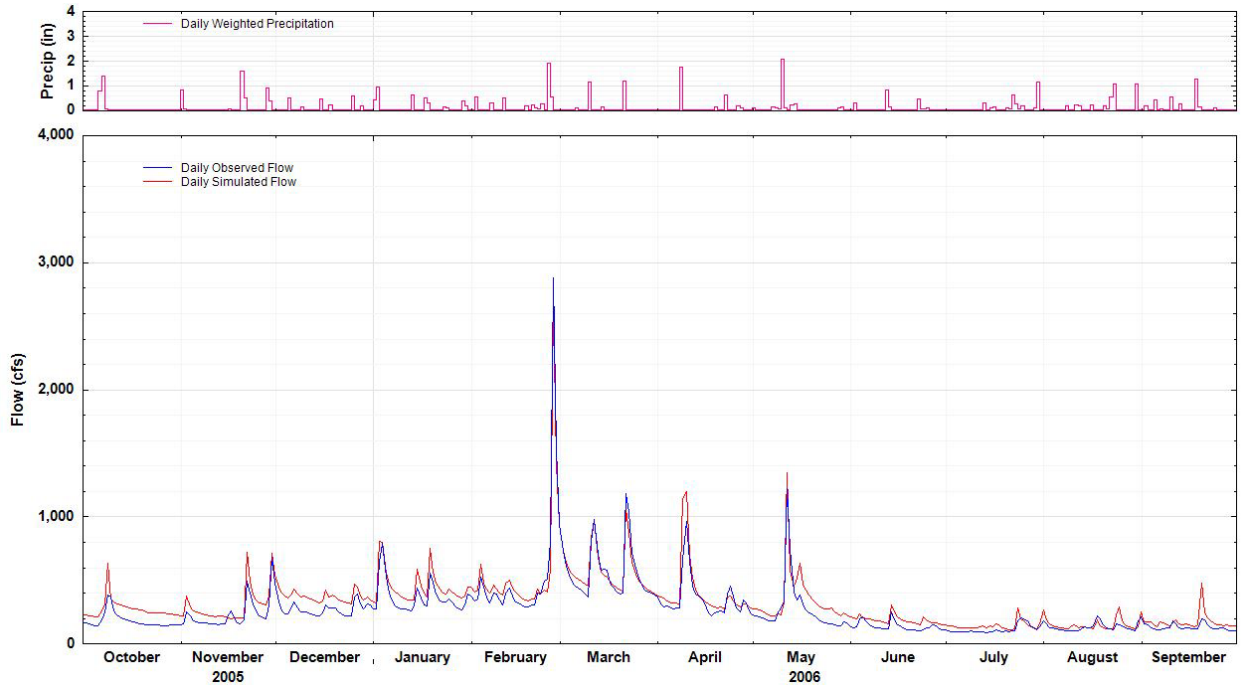


Figure 3-19. Flow in Upatoi Creek at McBride Bridge for Water Year 2006 for the Calibrated Perturbed Model.

Table 3-16. Comparison of Simulated and Observed Average Monthly Flow Volume (Inches) for Both Calibrated and Perturbed Model and Enhanced Baseline Model

		Calibrated Perturbed Model			Enhanced Baseline Model		
Month	**Observed**	**Simulated**	**Residual**	**Error**	**Simulated**	**Residual**	**Error**
Oct	0.56	0.72	0.16	28.4	0.66	0.10	18.2
Nov	0.75	0.82	0.08	10.2	0.77	0.02	2.4
Dec	0.90	0.96	0.06	6.8	0.92	0.02	2.0
Jan	1.21	1.17	–0.03	–2.8	1.20	0.00	–0.4
Feb	1.72	1.49	–0.23	–13.2	1.60	-0.12	–6.9
Mar	2.65	2.33	–0.32	–12.2	2.66	0.00	0.2
Apr	1.69	1.66	–0.03	–1.5	1.95	0.27	15.7
May	0.85	0.87	0.02	2.8	1.00	0.15	18.0
Jun	0.72	0.85	0.13	18.5	0.91	0.20	27.4
Jul	0.93	1.03	0.10	10.8	1.08	0.16	16.8
Aug	0.79	0.91	0.12	15.5	0.92	0.13	16.9
Sep	0.67	0.76	0.09	13.5	0.75	0.08	12.7
Totals	**13.42**	**13.57**	**0.16**	**1.2**	**14.42**	**1.01**	**7.5**

Hydrology calibration also requires comparing individual storm hydrographs. For the current calibration task, 66 individual storms were chosen during the calibration period for both models. The expert system calculates several storm statistics, as illustrated in Tables 3-13 and Table 3-14. The storm peaks and storm volumes were generally under-simulated by a small percentage for both models; however, both models were within the HSPEXP+ criteria. Each individual storm was plotted after the model run to compare the model performance for each individual storm. Examples of these plots for the calibrated perturbed model are shown in Figures 3-22, Figure 3-23 and Figure 3-24. The individual storm for September 2004 was added from the Enhanced Baseline Model for comparison. Based on the comparison, the peak simulated flow for the calibrated perturbed model is lower than that from the Enhanced Baseline Model (Figure 3-25) and the recession of the flow is also more gradual.

The final method used for comparing the observed and simulated values during calibration was the use of water balance components. Analyzing these values provides an additional check of consistency to ensure that the model represents a system that is close to reality. The final calibrated results are presented in Table 3-18 for comparison between the final water balance for the calibrated perturbed model and the Enhanced Baseline Model at the McBride Bridge on Upatoi Creek (Table 3-19). When comparing the two models, the calibrated perturbed model has less pervious surface runoff, significantly less interflow, slightly more baseflow, and the same impervious surface runoff than the Enhanced Baseline Model. For groundwater inflow, the calibrated perturbed model has slightly less deep groundwater inflow and more active groundwater inflow compared to the Enhanced Baseline Model. For evaporation, the calibrated perturbed model has overall similar total values but varies in the upper zone, lower zone, groundwater and baseflow portions compared to the Enhanced Baseline Model. Results for the water balance from various land uses for the calibrated perturbed model are presented in Table 3-19.

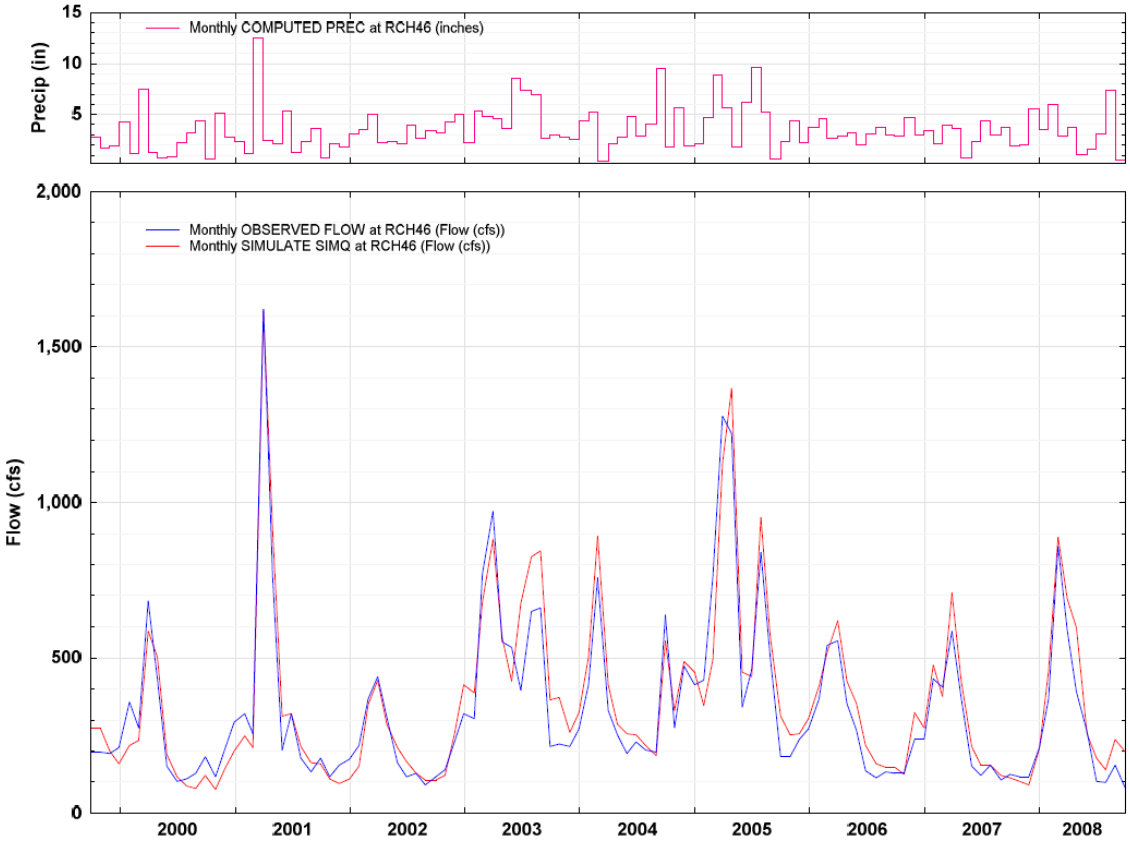


Figure 3-20. Monthly Flow Volume for the Calibration Period for the Enhanced Baseline Model.

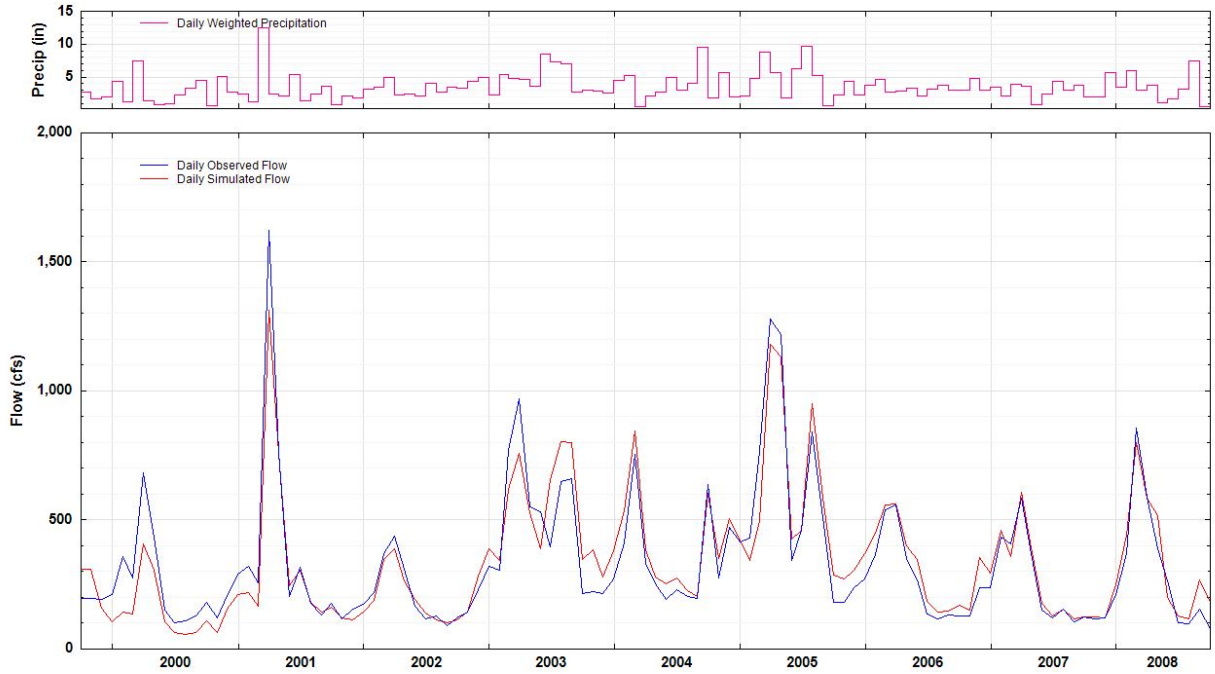


Figure 3-21. Monthly Flow Volume for the Calibration Period for the Calibrated Perturbed Model.

Table 3-17. Monthly and Daily Statistics of Flow Volume for Both Calibrated and Perturbed Model and Enhanced Baseline Model

	Calibrated Perturbed Model		Enhanced Baseline Model	
	Monthly	**Daily**	**Monthly**	**Daily**
Correlation Coefficient	0.940	0.919	0.957	0.886
Coefficient of Determination	0.883	0.844	0.916	0.785
Mean Error (cfs)	3.5	3.9	25.0	25.2
Mean Absolute Error (cfs)	67.0	90.0	64.0	105.0
RMS Error (cfs)	91.0	179.0	83.0	212.0
Nash Sutcliffe Efficiency	0.882	0.844	0.902	0.781

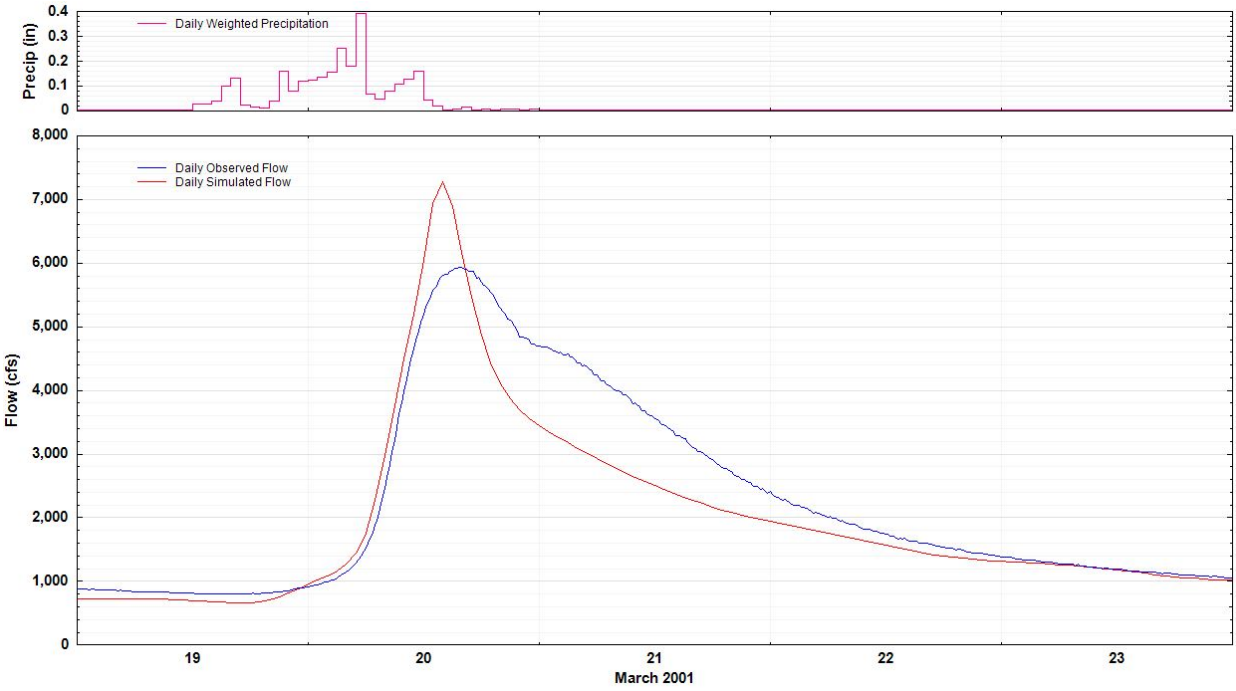


Figure 3-22. Hydrograph for Storm in March 2001.

3.5.4 Conclusions

A high-level comparison of the differences between the calibrated perturbed model and the Enhanced Baseline Model may indicate that the calibrated perturbed model achieved a higher level of accuracy. The calibrated perturbed model achieved an annual average flow error of 2.2 percent and met all annual average flow statistical criteria compared to an average annual flow error of 7.5 percent and achievement of 13 out of 15 of the annual average flow statistical criterion for the Enhanced Baseline Model. After a more in-depth review, the overall model-period annual averages are seen as not representing the actual level of accuracy because of more

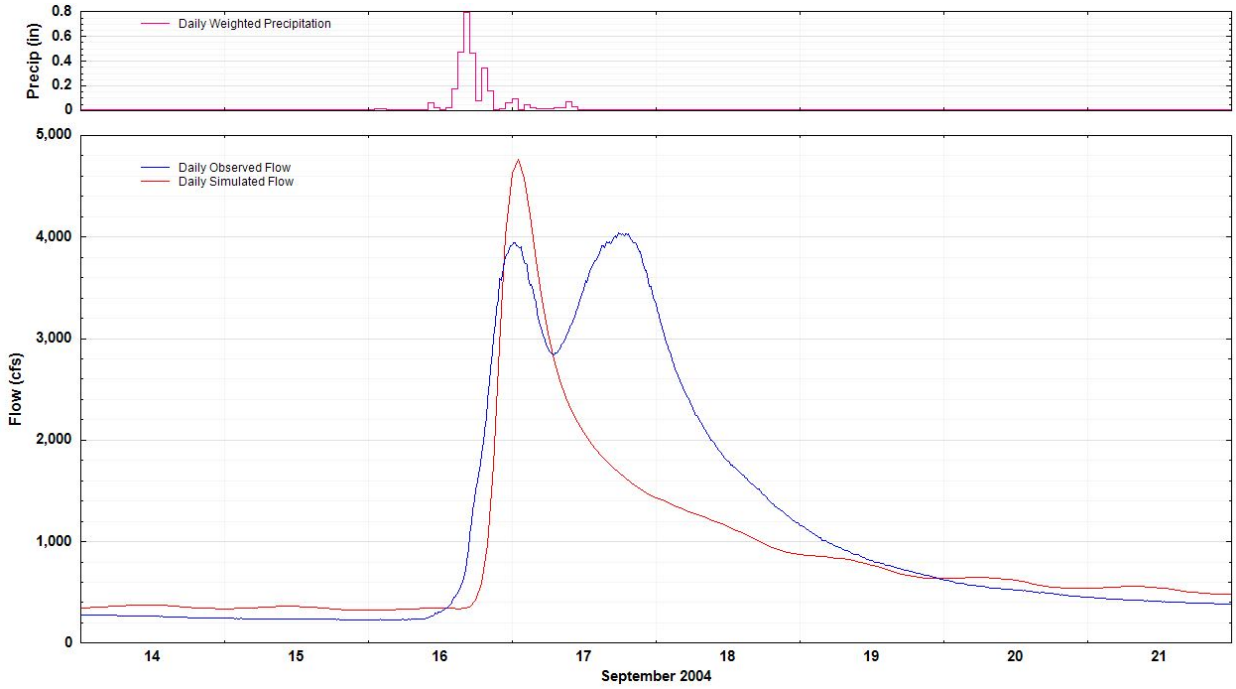


Figure 3-23. Hydrograph for Storm in September 2004.

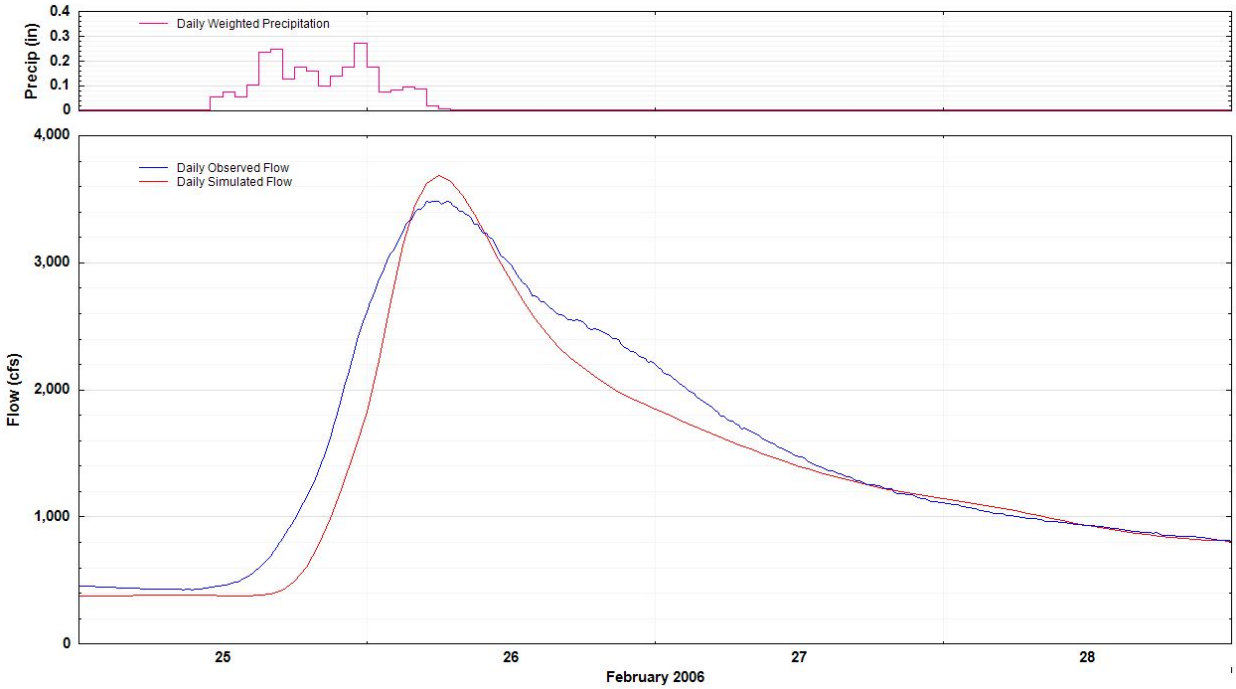


Figure 3-24. Hydrograph for Storm in February 2006.

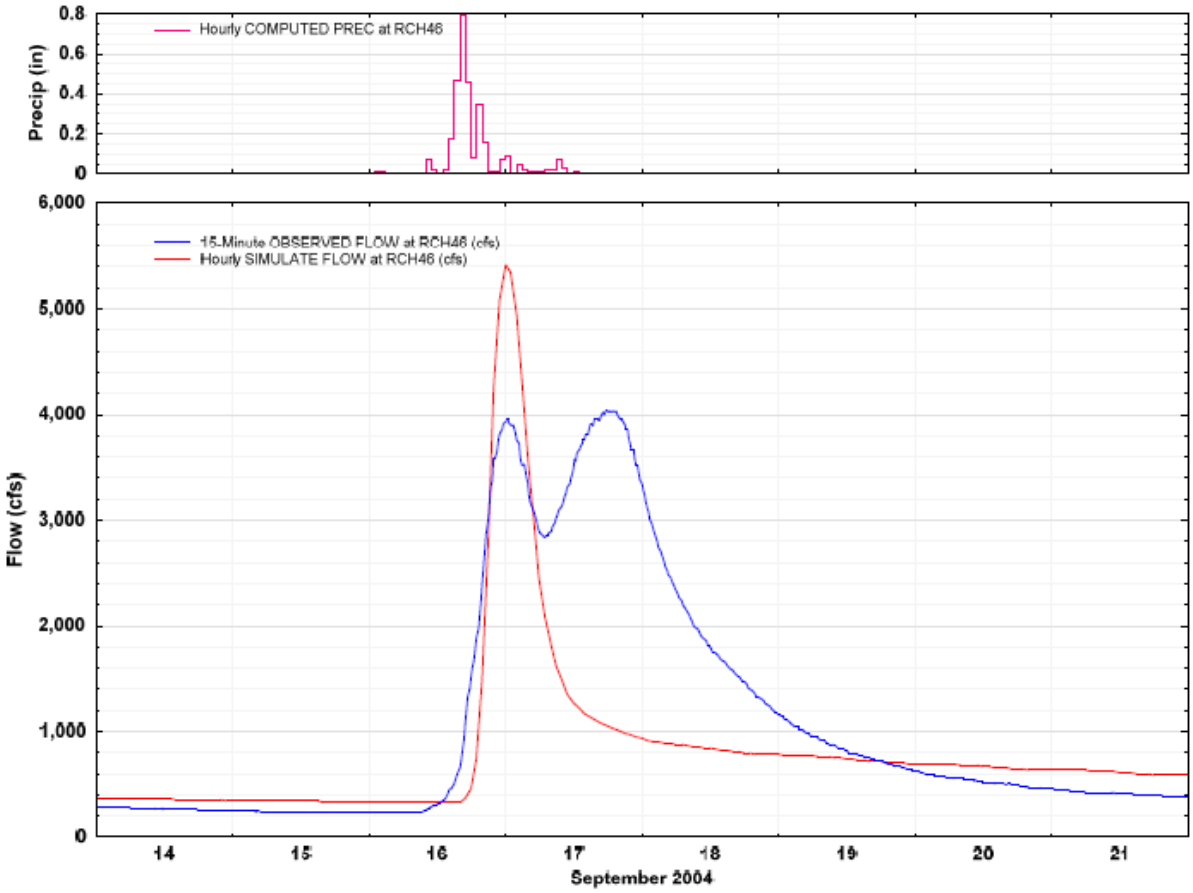


Figure 3-25. Hydrograph for Storm in September 2004 From the Enhanced Baseline Model.

extreme high- and low-error volumes seen in the annual and monthly flow volumes cancel out in the calibrated perturbed model. This difference is also supported by the flow-duration curve, which indicates overall similar accuracy for a large portion of the flows but very large discrepancies in the high-percentage flow exceedance range for the calibrated perturbed model. Further evidence of this is shown in the comparison between the overall water balance between the two models with the Enhanced Baseline Model more effectively simulating values expected in the real world. Although the calibrated perturbed model produces better high-level summary statistics, the Enhanced Baseline Model better simulates the hydrology at Upatoi Creek at McBride Bridge for the modeling period of 2000–2008.

To achieve better model results in the calibrated perturbed model, the individual calibrating should have more experience with previous hydrology calibrations. A deeper understanding of how the various parameters influence the overall hydrology would increase the accuracy and efficiency of the calibration process. For someone with little calibration experience, additional time would allow for further adjustments to be made along with better understanding of the parameters influence in the calibration process. However, the bottom line of this experiment is that the relatively inexperienced model user can attain a reasonably accurate simulation when provided guidance and consultation during the calibration effort.

Table 3-18. Water Balance Components at Upatoi Creek at McBride Bridge for Both the Calibrated Perturbed Model and Enhanced Baseline Model

	Calibrated Perturbed Model		Enhanced Baseline Model	
Location	**Upatoi Creek at McBride Bridge (R:46)**		**Upatoi Creek at McBride Bridge (R:46)**	
	in	acre-feet	in	acre-feet
Influx				
Rainfall	43.1	780,870	43.1	780,870
Runoff				
Surface-PER	0.6	10,416	0.9	16,354
Interflow	2.0	36,202	3.7	66,976
Baseflow	10.3	187,110	9.0	162,990
Total	12.9	233,728	14.4	260,390
Surface-IMP	0.8	14,067	0.8	14,067
GW Inflow				
Deep	0.3	5,202	0.4	7,057
Active	12.2	220,330	9.4	169,380
Evapotranspiration				
Potential ET	37.7	697,640	38.5	697,640
Interception	8.2	149,080	8.3	150,270
Upper Zone	8.6	156,400	10.8	196,270
Lower Zone	10.0	180,330	8.7	157,170
Ground Water	0.2	4,354	0.1	2,308
Baseflow	1.6	28,946	0.4	6,531
Impervious	0.2	3,219	0.2	3,219
Total Actual ET[(a)]	**28.5**	**517,660**	**28.4**	**514,330**

(a) Potential evapotranspiration is not included in the calculation for the total actual evapotranspiration.

ET = evapotranspiration.

Table 3-19. Water Balance Components by Land Use Category for Upatoi Creek at McBride Bridge

Land Use	Open Space	Low	Med	High	Unburnt	Cycle 1	Cycle 2	Cycle 3	Unburnt	Cycle 1	Cycle 2	Cycle 3	Unburnt	Cycle 1	Cycle 2	Cycle 3	Shrub/Scrub	Grass/Herb	Ag/Other	Paved Roads	Tank Trails	Heavy Maneuver	Unpaved Roads	Water/Wetlands	Watershed Average
	Urban Cantonment				Evergreen Forest				Deciduous Forest				Mixed Forest									Military			
Influx																									
Rainfall	42.6	42.7	43.1	44.1	43.9	40.6	44.2	43.5	43.2	44.2	43.7	40.6	42.8	41.3	40.6	40.7	41.1	40.6	40.8	40.4	40.2	40.6	40.5	40.5	43.1
Irrigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Runoff																									
Surface	2.6	2.5	2.7	0.1	0.1	0.8	0.1	0.5	0.5	0.6	4.6	5.7	0.9	2.0	0.7	0.6	0.5	0.6	0.5	0.7	0.4	0.5	5.6	5.7	0.6
Interflow	1.9	1.9	2.0	1.2	1.3	3.9	1.2	2.2	2.2	2.7	3.0	2.5	1.7	1.7	3.8	3.1	2.8	3.2	2.8	3.8	2.6	2.7	2.5	2.4	2.0
Baseflow	9.4	9.8	9.9	11.4	12.0	7.6	11.7	11.4	11.4	12.2	11.4	8.3	8.9	9.4	7.5	7.0	6.5	7.1	6.7	7.6	6.3	6.5	8.3	8.2	10.3
Total	13.9	14.2	14.5	12.7	13.3	12.3	13.0	14.1	14.1	15.5	19.0	16.5	11.5	13.1	12.1	10.6	9.8	10.9	10.0	12.1	9.3	9.7	16.4	16.4	12.9
GW Inflow																									
Deep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	3.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3
Active	9.6	9.5	9.7	13.5	14.1	9.7	13.8	12.8	12.8	13.6	11.2	8.1	12.0	9.2	9.6	8.9	8.4	9.1	8.6	9.7	8.2	8.4	8.1	8.1	12.2
Pumping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Evapotranspiration																									
Potential ET	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5
Interception	7.2	7.2	7.2	9.9	8.6	8.6	9.3	7.8	7.2	6.8	5.4	3.3	9.0	7.2	9.0	9.1	9.1	8.5	8.5	8.6	8.7	8.7	3.3	3.3	8.4
Upper Zone	10.1	10.2	10.3	7.5	8.2	12.3	7.9	8.4	8.7	9.2	13.4	15.0	8.6	9.8	11.8	10.8	10.3	11.4	10.8	12.1	10.4	10.4	15.0	14.9	9.1
Lower Zone	10.9	11.0	11.0	11.5	11.1	5.0	11.4	11.3	11.5	10.9	6.1	6.0	6.8	11.0	5.2	8.1	10.0	7.8	9.6	5.2	9.9	9.9	6.0	6.1	10.1
Ground Water	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0.0	0.2
Baseflow	0.4	0	0	2	1.9	1.8	1.9	1.6	1.6	1.6	0.0	0.0	0.7	0.0	1.8	1.8	1.8	1.8	1.8	2	2	2	0	0.0	1.6
Total Actual ET[(a)]	`	28.3	28.5	30.7	29.8	27.3	30.5	29.1	28.9	28.5	24.9	24.4	28.8	28.0	27.5	29.5	30.8	29.1	30.3	27.3	30.3	30.4	24.3	24.3	29.4

(a) Potential evapotranspiration is not included in the calculation for total actual evapotranspiration.
ET = evapotranspiration.

3.5.5 Replacement of FTABLEs With Original BASINS-Generated Values

The original BASINS-generated FTABLEs were recomputed for all of the model reaches. The methodology that BASINS uses to compute initial FTABLEs uses a small number of reach characteristics, specifically: (1) reach length, (2) overall reach slope, (3) drainage area, (4) constant values of channel and floodplain roughness, and (5) constant values of channel and floodplain shape (slope of channel side and floodplain). Simple equations based on a regional regression are used by BASINS with these characteristics to compute mean stream width and mean stream depth. The methodology uses all of the spatial information to compute the FTABLE data (i.e., depth, surface area, and volume) at a series of depths that extend into the floodplain. The Mannings equation is used to generate flows for each of these depths, and the system generates a formatted FTABLE.

The FTABLEs generated by this procedure were inserted into the model file, and the model was run and analyzed to determine the differences. Figures 3.26 through 3.37 show the comparisons of the flow-duration graphs for the six gage locations. Table 3.20 provides the statistical comparisons. In general, the results show very small differences caused by the additional data that was used to develop improved FTABLEs for the original model. The statistical measures of calibration confirm that the differences caused by FTABLE adjustment in this model are quite small. Furthermore, the statistics are only slightly more likely to show an improvement with the additional FTABLE data. Because the model was calibrated with the improved FTABLEs, we expected that reverting to using the original BASINS FTABLEs would cause the statistics to be somewhat worse. The results of our investigation are confirmed by the metric values in Table 3.20; in general the correlation metrics are lower for the results with the BASINS FTABLES, while the error metrics tend to be higher, consistent with expectations. Note that this conclusion is specific to the HSPF channel hydraulic representation and is not likely to apply where multi-dimensional issues are of concern (e.g., point source discharges and mixing zones) where higher resolution approaches may be needed.

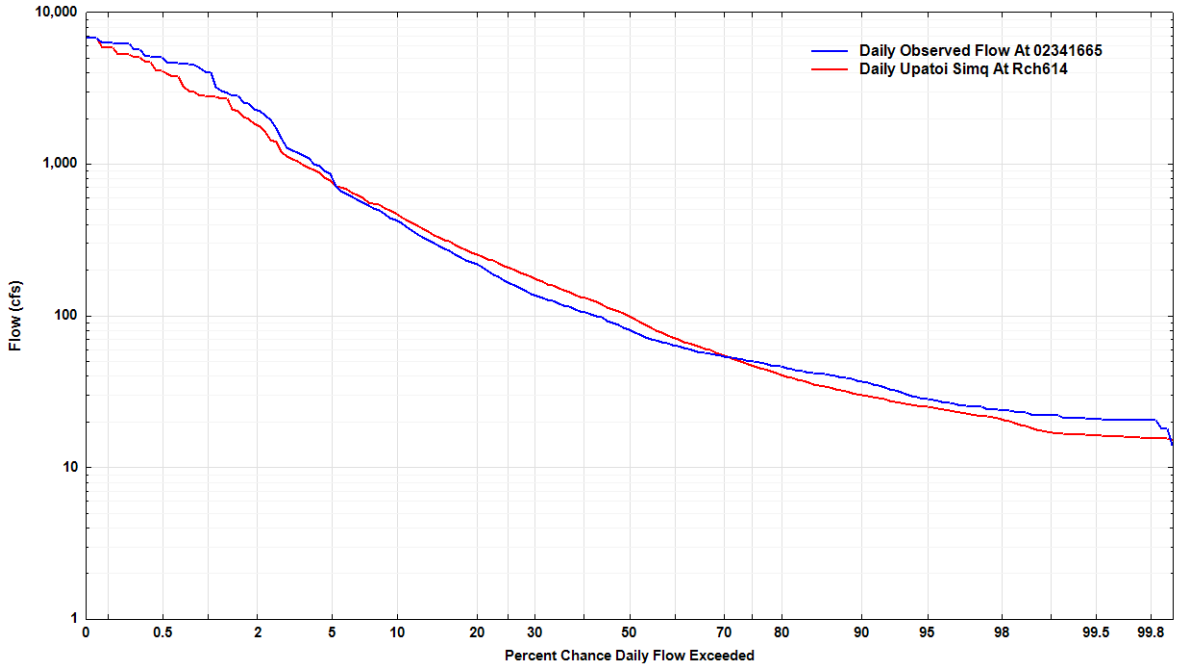


Figure 3-26. Flow-Duration Graph for Upatoi Creek Below Baker Creek–Recalibration.

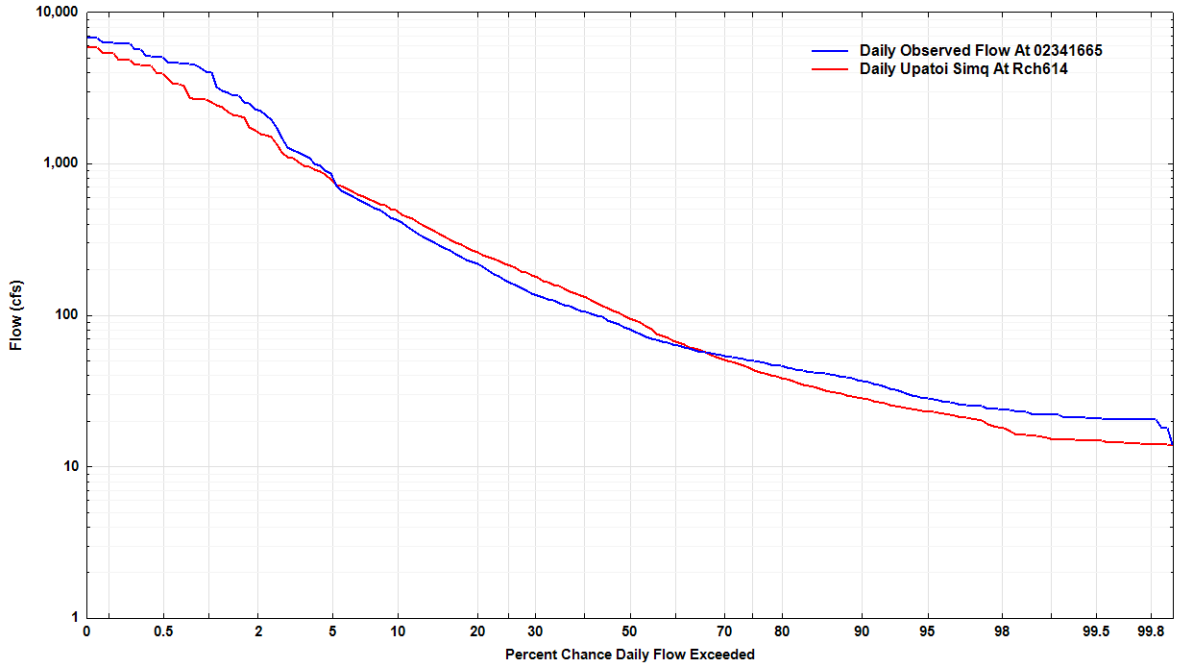


Figure 3-27. Flow-Duration Graph for Upatoi Creek Below Baker Creek–BASINS FTABLEs.

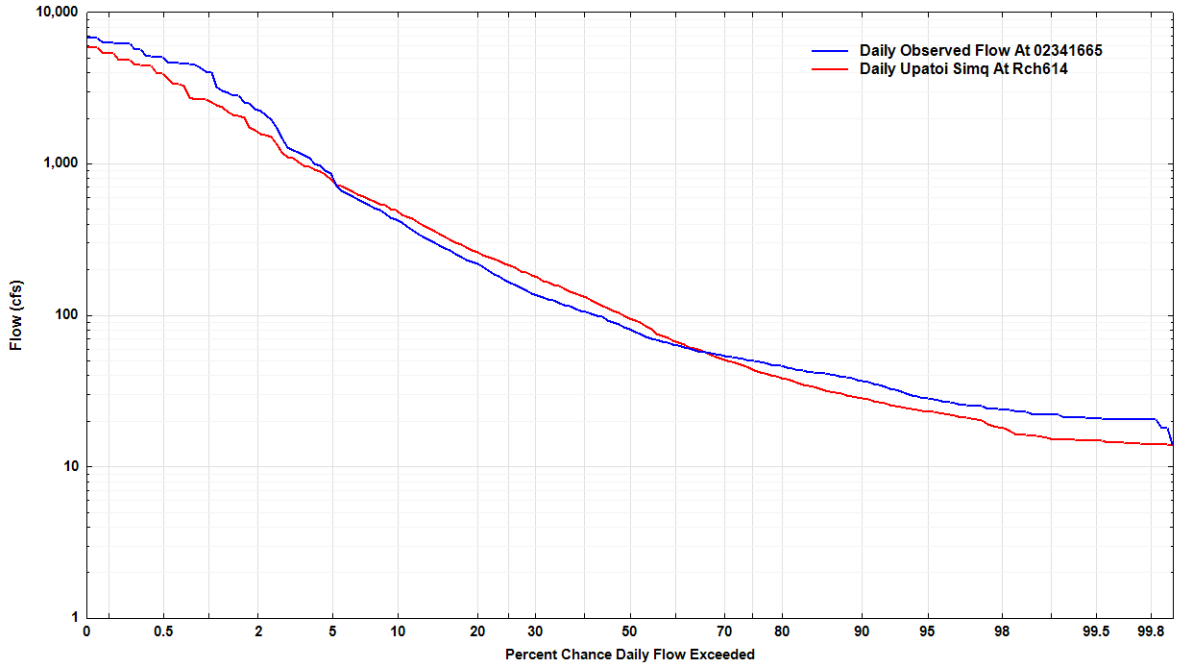


Figure 3-28. Flow-Duration Graph for Pine Knot Creek–Recalibration.

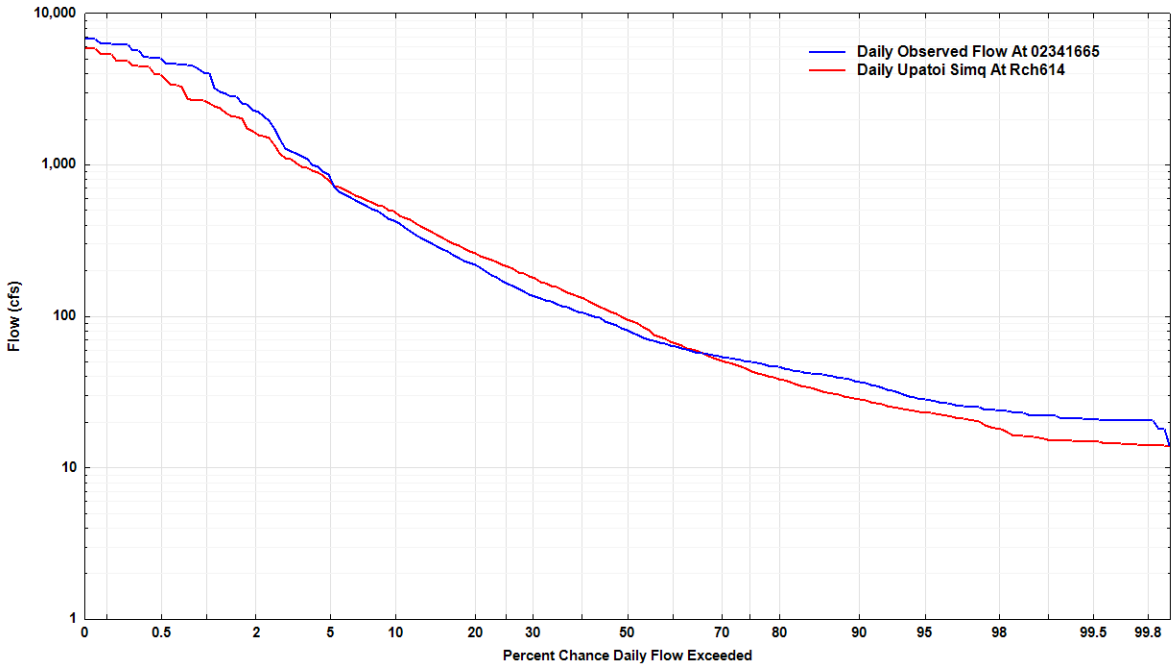


Figure 3-29. Flow-Duration Graph for Pine Knot Creek–BASINS FTABLEs.

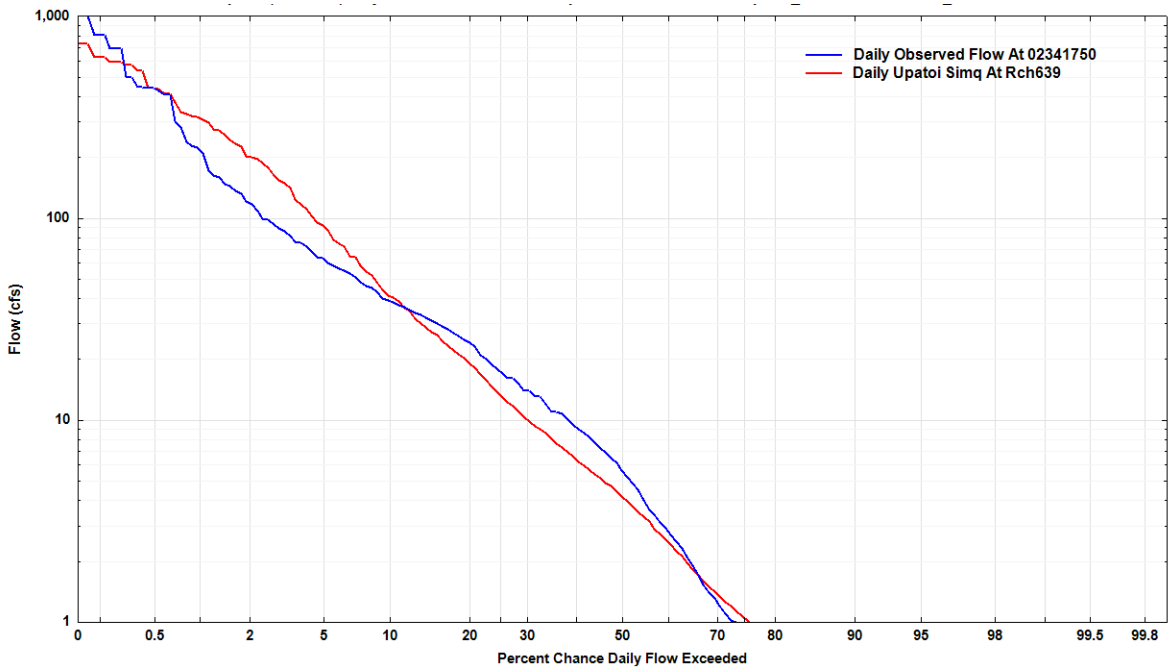


Figure 3-30. Flow-Duration Graph for Randall Creek–Recalibration.

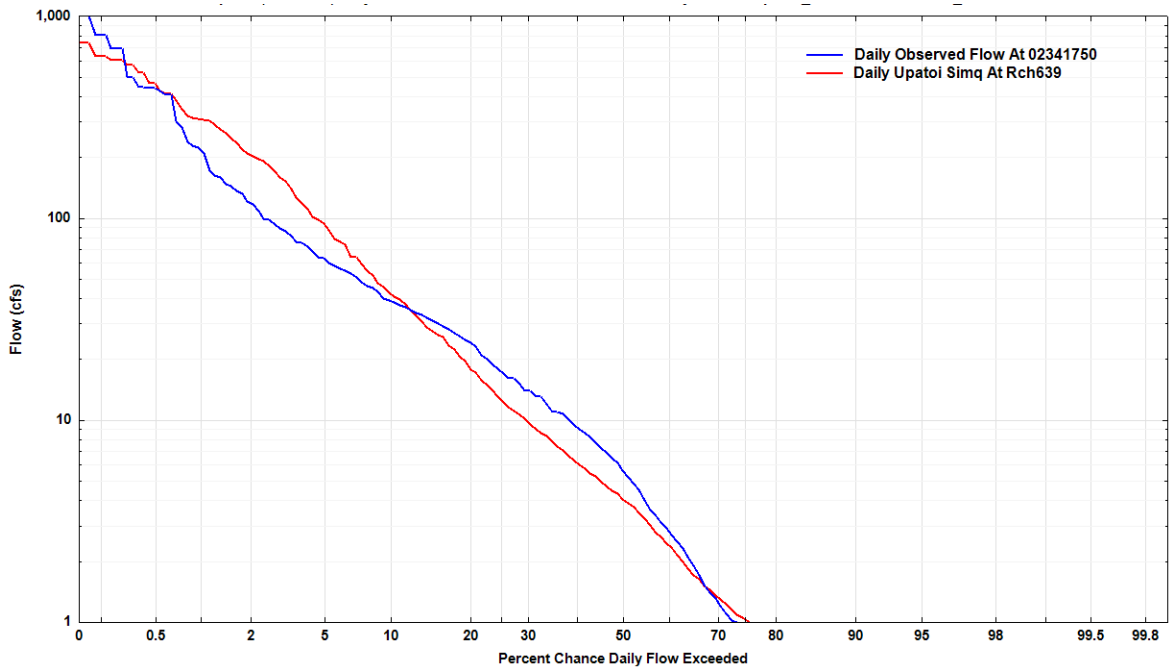


Figure 3-31. Flow-Duration Graph for Randall Creek–BASINS FTABLEs.

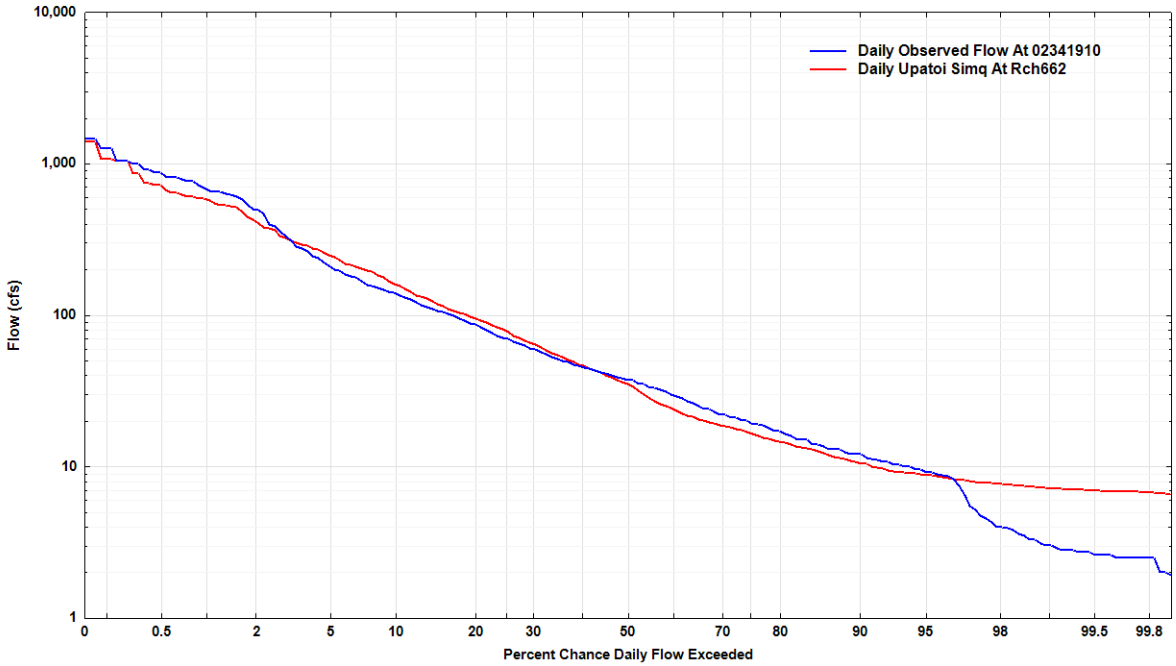


Figure 3-32. Flow-Duration Graph for Ochillee Creek–Recalibration.

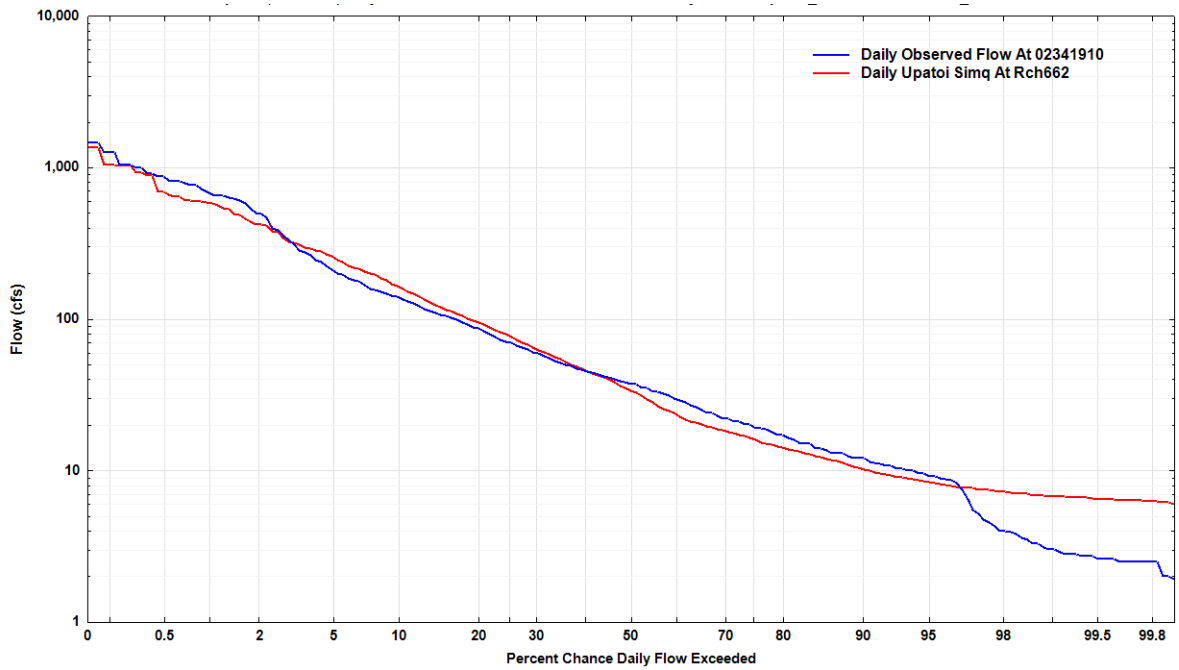


Figure 3-33. Flow-Duration Graph for Ochillee Creek–BASINS FTABLEs.

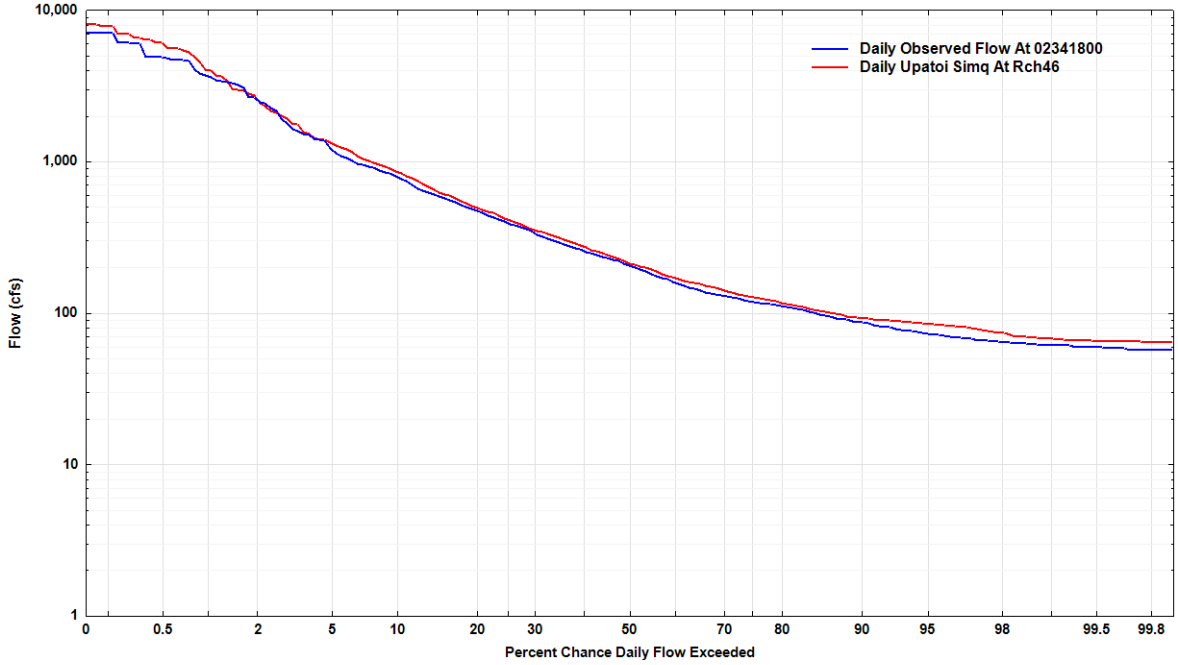


Figure 3-34. Flow-Duration Graph for Upatoi Creek at McBride Bridge–Recalibration.

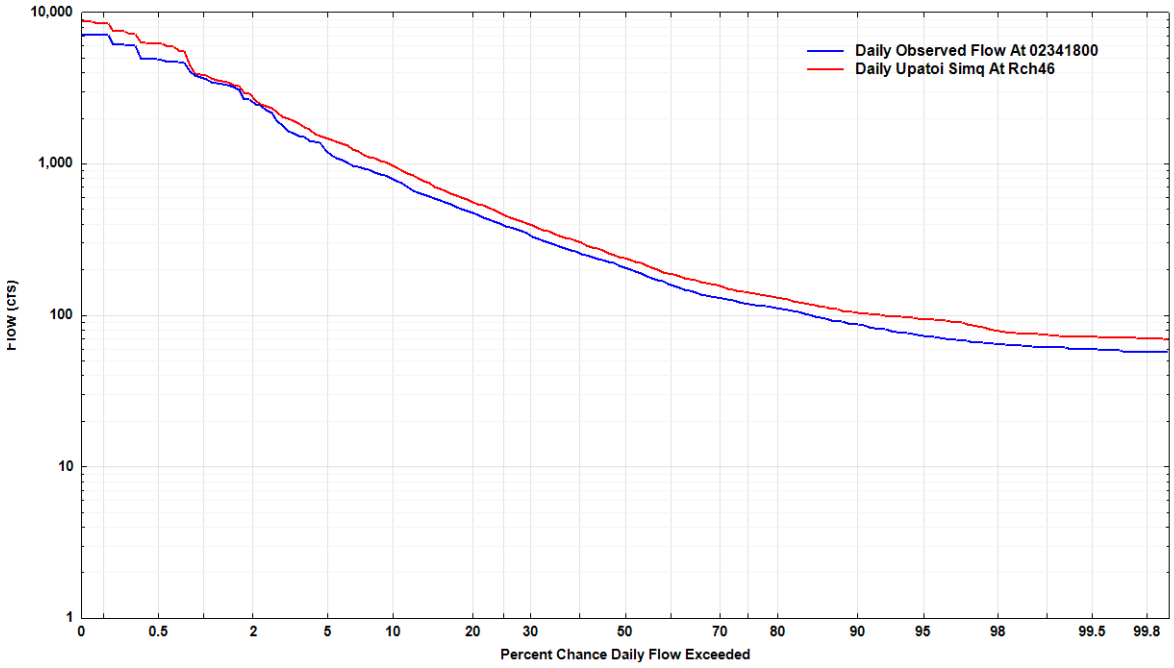


Figure 3-35. Flow-Duration Graph for Upatoi Creek at McBride Bridge–BASINS FTABLEs.

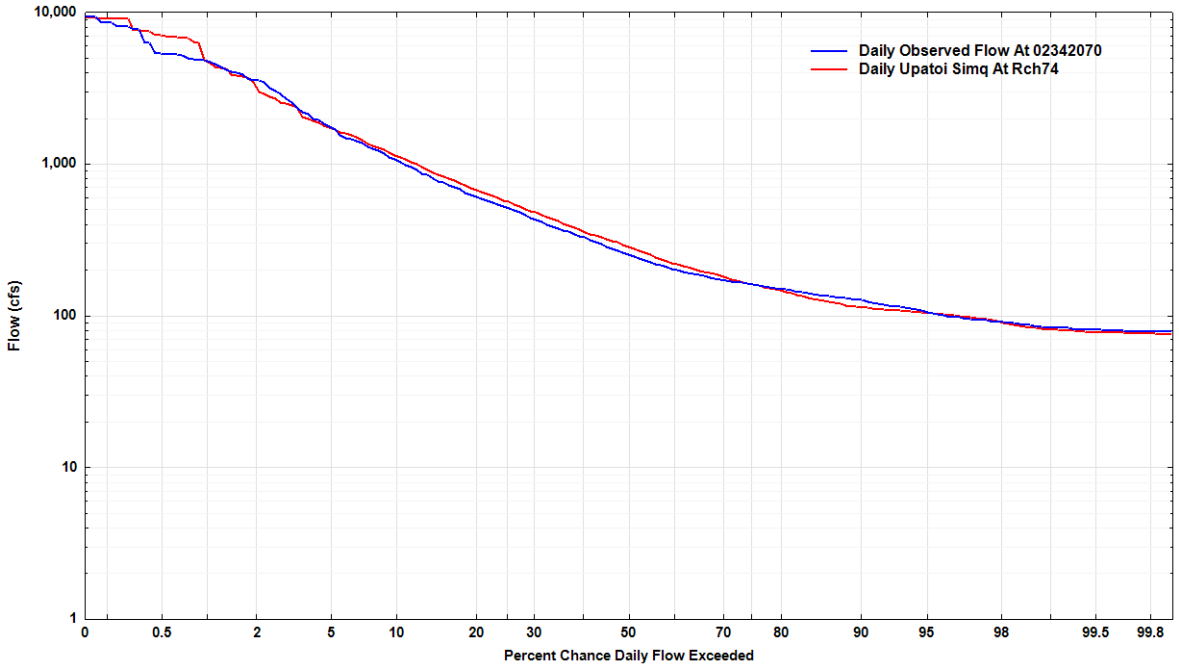


Figure 3-36. Flow-Duration Graph for Upatoi Creek at GA357–Recalibration.

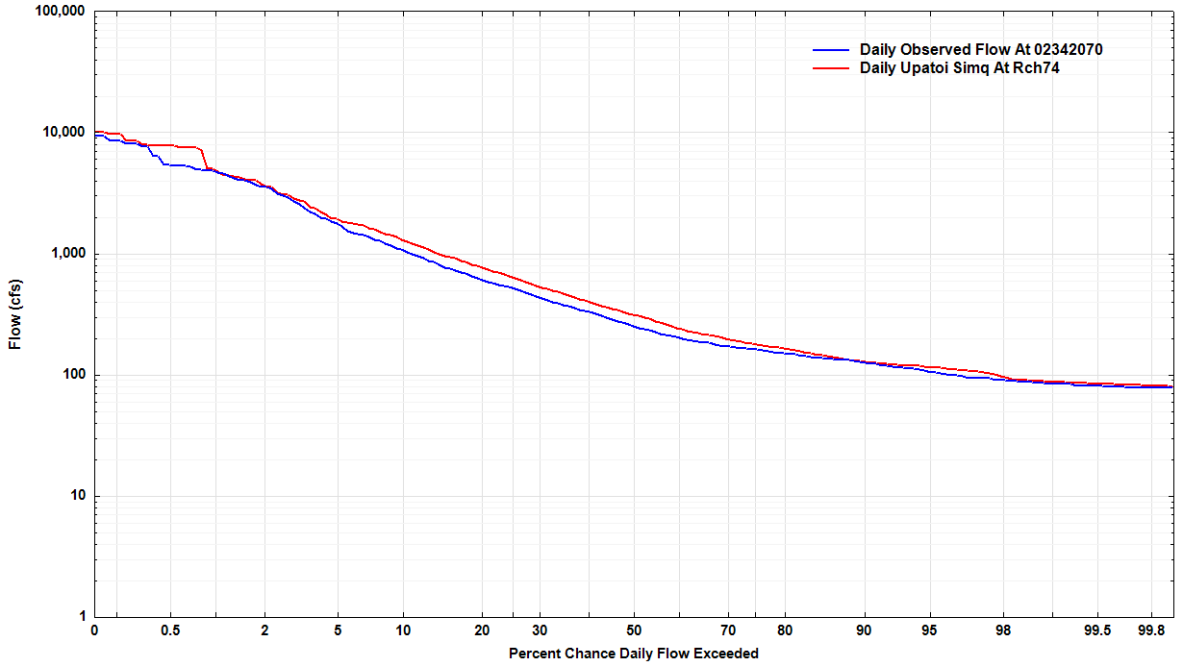


Figure 3-37. Flow-Duration Graph for Upatoi Creek at GA357–BASINS FTABLEs.

Table 3-20. Comparison of Statistics Between Calibrated Upatoi Model and Calibrated Model With Original BASINS FTABLEs

RECALIBRATED MODEL	Upatoi-Baker		Pine Knot		Randall		Upatoi McBride		Ochillee		Upatoi Outlet	
Statistics	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**
Correlation Coefficient	0.954	0.705	0.925	0.782	0.901	0.832	0.970	0.832	0.948	0.811	0.959	0.824
Coefficient of Determination	0.909	0.497	0.855	0.611	0.811	0.693	0.941	0.692	0.899	0.658	0.919	0.678
Mean Error (cfs)	–1.18	–2.0	–4.3	–4.3	1.276	1.234	27.94	27.1	0.578	0.415	30.8	29.9
Mean Error/Percent Bias (%)	–0.5	–0.8	–4.6	–4.7	6.4	6.2	7.0	6.8	0.8	0.58	5.9	5.7
Mean Absolute Error (cfs)	69.4	130.5	14.8	19.9	8.18	12.7	70.9	139.5	17.1	31.07	112.2	185.5
Mean Absolute Error (%)	29%	54%	16%	22%	41%	63%	18%	35%	24%	44%	21%	35%
RMS Error (cfs)	116.5	477	18.3	40.4	14.377	41.79	108.2	432.8	24.9	80.9	166.3	546.7
Model Fit Efficiency	0.883	0.456	0.702	0.53	0.804	0.689	0.937	0.637	0.879	0.640	0.916	0.623
RSR (RMSE/StdDev)	0.338	0.738	0.54	0.686	0.438	0.577	0.248	0.602	0.345	0.600	0.287	0.614
Total Volume Error	–0.8		–4.7		6.2		6.8		0.58		5.7	
Error in Storm Peaks	14.6		–10.1		–10.8		25.9		–2.1		10.8	

Recalibrated Model with BASINS FTABLEs

	Upatoi-Baker		Pine Knot		Randall		Upatoi McBride		Ochillee		Upatoi Outlet	
Statistics	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**	**Monthly**	**Daily**
Correlation Coefficient	0.948	0.703	0.925	0.778	0.901	0.832	0.964	0.791	0.947	0.83	0.956	0.804
Coefficient of Determination	0.898	0.495	0.856	0.605	0.811	0.693	0.93	0.626	0.897	0.689	0.914	0.646
Mean Error (cfs)	-6.24	-7.1	-4.1	-4.2	1.316	1.273	74.14	73.1	0.526	0.365	95.9	94.6
Mean Error/Percent Bias (%)	-2.6%	-2.9%	-4.5%	-4.6%	6.6%	6.3%	18.5%	18.3%	0.7%	51.10%	18.2%	18.0%
Mean Absolute Error (cfs)	73	128	14.8	20.4	8.2	12.9	96.4	158.4	17.2	30.28	134.9	204.0
Mean Absolute Error (%)	30%	53%	16%	22%	41%	64%	24%	40%	24%	42%	26%	39%
RMS Error (cfs)	126.2	469	18.4	41.1	14.37	41.86	142.4	531.9	25.2	76.48	202.4	638.4
Model Fit Efficiency	0.863	0.473	0.702	0.512	0.805	0.688	0.891	0.452	0.876	0.679	0.875	0.486
RSR (RMSE/StdDev)	0.366	0.725	0.54	0.698	0.437	0.558	0.327	0.740	0.348	0.567	0.349	0.717
Total Volume Error (%)	–2.9		–4.6		6.3		18.2		0.51		18.0	
Error in Storm Peaks (%)	6.6		–6.8		–10.3		43.7		–2.9		26.9	

Because the statistics were not significantly improved by using the additional data, we can infer that using additional stream characterization data is not as effective as some other types of data.

The McBride Bridge comparison shows larger differences; this is expected because the channel losses implemented in several mainstem reaches above the McBride Bridge gage during the incremental recalibration effort are not included in the run with the original BASINS FTABLEs. To a lesser extent, the Upatoi outlet gage at GA357 also shows significant differences for this same reason. In particular, some of the key statistical measures at the McBride Bridge gage were significantly improved by the modified FTABLEs in the recalibrated model; for example, the Mean Percent Error (PBIAS) decreased from 18.5 percent to 7 percent, and the NS model fit efficiency increased from 0.891 to 0.937. The average error in storm peaks also decreased from 44 percent to 26 percent. However, these differences are largely caused by the channel losses that were incorporated in the recalibrated model FTABLEs. Based on the results at the smaller gages, the improvement at the McBride Bridge gage is likely not strongly affected by the additional stream characterization information (i.e., cross sections and rating curves) and the resulting FTABLE changes included in the model.

3.6 DATA QUALITY

We consider both quantity and quality of collected data to be considerations in a full evaluation of data richness as related to model performance. This discussion is directed toward ultimately comparing the relative data uncertainty that is attributable to sampling, data collection, and analytical error to the modeling uncertainty that is attributable to potential errors in model parameterization. Thus, we assume that data quality is a direct reflection of the uncertainty in the collected data and the potential impact of this uncertainty on the assessment.

Following standard USGS practice, the metadata provided with the FB USGS flow datasets (and essentially all of the USGS flow data) assigns an accuracy rating of excellent, good, fair, or poor to the daily data for each gage site in Table 3-21.

Table 3-21. Expected Tolerance

Tolerance	Percent (%)
Excellent	5
Good	10
Fair	15
Poor	> 15

95 percent of values are within this tolerance of the true value.

Thus, an excellent rating indicates that approximately 95 percent of the values are within 5 percent of the true value, and similarly, for the other ratings. This rating system provides the basis for developing error bounds on the flow-duration curve, as well as the daily and annual flow volumes, developed from observed data. These accuracy ratings are stated as depending primarily on the stability of the stage-discharge relation and the frequency and reliability of the stage and discharge measurements [C. E. Novak, 1985].

For the FB gages, both of the long-term McBride Bridge gages, and the five other new gages, the USGS has assigned an accuracy rating of fair to poor uniformly across all gages, with a few exceptions of a good rating for selected years. These ratings indicate that the USGS expects that errors up to 15 percent or greater can be expected for all of the data collected at the gages.

As described in our Final Demonstration Plan, Performance Objective #8 of the project addresses and establishes uncertainty that is introduced into the modeling because of uncertainty in selecting values for the most sensitive model input and parameters. Model uncertainty runs with Monte Carlo analyses were analyzed to determine the 90 percent confidence interval range that represents the simulated values between the 5th and 95th percentiles and then used to calculate the percent uncertainty as the mean deviation from the calibrated model results. The results of these analyses showed uncertainty levels of about 30% for mean flow and 40% to 70% for high and low flows, respectively (Mishra and Donigian, 2017). Uncertainties for sediment/TSS were comparable, but generally they are expected to be higher due to the extreme variability of sediment dynamics.

We have performed similar uncertain analyses (UA) for a few other HSPF-modeled watersheds, and their results provide some basis for comparison. These watersheds include the Housatonic River Watershed (256 sq mi) in western Massachusetts [Donigian and Love, 2007] and the Illinois River Watershed (1,500 sq mi) in eastern Arkansas and western Oklahoma [Mishra and Donigian, 2015]. These UA efforts have produced similar results and indicate model uncertainties caused by parameter uncertainties of 10–15 percent for mean annual streamflow and runoff, uncertainties of 15–25 percent for high flows, and uncertainties of 25–45 percent for low flows. Our experience with watershed modeling, and specifically with HSPF applications, supports these ranges as being reasonable approximations of the expected uncertainty levels for the FB/Upatoi Watershed model.

Although this analysis is not currently precise, the level of uncertainty in the flow data observations (i.e., 15 percent or greater) is generally at a much lower level than the expected uncertainty in the model predictions (i.e., 10–45 percent). Thus, unless there are site-specific issues (e.g., a highly unstable bed, gage mechanical problems, or backwater effects), data quality is not expected to be a significant issue for uncertainty in the observed flow data when compared to the potential uncertainty in the model predictions. However, the same cannot be said for water quality data that are likely to have higher levels of uncertainty than noted here.

4.0 LESSONS LEARNED

Throughout this investigation, several lessons were learned regarding watershed modeling in general and to specific conditions evident for the FB and Upatoi Creek watershed conditions. Elucidating some of those lessons here may be beneficial both for watershed modelers and installation managers who may need to decide on data collection and modeling efforts on their lands and installations.

a. The highest priority for new data needs to be directed to precipitation monitoring. Without adequate coverage of precipitation gages, watershed modeling efforts will be severely inhibited. If tradeoffs need to be considered between additional precipitation gages or flow gages, a greater density of precipitation gages will likely provide a better foundation for the modeling, as long as an adequate number of flow gages are included. A reasonable rule-of-thumb would be to have **two to three times** as many precipitation gages as flow gages.

b. All efforts should be made to calibrate watershed models at a scale as close as possible to the scale at which decisions are or need to be made. This recommendation obviously presumes that data will also be collected at close to that same scale.

c. Calibration to a single flow gage on a mid-size watershed (i.e., greater than 100–300 sq mi), with the gage located at the midpoint or outlet of the watershed, may provide reasonable simulations for any and all tributaries, but the same or similar agreement with flow in tributaries is not guaranteed. Even though the land-surface features (e.g., land use, vegetation, slope, and soils) may be similar, the subsurface may demonstrate significantly different behavior and hydrologic response. This difference was evident in the Pine Knot Creek Subwatershed of Upatoi Creek, which is situated in the Coastal Plain physiographic province versus the Piedmont province for most of the rest of the Upatoi watershed. While Hortonian-type runoff models are appropriate for the Piedmont areas, non-Hortonian runoff mechanics are evident in the Coastal Plain where the shallow groundwater levels inhibit infiltration and drive the runoff process.

d. The expected uncertainty in flow measurements is expected to be significantly less than model uncertainty, but this same relationship may not apply to sediment and water quality measurements.

e. Novice model users with a water resources background can be expected to perform a credible job for model calibration if provided with expert guidance and consultation during the calibration effort.

f. Model results may not be highly sensitive to exact channel representation (e.g., cross sections and slopes) as long as they provide a reasonable approximation to the overall channel configuration. However, some water quality variables may be sensitive at extremely high or low flows, especially low flows, when approximations within the models may influence the model results produced. This sensitivity can occur at extreme low flows in the range of water depths of a few inches or less. Refinements, or adjustments, to the FTABLES (stage-discharge relationships) for low flows in HSPF may help to resolve issues for these conditions. Note that this conclusion is specific to the HSPF channel hydraulic representation and is not likely to apply where multi-dimensional issues are of concern (e.g., point source discharges and mixing zones) where higher resolution approaches may be needed.

5.0 REFERENCES

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APPENDIX A
INCREMENTAL RECALIBRATION HYDROGRAPHS

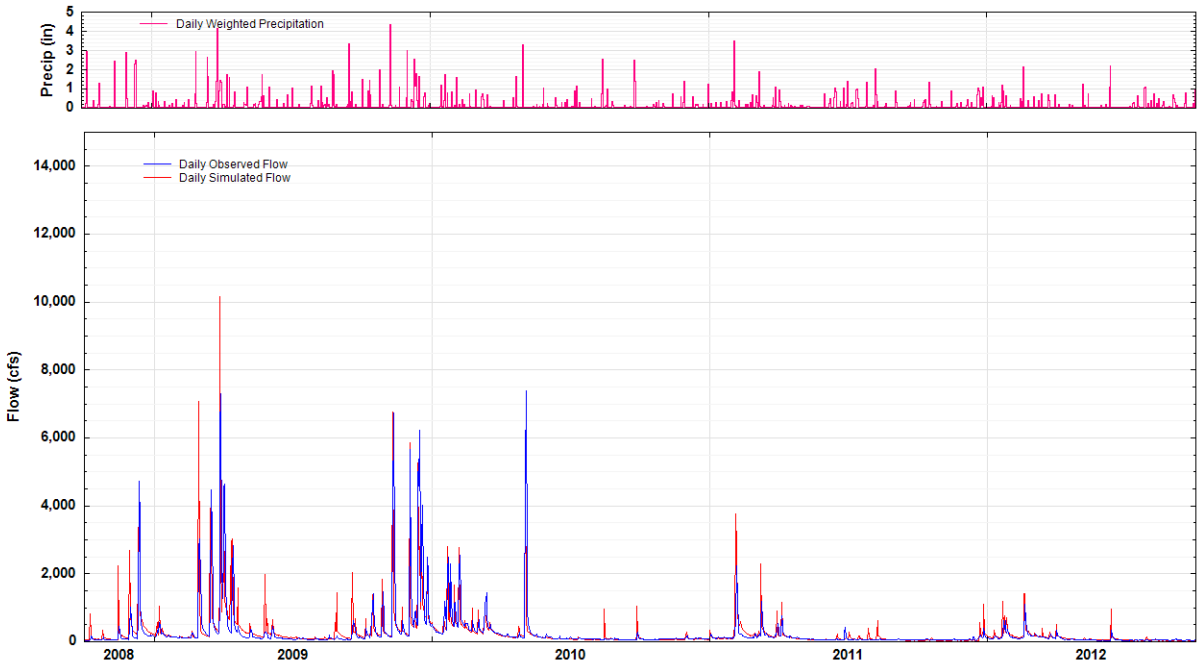


Figure A-1. Hydrograph for Upatoi Creek Below Baker Creek–Recalibration.

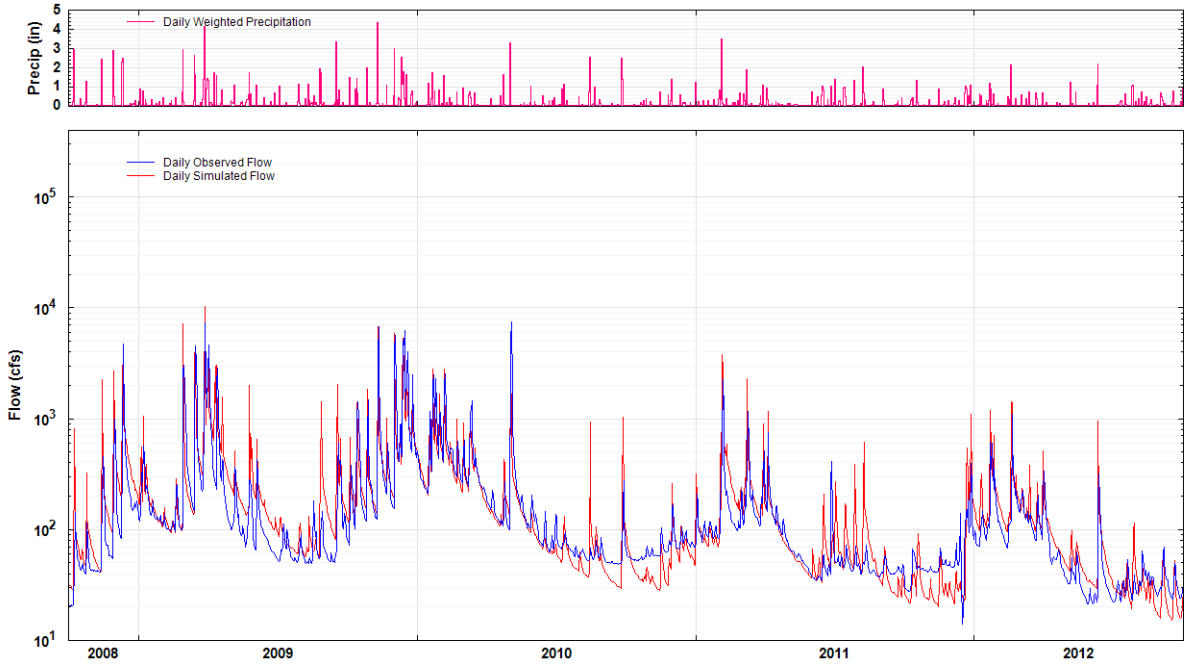


Figure A-2. Hydrograph (Log Scale) for Upatoi Creek Below Baker Creek–Recalibration.

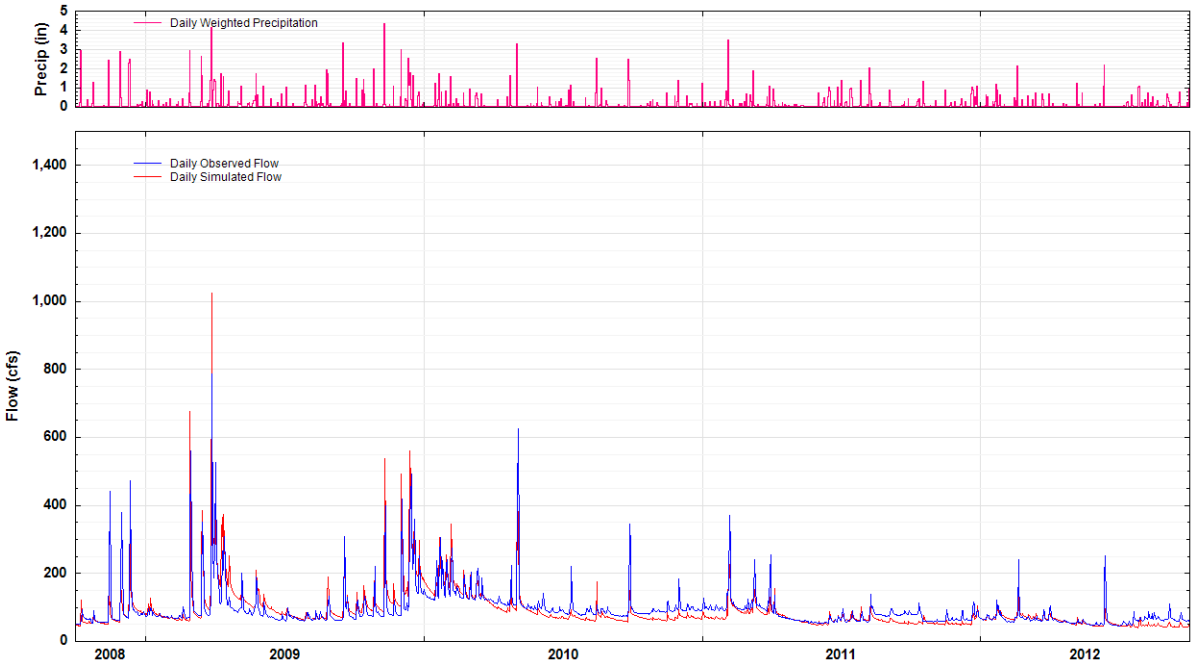


Figure A-3. Hydrograph for Pine Knot Creek–Recalibration.

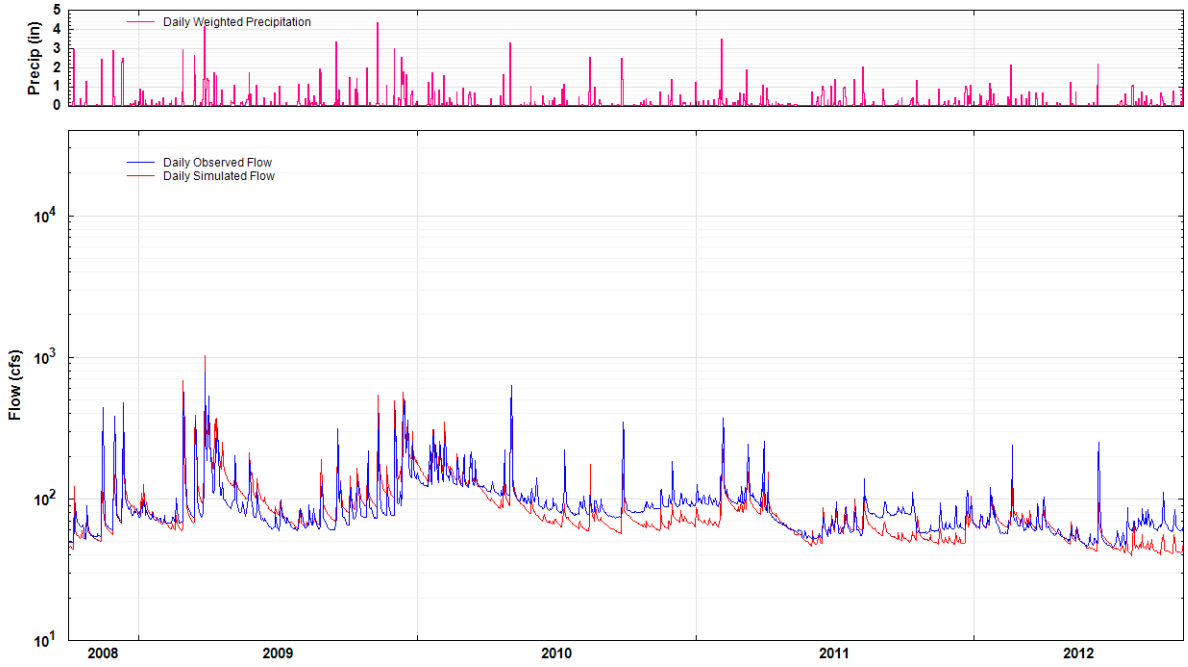


Figure A-4. Hydrograph (Log Scale) for Pine Knot Creek–Recalibration.

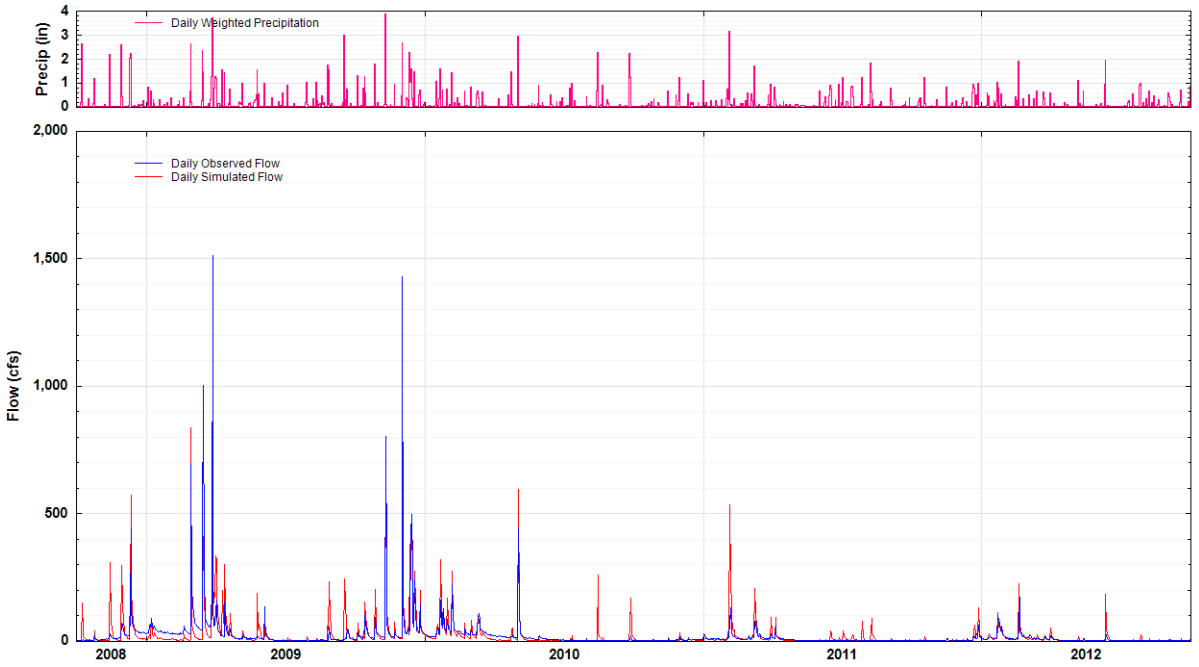


Figure A-5. Hydrograph for Randall Creek–Recalibration.

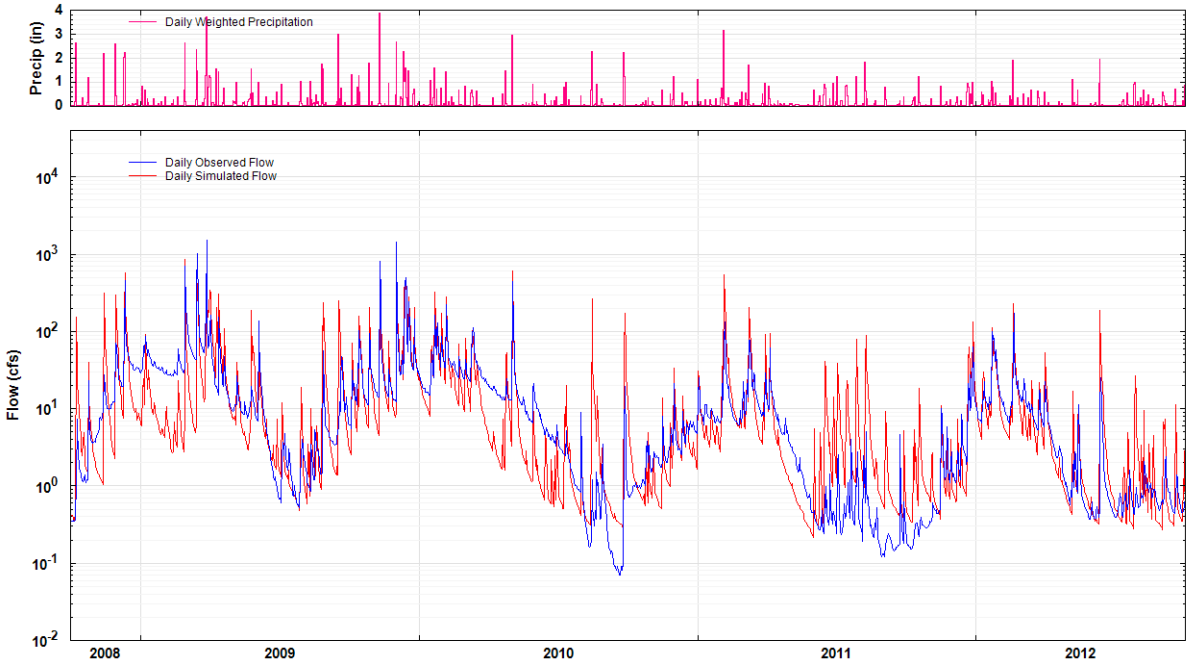


Figure A-6. Hydrograph (Log Scale) for Randall Creek–Recalibration.

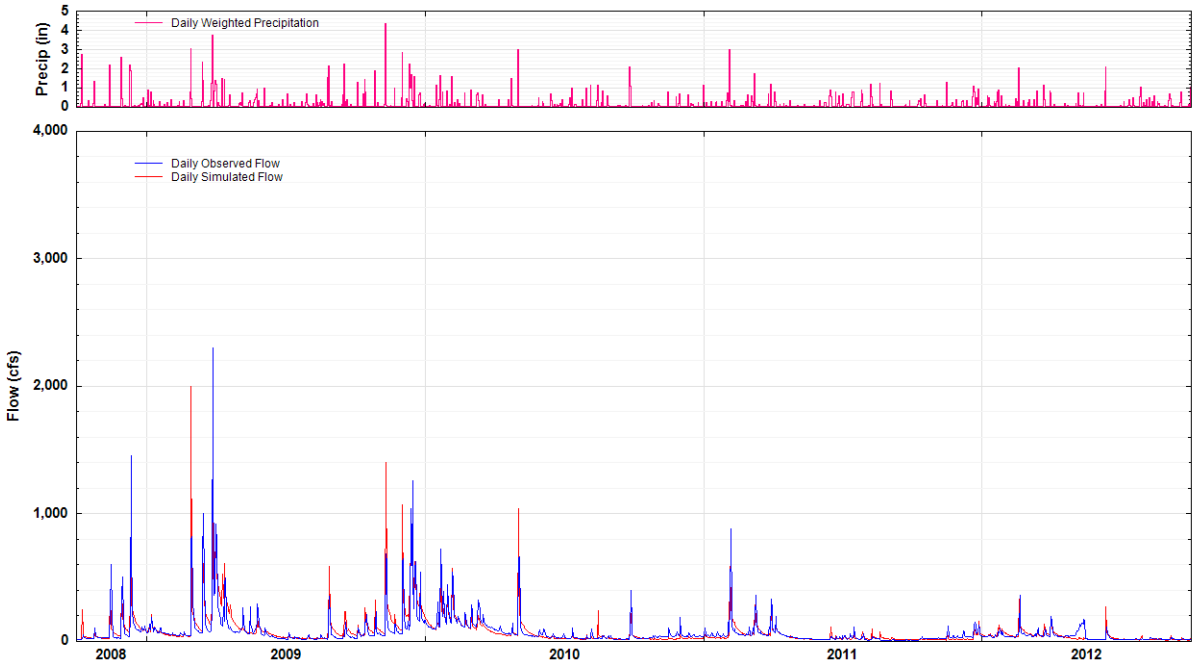


Figure A-7. Hydrograph for Ochillee Creek–Recalibration.

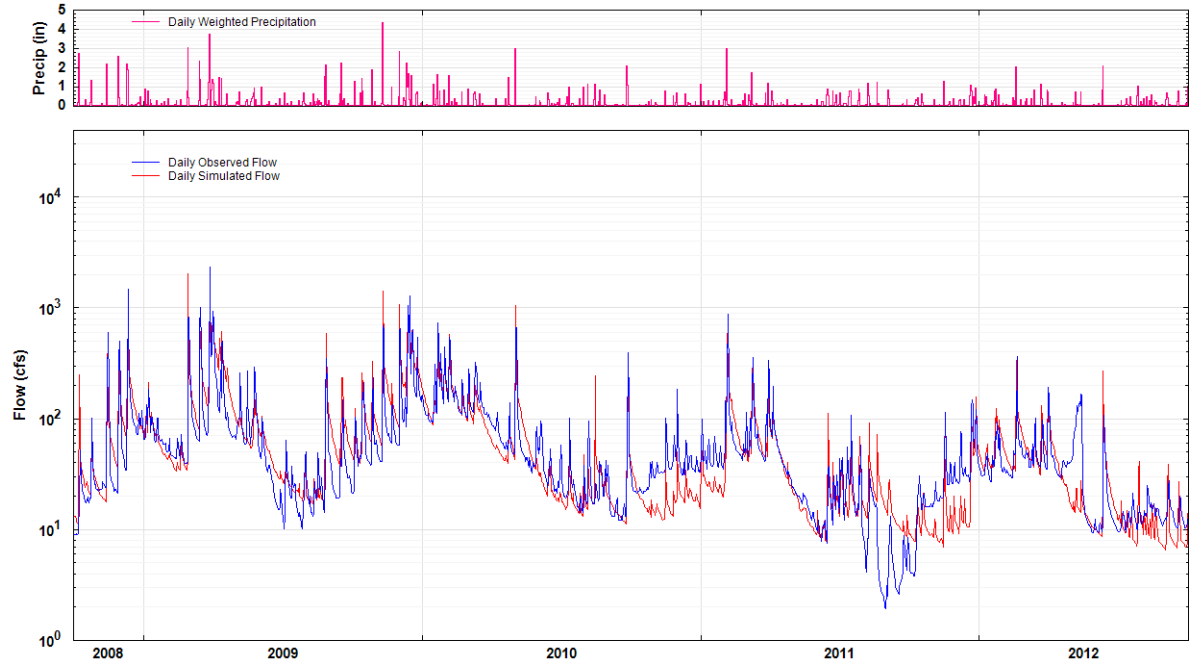


Figure A-8. Hydrograph (Log Scale) for Ochillee Creek–Recalibration.

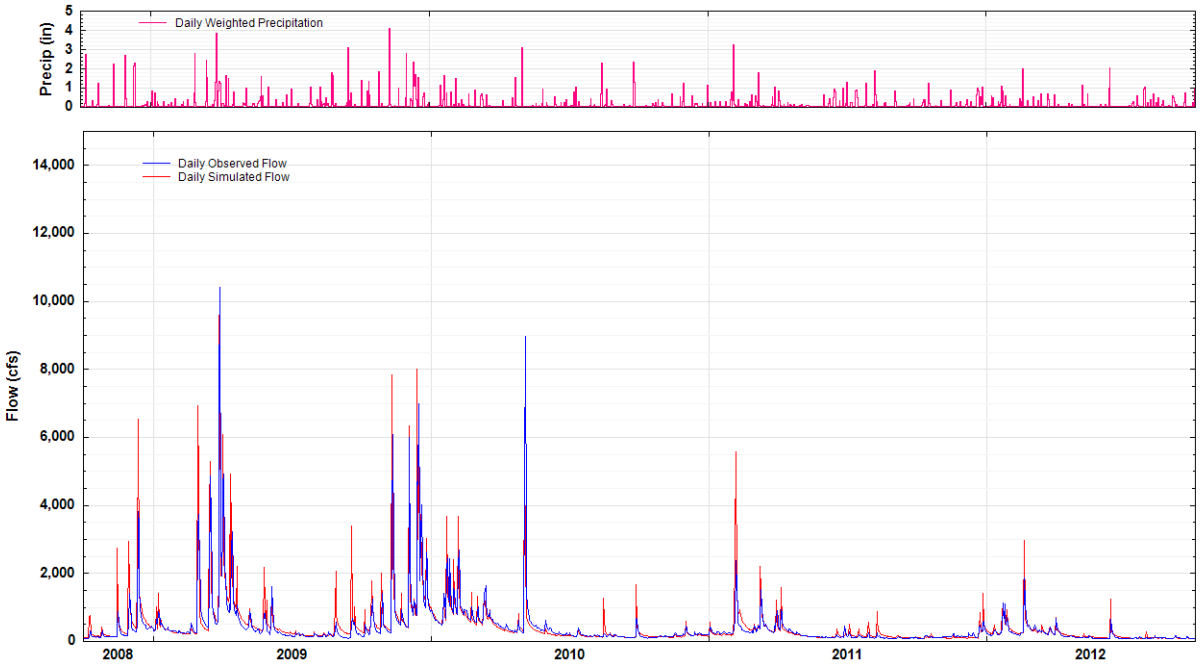


Figure A-9 Hydrograph for Upatoi Creek at McBride Bridge–Recalibration.

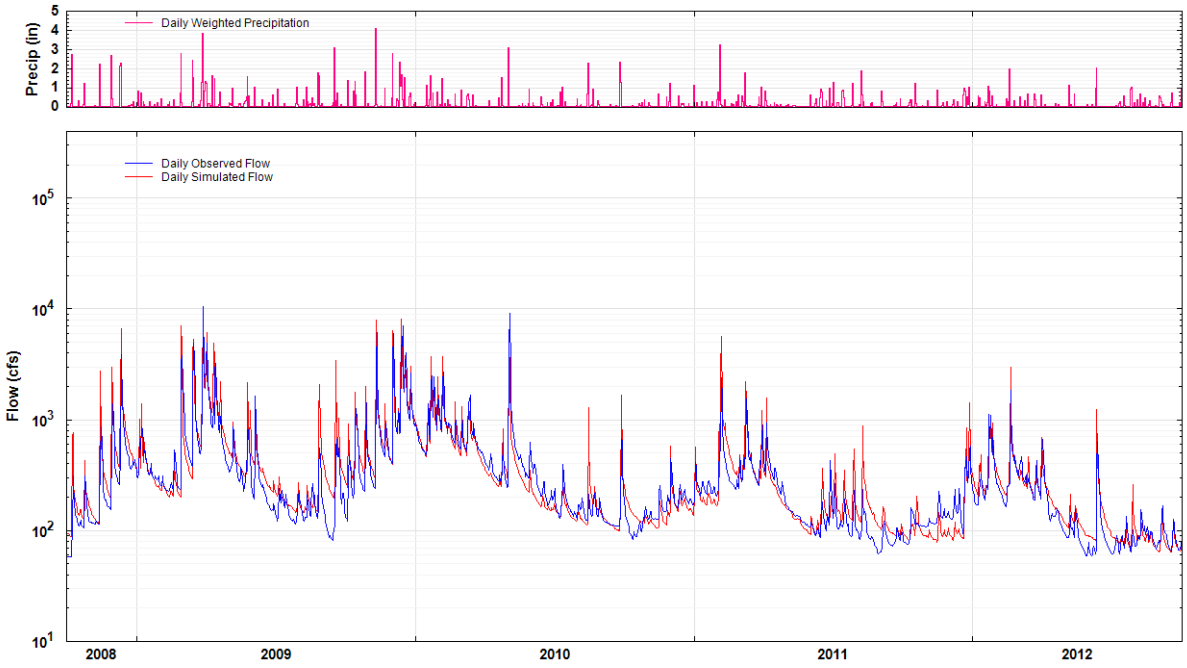


Figure A-10. Hydrograph (Log Scale) for Upatoi Creek at McBride Bridge–Recalibration.

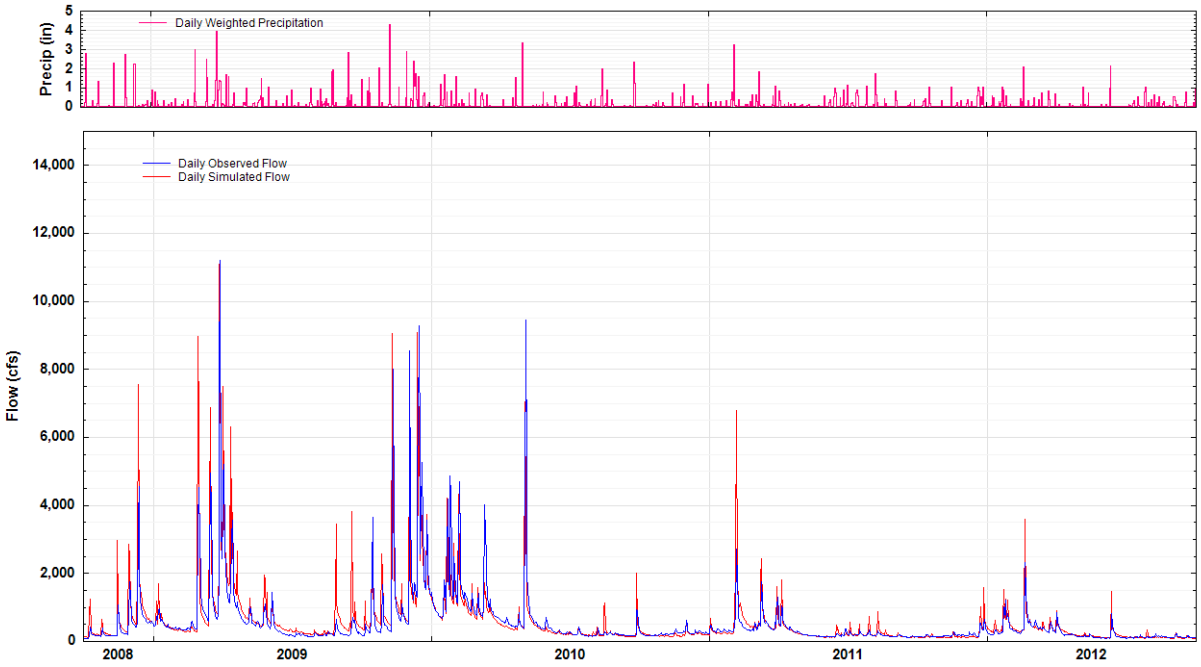


Figure A-11. Hydrograph for Upatoi Creek at GA357–Recalibration.

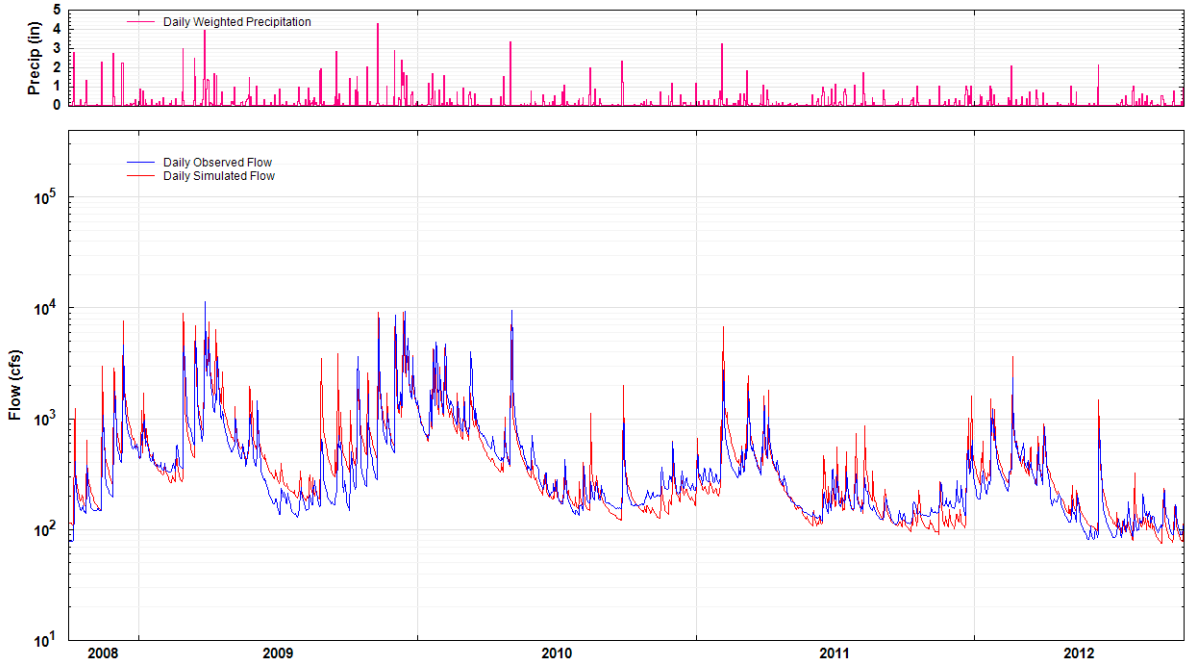


Figure A-12. Hydrograph (Log Scale) for Upatoi Creek at GA357–Recalibration.

APPENDIX B
HSPF PARAMETER ADJUSTMENT SUMMARY TABLE

Table B-1. HSPF Parameter Adjustment Summary Table (Page 1 of 7)

Parameter	Land Use	Original Values	Calibrated Values
LZSN (in)	U/C Open Space	4–5	8–9
	U/C Low	4–5	8–9
	U/C Med	4–5	8–9
	U/C High	4–5	8–9
	E Forest	4.5–5.5	8–9
	E Forest_C1	4.5–5.5	8–9
	E Forest_C2	4.5–5.5	8–9
	E Forest_C3	4.5–5.5	8–9
	D Forest	4.5–5.5	8–9
	D Forest_C1	4.5–5.5	8–9
	D Forest_C2	4.5–5.5	8–9
	D Forest_C3	4.5–5.5	8–9
	M Forest	4.5–5.5	8–9
	M Forest_C1	4.5–5.5	8–9
	M Forest_C2	4.5–5.5	8–9
	M Forest_C3	4.5–5.5	8–9
	Shrub/Scrub	4–5.5	8–9
	Grass/Herb	4–5.5	8–9
	Ag/Other	4–5.5	8–9
	Paved Roads	3.5	3.5
	Tank Trails	3.5	3.5
	Heavy Maneuver	3.5	3.5
	Unpaved Roads	3.5	3.5
	Water/Wetlands	10	10
INFILT (in/hr)	U/C Open Space	0.095	0.095
	U/C Low	0.095	0.095
	U/C Med	0.095	0.095
	U/C High	0.095	0.095
	E Forest	0.105	0.315
	E Forest_C1	0.075	0.075
	E Forest_C2	0.085	0.085
	E Forest_C3	0.095	0.095
	D Forest	0.105	0.315
	D Forest_C1	0.075	0.075
	D Forest_C2	0.085	0.085
	D Forest_C3	0.095	0.095
	M Forest	0.105	0.315

Table B-1. HSPF Parameter Adjustment Summary Table (Page 2 of 7)

Parameter	Land Use	Original Values	Calibrated Values
INFILT (in/hr)	M Forest_C1	0.075	0.075
	M Forest_C2	0.085	0.085
	M Forest_C3	0.095	0.095
	Shrub/Scrub	0.095	0.2
	Grass/Herb	0.095	0.2
	Ag/Other	0.095	0.2
	Paved Roads	0.095	0.095
	Tank Trails	0.05	0.05
	Heavy Maneuver	0.05	0.05
	Unpaved Roads	0.05	0.05
	Water/Wetlands	0.245	0.245
KVARY (1/in)	U/C Open Space	0	0.2
	U/C Low	0	0.2
	U/C Med	0	0.2
	U/C High	0	0.2
	E Forest	0	0.2
	E Forest_C1	0	0.2
	E Forest_C2	0	0.2
	E Forest_C3	0	0.2
	D Forest	0	0.2
	D Forest_C2	0	0.2
	D Forest_C3	0	0.2
	M Forest	0	0.2
	M Forest_C1	0	0.2
	M Forest_C2	0	0.2
	M Forest_C3	0	0.2
	Shrub/Scrub	0	0.2
	Grass/Herb	0	0.2
	Ag/Other	0	0.2
	Paved Roads	0	0.2
	Tank Trails	0	0.2
	Heavy Maneuver	0	0.2
	Unpaved Roads	0	0.2
	Water/Wetlands	0	0.2
AGWRC (1/day)	U/C Open Space	0.962	0.96
	U/C Low	0.96	0.95
	U/C Med	0.96	0.94

Table B-1. HSPF Parameter Adjustment Summary Table (Page 3 of 7)

Parameter	Land Use	Original Values	Calibrated Values
AGWRC (1/day)	U/C High	0.962	0.96
	E Forest	0.96	0.95
	E Forest_C1	0.96	0.94
	E Forest_C2	0.96	0.93
	E Forest_C3	0.972	0.995
	D Forest	0.96	0.995
	D Forest_C1	0.965	0.995
	D Forest_C2	0.97	0.995
	D Forest_C3	0.972	0.995
	M Forest	0.96	0.995
	M Forest_C1	0.965	0.995
	M Forest_C2	0.97	0.995
	M Forest_C3	0.95	0.995
	Shrub/Scrub	0.95	0.96
	Grass/Herb	0.95	0.96
	Ag/Other	0.95	0.96
	Paved Roads	0.93	0.93
	Tank Trails	0.93	0.93
	Heavy Maneuver	0.96	0.96
	Unpaved Roads	0.93	0.93
	Water/Wetlands	0.975	0.975
DEEPFR	U/C Open Space	0.008	0.008
	U/C Low	0.008	0.008
	U/C Med	0.008	0.008
	U/C High	0.008	0.008
	E Forest	0.008	0.008
	E Forest_C1	0.008	0.008
	E Forest_C2	0.008	0.008
	E Forest_C3	0.008	0.008
	D Forest	0.008	0.008
	D Forest_C1	0.008	0.008
	D Forest_C2	0.008	0.008
	D Forest_C3	0.008	0.008
	M Forest	0.008	0.008
	M Forest_C1	0.008	0.008
	M Forest_C2	0.008	0.008
	M Forest_C3	0.008	0.008

Table B-1. HSPF Parameter Adjustment Summary Table (Page 4 of 7)

Parameter	Land Use	Original Values	Calibrated Values
DEEPFR	Shrub/Scrub	0.008	0.008
	Grass/Herb	0.008	0.008
	Ag/Other	0.008	0.008
	Paved Roads	0.008	0.008
	Tank Trails	0.008	0.008
	Heavy Maneuver	0.008	0.008
	Unpaved Roads	0.008	0.008
	Water/Wetlands	0.008	0.2
BASETP	U/C Open Space	0.01	0.01
	U/C Low	0	0
	U/C Med	0	0
	U/C High	0	0
	E Forest	0.01	0.05
	E Forest_C1	0.01	0.05
	E Forest_C2	0.01	0.05
	E Forest_3	0.01	0.05
	D Forest	0.01	0.05
	D Forest_C1	0.01	0.05
	D Forest_C2	0.01	0.05
	D Forest_C3	0.01	0.05
	M Forest	0.01	0.05
	M Forest_C1	0.01	0.05
	M Forest_C2	0.01	0.05
	M Forest_C3	0.01	0.05
	Shrub/Scrub	0.01	0.05
	Grass/Herb	0.01	0.05
	Ag/Other	0.01	0.05
	Paved Roads	0	0
	Tank Trails	0	0
	Heavy Maneuver	0	0
	Unpaved Roads	0	0
	Water/Wetlands	0.01	0.03
AGWETP	U/C Open Space	0	0
	U/C Low	0	0
	U/C Med	0	0
	U/C High	0	0
	E Forest	0	0

Table B-1. HSPF Parameter Adjustment Summary Table (Page 5 of 7)

Parameter	Land Use	Original Values	Calibrated Values
AGWETP	E Forest_C1	0	0
	E Forest_C2	0	0
	E Forest_C3	0	0
	D Forest	0	0
	D Forest_C1	0	0
	D Forest_C2	0	0
	D Forest_C3	0	0
	M Forest	0	0
	M Forest_C1	0	0
	M Forest_C2	0	0
	M Forest_C3	0	0
	Shrub/Scrub	0	0
	Grass/Herb	0	0
	Ag/Other	0	0
	Paved Roads	0	0
	Tank Trails	0	0
	Heavy Maneuver	0	0
	Unpaved Roads	0	0
	Water/Wetlands	0.1	0.3
UZSN	U/C Open Space	0.564	0.66
	U/C Low	0.564	0.66
	U/C Med	0.564	0.66
	U/C High	0.564	0.66
	E Forest	0.564	1.26
	E Forest_C1	0.564	1.26
	E Forest_C2	0.564	1.26
	E Forest_C3	0.564	1.26
	D Forest	0.564	1.26
	D Forest_C1	0.564	1.26
	D Forest_C2	0.564	1.26
	D Forest_C3	0.564	1.26
	M Forest	0.564	1.26
	M Forest_C1	0.564	1.26
	M Forest_C2	0.564	1.26
	M Forest_C3	0.564	1.26
	Shrub/Scrub	0.564	0.72
	Grass/Herb	0.564	0.72

Table B-1. HSPF Parameter Adjustment Summary Table (Page 6 of 7)

Parameter	Land Use	Original Values	Calibrated Values
UZSN	Ag/Other	0.564	0.66
	Paved Roads	0.564	0.66
	Tank Trails	0.564	0.66
	Heavy Maneuver	0.564	0.66
	Unpaved Roads	0.564	0.66
	Water/Wetlands	0.564	0.66
INTFW	U/C Open Space	0.4	1
	U/C Low	0.4	1
	U/C Med	0.4	1
	U/C High	0.4	1
	E Forest	3.5	3.5
	E Forest_C1	3.5	3.5
	E Forest_C2	3.5	3.5
	E Forest_C3	3.5	3.5
	D Forest	3.5	3.5
	D Forest_C1	3.5	3.5
	D Forest_C2	3.5	3.5
	D Forest_C3	3.5	3.5
	M Forest	3.5	3.5
	M Forest_C1	3.5	3.5
	M Forest_C2	3.5	3.5
	M Forest_C3	3.5	3.5
	Shrub/Scrub	0.75	2
	Grass/Herb	0.75	2
	Ag/Other	0.75	2
	Paved Roads	0.4	1
	Tank Trails	0.4	1
	Heavy Maneuver	0.4	1
	Unpaved Roads	0.4	1
	Water/Wetlands	0.38	1
LZETP	U/C Open Space	0.1	0.2
	U/C Low	0.1	0.2
	U/C Med	0.1	0.2
	U/C High	0.1	0.2
	E Forest	0.1	0.2
	E Forest_C1	0.1	0.2
	E Forest_C2	0.1	0.2

Table B-1. HSPF Parameter Adjustment Summary Table (Page 7 of 7)

Parameter	Land Use	Original Values	Calibrated Values
LZETP	E Forest_C3	0.1	0.2
	D Forest	0.1	0.2
	D Forest_C1	0.1	0.2
	D Forest_C2	0.1	0.2
	D Forest_C3	0.1	0.2
	M Forest	0.1	0.2
	M Forest_C1	0.1	0.2
	M Forest_C2	0.1	0.2
	M Forest_C3	0.1	0.2
	Shrub/Scrub	0.1	0.2
	Grass/Herb	0.1	0.2
	Ag/Other	0.1	0.2
	Paved Roads	0.1	0.2
	Tank Trails	0.1	0.2
	Heavy Maneuver	0.1	0.2
	Unpaved Roads	0.1	0.2
	Water/Wetlands	0.1	0.2

APPENDIX C
MODEL PERFORMANCE METRICS DEFINED

APPENDIX C: MODEL PERFORMANCE METRICS DEFINED

These multiple statistics are used to compare the observed and simulated daily, monthly, and yearly time-series data.

CORRELATION COEFFICIENT, *R*

The correlation coefficient is the degree of linear relationship between simulated and observed data and ranges from –1 to 1. Negative values indicate a negative relationship; 0 indicates no relationship; and positive values indicate a positive relationship. A value of 1 indicates a perfect relationship.

$$R = \frac{S_{xy}}{\sqrt{S_{xx} S_{xy}}} \qquad \text{(C-1)}$$

where:

$$S_{xy} = \sum_{i=1}^{n} x_i y_i - \left(\frac{1}{n}\right)\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{y} y_i\right)$$

$$S_{xx} = \sum_{i=1}^{n} x_i^2 - \left(\frac{1}{n}\right)\left(\sum_{i=1}^{n} x_i\right)^2$$

S_{xx} = sum of squares of x (observed data)

S_{xy} = sum of $x - y$ products

n = sample size (number of observations)

x_i = i^{th} occurrence of observed flow volume (in)

y_i = i^{th} occurrence of simulated flow volume (in).

COEFFICIENT OF DETERMINATION, R^2

The coefficient of determination describes the proportion of the variance in simulated data, which is explained by the model. The value can vary from 0 to 1, and higher values indicate less error variance. Typically, values greater than 0.5 are considered acceptable.

$$R^2 = \frac{S_{xy}^2}{S_{xx} S_{xy}} \qquad \text{(C-2)}$$

MEAN ERROR (cfs)

Mean error, *e*, is calculated as the mean of differences in observed and simulated data.

$$e = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - x_i\right) \qquad \text{(C-3)}$$

MEAN ABSOLUTE ERROR (cfs), E

$$E = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - x_i\right| \qquad \text{(C-4)}$$

RMS ERROR (cfs), RMSE

$$e = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - x_i\right)^2 \qquad \text{(C-5)}$$

where:

$x_i = i^{\text{th}}$ occurrence of observed flow rate (cfs)

$y_i = i^{\text{th}}$ occurrence of simulated flow rate (cfs).

PBIAS/ MEAN PERCENT ERROR

$$PBIAS = \frac{\sum_{i=1}^{n}\left(y_i - x_i\right)}{\sum_{i=1}^{n} X_i} \qquad \text{(C-6)}$$

where:

$x_i = i^{\text{th}}$ occurrence of observed flow volume (in)

$y_i = i^{\text{th}}$ occurrence of simulated flow volume (in)

$x_{\text{mean}} = \sum_{i=1}^{n} X_i$, mean of the observed data (in).

NASH SUTCLIFFE EFFICIENCY, NSE

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(y_i - x_i\right)^2}{\sum_{i=1}^{n}\left(x_i - x_{\text{mean}}\right)^2}\right] \qquad \text{(C-7)}$$

RMSE-OBSERVATIONS STANDARD DEVIATION RATIO, RSR

$$RSR = \frac{\sum_{i=1}^{n}\left(y_i - x_i\right)^2}{\sum_{i=1}^{n}\left(x_i - x_{\text{mean}}\right)^2} \qquad \text{(C-8)}$$

APPENDIX C REFERENCES

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National Council of Examiners for Engineering and Surveying, 2016. *FE Reference Handbook,* Clemson, SC.

APPENDIX B

TASK 6 FINAL TECHNICAL MEMORANDUM

UNPAVED ROAD MODELING APPLICATION AT FORT BENNING, GEORGIA

EXTERNAL MEMORANDUM

To: Dr. Kurt Preston
Strategic Environmental Research and Development Program
Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 17D03
Alexandria, VA 22350

cc: Project Central File 2749 — Category A

From: John Imhoff
Mr. Anthony S. Donigian, Jr.
RESPEC
2685 Marine Way, Suite 1314
Mountain View, CA 94043

Date: January 18, 2018

Subject: Unpaved Road Modeling Application at Fort Benning, Georgia (Task 6 under RC-201307)

INTRODUCTION

It is a repeated message throughout forestry literature that road erosion is commonly the largest contributor to sediment production within forest watersheds, such as those that comprise Fort Benning and numerous other DoD lands. Since 2007 AQUA TERRA/RESPEC, in collaboration with the USFS's Rocky Mountain Research Station, has been investigating sediment erosion from unpaved roads at Fort Benning (FB). For SERDP Project RC-1547 we developed a watershed-scale hydrology and sediment model that represented 24 different land use types, one of which was unpaved roads. With forewarning that unpaved roads were likely a major contributor of eroded soils, we developed a hybrid model application in which we used EPA's watershed scale Hydrological Simulation Program Fortran (HSPF) (Bicknell et al., 2005) for modeling catchment-scale phenomena in combination with USFS's hillslope-scale Watershed Erosion Prediction Project (WEPP:Road) Model (Elliot et al., 1999). Using this hybrid modeling capability, the smaller-scale model used more detailed process formulations to estimate road-specific erosion quantities in the form of time series loadings that were subsequently represented baseline FB Model estimated that 28 percent of the total sediment erosion for the Installation's watershed was attributable to the less than 3 percent of land that comprises the unpaved road network (AQUA TERRA Consultants, 2010).

The hybrid model application that was performed for the SERDP project relied on literature values of sediment loss since monitoring data of actual sediment loss from unpaved roads on Fort Benning were not available. As a component of AQUA TERRA/RESPEC's current ESTCP project RC-201307, the issue of unpaved road erosion at Fort Benning has been re-visited. In 2014/2015 USFS collected runoff and erosion data resulting from storm events at two different unpaved road sites within Fort Benning: one

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site was unimproved, i.e., constructed of native soils, and the other had been re-engineered by rebuilding it in compacted layers of aggregate to improve trafficability and reduce erosion. Such improved roads are designated as "graded aggregate base" or GAB roads.

Prior to this ESTCP monitoring program at Fort Benning, watershed managers did not know the amount of sediment being lost from the original road management, nor the effects of the GAB road design. Monitoring-based estimates for mean annual sediment erosion from GAB roads are comparable to those estimated by the original FB model that was developed for SERDP under RC-1547, while those for the unimproved site were significantly greater. Site-specific WEPP:Road model applications at FB have been calibrated and validated as a component of the ESTCP project (Elliot et al., 2017).

This technical memorandum addresses the final component of the ESTCP unpaved road task, which is to evaluate the implications of the site-specific monitoring data and WEPP:Road validations to the overall representation of unpaved road erosion in the watershed-scale (and installation-scale) FB HSPF Model. The evaluation requires a look back at the original hybrid modeling approach and results that were developed under SERDP project RC-1547; re-visiting the results of the ESTCP monitoring and WEPP:Road modeling effort; and finally, providing a critical analysis and conclusions regarding the relevance and extensibility of the small-scale results to modeling watershed –scale erosion from Fort Benning's extensive unpaved road network. Increased understanding of site-specific unpaved road erosion at Fort Benning offers an opportunity to assess the issue of sediment loss from these unpaved roads, and subsequent delivery to stream channels, which is a classic problem for watershed-scale sediment modeling efforts.

FORT BENNING'S HYBRID UNPAVED ROAD MODELING

To make available a more robust set of formulations for simulating sediment washoff, USDA's Watershed Erosion Prediction Project (WEPP) Model (Flanagan and Steele, 1995) was used as a modeling 'partner' for HSPF. The WEPP application utilized modeling assumptions and data that are specific to unpaved roads and are components of the WEPP:Road interface developed by the U.S. Forest Service (Elliot et al., 1999). It should be noted that the most significant benefit that we perceived to introducing WEPP:Road into the Fort Benning modeling framework was not expectation of more accurate estimates of sediment washoff for unpaved roads. Rather, the most attractive aspect of the model was its greater level of detail in characterizing a variety of road types, and therefore its potential utility in supporting the representation and evaluation of sediment washoff from a variety of alternative road types and management practices.

WEPP-ROAD APPLICATION TO FORT BENNING UNDER SERDP RC-1547

Figure 1 provides a flowchart of the application components and sequencing that were required for the Fort Benning WEPP:Road demonstration application as part of SERDP project RC-1547. The approach featured the following requirements and/or assumptions:

1. In a parallel manner to the watershed-scale HSPF simulation scheme for unpaved roads (and other land use types), a 'representative' road segment was selected for each of the 14 different weather segments into which the FB watershed model is divided. Net unit area erosion delivered to the stream system by travel across the flow path (road surface, fill slope, forest buffer) for each of the representative road segments was simulated.
2. For the purpose of mapping WEPP:Road results to the previous HSPF results, the unpaved road area estimates for each of the 14 sub-areas were assumed to include both the road surface and fill slope overland flow elements (OFEs) represented in the WEPP:Road modeling scheme. Thus, the forest buffer OFE associated with each road segment was not considered to be a

component of the road area for purposes of computing unit area sediment delivery to the stream system. Instead, the same delivery ratio utilized for other HSPF land use types was also applied to the sediment washoff from road surface and fillslope.

3. The WEPP:Road interface typically utilizes regionalized *daily* weather data, whereas the FB Watershed Model utilizes 14 much more localized *hourly* observed weather datasets to represent the sub-areas of the Installation. In the context of the Fort Benning hybrid modeling exercise the localized weather data were reformatted (using a "wrapper") into a breakpoint file, which enabled a 'stand-alone' version of the WEPP Model (i.e., not the model version integrated into WEPP:Road) to perform its simulations using the same hourly data that drives the HSPF model and was used to simulate sediment washoff from all the other land use areas.
4. After de-coupling the weather data that are typically provided by the WEPP:Road Interface to the WEPP Model, it was still necessary to provide to WEPP:Road input parameter values that define the road characteristics and physical settings for each of the 14 representative road segments so that the Interface could translate and generate the contents of three input files (Soils, Slope, Vegetation) that provide parameter values for all the rest of the input required by the WEPP Model. Our approach was to maintain as much consistency between the physical meaning implied/imposed by parameters/values that were originally used for modeling unpaved roads using HSPF and the parameters/values subsequently required for modeling the same unpaved roads using WEPP:Road.
5. The input provided to WEPP:Road for all representative road segments at Fort Benning characterized the roads as outsloped; comprised of native materials; lacking addition of gravel or rock; and subject to heavy traffic.

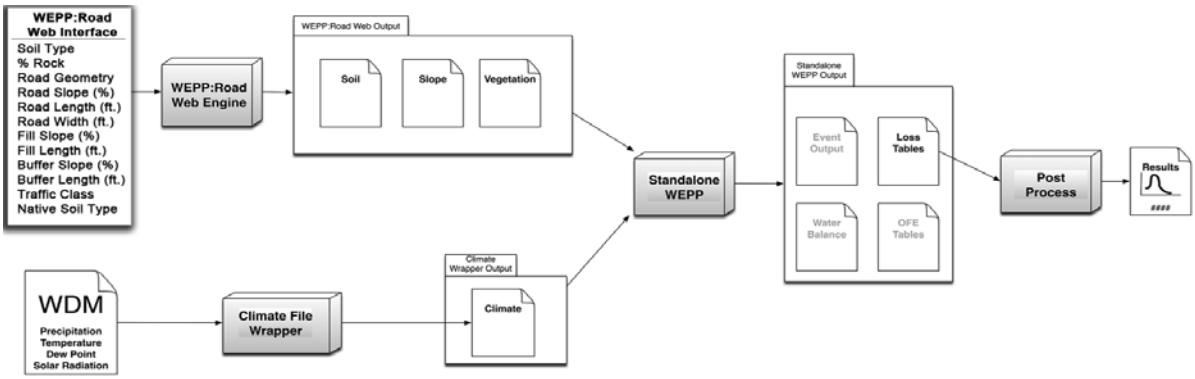


Figure 1. Flowchart for Application of WEPP:Road to Estimate Sediment Loadings from Fort Benning's Unpaved Roads Under SERDP RC-1547

CALIBRATION OF WEPP:ROAD TO FORT BENNING'S UNPAVED ROADS

Refinements of the HSPF sediment washoff calibration for all land use types progressed to a point where confidence was gained in the estimates that the model generated for unit area sediment washoff. When this had been accomplished, it was justifiable to use the HSPF annual unit area sediment washoff results (expressed as tons/acre/year) that were estimated for unpaved roads using HSPF as calibration targets for the parallel WEPP:Road simulations. (Recall that the primary objective of introducing WEPP:Road into the Fort Benning modeling framework was not expectation of more accurate estimates of sediment washoff for unpaved roads, but rather having available its greater level of detail in characterizing a variety of road types, and therefore its potential utility in supporting the representation and evaluation of a variety of alternative road management practices.)

INTEGRATING WEPP RESULTS INTO HSPF TO ACHIEVE HYBRID MODELING

Figure 2 depicts the logistical linkage that was established for demonstrating a hybrid modeling methodology using the WEPP model to provide unit area sediment washoff data for the HSPF watershed model. Sediment washoff loadings that the HSPF model had previously estimated were replaced with sediment washoff loadings that were generated by the WEPP Model. Both loading estimates relied on the simulated HSPF flow values. The mechanics of this process were as follows:

- Output from 14 WEPP simulations was processed to get daily loads (kg/m^2) at the edge of the fill slope overland flow element (OLE).
- Daily loads were imported to the watershed data management (WDM) file and units were converted from kg/m^2 to tons/acre.
- Daily loads were distributed to hourly intervals according to the hourly input precipitation pattern, with an initial set aside of 0.2 inch to accommodate for depression storage.
- Hourly unit area loads were multiplied by unpaved area acreages and used as input to each HSPF stream reach.

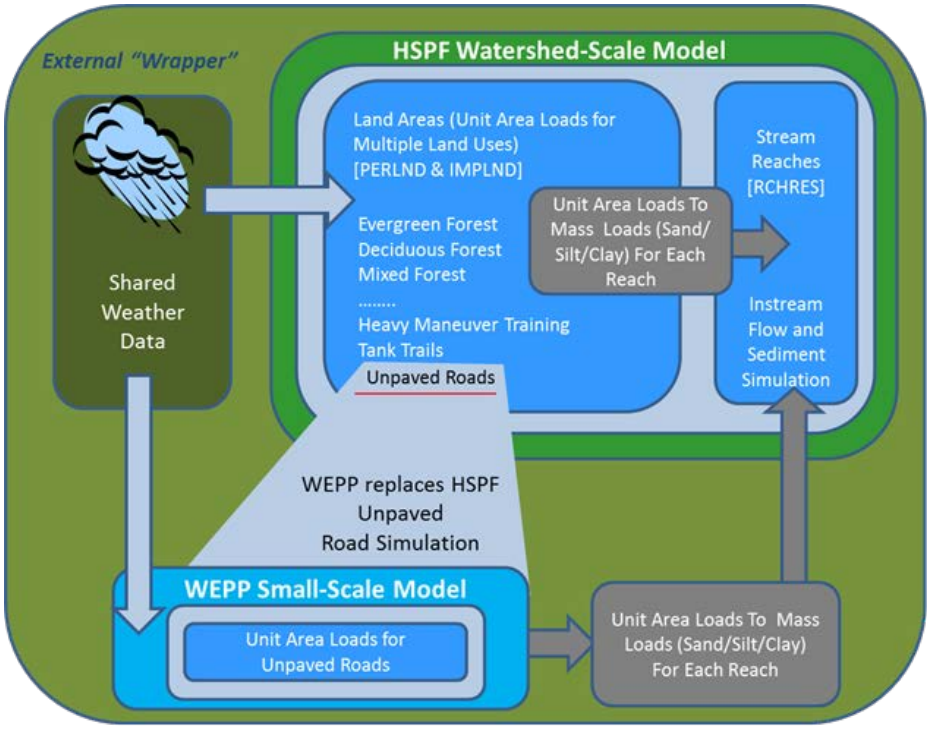


Figure 2. HSPF/WEPP Linkage for Performing Hybrid Modeling Under SERDP RC-1547

HYBRID MODELING RESULTS

Simulated unit area edge-of road sediment washoff for the 14 meteorological segments for WEPP road segments (road plus fillslope) ranged from **1.3 to 2.9 tons/acre/year**. These results fall on the lower end of the expected range of values for unpaved road erosion. In an extensive literature search performed for RC-1547, Imhoff and others (2010) derived a possible range of **2 to 20 tons/acre/year** for unit area erosion from unpaved roads (see Figure 3).

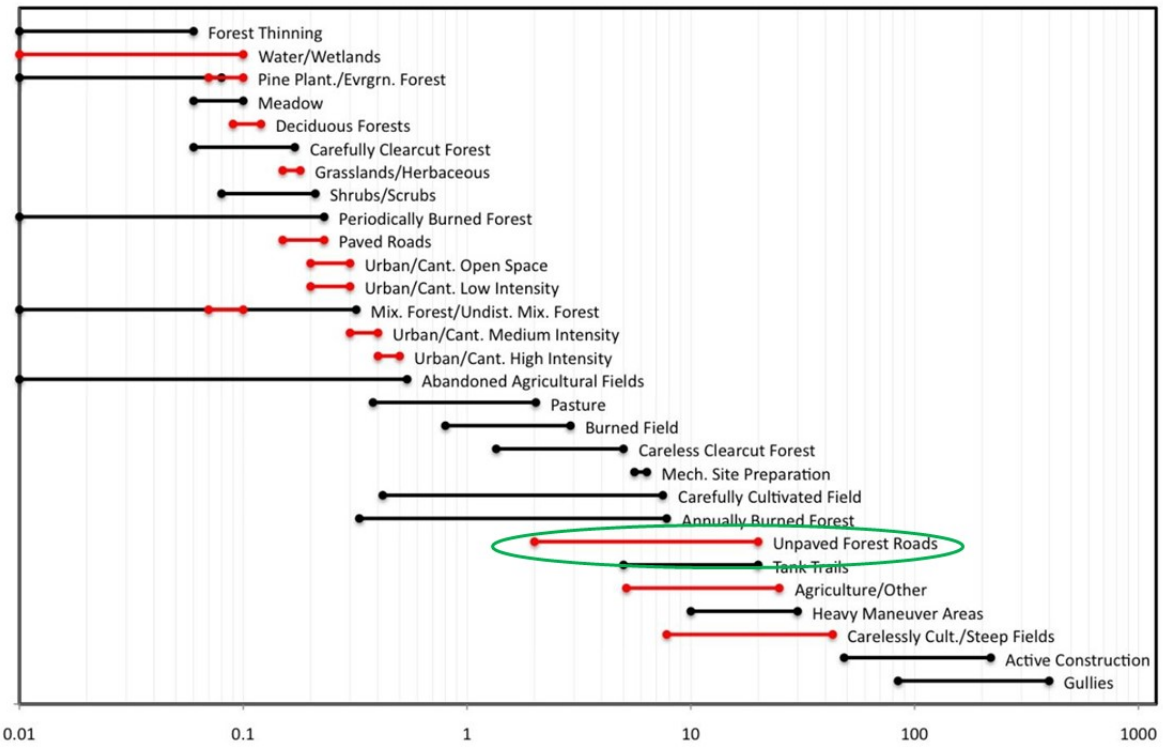


Figure 3. Unit Area Erosion Values (tons/ac/yr) for different land use types or activities (Imhoff et al. 2010).

RC-201307 SEDIMENT EROSION MONITORING AND WEPP ANALYSIS

Data to define road topography (i.e., slope, length and width of road segments) and runoff/erosion for two road types and levels of traffic intensity were collected at the sampling sites selected by the USFS. The two types of roads sampled were those with a natural road base and those with a graded aggregate base (GAB). GAB roads are designed to accommodate tank travel and training exercises. Both road types experience maintenance activities, with the natural base roads receiving gravel applications as needed after intense rainfall/erosion events, and the GAB roads typically being repaired after military training events. A GAB test site was selected that has relatively low vehicular traffic, and a natural base road was selected that experiences heavy traffic. Data that were collected and incorporated in the calibration and validation of WEPP include: soil water content, rainfall, total runoff, sediment delivered to sediment boxes, and suspended sediment concentration and yield.

Data collection took place in the months of March, June, and July of 2014 and 2015. As described fully by Elliot and others (2015, 2017) a combination of manual grab samples and automatic mechanical sampling was employed to collect data that could in turn be used to estimate storm runoff and erosion volumes. Edge-of-road sediment washoff estimates from the unimproved road were achieved for 25 storms, and 27 estimates were achieved for the GAB roads.

Calibration of the WEPP model for runoff and erosion was implemented, randomly assigning approximately half of the storm events at each site to "calibration", and half to "validation." From the recording rain gages, single storm "breakpoint" precipitation files for the WEPP model calibration were built for each storm and each gage.

Finally, in order to capture the range of precipitation variability that is necessary to estimate expected mean annual runoff and sediment washoff values, the calibrated parameter values resulting from the 2014/2015 sampling program were used in conjunction with a longer (100 years), stochastic precipitation record that had been previously developed for a nearby precipitation station.

SAMPLING AND MODLEING RESULTS

Edge-of-road sediment washoff from the unimproved road ranged from zero to **8 tons/acre** (18 t ha^{-1}) for individual storms. The unimproved road site had less runoff, but still generated nearly ten times as much sediment per mm runoff compared to the improved road design at a rainfall storm volume of 20 mm. Edge-of-road sediment washoff from GAB roads ranged from zero to **3.3 tons/acre** (7.5 t ha^{-1}) from individual storms.

Table 1 summarizes the WEPP soil erodibility properties that resulted from calibration/validation of WEPP:Road at the two sample sites. For comparison the far-right column provides values that have been previously established for the soil/condition that is considered the most highly erodible.

Table 1. WEPP soil erodibility values for GAB (at DMPRC) and natural material (at Hourglass Road) sampling sites.

Erodibility Parameter	Unimproved (Hourglass)	Improved (GAB on DMPRC)	WEPP Road for Sandy Loam High Traffic
Hydraulic Conductivity (mm h^{-1})	3.0	1.3	10.2
Interrill Erodibility (kg s m^{-4})	1,000,000	1,000,000	2,000,000
Rill Erodibility (s m^{-1})	0.09	0.0008	0.0004
Critical Shear (Pa)	0.0001	1.5	2

Using the parameter values that are reported in Table 1, WEPP was run using a stochastic precipitation record 100 years in length that had been developed for the nearby Talbotton, Georgia meteorological station. Simulations were performed for six scenarios that are considered relevant to the Fort Benning setting. The estimated average annual edge-of-road erosion rates are presented in Table 2. Overall, Elliot (2016) concluded that the unimproved road site generated more than 3.5 times as much sediment as the improved GAB site.

Table 2. Average annual erosion rates for different management methods on three different road length and steepness combinations. Model parameterization is based on ESTCP monitoring data for the 2015/2016 sampling period.

Road Topography		Edge-of-Road Sediment Washoff (tons/acre/year)	
Segment Length (ft)	Segment Gradient (%)	Unimproved	GAB
300	1	25	10
200	2	70	10
120	3	120	11

The results shown in Table 2 suggest that the estimated edge-of-road sediment washoff from GAB roads was generally about **10 tons/acre/year**, regardless of topography. The unimproved road tended

to be much more affected by the terrain, with edge-of-road sediment washoff ranging from **25 tons/acre/year** for the lowest gradient to **120 tons/acre/year** for the 3 percent gradient. Elliot (2016) suggests that viewed as a whole, a reasonable estimate of annual edge-of-road erosion for Fort Benning roads would be **10 tons/acre/year** at the GAB road site and **70 tons/acre/year** on the unimproved road site.

ANALYSIS AND CONCLUSIONS

Recall that Imhoff and others (2010) derived a possible range of **2 to 20 tons/acre/year** for unit area edge-of-road sediment washoff from unpaved roads (refer back to Figure 3). Elliot's estimation of **10 tons/acre/year** for edge-of-road erosion from Fort Benning's GAB roads fits comfortably into the middle of this range. However, we believe that the **70 tons/acre/year** estimate that Elliot derived using the monitoring data (and generated rainfall) from the unimproved road site more closely approximates a worst case scenario: the road section that Fort Benning and USFS staff selected as the monitoring site was steeper than most roads in Fort Benning's unpaved road network, and it experienced heavier traffic than most roads, including tank traffic. As a result, rutting was prevalent, and erosion was extreme.

The current FB Watershed Model utilizes a uniform sediment calibration target for all the Installation's unpaved roads; at the time of the model development, the only available unpaved road coverage for the Installation watersheds did not identify/distinguish alternative categories of unpaved roads (i.e., differences in construction practices, traffic intensity, etc.). Estimated erosion is, however, subject to model segment-specific differences in overland flow length and slope. At the time the model was developed, information was not readily available that would allow us to define the areal coverage and geographical distribution of *more than one type* of unpaved road, either in terms of traffic, maintenance, road surface erodibility and/or other physical or geometrical characteristics. Modeling roads at the current level of detail requires approximation of a *single* unit area edge-of-road erosion rate for each model segment. Since the edge-of-road value derived from monitoring the GAB site essentially falls in the middle of the range of literature values that we originally collected and used in conjunction with professional judgment to establish sediment loading rates for the FB Watershed Model's 14 meteorological segments, we believe that there is no justification for adjusting the current model's representation of the unpaved road component of sediment delivery to Fort Benning's stream network.

In addition, based on our experience with the watershed model and sediment calibration, we feel it would be difficult, if not impossible, to calibrate the model predictions to observed instream sediment concentrations with unpaved road sediment loading rates **higher by more than an order-of-magnitude,** as defined by the results of the WEPP:Road and USFS data collected. The key missing element with the WEPP:Road unpaved road loading rates is the fraction of those rates that are actually **delivered** to the stream. As noted earlier, this has been somewhat of a 'holy grail' for sediment modeling at the watershed scale. Below we cite a study that may provide a template to investigate and attempt to quantify sediment delivery for watershed scale modeling.

RECOMMENDATIONS

In light of the WEPP:Road study results and the analysis above, we offer the following recommendations:

1. We recommend that Fort Benning road engineers take full advantage of the validated WEPP:Road Model as a tool for road design to support site-specific design and construction decisions.

2. We recommend that both Fort Benning engineering staff and SERDP/ESTCP consider the unpaved road erosion estimates derived by the final version of the watershed model that was developed for SERDP RC-1547 as reasonable at a watershed scale.
3. Fort Benning has continued to improve and discretize its coverages for unpaved roads during the years that have followed the completion of the SERDP project in 2011. It is our understanding that a basis may now exist for characterizing and modeling up to three different categories of unpaved roads, each with significantly different erosion potential. To the extent that Fort Benning has interest in fine-tuning the resolution of unpaved road erosion to a more discrete scale, an update of the FB HSPF Watershed model (road surface areas; spatial distribution of the different road types; road surface erodibility characterization for multiple road types) to take advantage of new and better data, we see the opportunity for model refinement that can provide an improved tool for FB staff.
4. Recent studies have adapted the technique of 'radiometric fingerprinting' to estimate sediment apportionment for agricultural watersheds, helping to define how much of instream sediments are derived from field and non-field sources (Whiting et al., 2005; Schottler et al., 2010). The technique is based on measurements of radioisotopes, ^{210}Pb and ^{137}Cs, in both surface soils and instream sediment (TSS) samples, and using the differences in the signatures to define where the instream sediment originated, i.e., from surface erosion (field sources) or streambanks, ravines, channel bluffs, etc. (non-field sources). Performing these analyses on nested, or successive sites along a channel or river system could help to assess and quantify sediment delivery processes that are often problematic in watershed scale sediment modeling efforts. SERDP and/or ESTCP might consider funding such an effort at FB which could help improve the representation of unpaved road contributions in the FB model, and provide a significant contribution to the issue of sediment modeling on many military installations.

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APPENDIX C

TASK 6 PRODUCT

ASABE PAPER NO. 152181402
IMPACTS OF ROAD DESIGN ON SEDIMENT GENERATION

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An ASABE Meeting Presentation

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Impacts of Road Design on Sediment Generation

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Abstract. *The design of a forest road is important in controlling runoff flow paths and hence erosion from the road surface. When applying a process based erosion model, WEPP (Water Erosion Prediction Project) to forest roads, it was discovered that predicted erosion was much greater from roads that tended to concentrate water in eroding ditches or wheel ruts than roads that did not concentrate water on the surface, or had ditches that were armored with gravel to prevent ditch erosion. In order to validate these predictions, a study was installed on two road designs in Fort Benning, Georgia. One design followed the recent practice of starting with a native material road and adding gravel and grading as required. Rutting on the road surface and erosion were common occurrences on this type of road. The other design was a graded aggregate base (GAB) design, built in compacted layers, with rocked ditches. The GAB roads tended to shed water to rocked ditches. Runoff and sediment delivery were measured from ten plots ranging in size from 65 to 200 m^2. Runoff depths up to 50 mm occurred from daily rainfall amounts up to nearly 70 mm. Delivered sediment ranged from zero to more than 20 Mg ha^{-1} from individual storms. Both road designs had similar runoff coefficients, but the unimproved roads generated more than ten times as much sediment per mm runoff. Calibration and validation work for the WEPP model is ongoing. Initial results suggest that the hydraulic conductivity is similar to newly constructed roads and rill erodibility higher for these two road designs than had been measured on road erosion studies in the western U.S.*

Keywords. *Road Design, Erosion, WEPP*

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Introduction

All federal agencies, including the Department of Defense (DoD), are required to manage federal lands including vegetation, wildlife, water, and other natural resources. In 2007, AQUA TERRA Consultants began a four-year project funded by DoD's Strategic Environmental Research and Development Program (SERDP) to develop a comprehensive watershed management model for Fort Benning, Georgia. The model used EPA's BASINS modeling system (USEPA, 2007) and the EPA Hydrological Simulation Program – FORTRAN (HSPF) watershed model (Bicknell et al., 2005). The resulting Fort Benning model addressed impacts on watershed hydrology, water quality and related ecosystems resulting from military activities and natural resources management (AQUA TERRA Consultants, 2012).

Unpaved roads comprise one of twenty-four land use types that were represented and simulated in the Fort Benning model. While roads typically represent a small fraction of watershed area, road erosion is commonly a major contributor to the total sediment production within forested watersheds (Elliot, 2013). Design, construction and management of unpaved roads at Fort Benning required methods and models for estimating road erosion that provided a high level of detail. The full impact of road management measures ultimately needs to be evaluated within the holistic watershed context. To address this need, HSPF was used for modeling catchment-scale phenomena, while USDA's Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995) was run in parallel to estimate hillslope-scale sediment delivery from Fort Benning's unpaved roads (Imhoff et al., 2010).

The HSPF watershed model routed the delivered sediment from unpaved roads, combined with the watershed's other twenty-three land use types to provide estimates of total sediment delivery from the main stream exiting the base, Upatoi Creek (Figure 1) (AQUA TERRA Consultants, 2012). Upatoi Creek merges with the Chattahoochee River at the western boundary of the base, one of the most important sources of water to the states of Georgia and Florida. The quality and quantity of water in this river is closely monitored by state and the federal government agencies.

Subsequent to the completion of the SERDP-funded watershed modeling project, Fort Benning leadership developed and implemented an enhanced road design in many areas of the military base that consisted of building roads in compacted layers of aggregate to improve trafficability and reduce erosion. Improved roads were designated as "graded aggregate base" or GAB roads. In addition, the DoD opted to continue funding to AQUA TERRA through the Environmental Security Technology Certification Program (ESTCP). Since the ESTCP program places strong emphasis on the validation of technology products (in this case the HSPF and WEPP models), AQUA TERRA was specifically instructed to collect sufficient data for performance validation or testing for the unpaved road design and maintenance component (i.e. the WEPP modeling component) rather than rely strictly on literature values and/or erosion data from other watersheds. The monitored data, as well as the revised WEPP model results will be used to refine the representation of unpaved road simulation as a component of the watershed-scale HSPF model. AQUA TERRA retained USDA Forest Service (USFS) as a subcontractor with responsibility for designing the erosion monitoring network, collecting and analyzing erosion (and runoff) samples, re-applying the WEPP model, and summarizing and evaluating the model results.

The WEPP model is a physically-based hydrologic and soil erosion model that can be run in continuous mode for long periods of time using observed or stochastic weather input (Laflen et al., 1997), or in single storm mode, a feature that is useful for model parameterization and validation (Flanagan and Livingston, 1995). WEPP models the processes that cause erosion, including infiltration, runoff, soil water balance, and sediment detachment, transport, deposition and delivery.

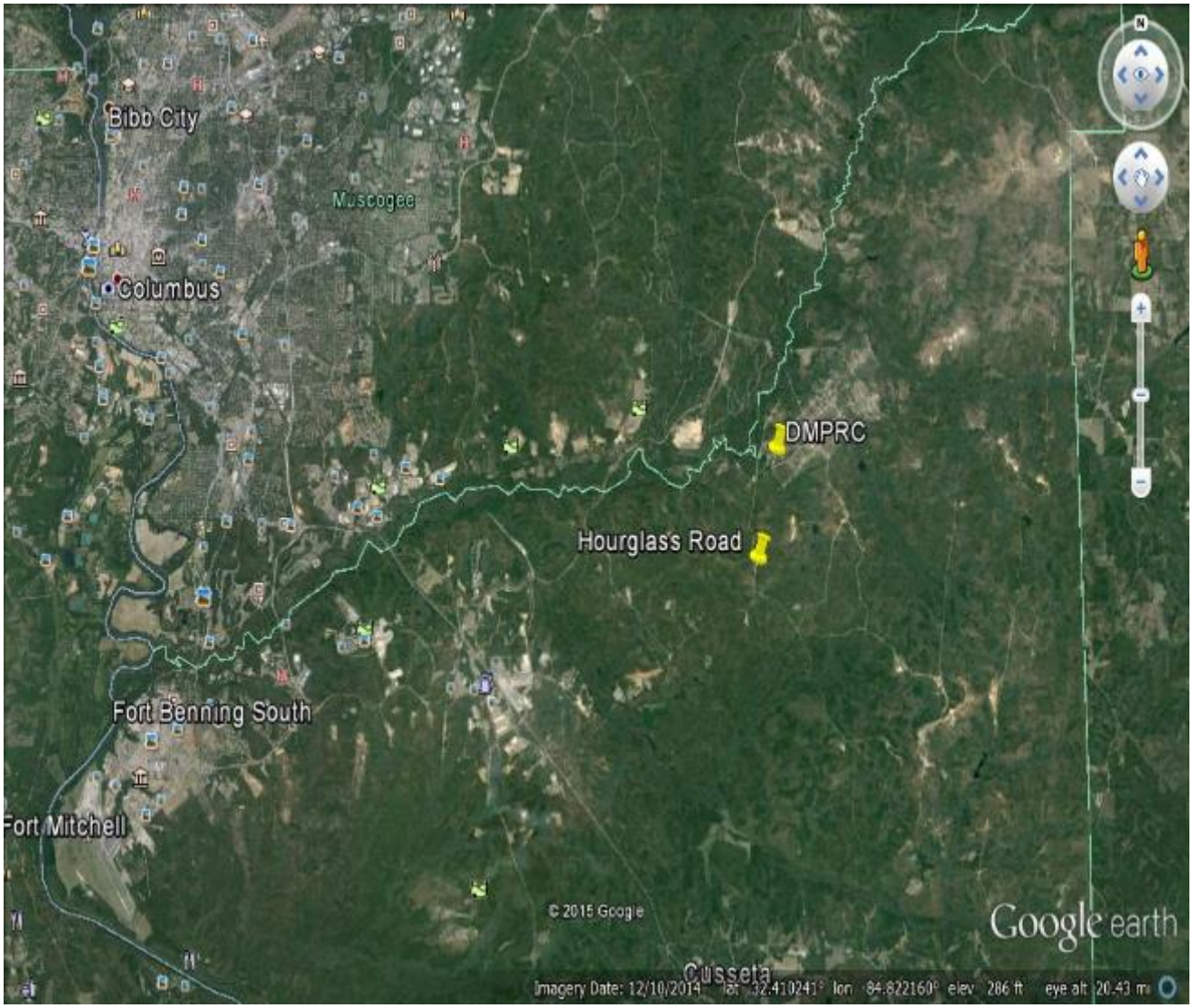


Figure 1. Location of the two sites within Fort Benning. The jagged green line just to the north of the sites is Upatoi Creek. The Chatahoochee River is on the left of the map.

For predicting road erosion, WEPP requires road segment length and gradient information, daily weather with sub-daily precipitation information, and soil properties including texture, depth, hydraulic conductivity, rill and interrill erodibility, and critical shear (Flanagan and Livingston, 1995). The erodibility values have generally been determined from rainfall simulation studies (Foltz et al., 2009 and 2011), but natural rainfall and runoff plots have also provided data to calibrate or validate the WEPP model for a given condition (Elliot et al., 1994; Robichaud et al., 2011). Determining WEPP erodibility values from natural rainfall can be challenging, as the erosion variables are not independent, and there may be more than a single optimal solution from a given set of data (Page, 1988).

This paper describes the background and some initial observations in a project to monitor sediment leaving unimproved and GAB road segments, and to evaluate the ability of the WEPP model to accurately predict sediment delivery from roads in Fort Benning.

Methods

Field Data Collection

Plots to measure road erosion were installed on unimproved and improved GAB road sites. The GAB site was on the Digital Multipurpose Range Complex (DMPRC), a site heavily used for military tank training. The nearby unimproved road site was on Hourglass Road (HG), a heavily trafficked road used

Table 1. Locations and descriptions of plots within site locations.

Site*	Plot Name	Plot Sampling Type	Plot Area (m^2)	Plot Length (m)	Road Plot Gradient (%)
DMPRC – GAB road	DMRP1	Automatic	97.93	18.37	11.04
	DMRP2	Automatic	102.71	18.35	11.87
	DM4P1	Manual	58.63	12.30	10.76
	DM4P2	Manual	62.51	12.44	3.66
	DM5P1	Manual	62.91	12.10	7.94
	DM5P2	Manual	62.91	12.10	7.04
HG – unimproved road	HGP1	Manual	65.10	12.23	6.32
	HGP2	Manual	67.48	12.27	6.02
	HGRP3**	Automatic	342.15; 146.68	54.41; 24.45	4.52; 3.97
	HGRP4**	Automatic	213.32; 148.56	35.66; 24.32	3.54; 3.38

* DMPRC is the Digital Multipurpose Range Complex; GAB is a Graded Aggregate Base, improved road design and HG is Hourglass Road, the unimproved road site

** HGRP3 and HGRP4 plots were shortened after the first runoff event overwhelmed the monitoring equipment

by a wide range of vehicles including trucks of all sizes and tracked vehicles. Hourglass Road is graveled as needed and regularly graded to prevent excessive rutting. All plots are on ridge top roads in relation to Upatoi Creek. The plots for both road designs had to be in close proximity to each other to facilitate plot management. The two sites selected, DMPRC and HG, were within about 3.5 km of each other (Figure 1). Plots needed to be sufficiently long to ensure that both interrill and rill erosion processes were occurring, but not too long as to overwhelm the monitoring equipment during a heavy thunderstorm (Table 1).

The study had two types of plots: “automatic sampling plots” which were continuously monitored by recording equipment and “manual sampling plots” that were monitored by manually grab sampling during runoff events. Both types collected road runoff from roadside sheet metal gutters except for the two auto-sampled plots on Hourglass Road. The DMPRC site contained two automatic sampling plots and four manual sampling plots for a total of six plots. The HG site contained two automatic sampling plots and two manual sampling plots for a total four plots. (Table 1). The runoff from the unimproved plots was concentrated in road ditches, and the ditch flow was diverted to a pipe leading to the auto-sampler equipment. The samples collected from both types of monitoring plots were analyzed at the US Forest Service Rocky Mountain Research Station soils lab in Moscow, Idaho, to determine runoff rate and sediment concentration by gravimetric methods by drying the collected runoff at 105 ° C.

No additions or alterations to the existing roads impeded traffic. No sampling or access was allowed in the DMPRC when it was in use for training activities, but access was available early mornings, evenings and on weekends for manual sampling if there was a rainfall event.

Data collection took place in March, June, and July of 2014 and planned for the same months in 2015. All plots were initially installed during the last week of February and first week of March, 2014. The automatic samplers were removed at the end of March and reinstalled for the June and July collection period.

Manual Sampling Plots

At manual sampling plots, timed grab samples of runoff were taken at approximately 5-minute intervals from each plot during a storm. Manual sampling plots were installed in pairs so that for a given storm, a runoff sample could be collected from two plots sequentially. From the manual samples collected, the total storm runoff and sediment yield were estimated by integrating the observed runoff and sediment concentration samples for the duration of the runoff event.



Figure 2. Grab sample plot on the DMPRC. Note the natural slope break serving as the top of the plot, and the shallow trench diverting water from the bottom of the plot to the collection point.

Manual sampling plots on the DMPRC site were established on the short road segments that led up to flat concrete firing stations (Figure 2). The locations had a concrete turning pad on the main road followed by two short treated road sections, one leading to another concrete turning pad the other leading to the firing berm. A diversion trench was dug 25 mm deep, 100 mm wide at the top and bottom of the road section near the concrete turning pad to define the plot boundary. L-shaped border gutters of approximately 12 m in length were constructed using 16 gauge sheet metal at the edge of the road to collect runoff. The diversion trench directed runoff during rainfall events to the gutters to catch runoff and sediment and divert it into the headwall outlet where samples were collected.

Manual sampling plots at the HG site used the existing grader-created ditches that led to turn outs to define the plot boundary. The runoff was diverted to an L-shaped headwall outlet where samples were collected.

Automatic Sampling Plots

For automatic sampling plots, runoff was diverted from the road plot to a box containing a 180-L sediment tank, a depth data logger, a weir for measuring runoff rate, and a proportional sampler for collecting samples that could determine suspended sediment concentration leaving the sediment tank (Figures 3 and 4). The sediment boxes at each automatic sampling plot were anchored to 150 mm diameter, 450 mm deep concrete piers.

The two DMPRC automatic sampling plots were installed between the two firing stations where the manual sampling plots were located (Figure 3). The DMPRC automatic sampling plots used the natural break in slope near the firing station as the upper plot boundary and a 25 mm deep, 100 mm wide diversion path to define the lower plot boundary. A series of 16 gauge sheet metal borders on the side of the road section were installed at both plots, diverting runoff into a 200 mm diameter plastic culvert connected to the sampling box, located 5 to 6 m from the road.

The two HG automatic sampling plots used grader-incised earthen ditches that routed water from the road surface to the road ditch runoff turnout. Natural breaks in slope were used as the upper and lower watershed boundaries. A diversion in the turnout was installed to guide the runoff into a 200 mm diameter plastic culvert that conveyed the runoff to the sampling box located 18 to 20 m from the road (Figure 3). During the first storm event of the study, the sediment box on the longest HG plot overflowed from a 60-mm rainfall event. Both HG automatic sampling plots (HGRP3 and HGRP4) were



Figure 3: Automatic sampling box with pipe leading to the box removed during a cleanout period along the HG site

shortened for the remainder of the study so as to not overwhelm the monitoring equipment (Table 1).

Weather Station and Rain Gages

A weather station was installed in a cleared area southeast of the DMRPC site 5 grab sample plots (Figure 5). The station recorded precipitation, temperature, humidity, solar radiation, wind direction and wind speed. Four additional tipping bucket rain gages were installed near each of the automatic sampling plot locations to record precipitation.

On the manual plots, a portable tipping bucket recording rain gage was set up adjacent to the plots prior to sampling, and the resulting distribution of rainfall received during the sampling period recorded.

Data Analysis

From the recording rain gages, spreadsheet analyses were used to estimate peak rainfall intensities, and total rainfall for each event. In some cases with the automatic samplers, rainfall and runoff may have started before midnight on one day and finished after midnight the following day. For such storms, the date assigned to the storm was the day the storm ended.

For both the manual and the automatic plots, instantaneous flow rates were integrated in spreadsheets using Simpson's Rule (Whyte, 1976) to determine total runoff. If there were fewer than three observations, then the integration was carried out using the Trapezoidal Rule (Whyte, 1976). Care was needed as there were periods within a single storm event when precipitation and runoff rates were near or at zero.

On the automatic sampling plots, suspended sediment that exited through the weir was determined the same way as the runoff. The exiting sediment was added to the suspended and settled sediment in the sediment tank to determine sediment delivery from each runoff event.

The runoff coefficient *RC* (Runoff ÷ Rainfall) was calculated for each runoff event. Calculated sediment delivery was divided by plot area to determine erosion rates.

Model Calibration and Validation

In this paper, an initial calibration of the WEPP model for runoff amounts was implemented based on 2014 data from two plots (HGRP3 and DMRP1), which were chosen because of the completeness of

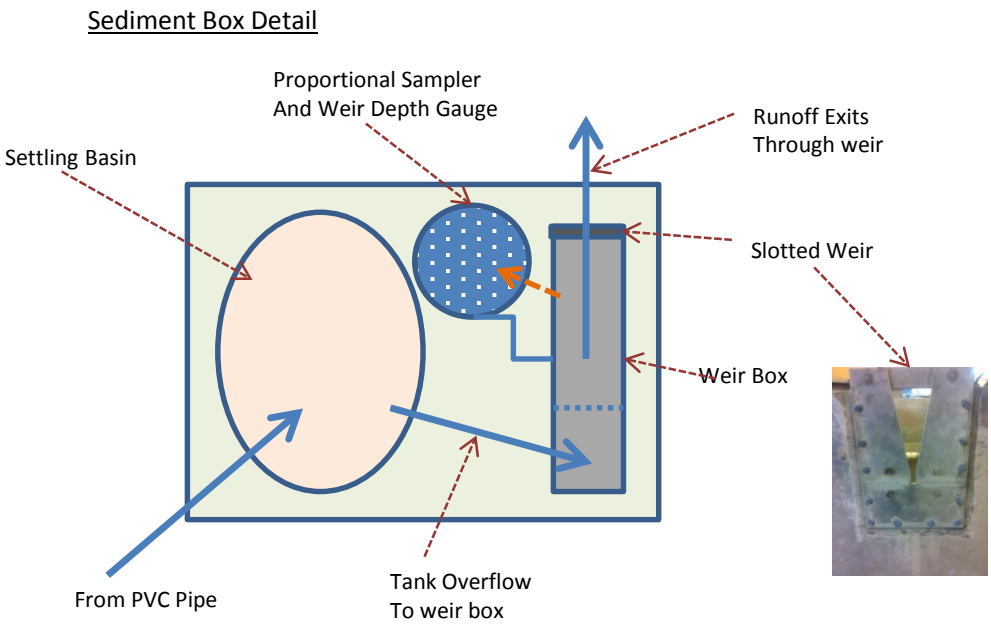


Figure 4. Diagram of components within the sediment box at automatic sampling plots.

the collected dataset. There were four runoff events from HGRP3 and 3 runoff events from DMRP1 suitable for calibration in 2014. From the recording rain gages, single storm "breakpoint" precipitation files for the WEPP model calibration were built for each storm and each gage (Flanagan and Livingston, 1995). Other weather information on the day of each event (maximum and minimum temperatures, wind speed, humidity, solar radiation, etc.) were obtained from the weather station located at the DMPRC (Figure 5). An initial manual calibration determined that critical shear was very low and it was set equal to 0.03 Pa for subsequent analyses. The interrill erodibility values were fixed at typical values for roads (1,000,000 kg s m^{-4}), as the model is less sensitive to interrill erodibility and critical shear than it is to rill erodibility (Nearing et al., 1989). The hydraulic conductivity was then manually adjusted in increments of 0.1 mm h^{-1} to obtain a minimal value for the sum of the squares of the difference between observed and predicted storm runoff. Once the optimal estimate for hydraulic conductivity was defined for the two plots, the rill erodibility was adjusted until a minimal error sum of squares of the difference between observed and predicted sediment delivery was determined. Using the optimal rill erodibility value, optimal values were determined for critical shear and interrill erodibility. Rill erodibility was checked a final time to ensure that it was still the value that resulted in the least error sum of squares value. The model performance was then tested with observations from the two validation plots (6 events on HGRP4 and 3 events on DMRP2).

Results

Field Observations

As of writing this paper, only the data collected in 2014 has been processed. During March, June and July, 2014, there were 40 days with precipitation measured by at least one rain gage near the monitoring sites. Runoff was collected on only 3 of these days for the automatic samples on the improved road plots, 4 days on one of the unimproved plots, and 7 days on the other (Table 2). The range of precipitation depths in Table 2 for each runoff event are from the nearest functioning rain gage to each plot. Because of spatial variability in rainfall, there were dates when runoff was recorded at one site, but not at the other. For example, on July 11, runoff was collected from both plots on the unimproved site, but there was no runoff from the improved plots. The July 21 runoff event recorded on plot HGRP4 was not recorded on the other three plots as there was insufficient time to clean out the accumulated sediment from the July 19 storm on all four sites before July 21.

For the automatic sampled plots (Table 2), the unimproved road site plots generated an average total runoff of 91.1 mm from 167 mm of precipitation, compared to the DMPRC GAB road plots where an average of 95.3 mm of runoff was measured from 126 mm of precipitation. Average runoff coefficients were 0.49 for the unimproved roads and 0.59 for the improved roads. Even though the improved roads generated more runoff, the sediment yields were about 1/10 of the unimproved roads. The total sediment delivery was 0.68 kg m^{-2} for the improved site, compared to 6.87 kg m^{-2} for the unimproved plots.

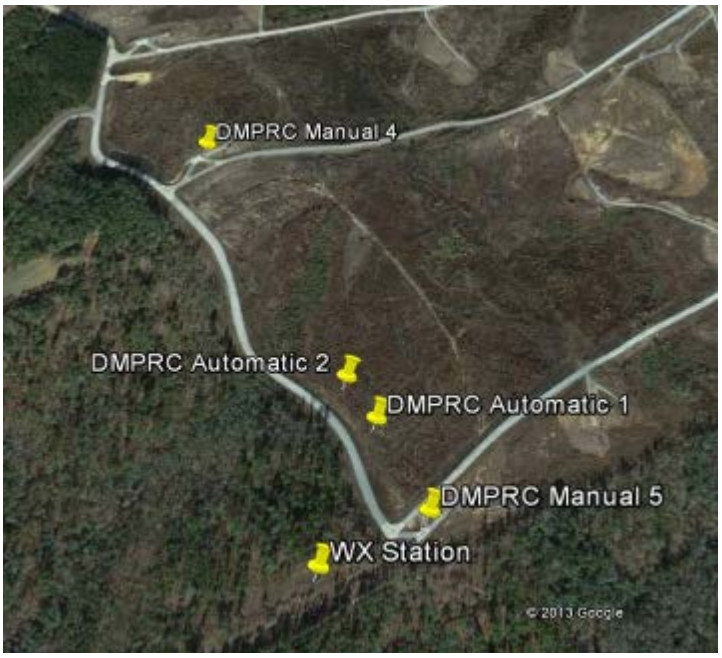


Figure 5. Locations of the automatic sampling plots, manual sampling plots and weather station (WX) on the DMPRC site.

The manual sample summary is presented in Table 3. Manual data were collected for 5 events on the unimproved roads, 4 events on one of the improved road sites, and 2 events on the other. For a given storm, only two adjacent plots could be sampled sequentially as shown in Table 3. The precipitation depths given for each runoff event are those observed by the nearest working rain gages to each of the sites or the portable rain gage. Runoff was generated from smaller storm events on the manual plots than from the auto sampler plots as can be noted by comparing Tables 2 and 3.

On July 21, there was more runoff collected than the observed precipitation depth on both of the unimproved road plots. This is likely due to severe rutting on the road routing water from outside of the plot to the collection troughs. We do not anticipate using these data for our expanded study, but have reported the values to give the reader a sense of some of the challenges associated with collecting road erosion data.

Calibration and Validation

Tables 4 and 5 show the results of the initial modeling work from four plots, two plots used for calibration (HGRP3 and DMRP1) and two plots used for validation (HGRP4 and DMRP2), to demonstrate the nature of the data set. Table 6 shows the erodibility values for the unimproved and improved plots, and the Sum of Squares of the Errors (SSE) for both calibration and validation. The hydraulic conductivity was greater on the improved road plots (1.3 vs. 0.4 mm h^{-1}), and the rill erodibility was less (0.0014 vs. 0.065 s m^{-1}). The critical shear was greater on the improved plots (1.8 Pa) than on the unimproved plots (0.0001 Pa). We could not discern any difference in the interrill erodibility values for the two road surfaces from this data set. The Sum of Squares error was generally greater for the unimproved analysis, likely due to generally greater amounts of runoff and sediment delivery.

Discussion

Field Observations

During all three months of the 2014 study period, the precipitation was dominated by small area, high intensity scattered thunderstorms. For example, on July 19, recorded precipitation was 18 mm on the improved plots but 31 mm on the unimproved plots.

Precipitation as low as 2.5 mm produced runoff from manually sampled plots on the improved roads, on March 29 (Table 3) most likely because the soil was saturated from a 49-mm storm on March 28 (Table 2). Generally, most runoff events were associated with storms generating more than 10 mm of precipitation. The difference in runoff between the automatic and manual sampling plot types (Tables

Table 2. Summary of 2014 events for the Automatic Sampling Plots

Plot	Month	Day	Precip. (mm)	Runoff (mm)	Sediment (kg/m^2)
DMRP1	3	16	58.93	53.98	0.322
Improved	3	28	49.02	26.59	0.034
	7	19	18.03	22.46	0.293
DMRP2	3	16	58.93	53.45	0.581
Improved	3	28	49.01	23.01	0.046
	7	19	18.03	11.07	0.091
HGRP3	3	28	46.23	36.29	0.710
Unimproved	6	23	40.64	15.32	5.891
	7	11	16.00	6.04	0.809
	7	19	31.50	17.01	1.580
HGRP4	3	16	68.83	12.49	0.745
Unimproved	3	28	46.23	47.33	0.554
	6	23	39.37	13.90	1.103
	6	30	10.41	0.71	0.153
	7	11	13.72	3.23	0.367
	7	19	30.99	11.02	0.732
	7	21	33.02	18.86	1.092

2 and 3) is likely because the manual sampling plots were shorter in length than the automatic sampling plots (compare the improved plot manual samples to automatic samples on March 16, or the unimproved manual to automatic plots on March 28). When comparing manual sampling times to the recording rain gages, is was noted that there may have been additional times of precipitation during that day when samples were not being collected. Because manual samples were not collected from both sites from the same storms, direct comparison of the results is not possible. Evaluation of the differences between this set of plots will be better determined when a full validation and calibration study is carried out for the full two years of data.

Overall, the unimproved site is generating more than 10 times the sediment than the improved site. Onsight observations following events suggested that the unimproved ditches were frequently areas of deposition of material eroded from the road surface. Had gutters been installed on the unimproved plots as was done on the improved sites, even more sediment may have been captured from some events.

Figure 6 compares the relationships between sediment delivery and runoff. The general relationships were reasonable as sediment delivery increases with runoff. Runoff, delivered sediment, and the amount of sediment delivered per mm runoff are all greater on the unimproved road plots with 89 g/mm compared to 8 g/mm for the improved plots

Calibration and Validation

The calibration results in Table 6 reflect the greater amounts of runoff and sediment collected from the unimproved site.

Even though the runoff coefficients were greater for the improved roads, the calibrated hydraulic conductivity was also greater. This may be because more small events were sampled from the unimproved site, which tended to result in lower runoff coefficient values, because the calibrated hydraulic conductivity was lower.

Table 3. Summary of 2014 events for the Manual Sampling Plots

Plot	Month	Day	Precip. (mm)	Runoff (mm)	Sediment (kg/m^2)
DM5P1	3	12	7.62	1.25	0.018
Improved	6	30	16.76	18.66	0.240
	7	19	29.21	38.99	0.256
	7	20	8.64	0.814	0.001
DM5P2	3	12	7.62	1.19	0.044
Improved	6	30	16.76	19.40	0.263
	7	19	29.21	21.16	0.142
	7	20	8.64	1.19	0.002
DM4P1	3	16	26.16	23.87	0.233
Improved	3	29	2.54	1.247	0.001
DM4P2	3	16	26.16	21.15	0.118
Improved	3	29	2.54	0.544	0.001
HGP1	3	6	8.13	12.23	0.157
Unimproved	3	28	14.48	22.27	0.105
	6	23	33.53	49.29	5.207
	7	11	16.51	10.62	0.438
	7	21	31.50	76.45	1.949
HGP2	3	6	8.13	6.62	0.063
Unimproved	3	28	14.48	20.66	0.097
	6	23	33.53	46.52	4.803
	7	11	16.51	10.23	0.378
	7	21	31.50	74.95	2.630

Grace and Elliot (2008) determined that the online WEPP:Road predictions were reasonable when compared to observed sediment delivery from forest roads in the Conecuh National Forest, 230 km southwest of the study site. The current WEPP:Road database has a hydraulic conductivity for a sandy loam road soil of 3.8 mm h^{-1} for a native surface road, and 10.2 mm h^{-1} for a graveled road, both values are higher than was observed on these plots. In recent studies, Foltz has observed hydraulic conductivity values on roads around 8 mm h^{-1} (Foltz et al., 2009, 2011). The lower values for hydraulic conductivity in this study may be due to higher clay contents on these soil for the unimproved plots than generally the case in the western U.S. where all the data were collected for the WEPP database. Also, the level of traffic on these roads is much greater than was observed on the above forest road studies. On the improved roads in this study, the compacted layers of aggregate likely contributed to lower hydraulic conductivity values, as these practices are uncommon on the forest roads measured in previous studies. Similar low values, however, were reported by Elliot et al. (1994) on newly constructed roads in the Western U.S., where time had been too short for macropores to form as likely occur on lower traffic roads.

Rill erodibility is much lower in the WEPP:Road database, typically 0.0004 s m^{-1} (Elliot, 2004) compared to 0.0014 for the improved roads and 0.065 for the unimproved road plots. The constant heavy traffic coupled with regular maintenance on the unimproved may have increased sediment availability and hence the erodibility. Traffic volume is one of the major factors contributing to increased erosion on unpaved roads (Reid and Dunne, 1984; Foltz, 1996; Luce and Black, 1999; Ziegler et al., 2001; Sheridan et al., 2006; Fu et al., 2010). The calibration will likely be improved when more observations become available in 2015, but the general trend of higher erodibility on these military roads than on forest roads is noteworthy. The only other recent study noting that erodibility values in

Table 4. Results of calibration and validation analyses on the unimproved Hourglass plots

Calibration with HGRP3					
	Observed			Predicted	
Date	Precip. depth (mm)	Runoff (mm)	Sediment (Mg ha^{-1})	Runoff (mm)	Sediment (Mg ha^{-1})
28 March	46.23	36.29	7.10	35.03	12.70
30 June	10.41	0.70	1.55	6.35	2.28
11 July	16.00	6.04	8.09	11.44	3.95
19 July	31.5	17.01	15.80	18.44	6.69
Validation with HGRP4					
	Observed			Predicted	
Date	Precip. depth (mm)	Runoff (mm)	Sediment (Mg ha^{-1})	Runoff (mm)	Sediment (Mg ha^{-1})
28 March	46.23	47.33	5.54	34.89	10.61
23 June	39.37	13.9	11.03	30.40	9.07
30 June	10.41	0.71	1.53	5.88	1.79
11 July	13.72	3.23	3.67	9.13	2.67
19 July	30.99	11.02	7.32	17.52	5.33
21 July	33.02	18.86	10.92	27.28	8.16

WEPP were likely too low was that by Welsh (2008) who found that WEPP:Road under predicted observed sediment delivery by a factor of six on the highly erodible Pikes Peak Batholith in Colorado, USA.

Final model calibration and validation are awaiting the completion of data collection and lab analysis from the 2015 data collection period.

Summary

This paper reports the first year of a study measuring road erosion from individual storms on two types of road design in Fort Benning, Georgia, USA. The study found that there was more runoff and sediment delivery from unimproved roads. Hydraulic conductivity values are lower and rill erodibility values are greater than currently assumed for forest roads in online interfaces to the WEPP model to predict road erosion. In the preliminary calibration and validation analysis, the WEPP technology was able to consistently reflect the effects of precipitation amount, topography and road management on sediment delivery.

Acknowledgements

The authors wish to acknowledge the Department of Defense ESTCP program who provided much of the funding for this study. We are also indebted to Mr. Ben Kopyscianski, hydrologist with the Rocky Mountain Research Station who spent many long, hot days installing and maintaining the plots, and collecting grab samples during storms that could occur any time during the day or night. We greatly appreciated the assistance provided by Carlton Cribb, Site Supervisor of the DMPRC site where the improved road plots were installed.

Table 5. Results of calibration and validation analyses on the improved DMPRC plots

Calibration with DMRP1					
	Observed			Predicted	
Date	Precip. depth (mm)	Runoff (mm)	Sediment (Mg ha^{-1})	Runoff (mm)	Sediment (Mg ha^{-1})
16 March	58.93	53.98	3.22	47.0	3.37
28 March	49.02	26.59	0.34	33.86	0.31
19 July	29.21	22.46	2.93	17.62	0.08
Validation with DMRP2					
	Observed			Predicted	
Date	Precip. depth (mm)	Runoff (mm)	Sediment (Mg ha^{-1})	Runoff (mm)	Sediment (Mg ha^{-1})
16 March	58.93	53.45	5.81	47.00	4.50
28 March	49.01	23.01	0.46	33.86	0.69
19 July	29.21	11.07	0.91	17.62	0.12

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Table 6. Soil calibrated soil erodibility values and sum of squares errors (SSE) for calibration and validation of Unimproved (Hourglass) and Improved (DMPRC) plots

	Unimproved			Improved		
Variable	Value	Cal. SSE	Val. SSE	Value	Cal. SSE	Val. SSE
Hyd. Cond. (mm h^{-1})	0.4	64.62	601.75	1.3	125.0	202.2
Rill Erode. (s m^{-1})	0.065	132.06	42.16	0.0014	8.15	2.40
Crit. Shear (Pa)	0.0001			1.8		
Interrill Erode. (kg s m^{-4})	1,000,000			1,000,000		

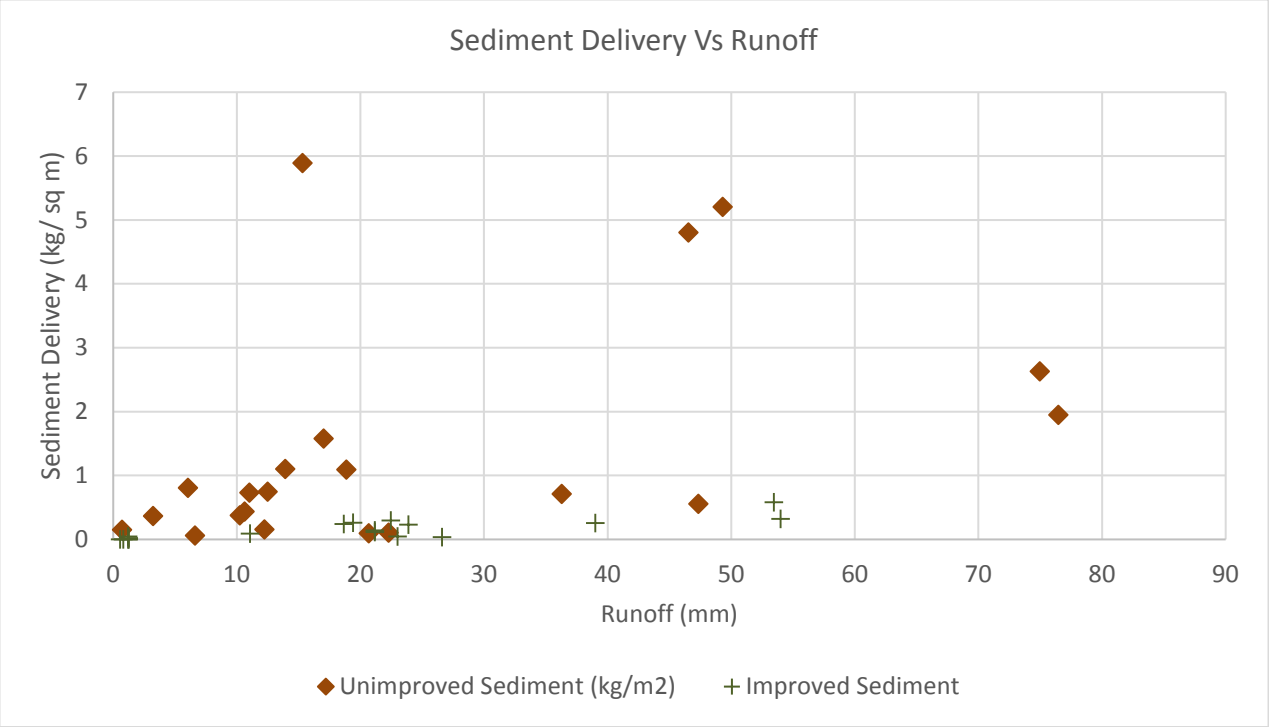


Figure 6. Sediment Delivery versus Runoff for 2014 calibration and validation Plots.

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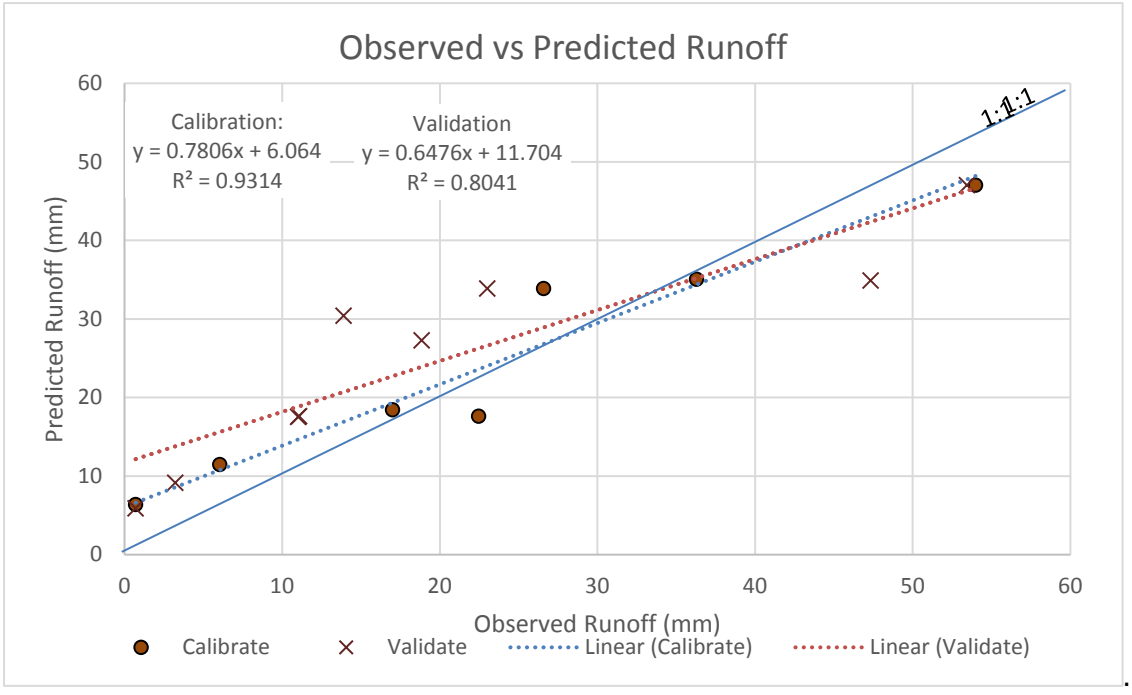


Figure 7 Observed vs. Predicted Runoff for Validation and Calibration Plots.

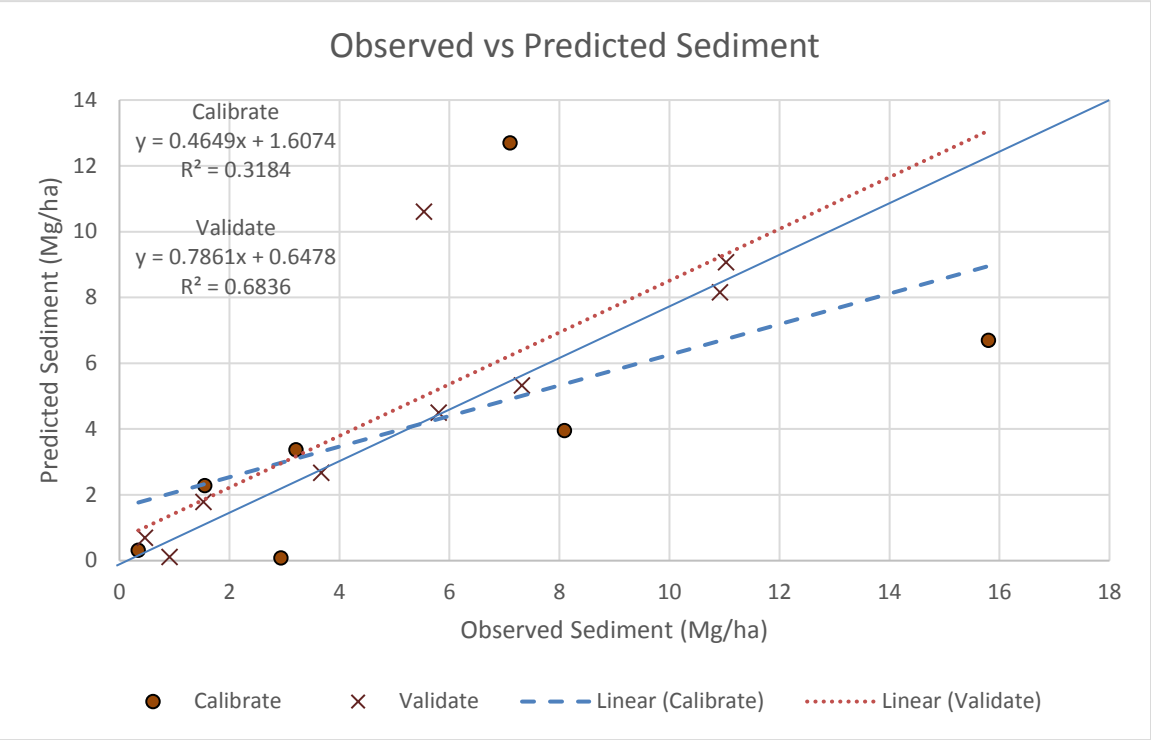


Figure 8. Observed vs. Predicted Sediment Delivery for Validation and Calibration Plots.

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APPENDIX D

TASK 6 PRODUCT

VALIDATION OF WEPP EROSION PREDICTION ABILITY ON MILITARY ROADS

Validation of WEPP Erosion Prediction Ability on Military Roads

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Military vehicles drive past intake to erosion monitoring equipment

Background

- Managers are challenged to maintain the water quality of streams draining military bases
- The greatest pollutant in base drainage water is sediment
  - Other pollutants, such as heavy metals and nutrients are generally attached to eroding sediments
- The greatest source of sediments on most military bases is the road network
- Predictive models can be useful in identifying road segments that are the greatest sources of sediment, and targeting those segments for mitigation

W. Elliot, PE, PhD, USDA Forest Service
Rocky Mountain Research Station

Requirements for a Road Erosion Predictive Model

- A model to estimate road erosion must be able to incorporate the following factors:
  - Road segment topography (length, grade, distance to streams)
  - Soil erodibility of road surfaces and buffers
  - Road management practices
    - Paving
    - Grading
    - Ditch treatments
  - Local climate
    - Average years and extreme events
    - Future climates



Weather station near road plots

Why select the WEPP Model for military base soil erosion prediction?

- Characteristics of the **W**ater **E**rosion **P**rediction **P**roject (**WEPP**) Model:
  - Collaboratively developed with the USDA Ag Research Service, Natural Resource Conservation Service and Forest Service
  - Models erosion processes including infiltration, runoff, sediment detachment, transport, deposition and delivery from complex hillslopes
  - Generally run for 30-100 years with a daily stochastic climate
    - Climates can be developed for anywhere in the world
  - Can be run in single storm mode for model development

W. Elliot, PE, PhD, USDA Forest Service
Rocky Mountain Research Station

Background to ESTCP Study

- In a recent study, WEPP sediment generation was linked to the HSPF watershed model, predicting road sediment generation with WEPP and watershed sediment delivery with HSPF
- This study was installed at Fort Benning, GA, to measure sediment delivery from road segments
  - For longer and shorter lengths
  - For unimproved and improved road designs
  - A Total of 10 plots were monitored in March, June and July in 2014 and 2015, with up to 16 runoff events per plot

Range of Variables

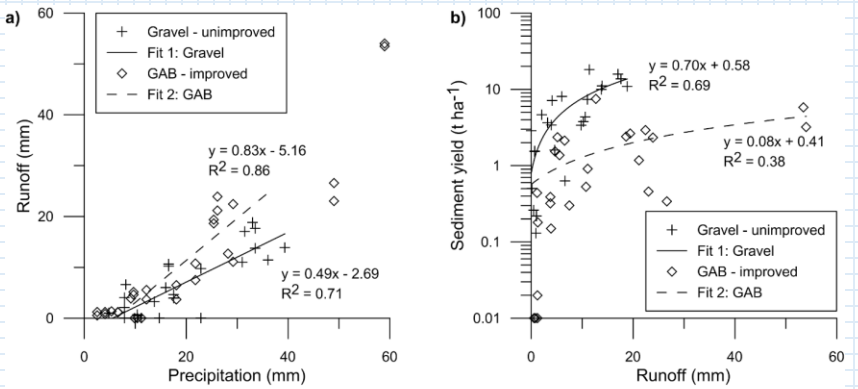
- Segment Lengths: 12 – 54 m
- Gradients: 4 – 14 %
- Storms that generated runoff: 2.5 – 58 mm
- Treatments:
  - Adding gravel and grading as needed
  - Graded Aggregate Base (GAB) compacted subgrade design



Pipe to erosion monitoring equipment

W. Elliot, PE, PhD, USDA Forest Service
Rocky Mountain Research Station

Observed runoff and sediment yields



Note: More Runoff from GAB Plots, but more sediment from Gravel Plots

WEPP Erodibility Parameters

Half the data were used for model **calibration**, and half for **validation**

Input variables were optimized to best match
predicted runoff and erosion with observed values

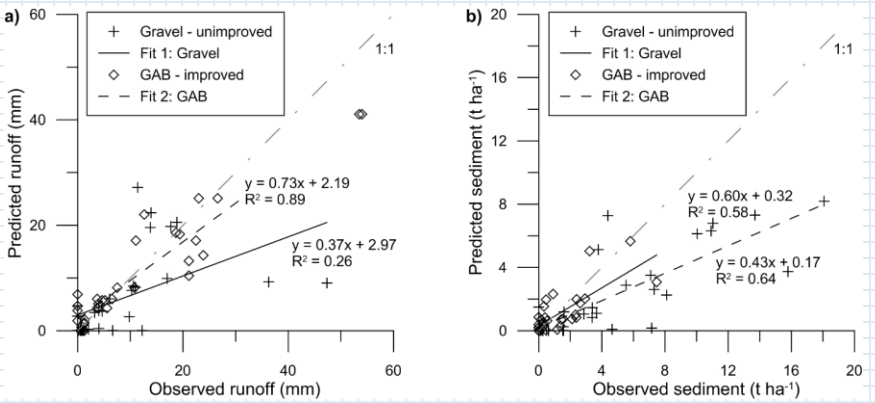
Variable	Unimproved Gravel	Improved GAB
Hydraulic Conductivity	3.0 mm/h	1.3 mm/h
Rill Erodibility	0.09 s/m	0.0008 s/m
Critical Shear	0.0001 Pa	1.5 Pa
Interrill Erodibility	1 x 10^6 kg-s/m^4	

Comment: The unimproved gravel rill erodibility value (0.09 s/m) was the largest ever measured in cropland, rangeland and forest WEPP field studies in the U.S. since studies started in 1986!

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Rocky Mountain Research Station

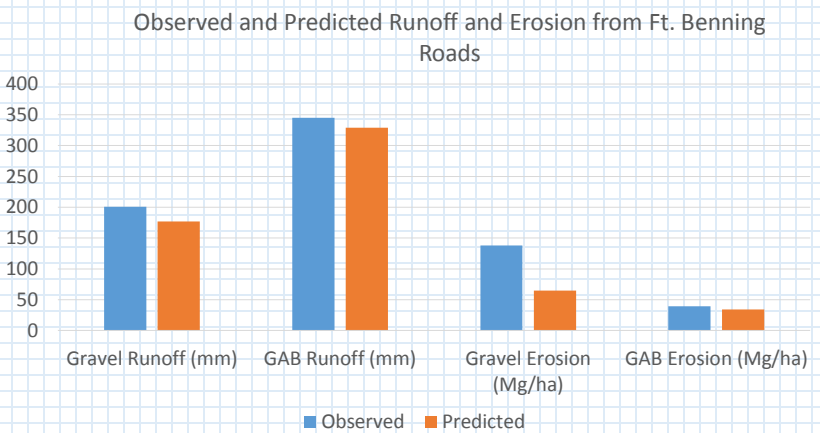
WEPP's Performance

Predicted vs Observed runoff and erosion



Comments: Under prediction on largest events likely due to runoff from outside of the plot.
Predictive models typically overpredict small events and under predict larger events

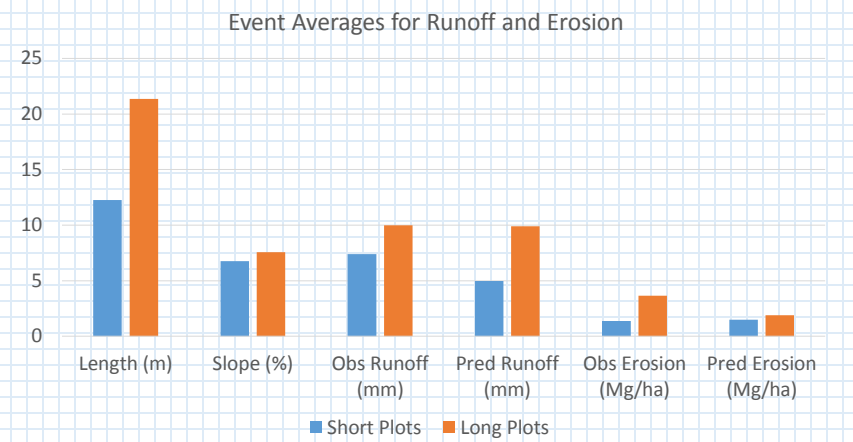
WEPP's Sensitivity to Road Management



Comment1: More runoff, but less sediment from GAB roads
Comment2: Observed erosion from gravel plots may have included sediment from outside plot

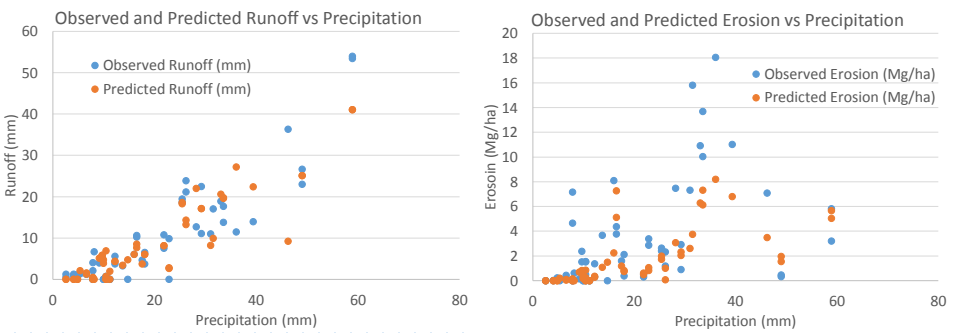
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WEPP's Sensitivity to Road Length



Comment: Observed long plot erosion may have included sediment from outside plot

WEPP's Sensitivity to rainfall amount for runoff and erosion



Comments: Observed higher erosion rates may have included sediment from outside plot.
High variability in observed erosion rates is typical of erosion studies

Statistical Analyses

- There were no significant differences between observed and predicted runoff rates or erosion rates
- There were no interactions between erosion predictions and plot length, road management, and precipitation, confirming the WEPP can address such site variability
- There was a significant interaction (P = 0.04) between predicted erosion and slope.
  - May be because the steepest plots were GAB plots that had the lowest erosion rates. On gravel plots, steeper slopes had higher predicted erosion rates

Conclusions

- GAB road designs reduce road erosion
- WEPP can predict differences in erosion due to precipitation depth, road management, and plot length
- Plot steepness effect was confounded by plot length and treatment, so study could not show WEPP's ability to address slope effects

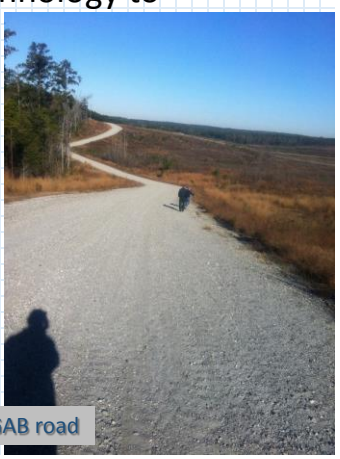


Comment: Emptying sediment collection tank following a large erosion event

W. Elliot, PE, PhD, USDA Forest Service
Rocky Mountain Research Station

Next Steps

- Tools need to be developed to aid specialists at military bases to use the WEPP technology to identify road segments that are the greatest contributors of sediment
- Publish results in a journal



Comment: Identifying location for plot on GAB road

Contact Information

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APPENDIX E

TASK 7 FINAL REPORT

DEMONSTRATION OF BASINS.MIL CAPABILITIES FOR EVALUATING CLIMATE NON-STATIONARITY

Demonstration and Validation of BASINS Watershed Modeling System Enhanced for Military Installations

DEMONSTRATION OF BASINS.MIL CAPABILITIES FOR EVALUATING CLIMATE NON-STATIONARITY (TASK 7)

RC-201307
ATC Project No: 23013
RESPEC Project No: 02749

December 16, 2016

John C. Imhoff
Paul B. Duda
Anthony S. Donigian, Jr.

AQUA TERRA Consultants,
A Division of RESPEC Consulting and Services
Mountain View, CA 94043

EXECUTIVE SUMMARY

ESTCP Project No. RC 201307 is designed to demonstrate specific components of the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) Modeling System (USEPA, 2013a), originally developed by US EPA for total maximum daily load (TMDL) assessments and recently enhanced through a SERDP-funded project (RC-1547) for application on military installations; the military-enhanced version is referred to as BASINS.MIL (AQUA TERRA Consultants, 2012; available at https://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Natural-Resources/Watershed-Processes-and-Management/RC-1547).

The BASINS Modeling System is a GIS-based system and features a well-developed interface for different dynamic watershed models, and numerous pre- and post-processing tools that are shared by the models. Two types of enhancements, using the Hydrological Simulation Program – FORTRAN (HSPF) as the primary modeling code, were developed for the BASINS modeling system for military-specific applications: (1) data and methodologies that address key military land stressors (i.e., urban encroachment, prescribed burning, timber harvesting, military training, and unpaved roads), and (2) software refinements related to model linkages and algorithms.

The effects of future climate change and future residential (or cantonment) and training area development all have important management implications for military installations. BASINS.MIL provides the necessary tools and methods to help watershed managers understand and manage the potential impacts (combined or separately) of climate change and land use change on water resources at the watershed scale. Moreover, because climate and residential development can result in similar types of impacts, e.g. higher peaks and lower low flow conditions, the management of land use impacts is a potentially important adaptive strategy for increasing resilience to climate change (Pyke et al., 2011).

An assumption that long-term climate is ‘stationary’ has traditionally been a guiding principle and foundation of water management and policy. Stationarity implies the following (Milly et al. 2008):

1. Over the timescales relevant to water resource management (e.g., 20-50 years), natural systems fluctuate within unchanging boundaries.
2. The probability of any event (e.g. a 100-year flood peak flow, or a drought of a given magnitude) does not change over these timescales.
3. Probabilities can be reasonably estimated from observation.

Global temperature increases serve as a forcing function to disrupt historical climate patterns, resulting in increased ‘non-stationarity’. These climatic changes introduce the potential to further widen the range between extremes of streamflow and water quality conditions, and by doing so, the changes tend to amplify the limitations of utilizing observational records and traditional water resources analysis techniques. Practically speaking, introduction of more frequent or greater magnitude events (e.g., droughts, floods) can exacerbate existing problems (e.g. aging infrastructure, user conflicts, endangered/exotic species).

The objective of this climate non-stationarity assessment is to demonstrate the usefulness of BASINS.MIL model methodologies and results in enabling military planners to characterize changes in hydrology and sediment that may result from changed climate and future land use as they are represented in plausible change scenarios. The climate change scenario and modeling ensemble that are utilized for this demonstration originate from widely-respected climate scientists and modelers. A plausible future land use scenario for Fort Benning's largest watershed was formulated with guidance from ESTCP.

The exercise that is central to the ESTCP demonstration of a BASINS.MIL HSPF application to evaluate the impacts of climate non-stationarity is a one-to-one comparison and evaluation of two alternative sets of modeling results for the Upatoi Creek Watershed (UCW) (453 mi^2), the major watershed containing Fort Benning: one set of results generated by EPA's previous coarser (i.e., larger scale) application (USEPA, 2013b) of HSPF to the entire Apalachicola-Chattahoochee-Flint (ACF) River Basin (19,869 mi^2), and results generated by the current effort for a second finer-scale Fort Benning application in which the UCW comprises the majority of the Fort Benning HSPF Watershed Model. The Upatoi Creek Watershed comprises approximately *two percent* of the ACF Watershed.

Results and climate change deltas (i.e., changes in magnitude, intensity and timing of precipitation plus changes in air temperature from a 'baseline' climate condition) for the USEPA's regional HSPF climate change study of the ACF Basin, which includes the FB Model domain, were used to develop a comparable climate change scenario that was evaluated using the Upatoi Creek Watershed (UCW) within the FB Model. The climate change scenario that is depicted is the Weather Research and Forecasting (WRFP) scenario for the Year 2050 as described in USEPA (2013c).

Mean annual stream flow, flood frequency, and mean annual sediment loss are the quantitative metrics that are used to establish reasonableness and consistency of simulation results. Flood frequencies for 100, 50 and 25 year events are determined through a Log Pearson III analysis of the annual peak flows. Mean annual sediment loss is measured by total suspended solids (TSS). Comparison of observed and simulated flow duration and continuous time series of daily flow are used as qualitative measures of success. Visual comparison of flow, flow duration and linear regression results that are generated for the Year 2050 climate change scenario by the ACF Model to those generated by the FB model provides an additional set of *qualitative* metrics. That is to say, visual similarity of results from the two models suggests 'success' in achieving our demonstration/validation objective.

It is a reasonable expectation that the impacts on flow and sediment loadings that are estimated by the two HSPF models will be reasonably consistent in terms of the direction, magnitude and frequency of change from their baseline simulations. It is for satisfying this qualitative definition of 'success' that the task's success criteria have been established. The success criteria for performance objectives for annual stream flow and flood frequencies simulated by the FB Model are expected to be in the same direction and within 15-20% of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed. Mean annual sediment loss is expected to be in the same direction and within 20-35% of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed. Qualitatively, the graphical comparisons of the FB Model's simulated values for the baseline condition and climate scenario for flow, flow duration, and linear regression denote success if they demonstrate similar patterns (i.e., shape,

magnitude) and the same direction of change as the ACF climate scenarios results for the Upatoi Creek Watershed. The demonstration satisfied all these performance objectives.

To develop and simulate *land use change* scenarios (and their potential impacts) that most effectively demonstrate the utility of BASINS.MIL for land use analysis/management called for a somewhat different approach. Since the intent of EPA's ACF study was to assess the general sensitivity of underlying watershed processes to changes in climate and urban development and not to develop detailed, location-based models that represent management and operational activities in full detail, potential future changes in management and operational activities were not considered or represented in EPA's future scenario (Year 2050) for the Upatoi Creek Watershed. In lieu of comparing results for FB and ACF land use change scenarios, the land use change modeling demonstration that is presented in this report focuses on comparing consistency and credibility of the impacts of two very different, but plausible land use change trajectories for Fort Benning.

The UCW land use change demonstration first required an update of current land conditions to reflect our best understanding of land use conditions in Year 2013, a point in time where the manifestations of the 2005 Base Realignment and Closure (BRAC) on Fort Benning had stabilized. Two alternative Year 2050 scenarios were defined by representing additional changes to the Year 2013 post-BRAC baseline: Scenario 1 estimated installation land use change (with a focus on cantonment and training areas) consistent with a "limited-aggression world", and Scenario 2 estimated installation land use change consistent with a "heightened-aggression world". The objective of the land use change assessment demonstration was achieving reasonable results, and we believe that this objective was also achieved.

This ESTCP task is the first demonstration of utilizing the HSPF model to assess potential military-centric environmental impacts resulting from climate non-stationarity. The central need that was demonstrated was the marriage of a site-appropriate high end climate change scenario with a highly detailed characterization of an installation-scale watershed. As a result, a more tangible assessment of the impact of changed climate on specific military land use types and activities can be achieved. In performing this demonstration, we found nothing unique about military settings, or the necessary customization of model development and assessment procedures, that imposes significant limitations on the utility of the modeling technology in a military setting. Rather, we find ample opportunity and utility for such model assessments.

Using simulated mean annual streamflow as a performance metric, the UCW simulation using the FB Model successfully captures the effects of the WRFP climate change scenario shown in the ACF Model. The ACF model shows a decrease of 19.5 percent in mean annual streamflow at the upper Upatoi pour point, and a decrease of 20.0 percent at the lower Upatoi point. The FB Model shows a nearly identical change, from 19.8 percent at the upper pour point to 19.7 percent at the lower pour point. At the upper Upatoi pour point, the ACF model predicts slight increases in flood event peak magnitudes while the FB Model shows slight decreases. In contrast, at the pour point from the entire Upatoi, both the ACF and Fort Benning model simulations predict slight increases in flood event peak magnitudes. The fact that the models show slightly different results at the upper pour point can be attributed to a difference in spatial resolution between the two models, where the ACF model consists of only one subbasin and stream reach at the pour point, while the FB Model consists of 17 for each. The effect of the difference in spatial resolution is less pronounced further downstream, which is consistent with expectations of the peak flows moderating with additional travel time. Graphical comparisons between FB

simulated values and observed data for flow duration, daily flow timeseries, and flow linear regression are similar to ACF climate scenario results for the Upatoi Creek Watershed. Each set of plots shows a similar trend when comparing the effects of the climate change scenario on the ACF and Fort Benning model results. The climate scenario shows higher peak flows for some storm events, but most often shows reduced flows overall.

The ACF Model shows lower erosion amounts than the FB Model, while the FB Model shows lower sediment transport/loss than the ACF Model. However, the percent changes are relatively similar, with the Fort Benning model within 18.2 percent of the ACF model change at the upper pour point, and a much closer 6.7 percent difference at the lower pour point. The fact that the models show significant difference in the amount of sediment transport/loss can be attributed to the apparent assumption in the ACF Model that the stream channels are stable and are neither scouring nor depositing. In the FB Model, the sediment (silt and clay) scour and deposition parameters were calibrated to available TSS/sediment data, and the results demonstrated more dynamic changes to the channel through both scour and deposition.

The difference in scale and resolution between the ACF and FB models also provides important insight in the use of models for smaller scale assessments, such as might be needed for EISA 438 issues, hydromodification, local flooding, etc. It is clear from the model comparisons that when models are used for watershed planning and management, the scale of the modeling assessment (or decision to be made) should be as close as possible to the scale of the watershed change or BMP being evaluated, so that scale differences will not unduly impact the evaluation. Thus the FB model would be a much better choice for assessments on FB than the ACF model as its smaller scale and higher resolution provides a better and finer representation of the watershed and drainage processes that need to be accurately depicted.

Both land use change scenarios that were simulated resulted in less than one percent change in both mean annual streamflow and mean annual sediment transport. This small increase is expected, since the actual increase in urbanized area (an increase of approximately 15 percent more urbanized acreage for the ‘Heightened Aggression’ scenario) is relatively small on a watershed-wide basis, from 7.8 percent of the watershed in the post-BRAC baseline to 9.0 percent of the watershed in the ‘Heightened Aggression’ scenario; a difference of only 1.2% of the watershed. Experience with prior modeling studies that assessed the impact of urbanization have shown significant, and sometimes dramatic, increases in peak flows, sediment loss/transport, and channel alterations, but these types of changes are usually observed when changes in the effective impervious area (i.e. EIA, or directly-connected impervious area) begin to exceed 10% or more of the watershed (Booth and Jackson, 1994). Impacts continue to mount and accelerate as that percentage increases further. The changes in EIA for our scenarios are considerably less, in the range of 1 to 2%, so the minimal impacts in our simulations are expected.

With DoD’s institutional commitment to further reducing stormwater by means of implementing green infrastructure practices, it is likely that the major focus of concern with impacting streamflow and sediment phenomena by land use change will focus on the training lands.

As is often the case in watershed modeling perhaps the biggest challenge we faced in performing this demonstration centered on defining justifiable and insightful change scenarios. For example, at the planning stage of our land use change assessment demonstration, we anticipated

representing and assessing a major increase in Heavy Maneuver Areas (HMAs) in the Upatoi Creek Watershed (UCW) during the course of development from pre-BRAC to Year 2050. Instead we discovered that the development and use of HMAs in the UCW that had been planned as a component of BRAC 2006 had never really been implemented due to unresolved issues related to potential impact on the Red Cockaded Woodpecker population. Further, Fort Benning had resolved to permanently re-locate (by summer 2016) the majority of the tank training activities that had been planned for the UCW to the Good Hope Area outside of the watershed that we had selected for our demonstration. As a result, we were unable to justify and demonstrate a Year 2050 land use alternative in the UCW that addressed both the simultaneous impacts of cantonment/urban growth **and** the potential impacts of a high level of vehicular training at a military installation.

In many, if not most watersheds the process of developing land use change scenarios is focused on estimating (1) where and how quickly non-urban land use areas will be converted to urban land use areas and (2) where and how quickly urban land use areas will increase in population density and imperviousness. The land use change trajectories for military installations do not typically follow this paradigm. Instead they often focus on transition of non-urban (undisturbed) land use types into training areas with specialized landscape alterations. Increases in the size or imperviousness of cantonment areas may accompany changes in training areas, but are rarely the most influential impact on hydrology. Further, land use changes typically occur in response to distinct realignment decisions for military training locations/methods, and these decisions/actions cannot be readily anticipated in the more distant future (e.g., in the year 2050). Offsite increases in the built environment to accommodate increased troop levels are an additional factor that must be considered. Hence an additional necessary element of developing future land use change scenarios for watersheds that contain both military and non-military lands is approximating a correlation between cantonment growth within the installation area and expected urban development in the adjacent non-military areas. To respond to such a complex and volatile planning and management environment, a general need (i.e., not just for climate change applications) exists at installations to develop and apply watershed-based models as an active component of their planning process.

Study results have several implications for future planning and management of the water resources within the FB installation. In interpreting the results of the future climate scenario, it is important to be mindful that the WRFP scenario that was depicted is the hottest and driest scenario of all those that were produced by EPA's GCM/RCM model ensemble. As such, the scenario results arguably offer a 'worst case' depiction of low flow conditions in the Upatoi Creek Watershed. While beyond the scope of this demonstration project, a broadening of the investigation to include consideration of the impacts of reduced streamflow on dissolved oxygen and/or threatened species could provide the installation with a means of evaluating potential climate change impacts on additional management concerns (e.g., aquatic habitats).

Another streamflow-related result that has potential implications to the installation is the FB Model's predictions of slight <u>increases</u> in flood event peak magnitudes despite the fact that the WRFP scenario depicts an average annual reduction in precipitation of approximately 10 percent. Simulated flood peaks are clearly increased by the scenario's representation of storm precipitation intensification. Since results from all the other GCM/RCM models that EPA used to simulate this region predict greater streamflow than the WRFP scenario, it is justifiable for

Fort Benning planners to be concerned that flood peak magnitudes at various locations within the installation may, indeed, increase in future years as a result of climatic change. Local storm peaks in cantonment areas that are not explicitly addressed in this demonstration could be problematic.

The results of the land use change demonstration suggest that cantonment/urban growth at Fort Benning and in nearby non-military lands is not likely to have comparable impacts on streamflow and erosion as would development of additional training facilities. With DoD's institutional commitment to further reducing stormwater by means of implementing green infrastructure practices, it is likely that the major focus of concern with impacting streamflow and sediment phenomena by land use change at Fort Benning will continue to focus on the training lands.

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ACRONYMS

ACF	Apalachicola-Chattahoochee-Flint River Basin
BASINS	Better Assessment Science Integrating point and Non-point Sources
BASINS.MIL	Military Enhanced BASINS Modeling System
BRAC	Base Realignment and Closure
CAT	EPA Climate Assessment Tool
CBP5	Chesapeake Bay Program HSPF Phase 5.3 Model
DoD	Department of Defense
EBM	Enhanced Baseline Fort Benning Model
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FAPH	Fort AP Hill
FAPH Model	Fort AP Hill BASINS.MIL model
FB	Fort Benning
FB Model	Fort Benning BASINS.MIL model
FEMA	Federal Emergency Management Agency
FTABLE	HSPF Model Hydraulic Function Table
GA	State of Georgia
GIS	Geographic Information System
HSPF	Hydrological Simulation Program FORTRAN
IMPLND	HSPF Model Impervious Land Segment Used for Landscape Simulation
LID	Low Impact Development
MCOE	Fort Benning Maneuver Center of Excellence
NARCCAP	North American Regional Climate Change Assessment Program
NCDC	National Climatic Data Center
NLCD	National Land Cover Data
INRMP	Installation Natural Resources Master Plan
NSE	Nash-Sutcliffe Efficiency
OV	Observed Value
PERLND	HSPF Model Pervious Land Segment Used for Landscape Simulation
PI	Principal Investigator
PO	Performance Objective
R	Correlation coefficient
R2	Coefficient of Determination
RCHRES	HSPF Model Stream or Reservoir Reach Used for Channel Simulation
SERDP	Strategic Environmental Research and Development Program
TSS	Total Suspended Solids
UCW	Upatoi Creek Watershed (Georgia)
USEPA	United States Environmental Protection Agency
USGS	United States Geologic Survey
WDM	Watershed Data Management file structure for storage of model data (USGS)

SECTION 1.0
INTRODUCTION

1.1 Background

ESTCP Project No. RC 201307 is designed to demonstrate and validate specific components of the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) Modeling System (USEPA, 2013a), originally developed by US EPA for total maximum daily load (TMDL) assessments and recently enhanced through a SERDP-funded project (RC-1547) for application on military installations; the military-enhanced version is referred to as BASINS.MIL (AQUA TERRA Consultants, 2012; available at https://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Natural-Resources/Watershed-Processes-and-Management/RC-1547).

The BASINS Modeling System is a GIS-based system and features a well-developed interface for different dynamic watershed models, and numerous pre- and post-processing tools that are shared by the models. Two types of enhancements, using the Hydrological Simulation Program – FORTRAN (HSPF) as the primary modeling code, were developed for the BASINS modeling system for military-specific applications: (1) data and methodologies that address key military land stressors (i.e., urban encroachment, prescribed burning, timber harvesting, military training, and unpaved roads), and (2) software refinements related to model linkages and algorithms.

BASINS.MIL was used to build a continuous computer simulation model of hydrology and water quality for the watersheds on and surrounding Fort Benning, Georgia. This model is referred to as the FB Model (or FB Enhanced Baseline Model). Preliminary model applications of the FB Model were performed as a component of the SERDP project to provide a proof-of-principle demonstration of the modeling system and the model enhancements to support watershed management decisions on the Installation.

The subsequent ESTCP BASINS.MIL demonstration/validation leverages the watershed model developed on Fort Benning (FB) by conducting further modeling applications on FB, and by developing a watershed model for another installation that will be used to further demonstrate the technology. Fort AP Hill (FAPH), Virginia was selected as the second site since it provides a unique opportunity to (a) demonstrate the transferability of the BASINS.MIL modeling framework to a new installation and (b) demonstrate the ability of BASINS.MIL to address TMDL issues. ESTCP has also requested that as part of this project a third demonstration site be identified that will provide additional opportunity for demonstration/validation.

The tasks that are being conducted on FB demonstrate the full utility of the modeling system through advanced model applications related to unpaved road sediment erosion, climate non-stationarity, a small-scale (i.e., subwatershed) management assessment, and an uncertainty analysis. In addition, as requested by ESTCP, this project's initial FB efforts focused attention on a series of modeling experiments designed to extend and supplement initial efforts in SERDP RC-1547 to address the degree to which data availability and quality can impact model performance. The FB model will be used to provide insight into the basic questions faced by installation managers as to how much data are needed for model applications and what

quantitative improvement in model performance can be expected as additional resources are committed to acquiring the field data for model calibration and validation.

1.2 Objective of this Demonstration

An assumption that long-term climate is 'stationary' has traditionally been a guiding principle and foundation of water management and policy. Stationarity implies the following (Milly et al. 2008):

1. Over the timescales relevant to water resource management, natural systems fluctuate within unchanging boundaries.
2. The probability of any event (e.g. a 100-year flood peak flow, or a drought of a given magnitude and frequency) does not change over these timescales.
3. Probabilities can be reasonably estimated from observation.

Global temperature increases serve as a forcing function to disrupt historical climate patterns, resulting in increased 'non-stationarity'. These climatic changes introduce the potential to further widen the range between extremes of streamflow and water quality conditions, and by doing so, the changes tend to amplify the limitations of utilizing observational records and traditional water resources analysis techniques. Practically speaking, introduction of more frequent or greater magnitude events (e.g., droughts, floods) can exacerbate existing problems (e.g. aging infrastructure, user conflicts, endangered/exotic species).

The objective of this climate non-stationarity assessment is to demonstrate the usefulness of BASINS.MIL model methodologies and results in enabling military planners to characterize changes in hydrology and sediment that may result from changed climate and future land use as they are represented in plausible change scenarios. The climate change scenario and modeling ensemble that are utilized for this demonstration originate from widely-respected climate scientists and modelers. A plausible future land use scenario for Fort Benning's largest watershed was formulated with guidance from ESTCP.

This objective correlates to an overarching aim to demonstrate the capability of applying BASINS.MIL in operational mode to assess alternative conditions and practices as advanced management scenario analyses.

The organization of this task report parallels that used for the project's overall Demonstration Plan (Donigian et al., 2014), which was approved in October, 2014:

- Technology/methodology overview (Section 2)
- Performance objectives (Section 3)
- Site descriptions (Section 4)
- Test design (Section 5)
- Performance assessment (Section 6)

SECTION 2.0
TECHNOLOGY/METHODOLOGY OVERVIEW

This demonstration task is focused on BASINS.MIL and its capabilities in assessing watershed impacts to changed climate and land use. Accordingly, it is necessary to describe not only technology/methodologies directly associated with this specific application of BASINS.MIL, but also those associated with formulating plausible descriptions of potential changes to climate and land use.

In this section an overview (Section 2.1) is provided that describes the overarching concept that drives the use of watershed models for assessing change impacts. In Section 2.1.1 the BASIN.MIL component that is central to this demonstration, EPA's Hydrological Simulation Program – FORTRAN (HSPF) is introduced, and the HSPF watershed modeling framework is briefly described. Next the two HSPF-derived models that provide the basis for this demonstration are described: the regional-scale Apalachicola-Chattahoochee-Flint (ACF) River Basin Model (Section 2.1.2) and the Fort Benning (FB) Watershed Model (Section 2.1.3). The description of task technologies/methodologies concludes by addressing methods for representing and evaluating changed climate (Section 2.1.4) and changed land use (Section 2.1.5).

The advantages and limitations of the central technology/methodology used in this demonstration are discussed briefly in Sections 2.2 and 2.3, respectively.

2.1 Overview

Water and watershed systems are influenced by the amount, form, seasonality, and event characteristics of precipitation, as well as air temperature, solar radiation and wind that affect evaporative loss. These are the meteorologic 'forcing functions' that drive the dynamic behavior of the watershed system. By altering precipitation and streamflow patterns within a watershed, climate non-stationarity can negatively impact the effectiveness of resource management strategies related to flood and erosion control, minimum flow and maximum water temperature maintenance. System vulnerability, or susceptibility to harm, is determined by watershed sensitivity to changed weather together with socio-economic factors influencing both changed land use and the ability to adapt to new conditions. An understanding of system sensitivity is thus a necessary foundation for conducting watershed-scale vulnerability analyses within military installations.

A range of plausible future climatic conditions and events have already been estimated in most areas *on a regional basis* using records of historical events and scenario-based model projections. Down-scaling this information *to an installation scale* can provide military managers with an understanding of the plausible range of climate change impacts, and help guide the development of strategies and practices to reduce the likelihood of future damage to installation landscape, biota and ecosystems. Installation-scale applications of regional climate change scenarios can enable evaluation of their estimated impacts as they are imposed on more discrete representations of hydrography, land use, and channel geometry. In the case of this demonstration, commonly applied land use classification schemes have been previously revised (i.e., in RC-1547) to more precisely represent military activities (e.g., prescribed burning, tank training areas, unpaved roads, cantonment areas) at Fort Benning.

2.1.1 BASINS.MIL Applications Using HSPF

This demonstration leverages a previously developed regional-scale model that utilizes HSPF as applied with EPA's BASINS modeling system. The ESTCP demonstration is performed using an installation-scale HSPF application that was previously developed using BASINS.MIL as its starting point. The streamflow and sediment loading changes resulting from imposing a specific climate change scenario on this application are characterized for relevant endpoints shared by both the ACF and FB models. Since both applications rely on HSPF, the model's general introduction is warranted.

HSPF (Bicknell et al., 2005) is one of the watershed modeling codes in BASINS. It is a comprehensive, process-based mathematical model used to simulate hydrologic and water quality processes in natural and man-made water systems. It uses input information such as the time history of rainfall, temperature, evaporation, and parameters related to land use patterns, soil characteristics, and land management practices to simulate the processes that occur in a watershed. The initial result of a HSPF simulation is a time history of the quantity and quality of water transported over the land surface and through various soil zones down to the groundwater aquifers. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations that result from the Installation's unique weather and land conditions can be predicted. The model then uses these land-derived loading results, and stream channel information, to simulate instream processes. From these, HSPF produces a time history of water quantity and quality at any point in the watershed's stream network.

HSPF simulates for extended periods of time the hydrologic and associated water quality, processes on pervious and impervious land surfaces and in streams and lakes/waterbodies. The model uses continuous rainfall and other meteorological records to compute streamflow hydrographs and pollutographs. HSPF simulates canopy interception, soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand, temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, zooplankton, and benthic algae. The program can simulate one or many pervious or impervious unit areas discharging to one or many river reaches or reservoirs. Frequency-duration analysis can be performed for any time series. Any time step from 1 minute to 1 day that divides equally into 1 day can be used. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, flow diversions, etc. Programs, available separately, support data preprocessing and post-processing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file.

A land segment is a subdivision of the simulated watershed. The boundaries are established according to the user's needs, but generally, a segment is defined as an area with similar hydrologic and water quality characteristics. For modeling purposes, water, sediment, and water quality constituents leaving the watershed move laterally to a downslope segment or to a reach/reservoir. A segment of land which has the capacity to allow enough infiltration to influence the water budget is considered pervious. In HSPF, PERLND is the module that simulates the water quality and quantity processes which occur on a pervious land segment.

Using various methods, the primary module sections in PERLND simulate snow accumulation and melt, the water budget, sediment produced by land surface erosion, and water quality constituents. Other sections perform the auxiliary functions of correcting air temperature for use in snowmelt and soil temperature calculations, producing soil temperatures for estimating the outflow temperatures and influencing reaction rates in the agrichemical sections, and determining outflow temperatures which influence the solubility of oxygen and carbon dioxide.

In an impervious land segment, little or no infiltration occurs, however, land surface processes do occur. Snow may accumulate and melt, and water may be stored or may evaporate. Various water quality constituents accumulate and are removed. Water, solids, and various pollutants flow from the segments by moving laterally to a downslope segment or to a reach/reservoir.

The HSPF IMPLND module simulates a number of processes with many of them similar to the corresponding sections in the PERLND module. In fact, since sections snow and air temperature components perform functions that can be applied to pervious or impervious segments, they are shared by both modules.

The RCHRES module simulates the processes which occur in a single reach of open or closed channel or a completely mixed lake or reservoir. For convenience, such a processing unit is referred to as a RCHRES. In keeping with the assumption of complete mixing, the RCHRES consists of a single zone situated between two nodes, which are the extremities of the RCHRES.

Flow through a RCHRES is assumed to be unidirectional. Water and other constituents which arrive from other RCHRES's and local sources enter the RCHRES through a single gate. Outflows may leave the RCHRES through one of several gates or exits. A RCHRES can have up to five outflow exits. Precipitation, evaporation, and other fluxes also influence the processes which occur in the RCHRES, but do not pass through the exits.

Under long term weather changes, such as those being considered in this demonstration task, it is possible to change the hydrologic regime in certain terrains. Such changes could re-route water flow by creating a loss of channels or creation of new subsurface flow paths. It should be noted that such potential changes to FB watersheds will not be addressed in this study, as such dynamic changes are not represented in the model.

2.1.2 Apalachicola-Chattahoochee-Flint Basins (ACF) HSPF Regional Watershed Model

The ACF HSPF Regional Watershed Model (USEPA, 2013b) represents one of the regional watersheds that USEPA developed as part of its large scale, watershed modeling effort that was designed to address gaps in knowledge of the sensitivity of U.S. streamflow, nutrient (nitrogen and phosphorus) and sediment loading to potential mid-21st century climate change. EPA's modeling also considered the potential interaction of climate change with future urban and residential development in these watersheds, and provided insights concerning the effects of different methodological choices (e.g., method of downscaling climate change data, choice of watershed model) on simulation results.

EPA provided detailed documentation of the overall structure of their effort – including sites, methods, models, and scenarios, and they provided comprehensive modeling output results and analysis for each of the study areas. A unique feature of the EPA study was the use of a consistent watershed modeling methodology and a common set of climate and land-use

change scenarios in multiple locations across the nation. It should be noted that several of the study watersheds are complex, highly managed systems. Given the difficulty and level of effort involved with modeling at this scale it was necessary to standardize model development for efficiency. EPA did not attempt to represent all these operational aspects in full detail. Their simulation results are thus not intended as forecasts. Rather, the intent of EPA's study was to assess the general sensitivity of underlying watershed processes to changes in climate and urban development and not to develop detailed, place-based models that represent all management and operational activities in full detail. Potential future changes in management and operational activities were also not considered in EPA's study.

2.1.3 Fort Benning (FB) HSPF Watershed Model

The FB HSPF Model was developed through SERDP Project RC-1547. In essence, the model constitutes the components of BASINS.MIL as it is applied to the FB watersheds, since the development and testing of BASINS.MIL was conducted on Fort Benning. As such, describing the FB Model provides a description of BASINS.MIL. AQUA TERRA Consultants (2012) provides a detailed discussion of the FB Model[1]; references and discussion of the component models mentioned below are available in the SERDP Final Report noted above. The following features of BASINS.MIL are based on the development of the FB Model:

1. WEPP/WEPP Road Enhancement – A hybrid modeling technique was developed that improves the ability to represent and evaluate combinations of sources and endpoints that have significantly different spatial scales. This technique incorporated the USFS Water Erosion Prediction Project (WEPP) Model and its interface WEPP:Road to generate sediment loads from unpaved roads at a finer scale than the HSPF watershed model. These finer-scale results were integrated into the watershed-scale HSPF model to more accurately depict the sediment contribution from unpaved roads.
2. Military Training Intensity Methodology – A methodology was developed to quantify the impact of military training activities on soil compaction and vegetation loss that enables subsequent impacts on runoff and sediment washoff/erosion rates to be modeled by adjusting infiltration rates and extent of vegetative land cover based on the training intensity level.
3. Complex channel modeling – The combination of the US EPA Environmental Fluid Dynamics Code (EFDC)/ Sediment transport algorithm for EFDC (SEDLZJ) and a bank erosion algorithm were investigated to evaluate their potential to improve simulated channel flows (particularly low and high flow events), sediment transport and stream bank erosion. The EFDC /SEDLZJ code, as it was applied in the FB Model, was judged to be too computationally intensive and required such high resolution spatial characterization as to be impractical for most watershed-scale installation applications. Thus, it has not been recommended for further demonstration/validation on FB or FAPH.
4. AQUATOX Linkage – HSPF hydrology and water quality results were used as input to the AQUATOX model, thereby enabling the evaluation of impacts of watershed

[1] The FB Model is referred to as the Enhanced Baseline Model (EBM) in AQUA TERRA (2012).

management practices on indicators of aquatic health at selected locations within the FB watersheds.

5. Multi-level Canopy Compartment – Improved representation of hydrologic and sediment processes for above-ground vegetation and forest canopy compartments was developed to better represent the impacts of prescribed burning practices on the FB watersheds.

For the SERDP project three sets of management alternative evaluations were conducted to demonstrate proof-of-principle of the FB Model: (1) impacts of 2005 BRAC (Base Realignment and Closures) Implementations (i.e., increased area of heavy maneuver training exercises); (2) impacts of best management practices (BMPs) on a single maneuver training area (i.e., the Good Hope Mechanized Training Area (GHMTA); and (3) linkage to the ecosystem effects model AQUATOX.

In addition to the climate and land use change demonstration that is described in this report, the current ESTCP project features additional refinement and application of the FB Model as follows:

1. A task is being performed that quantifies the change in performance of the FB hydrology model as a function of the number of observed flow data sites (gages) available for calibration within the watershed.

2. In the SERDP project WEPP/WEPP:Road was used to support the FB Model by providing improved estimates of erosion from unpaved roads. A task is being performed by USFS to collect and use data for unpaved road erosion at Fort Benning to validate the WEPP Model.

3. A task is being undertaken to achieve improvement in the performance of the FB Model's unpaved road erosion simulation based on the new loading rates that are estimated from collected data.

4. A task will demonstrate that an uncertainty analysis conducted with the BASINS.MIL FB Model can be used to quantify uncertainties in model results/predictions relevant to regulatory standards and/or indicators.

An additional task to demonstrate how the FB Model performs as a tool for small-site stormwater designs and EISA Section 438 compliance has been re-located to Fort APHill, VA.

2.1.4 Representing Climate Change in HSPF Applications

BASINS.MIL includes methods for representing changed climate that may be imposed on the model's meteorological time series manually or by utilizing the BASINS' Climate Assessment Tool (USEPA, 2009a). As a result, model applications that estimate impacts of climate non-stationarity on critical hydrologic and water quality endpoints can be performed. Climate change scenarios are created by selecting a base period of historical weather data that is subsequently adjusted to reflect any desired, or expected, future change or changes. After selecting a period of historical data to be modified (e.g., from an NCDC weather station used as meteorological input to a watershed model), one or more operations or adjustments are made to baseline timeseries of precipitation (e.g., uniform 'deltas', seasonal shifts, storm intensity adjustments) and air

temperature (typically uniform 'deltas') (see Section 5 and Appendix C) . To complete the future meteorological scenario, corresponding potential evapotranspiration (PET) time series are estimated by utilizing PET's relationship to changed (i.e., estimated future) air temperature as represented by the Hamon method (Hamon, 1961); alternatively, the more complex Penman-Monteith method (Neitsch et al., 2005) can be used to estimate PET based on changed air temperature plus additional changed meteorological time series for solar radiation, relative humidity and windspeed.

It should be noted that the mechanics of modeling potential installation – scale runoff and erosion impacts attributable to future changes to climate follow an informational progression that includes emissions storylines, emissions scenarios, general circulation models (GCMs), regional climate models (RCMs), watershed-scale models and one or more downscaling efforts to accommodate the spatial scale(s) of interest. Each step along the progression offers many different assumptions, methods and models.

At least a high-level familiarity with the emissions storyline, emission scenario, GCM, RCM and downscaling strategies that provide the basis for the climate non-stationarity evaluations that were generated by the ACF and FB models is an essential prerequisite to understanding and comparing the simulation results that the two models generate. Appendix A provides a necessary description of the process as it pertains to this ESTCP demonstration. The demonstration described in this report utilized what is commonly called the WRFP (Weather Research and Forecasting) climate scenario, one that depicts significantly hotter, drier conditions within the watershed that is the focus of this demonstration.

2.1.5 Representing Land Use Change in HSPF Applications

Application of HSPF and similar watershed models requires dividing the study area into individual land segments that are assumed to produce a homogeneous hydrologic and sediment erosion response. This segmentation strategy enables the modeler to assign identical model parameter values to those parts of the watershed that produce the same unit response of runoff and erosion for a uniform set of meteorological conditions. Where the weather patterns vary across a watershed, it is necessary to also divide the land segments to accurately reflect spatial meteorological variability and its effect on the hydrology and erosion of the watershed.

Accordingly, the major considerations in model land segmentation are meteorological variability, land use, soils, topography, hydrography, and land management/disturbance activities. Generally speaking soils, topography and hydrography are not subject to significant change moving forward in time, but land use is.

Typically land use change modeling scenarios are characterized by transition of land areas from undeveloped land use classes (e.g. forest, farmland, open space) to residential and urban uses. The future land use scenario that USEPA developed and simulated for the ACF Basin (and all of the 20 basins that EPA modeled) utilized demographic model projections and a standardized approach to re-adjust the current-condition land use classifications within selected basins by decreasing appropriate areas with non-urban classifications and increasing areas with urban classifications. A summary of USEPA's approach is provided in Appendix B.

Military planners realize benefit from estimating the potential impacts of future land use change on runoff and erosion, both as a stand-alone evaluation and in combination with estimations of parallel impacts produced by potential climate change.

At military installations developing a future land use scenario lends itself to unique challenges/opportunities:

- Given that watershed boundaries often include both installation and non-installation components, the consideration of residential change often has two components; the degree of projected residential change may be markedly different within, and peripheral to, installation boundaries. Increased troop populations will almost surely result in increased near-site but off-base development as well.
- Drastic land use changes on military lands quite often occur as a result of high-level realignment and closure decisions. Accordingly, relative to non-military areas, it is more challenging to develop and defend plausible military land use change scenarios 30-40 years into the future.
- Also unique to military lands is the opportunity for non-urban land classes to be transformed into training areas (as opposed to cantonment areas) that nonetheless exhibit significant changes to their hydrologic and erosion response.

Accordingly, definition of a plausible future land use change scenario that corresponds to a climate change sensitivity evaluation/demonstration occurring at a time decades in the future may benefit from a more complex and thoughtful scheme for adjusting the current condition land use classifications and distributions. One approach is to maintain an operational model for any given installation so that the model can be queried for changes in simulated futures as part of a periodic planning and assessment cycle including INRMP.

2.2 Advantages of the Central Technology / Methodology

DoD seeks technologies/methodologies to advance the management of land and water resources on its installations. Specifically, models and decision support tools associated with watershed hydrology, erosion, and impacts to receiving water bodies and their aquatic receptors are needed. BASINS.MIL offers DoD an advantageous option for acquiring a suite of capabilities that empower installation land managers across the nation to balance environmental compliance and stewardship with mission requirements. Using BASINS/HSPF as the core of BASINS.MIL enables immediate access to accepted modeling science for agriculture, forestry, urban and other land uses; national-scope databases that fuel model applications; and expedient methods for setting up HSPF models using the available data. Additional advantages are achieved by using the data, methodologies and model enhancements that were achieved in RC-1547 SERDP project.

Managing the risk associated with environmental variability has long been a principal focus of watershed management. Perhaps paramount among environmental variability is consideration of climate. Management plans are developed, and water infrastructure is designed and operated to be resilient to anticipated variability in climate. Changing weather and land use selectively affect each of a collection of management practices that are planned or implemented within an installation, with the possibility of producing either beneficial or adverse effects on objectives and outcomes of individual management practices.

The effects of future climate change and future residential (or cantonment) and training area development all have important management implications. BASINS.MIL provides the necessary tools and methods to help water managers understand and manage the potential

impacts (combined or separately) of climate change and land use change on water resources at the watershed scale. Moreover, because climate and residential development can result in similar types of impacts, e.g. higher peaks and lower low flow conditions, the management of land use impacts is a potentially important adaptive strategy for increasing resilience to climate change (Pyke et al., 2011).

A final advantage of this demonstration's methodology is achieved by imposing the climate scenario on a watershed for which a highly detailed representation of land use, including special military land use/conditions, has already been developed as part of a previous effort. As a result, the modeling product created by this demonstration can render results that are directly tied to military land use impacts.

2.3 Limitations of the Central Technology / Methodology

Current climate models (GCMs, RCMs) have a limited ability to predict climate at the local and regional scales needed by managers for watershed-scale analyses. Accurate predictions of future climate, however, should not be considered a necessary precursor to developing and implementing watershed-scale actions in response to climate change (Sarewitz et al., 2000). Even with uncertainty in predictions, managers can effectively manage risk by implementing practices and strategies that make systems robust to a wide range of plausible future conditions and events (Pielke and de Guenni, 2004).

Due to the uncertainties that still exist in modeling climate change, it is standard practice (1) to utilize a full ensemble of GCMs and RCMs that typically generate a broad range of results, and (2) to subsequently consider the collective results generated by all of them when attempting to understand and project climate change (and its potential impacts on water resources) for any given region. For the purposes of this ESTCP demonstration, the results from one climate model option are being considered, and consequently only one of many plausible projections is achieved. This approach cannot generate the breadth of results/analysis that could be justifiably used to support planning decisions.

In many, if not most watersheds the process of developing land use change scenarios is focused on estimating (1) where and how quickly non-urban land use areas will be converted to urban land use areas and (2) where and how quickly urban land use areas will increase in population density and imperviousness. The land use change trajectories for military installations do not typically follow this paradigm. Instead they often focus on transition of non-urban (undisturbed) land use types into training areas with specialized landscape alterations. Increases in the size or imperviousness of cantonment areas may accompany changes in training areas, but are rarely the most influential impact on hydrology as the cantonment areas tend to be a small fraction of the more extensive training areas. Further, land use changes typically occur in response to distinct realignment decisions for military training locations/methods, and these decisions/actions cannot be readily anticipated in the more distant future (e.g., in the year 2050). Offsite increases in the built environment to accommodate increased troop levels are an additional factor that must be considered. Hence an additional necessary element of developing future land use change scenarios for watersheds that contain both military and non-military lands is approximating a correlation between cantonment growth within the installation area and expected urban development in the adjacent non-military areas. Consequently, a greater level of guesswork is inevitable in offering up a land use change scenario that is further distant in the future than is the planning process for a military installation.

SECTION 3.0
PERFORMANCE OBJECTIVE

3.1 Objective and Relevance

The objective of this climate non-stationarity assessment is to demonstrate the usefulness of a BASINS.MIL model (i.e., FB Model) results to characterize changes in hydrology and sediment associated with potential future climate and land use change scenarios. This correlates to an overarching aim to demonstrate the capability of applying BASINS.MIL in an operational mode to assess alternative conditions and management practices of concern to military watershed planners.

It should be emphasized that the objective *of this particular task* is limited to demonstration of this capability, not its validation. Neither the state of the art in climate change modeling nor the nature of performing estimations of plausible future weather and land use conditions support an effort to validate model results. In this context metrics and success criteria take on a different role/meaning than they have for most ESTCP demonstration/validation efforts. While both can still play an important role, their interpretation is more suited to establishing 'reasonableness' and 'consistency' of simulation results, as opposed to 'success' or 'failure' of a tool or methodology. A semi-quantitative evaluation of the reasonableness of results from the FB climate non-stationarity demonstration is achieved by a combination of comparisons with (1) historical benchmarks such as a 100 year flood benchmark, and (2) results that are generated by a regional-scale model. USEPA's Apalachicola-Chattahoochee-Flint Basin (ACF) Regional HSPF Model is ideally situated and suited for evaluating the reasonableness of the results from the FB climate scenario simulations.

3.2 Description of Metrics

Mean annual stream flow, flood frequency, and mean annual sediment loss are the quantitative metrics that are used to establish reasonableness and consistency of simulation results. FEMA has accepted the Log Pearson III analysis as most appropriate for estimation of extreme events; accordingly flood frequencies for 100, 50 and 25 year events for this project are determined by performing a Log Pearson III analysis of the annual peak flows. An assumption is made that this same analysis method is appropriate for analysis of streamflow generated by simulation of a future scenario. Whether or not this is well-founded is likely an issue that warrants further research.

Mean annual sediment loss is measured by total suspended solids (TSS); sediment measures for shorter time intervals, e.g., peak monthly sediment loss, peak sediment concentration, sediment concentration-duration curves, can also be considered. Comparison of observed and simulated flow duration and continuous time series of daily flow are used as qualitative measures of success. Note that for reasons that will be subsequently explained and justified, comparison of ACF and FB Model results are limited to the climate change simulations; i.e., the two models' simulation results for land use change are not compared as an element of this demonstration.

3.3 Data Requirements

Results and climate change deltas (i.e., changes in magnitude and intensity of precipitation plus changes in air temperature from a 'baseline' climate condition) for the Columbus/FB region within USEPA's regional HSPF climate change study of the Apalachicola-Chattahoochee-Flint

(ACF) Region, which includes the FB Model domain, are used to mimic and simulate a similar climate change scenario by applying this information to the weather time series that are used to characterize the watershed-scale FB Model. By doing so, one of the regional (ACF) climate change scenarios modeled in the ACF Study is subsequently simulated using the FB Model. The land use change scenario (expressed as increases in impervious area) evaluated by the ACF Study was originally considered an important data source. However, when it was investigated to assess its usefulness as a reference point for developing the land use change scenario that was to be developed and simulated using the FB Model, it was determined to be inadequate. Instead a plausible future land use scenario for Fort Benning's largest watershed was formulated with guidance from ESTCP, and by utilizing the most recent land management documents available from Fort Benning and the greater Columbus area. This data provides a starting point for estimating both installation land use changes and correlated off-base changes. EPA's ACF modeling characterized the sensitivity of streamflow, nutrient (nitrogen and phosphorus), and sediment loading to a range of plausible mid-21st Century climate change and urban development scenarios. As Table 3.1 and Section 3.4 below indicate we have focused our performance objective on streamflow and sediment only.

3.4 Success Criteria

The 'success' of the climate non-stationarity component of this demonstration is based on comparing the model results that are generated by the ACF Model with those generated by the FB Model for baseline simulations and for a shared climate change scenario. Comparisons are performed on results within one subwatershed (Upatoi Creek Watershed), which is discretely represented by both models, and is the major watershed containing Fort Benning lands. The two models characterize this watershed using different segmentation schemes, data from different meteorological weather stations, a different land use classification scheme, and different instream flow and sediment calibration data (see Section 4). Hence their simulation results are expected to differ. However, it is a reasonable expectation that the impacts on flow and sediment loadings that are estimated by the two models will be reasonably consistent in terms of the direction, magnitude and frequency of change from their baseline simulations. It is for satisfying this *qualitative* definition of 'success' that the task's success criteria have been established.

The tolerance levels used to determine success for the threshold values are based on comparison of two HSPF models, one at a regional scale and the other at the scale of the Installation. A model-to-model comparison does not have the same degree of variability as when comparing a model to measured data. Thus, it seemed appropriate to have a tolerance level for this demonstration task that is less than the level expected for performance objective(s) in this ESTCP project that feature model-to-monitored data evaluations (i.e., PO #3 and PO #6) (see Donigian et al., 2014). Consequently, the success criteria for this performance objective for annual stream flow and flood frequencies are expect to be in the same direction and within 15-20% (as opposed to 20%) of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed. Mean annual sediment loss is expected to be in the same direction and within 20-35% (as opposed to 50%) of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed.

Qualitatively, the graphical comparisons of the FB Model's simulated values for the baseline condition and climate scenario for flow, flow duration, and linear regression denote success if

they demonstrate similar patterns (i.e., shape, magnitude) and the same direction of change as the ACF climate scenarios results for the Upatoi Creek Watershed.

Note that it is impossible to say with certainty that one model provides 'better' results than the other. However, as will be further discussed in Section 6, it is *reasonable* to consider the results of the data-rich FB Model more plausible.

Table 3.1 provides a summary of the demonstration's performance metrics and how they have been used to anchor measurements of testing success.

Table 3.1 Summary of Performance Objective, Performance Metrics, Data Requirements and Success Criteria for Demonstration of BASINS.MIL Capabilities for Evaluation of Climate Non-stationarity

Performance Objective	Metric	Data Requirements	Success Criteria
Climate Non-Stationarity Assessment			
PO FB #4: BASINS.MIL can predict changes in hydrology and sediment resulting from potential climate change alternatives along with land use changes.	• Mean annual stream flow • Flood frequency (i.e., 100, 50 and 25 year events) based on a Log Pearson III analysis • Comparison of simulated flow duration and continuous time series of daily flow (between models and between scenarios) (qualitative) • Mean annual sediment loss (measured by total suspended solids or TSS)	• Climate change deltas used by the Apalachicola-Chattahoochee-Flint River Basin (ACF) Climate Change Study[a] for the Upatoi Creek Watershed • Modeling results for flow and sediment of ACF Climate Change Study Model at a scale and location consistent with the FB Upatoi Creek Watershed ModelRecent land management documents available from Fort Benning and the greater Columbus area	• Annual stream flow results are within 15-20% of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed • Flood frequencies are within 15-20% of the change predicted by ACF climate scenarios study results for the Upatoi Creek Watershed • Graphical comparisons between simulated values for flow, flow duration, and linear regression are similar to ACF climate scenario results for the Upatoi Creek Watershed (qualitative) • Mean annual sediment loss is within 20-35% of the change predicted by ACF climate scenarios results for the Upatoi Creek Watershed

Note that Table 3.1 has been developed specifically to define the performance objective(s) for the *climate change* component of this demonstration. To develop and simulate *land use change* scenarios (and their potential impacts) that most effectively demonstrate the utility of

BASINS.MIL for land use analysis/management called for a somewhat different approach, which is fully explained in Section 5.2**.** The necessary differences in approach precluded making meaningful comparisons between the ACF and FB Models; instead the presentation and discussion of results focuses on comparing consistency and credibility of the impacts of two very different, but plausible land use change trajectories for Fort Benning.

SECTION 4.0
SITE DESCRIPTIONS

This section provides site descriptions as parameterized in the ACF and FB Models. In each case a general description of the full geographic extent of the model is provided first, followed by a more detailed description of how the model represents the Upatoi Creek Watershed.

4.1 ACF Watersheds

4.1.1 Full ACF Model

The Apalachicola-Chattahoochee-Flint (ACF) River basin is located in Georgia, Alabama, and Florida (Figure 4.1). The Chattahoochee and Flint Rivers merge to form the Apalachicola River, which flows through the panhandle of Florida into the Apalachicola Bay and into the Gulf of Mexico. The composite watershed consists of 12 of the 13 HUC8s that make up HUC 0313 (excluding one small, separate coastal drainage), with a total area of 19,869 mi^2. Approximately 64 percent of the basin is forested. Agricultural land represents a mix of cropland, pasture, orchards, and areas of confined feeding for poultry and livestock production. The dominant agricultural land use in the Piedmont Province is pasture and confined feeding for dairy or livestock production. Most of the poultry operations in the ACF River basin are concentrated in the upper part of the Chattahoochee River basin. Row-crop agriculture, orchards, and silviculture are most common in the Coastal Plain areas. Common crops in the watershed include peanuts, corn, soybeans, wheat, and cotton. The largest concentration of urban land in the basin is in the Atlanta area. Nearly 90 percent of the total population in the basin lives in Georgia, and nearly 75 percent live in the Atlanta metropolitan area.

The ACF River basin is characterized by a warm and humid, temperate climate. Precipitation is greatest in the mountains and near the Gulf of Mexico, lowest in the center of the basin. Average annual precipitation in the basin is about 55 inches, but ranges from a low of 45 inches in the east-central part of the basin to a high of 60 inches in the Florida panhandle. Throughout the ACF River basin, low flows usually occur from September to November and peak flows usually occur from January to April when rainfall is high and evapotranspiration is low.

Land Use Representation in ACF Basin Model

Land use/cover in EPA's ACF Model is based on the 2001 NLCD coverage. NLCD land classes were aggregated to achieve those shown in Table 4.1. The result was then overlain with the Hydrologic Soils Group grid. Pervious and impervious lands are specified separately for HSPF, so only one developed pervious class was used, along with an impervious class. HSPF simulates impervious land areas separately from pervious land. Impervious area distributions were also determined from the NLCD Urban Impervious data coverage. Specifically, percent impervious area was calculated over the entire watershed for each of the four developed land use classes. These percentages were then used to separate out impervious land. NLCD impervious area data products are known to underestimate total imperviousness in rural areas. However, the model requires properly connected (or effective) impervious area, not total impervious area, and the NLCD tabulation is assumed to provide a reasonable approximation of connected impervious area (USEPA, 2013b).

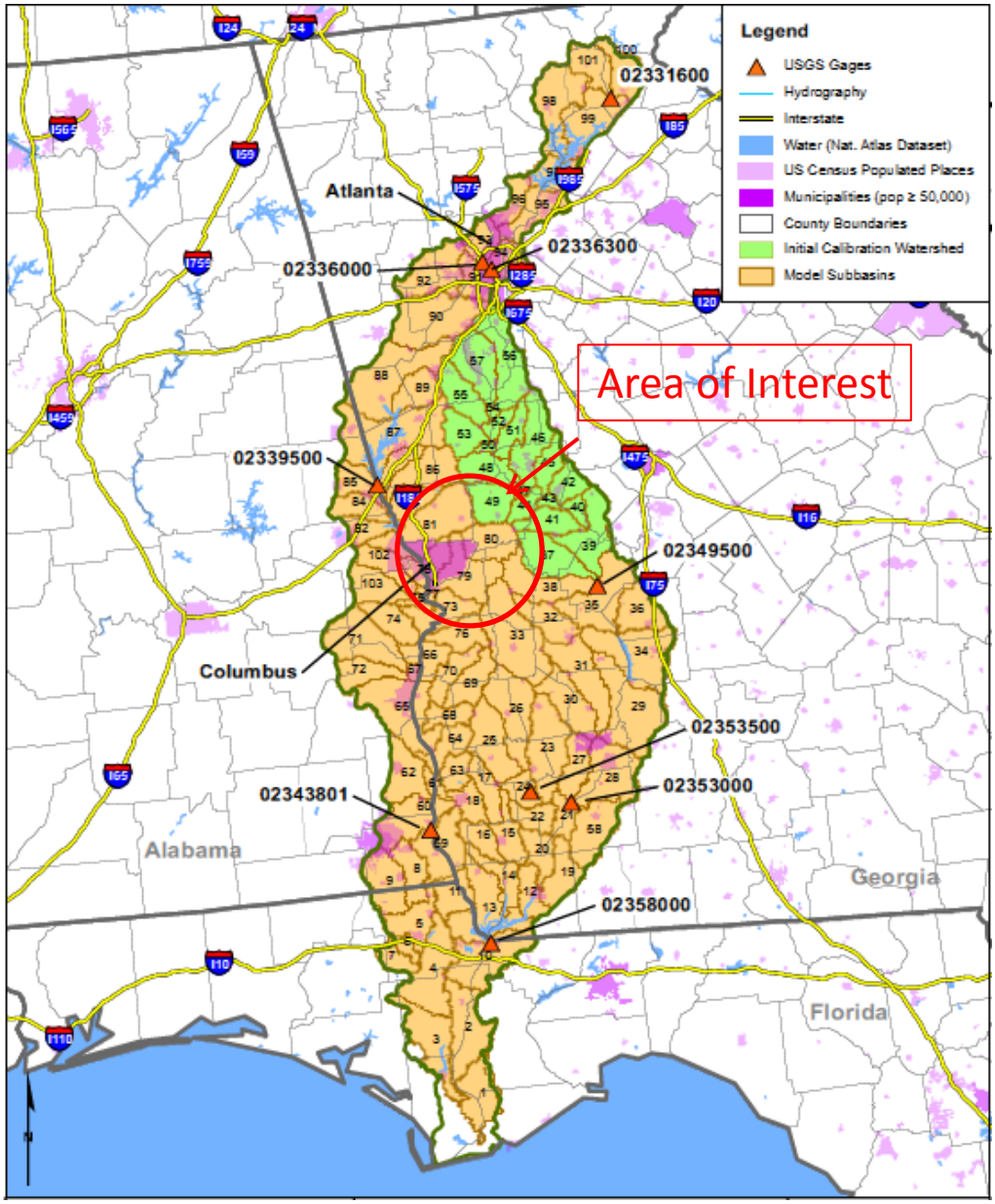


Figure 4.1 ACF watershed boundaries and subbasins. In this figure the Upatoi Creek Watershed comprises the subbasins numbered '79' and '80'. (This number scheme is for the ACF SWAT Model; the identical subbasins in the ACF HSPF Model Are numbered '101' and '21', respectively.)

Meteorological Data for ACF Basin Model

The required meteorological data for the ACF Model are time series of precipitation, air temperature and potential evapotranspiration. These were obtained from the BASINS4 Meteorological Database (USEPA, 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. EPA's scenario application required simulation over 30 years, so the available stations used were those with a common 30-year period of record (or one that could be filled from an approximately co-located station). A total of

37 precipitation stations were identified for use in the ACF basin model with a common period of record of 10/1/1972-9/30/2002 (Figure 4.2). Temperature records were sparse; where these were absent, temperature was taken from nearby stations with an elevation correction. For each weather station, Penman-Monteith reference evapotranspiration was calculated for use in HSPF using observed precipitation and temperature coupled with the SWAT weather generator (Neitsch et al., 2005) estimates of solar radiation, wind movement, cloud cover, and relative humidity.

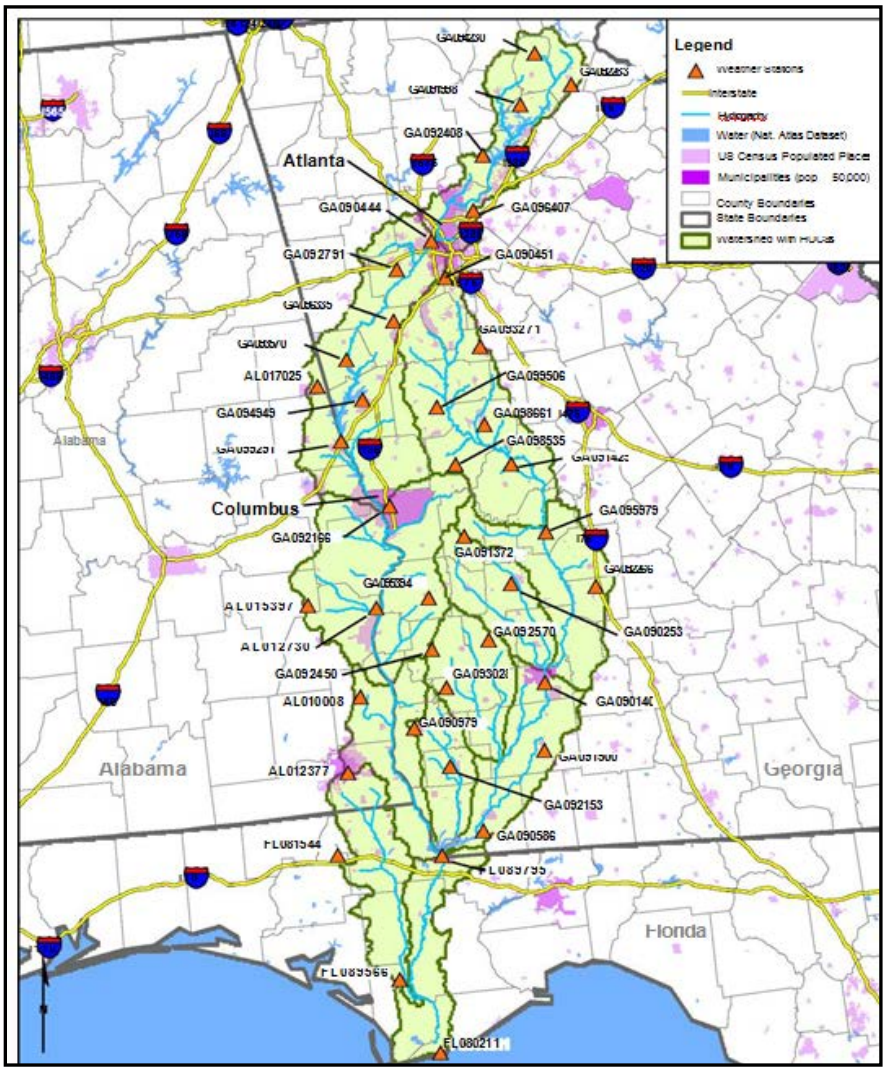


Figure 4.2 Meteorological Stations providing data for the ACF HSPF Model.

ACF Basin Segmentation

HSPF models are set up on a Hydrologic Response Unit (HRU) basis. For the ACF Model, HRUs were formed from an intersection of land use and hydrologic soil group, and then further subdivided by precipitation gage. Average slopes (which tend to correlate with soils) were calculated for each HRU. Slopes in most of the watershed are relatively mild (1-5 percent), therefore HSPF HRU's were not further subdivided by slope. The ACF Basin was divided into 101 subwatersheds (shown in Figure 4.1) for the purpose of modeling.

4.1.2 ACF Model Upatoi Creek Watershed (UCW) Representation

The land use classification scheme, meteorological record selection scheme/requirements and resulting segmentation scheme that were used to develop the ACF HSPF Model resulted in utilization of **20** land use classes, **two** meteorological stations, and therefore **two** modeling subwatersheds to perform simulation of the UCW.

ACF Model UCW Land Use Representation

Table 4.1 summarizes the ACF Model land use representation of the baseline condition for the UCW. Note the following:

- Only a small amount (6%) of the watershed is classified as developed, and therefore EPA's methodology for developing a land use change scenario inevitably resulted in a correspondingly small change in land use, and therefore land use change impact on the watershed's flow and sediment erosion behavior.
- Likewise, the amount of land classified as barren, and therefore more susceptible to erosion, is also small (1%).

Table 4.1 Land Use Classes, Areas and Watershed Percentages Characterizing the Upatoi Creek Watershed in the ACF Model

Class	Area (acres)	Percent of Watershed Area
Forest (4 classes)	196958	68.0%
Shrub (4 classes)	6973	2.4%
Grassland (4 classes)	39757	13.7%
Agriculture (4 classes)	7591	2.6%
Developed	17040	5.9%
Barren	2972	1.0%
Water	1138	0.4%
Wetland	17366	6.0%

ACF Model UCW Meteorological Data

The standardized procedure that EPA used to determine availability of suitable meteorological stations (recall that 37 stations were identified that had the necessary basin-wide shared length of record) and then associate appropriate stations with each of the ACF Model's 101 subwatersheds resulted in two meteorological stations being used to represent the UCW: one for the ACF model segment that represents the upper half, and one for the ACF model segment that represents the lower half. The upstream segment of the UCW utilizes precipitation and air temperature records from the Talbotton weather station (labeled GA098535 in Figure 4.2), and the downstream segment utilizes precipitation and air temperature records from the Columbus AP weather station (labeled GA092166 in Figure 4.2). Potential evapotranspiration values are estimated from the air temperature records using the Penman-Monteith method (Neitsch, 2005).

ACF Model UCW Segmentation

Figure 4.3 depicts the areas contained in the two segments used to perform simulation in the ACF HSPF Model. One channel reach is associated with each of the modeling segments, so these channel reaches are extremely long when compared to the FB model reaches (discussed below).

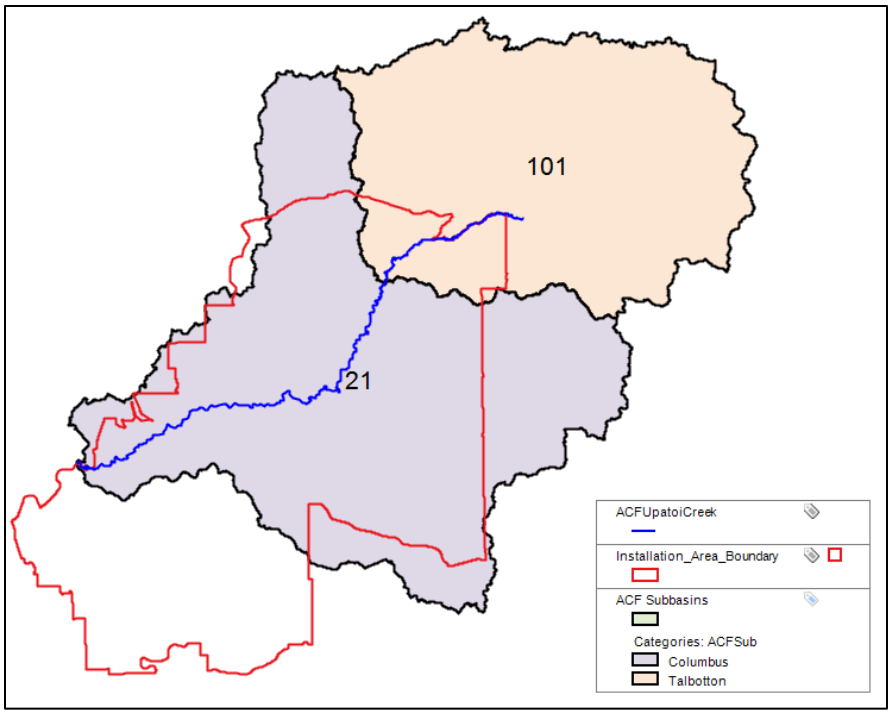


Figure 4.3 Segments used to simulate Upatoi Creek Watershed in the ACF HSPF Model.

4.2 Fort Benning Watersheds

4.2.1 Full FB Model

Fort Benning is a United States Army installation, located mostly in west-central Georgia with portions in east-central Alabama. The installation boundary is shown in relation to the Upatoi Creek model segments in Figure 4.3. Fort Benning is southwest of Columbus in Muscogee and Chattahoochee counties in Georgia and Russell County, Alabama. Fort Benning encompasses approximately 285 square miles within the USGS Hydrologic Unit 03130003, Middle Chattahoochee-Walter F. George Reservoir.

The Chattahoochee River runs through the western portion of the installation. Watershed Management Units (WMUs) have been established for the area around and including Fort Benning. The Watershed Management Units and associated streams are shown in Figure 4.4. These WMUs contain about 682 square miles of area, and were used to define the study area and boundary of the model domain for the Fort Benning Watershed Model.

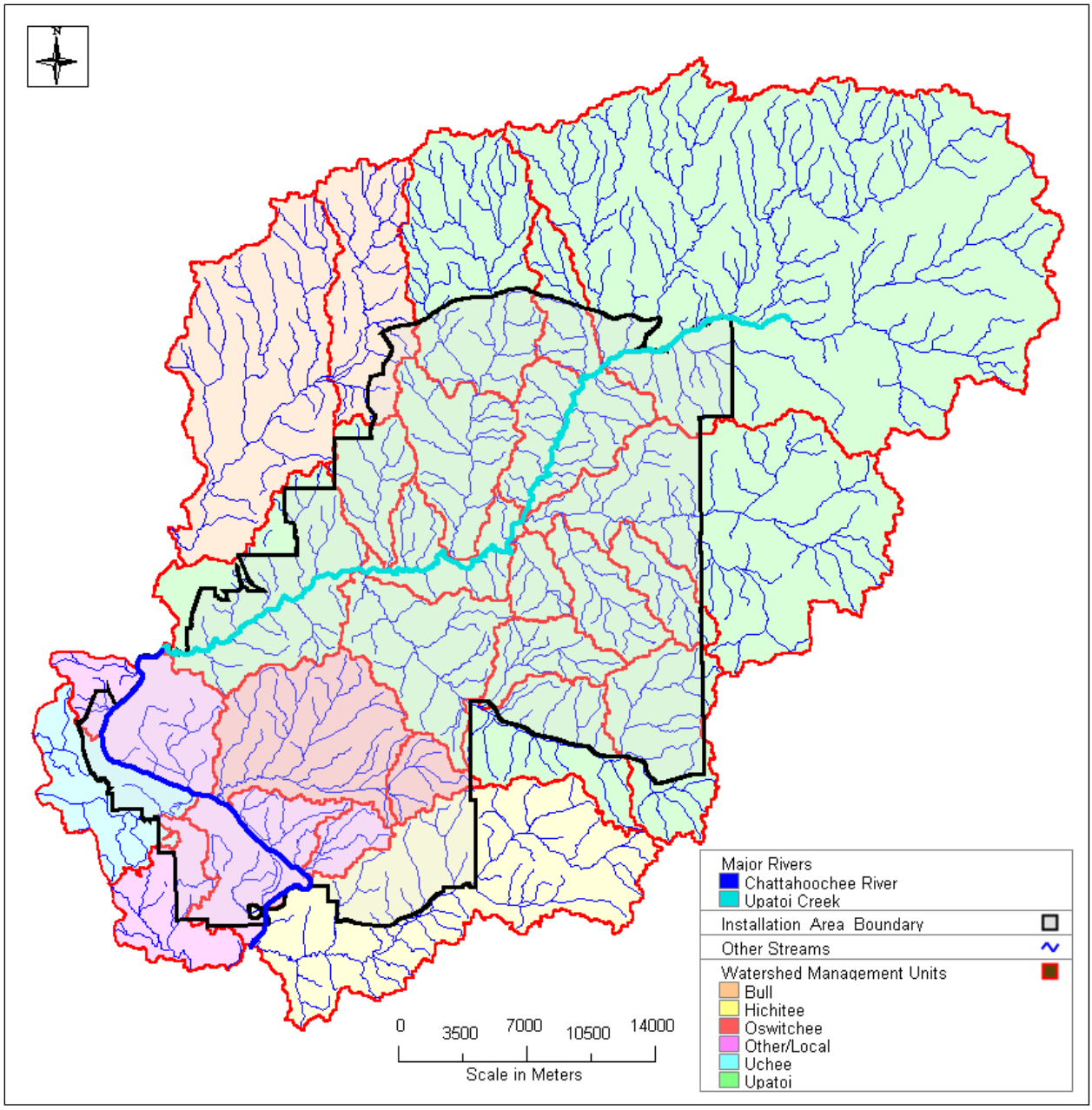


Figure 4.4 Fort Benning Watershed Management Units

Land Use Representation in FB Watersheds Model

The 2001 NLCD land use data layer was used as the primary basis for characterizing land use in the FB Model. Some grouping was conducted to simplify the land use distribution. For example, the open water area was limited in the FB watersheds and mostly represented the surface area of the streams and other waterbodies; any remaining water surface was combined with wetlands into a single category. The barren, pasture, and cultivated crops were combined as an 'ag/other' category. The NLCD urban categories were combined and equated as cantonment area.

The NLCD land use layer lacked necessary coverage of categories representing the extensive road network, tank trails and training maneuver areas which are a primary focus of the FB

Model. AQUA TERRA Consultants (2010) describes the various sources and methods that were used to modify the NLCD data layer to include land use categories for paved roads, unpaved roads, tank trails and heavy maneuver areas.

Land management at Fort Benning includes prescribed burning to promote healthy habitat for the Red-Cockaded Woodpecker (RCW) currently on the endangered species list. The land managers at Fort Benning follow a three-year prescribed burn cycle, where 30% of the forested areas in Fort Benning are burnt every three years. A GIS data layer obtained from SERDP contained information about the areas that were burnt during each fiscal year (FY) in Fort Benning, with the burn parcels normally following training compartment boundaries. The prescribed burn data for 7 FYs from 1999 to 2006 were compiled to estimate the areas that are burned at regular intervals. All the areas ever burned were assigned to one of three burn cycles; cycle 1 (FY 1999, FY 2002, and FY 2005), cycle 2 (FY 2000, FY 2003, and FY 2006), and cycle 3 (FY 2001, FY 2004, and FY 2007). These cycles were combined with the land use data to represent the type of forest burnt in each cycle. Expanding and adjusting the NLCD2001 classes to include the military training categories and the three burn cycles for the various forest categories resulted in simulation of **24** land use classes in the FB Model (listed in Table 4.2).

Meteorological Data for FB Watersheds Model

Precipitation data are available through a previous Ecosystems Characterization and Monitoring Initiative (ECMI) (Leese, 2005) monitoring effort at FB as well as data available through BASINS. Within the Fort Benning installation, ECMI recorded precipitation every 30 minutes at **10** stations. The 10 stations provide a reasonable spatial coverage throughout the installation. However, these records are not complete; i.e. they have months of missing periods in many cases. For use in the simulation, the values for missing periods were filled in using nearby stations by a process described in AQUA TERRA Consultants (2010).

The precipitation data were applied to selected model segments based on a Thiessen network analysis, which is a standard hydrologic technique to define the watershed area that will receive the rainfall recorded at available gages. Figure 4.5 shows the Thiessen polygons generated from the stations the ECMI stations.

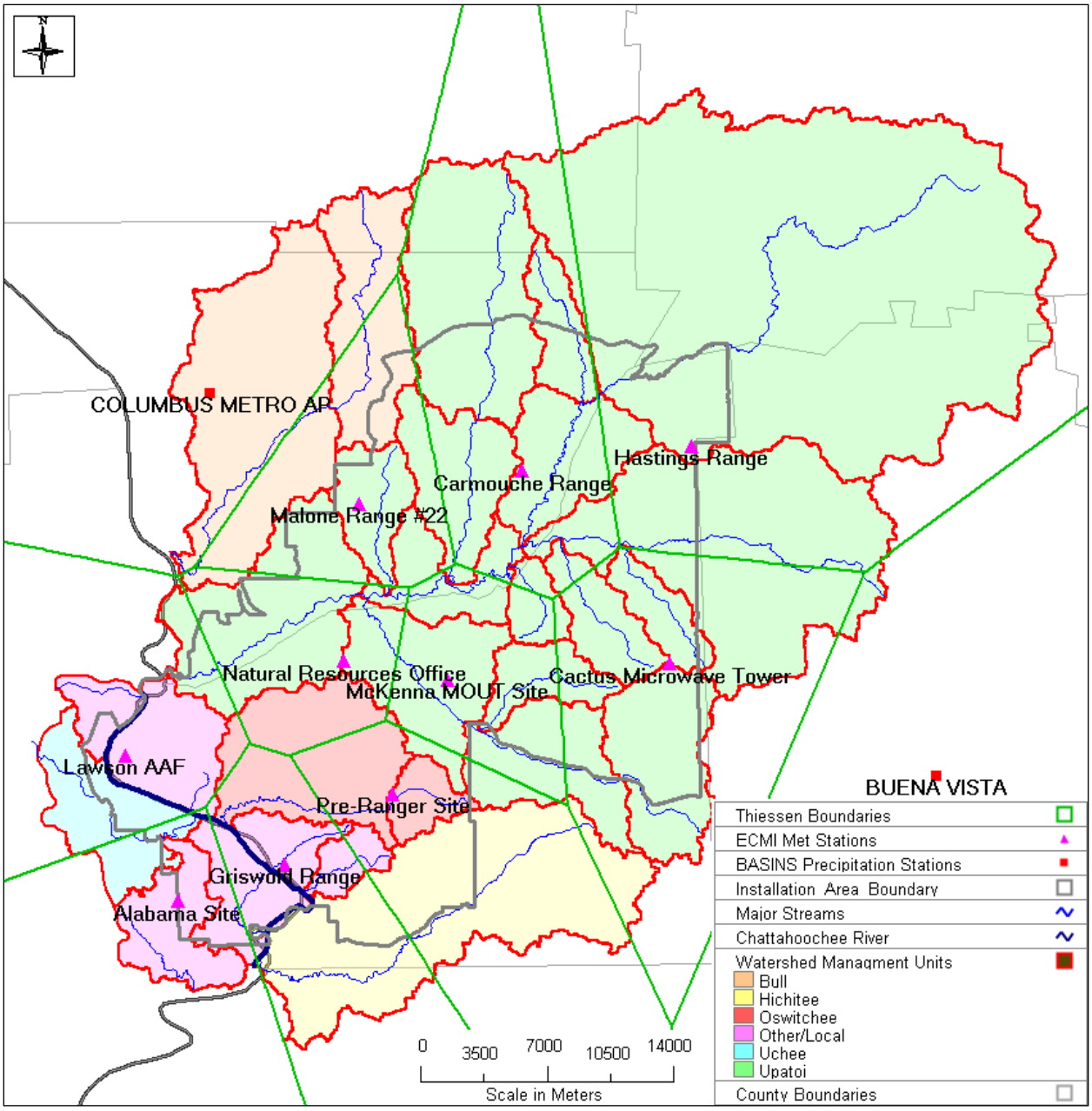


Figure 4.5 Thiessen polygons for ECMI precipitation stations

FB Watersheds Model Segmentation

The major considerations in land segmentation are meteorologic variability, land use, soils, topography, hydrography, and land management/disturbance activities. GIS data layers were obtained for each attribute and overlaid with each other, and matrix operations were used to group lands expected to exhibit similar hydrologic response (details are available in AQUA TERRA Consultants, 2010). The final segmentation scheme featured 133 subbasins, with an average size of about 3.4 square miles within the Base and 8.1 square miles outside the Base. These subbasins were overlaid with Thiessen network boundaries to define meteorological regions across the watershed. The Thiessen network boundaries were developed using the

location of ECMI meteorological stations in and around Fort Benning. Subbasins that are relevant to this ESTCP demonstration are shown in Figure 4.5.

4.2.2 FB Model Upatoi Creek Watershed (UCW) Representation

The land use classification scheme, meteorological record selection scheme and resulting segmentation scheme that were used to develop the FB HSPF Model resulted in utilization of **24** land use classes, **seven** meteorological stations, and **92** modeling subwatersheds to perform simulation of the UCW.

FB Model UCW Land Use Representation

Table 4.2 summarizes the FB Model land use representation of the baseline condition for the UCW.

Table 4.2 Land Use Classes, Areas and Watershed Percentages Characterizing the Upatoi Creek Watershed in the FB Model

Class	Area (acres)	Percent of Watershed Area
Forest (12 classes)	189965	65.7%
Shrub	6408	2.2%
Grassland	25030	8.7%
Agriculture	18538	6.4%
Developed (4 classes)	11365	3.9%
Paved Roads	8306	2.9%
Unpaved Roads	8782	3.0%
Tank Trails	212	0.1%
Heavy Maneuver Area	2289	0.8%
Water/Wetlands	18383	6.4%

FB Model UCW Meteorological Data

Filled-in and extended precipitation records from seven of the 10 ECMI stations are used represent the precipitation for UCW model segments for the period 1980 – 2012. The stations can be located on Figure 4.4 and include Natural Resources, McKenna MOUT, Cactus Microwave, Hastings Range, Carmouche, Malone Range and Lawson AAF.

Data from the Columbus Metro Airport are used to represent air temperature for the entire UCW, and potential evapotranspiration values are estimated from the Columbus air temperature values using the Hamon method (1961).

FB Model UCW Segmentation

The FB Model segmentation scheme is illustrated in Figure 4.6. The UCW is segmented into 92 subbasins, with an average size of about 4.9 square miles.

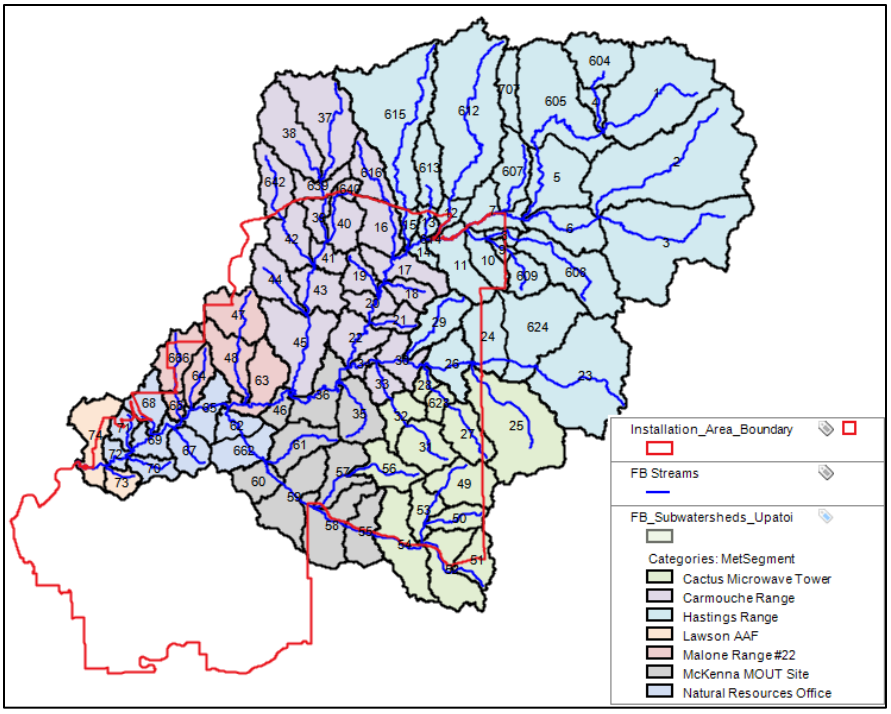


Figure 4.6 Segments used to simulate Upatoi Creek Watershed in the FB HSPF Model.

SECTION 5.0
DEMONSTRATION DESIGN

To review, two independent demonstrations are performed. A demonstration of the application of BASINS.MIL to assess the impacts of climate non-stationarity is performed on streamflow and sediment loadings. The magnitude of change in Fort Benning Model results between the baseline condition and a Year 2050 climate scenario is determined for a collection of metrics. As a basis of gauging 'success', the magnitude of change for metrics is compared with the results of a parallel analysis performed earlier by EPA (2013b).

The second demonstration addresses the application of BASINS.MIL to assess the impacts of land use change, and is also focused on streamflow and sediment loadings. This demonstration varies from the climate non-stationarity demonstration in three noteworthy ways. First, in order to be relevant and effective, we developed and used a different reference condition against which to compare land use change. EPA's ACF simulation of UCW provided analysis of change (climate and land use) starting with *a pre-BRAC baseline condition* and ending with Year 2050. In demonstrating climate change analysis for the UCW using the FB Model, we believed it was useful to do the same, since an important part of this demonstration entails comparing the simulation results (flow & sediment) that are estimated by the ACF and FB models. However, in the ESTCP Fall 2015 In Progress Review (IPR), agreement was reached that comparing the land use change impacts of the ACF and FB models had little utility. This being the case, we felt that the most useful comparison that we could offer in the land use demonstration was between a **post-BRAC baseline** (circa 2010) and projected 2050 conditions. Second, two alternative land use change scenarios were developed and assessed for Year 2050 conditions. Finally, since the analysis of the future land use that was represented and assessed in EPA's ACF simulation was deemed irrelevant as a reference point for assessing the success of the Fort Benning model land use change demonstration, success criteria were not deemed relevant for the land use demonstration.

5.1 Climate Non-Stationarity Demonstration

The objective of the climate non-stationarity assessment is to demonstrate the usefulness of BASINS.MIL model methodologies and results in enabling military planners to characterize changes in hydrology and sediment that may result from changed climate and future land use as they are represented in plausible change scenarios. The climate change scenario and modeling ensemble that are utilized for this demonstration originate from widely-respected climate scientists and modelers. In addition, a plausible future land use scenario for Fort Benning's largest watershed was formulated and simulated with guidance from ESTCP.

The exercise that is central to the ESTCP demonstration of a BASINS.MIL HSPF application to evaluate the impacts of climate non-stationarity is a one-to-one comparison and evaluation of two alternative sets of modeling results for the Upatoi Creek Watershed (UCW) (453 mi^2): one generated by EPA's previous coarser (i.e., larger scale) application of HSPF to the entire ACF River Basin (19,869 mi^2), and a second finer-scale Fort Benning application in which the UCW comprises the majority of Fort Benning HSPF Watershed Model. The Upatoi Creek Watershed comprises approximately *two percent* of the ACF Watershed.

Results and climate change deltas (i.e., changes in magnitude, intensity and timing of precipitation plus changes in air temperature from a 'baseline' climate condition) for the

USEPA's regional HSPF climate change study of the Apalachicola-Chattahoochee-Flint (ACF) Region, which includes the FB Model domain, were used to develop a comparable climate change scenario that was evaluated using the Upatoi Creek Watershed (UCW) within the FB Model.

The comparison of ACF and FB model results that offers the basis for comparison focuses on a *single* climate scenario representative of *one* emissions storyline, *one* downscaling method from a specific GCM to a specific RCM model. The regional weather 'deltas' and change in precipitation intensity inherent in the RCM scenario that was represented in the ACF model have been applied to the meteorological data that drives the watershed-scale FB model.

This demonstration then provides the foundation for evaluating a broader range of endpoint sensitivities to both natural and management perturbations, using an installation-scale model that features finer segmentation, expanded land use types and more detailed management scenarios.

A semi-quantitative evaluation of the reasonableness of results from the FB climate non-stationarity demonstration is achieved by a combination of comparisons with (1) historical benchmarks such as a 100 year flood benchmark, and (2) regional-scale models. USEPA's Apalachicola-Chattahoochee-Flint Basin (ACF) Regional Model is ideally situated and suited for evaluating the reasonableness of the results from the FB climate scenario simulations.

5.1.1 Conceptual Demonstration Design

As shown conceptually in Figure 5.1, the full BASINS.MIL ESTCP project incorporated two categories of technical components; those that are applied to build the actual BASINS.MIL models and those that are being used to compare the modeling results of those models to results produced from an existing alternative approach. Additionally, two types of technical components are being applied to build the BASINS.MIL models: data/methodologies and internal/external enhancements. Each task area applies a combination of these components that is designed to address a sub-set of the project's nine individual performance objectives. The climate non-stationarity demonstration task (highlighted in Figure 5.1) utilizes the functionality of BASINS.MIL's Climate Assessment Tool (CAT) to develop and demonstrate a climate change assessment and then compare it to results from USEPA's ACF Study for the same watershed. The technical components of this BASINS.MIL climate non-stationarity demonstration are further described in the following sections in terms of first the baseline characterization and preparation (Section 5.1.2), and then the demonstration layout and methodology (Section 5.1.3).

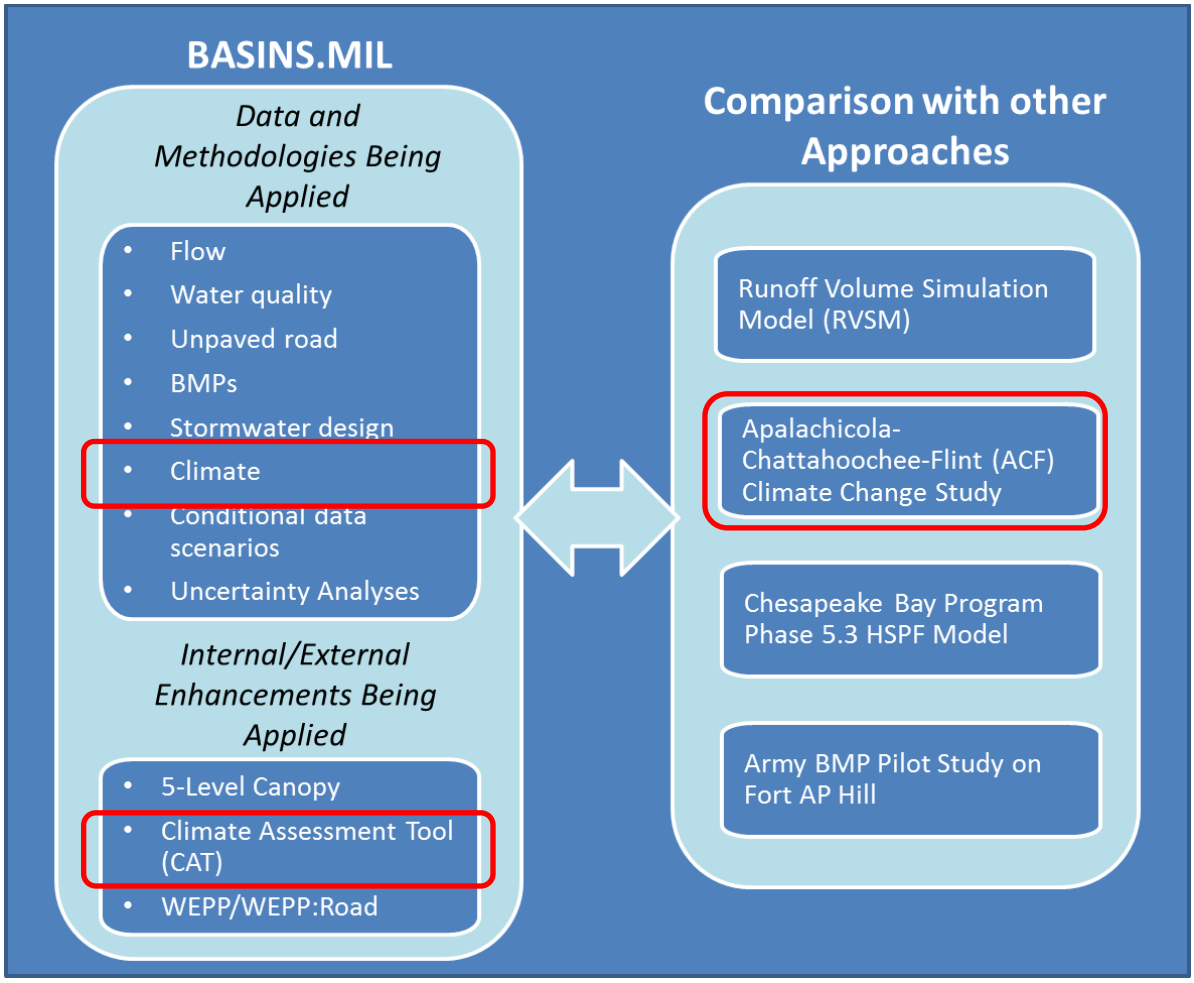


Figure 5.1 Technical components of the complete ESTCP BASINS.MIL demonstration

5.1.2 Baseline Characterization and Preparation

In many watershed model applications, the term "baseline" is reserved to connote the weather/landscape conditions against which alternative scenarios are developed, simulated and compared. Quite often (but not always) modeling the *baseline condition* is synonymous with representing the *current* land conditions and simulating hydrologic/erosion processes that result from historical weather. The term connotes a watershed's land use and management condition at a single reference time.

Our use of the word "baseline" in the context of this ESTCP demonstration requires careful definition, because it differs from the traditional meaning of the term to watershed modelers. The objective of the ESTCP demonstration is to exercise a specific capability of the BASINS.MIL modeling system, first explaining the rationale and method of the demonstration, and then assessing the reasonableness of the results that are generated. The focus of this exercise is looking forward in time to the year 2050 at a spatial scale relevant to military installations. In doing so, one plausible climate change scenario and one plausible land use change scenario are developed, and their potential impact on runoff and erosion are simulated.

Simply stated, the **baseline** for our demonstration is the currently existing information. The **demonstration** entails the use of this information to set up, perform and review a climate non-stationarity exercise using the BASINS.MIL representation of the Upatoi Creek Watershed that comprises the majority of Fort Benning.

In this context the "baseline" for our exercise includes already existing knowledge and model results that are available for characterizing the Upatoi Creek Watershed (UCW) **both** under current conditions **and** under Year 2050 conditions. That is to say, existing information about Year 2050 that was generated by previous modeling is an important component of the information "baseline" that is used, first to design our demonstration, and then to assess the reasonableness of results. Building on this definition/understanding, the baseline components that needed to be characterized and prepared for this demonstration included the following:

- EPA's ACF Model. We requested and acquired the ACF baseline input (HSPF User Control Input, or UCI) from EPA's contractor for the 20 Watersheds Study. To confirm this input we ran the ACF baseline model and reproduced published results on the Upper Chattahoochee and at the ACF outlet. We confirmed ACF results for flow and sediment on a full-basin basis using the results shown in the Final Report (USEPA, 2013b).
- ACF Model of Upatoi Creek Watershed. We confirmed a correspondence of the ACF model segments that represent the UCW to the watershed's representation in the FB Model by comparing the model-designated sum of areas for the ACF Model Upatoi segments (aka 21 & 101) to the sum of areas designated for the FB Upatoi Creek subwatersheds as represented in FB model (453 sq. mi.). We pared the ACF Model down to two segments and re-generated/summarized ACF UCW results, mining additional output at the two segment pour points. We determined the meteorological stations (Columbus, Talbotton) that are used to represent the UCW in the ACF Model. We isolated and summarized the ACF Model baseline representation of land use classes/areas in the UCW, specifically NLCD land use classes 21-24. We extracted and represented composite flow and sediment results for only the two UCW segments for the baseline scenario. Required results included annual stream flow; flood frequencies; mean annual sediment loss; and graphical representation of simulated timeseries values for flow, flow duration, and linear regression.
- BASINS.MIL Model of Upatoi Creek Watershed. Under a parallel task (Conditional Data Scenario, in Figure 5.1) we extended hourly precipitation and air temperature timeseries at Columbus for the Fort Benning model, using BASINS data for 2009 and disaggregated TMAX/TMIN data for 2010 through 2012. We extended the simulation period for the baseline condition through 2012 and produced results for annual stream flow; flood frequencies; mean annual sediment loss; and graphical representation of simulated timeseries values for flow, flow duration, and linear regression. Since the unpaved roads in the UCW are simulated using the WEPP model, the baseline sediment erosion results from WEPP were also extended to 2012 and imported into the HSPF UCW Model.
- EPA's 2050 climate and land use change scenario characterization. We also requested and acquired the ACF WRFP weather scenario input (UCI) from EPA's contractor. To confirm this input we ran the ACF WRFP scenario and reproduced published results on the Upper Chattahoochee and the ACF outlet. Using a script, we modified the baseline air

temperature and precipitation records using the published additive/multiplicative factors for the full-basin ACF WRFP climate scenario, and we verified that the results exactly match those in the WRFP climate scenario time series. This same script was therefore available for modifying FB UCW weather time series to represent the WRFP scenario.

Table 5.1 summarizes the WRFP scenario 'deltas' that result from the WRFP scenario for the UCW region. The scenario results in an annual loss of 4.6 inches of precipitation from the baseline average; an average increase of 4.7 degrees F in air temperature; and an annual increase in PET of 6.6 inches.

Table 5.1 WRFP Monthly Deltas for Precipitation, Air Temperature and PET

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum/Avg.
Baseline	PREC (in)	3.8	4.2	5.5	3.4	3.2	3.5	4.6	3.7	2.9	2.4	3.9	4.2	45.4
	ATEM (deg F)	46.9	50.7	57.8	64.7	72.8	79.2	81.5	80.8	75.8	65.6	56.6	48.8	65.1
	PEVT (in)	1.1	1.3	2.2	3.0	4.6	5.7	6.2	5.5	3.9	2.4	1.5	1.1	38.4
WRFP	PREC (in)	3.3	4.7	5.8	2.6	2.6	2.8	3.8	2.6	1.9	2.5	4.0	4.2	40.8
	ATEM (deg F)	50.6	54.2	61.1	67.7	77.0	85.4	87.8	86.4	80.6	70.9	60.7	54.8	69.8
	PEVT (in)	1.2	1.5	2.4	3.3	5.2	6.9	7.5	6.5	4.5	2.9	1.7	1.3	44.9
Effective Deltas	PREC (in)	-0.6	0.5	0.3	-0.8	-0.6	-0.7	-0.7	-1.0	-1.1	0.0	0.1	0.1	-4.6
	ATEM (deg F)	3.8	3.5	3.3	3.0	4.1	6.2	6.4	5.6	4.9	5.2	4.0	6.0	4.7
	PEVT (in)	0.2	0.2	0.3	0.3	0.6	1.2	1.3	1.0	0.6	0.4	0.2	0.3	6.6

As previously introduced, the discussion above focuses on *baseline information/materials* that are available for performing the demonstration. In modeling exercises it is necessary to define the **'baseline condition'**; i.e., the weather/land conditions against which alternative scenarios are developed, simulated and compared. The term connotes a watershed's condition at a single reference time. Reasonableness of comparing the ACF and FB model results for this non-stationarity demonstration is anchored in the fact that both models share a similar (in time and primary source) baseline condition and future scenario. That is to say, both models utilize NLCD 2001 as the foundation for defining the land condition of the UCW (although the FB Model features a partial customization of NLCD to define additional military use land use classes), and both models simulate the same WRFP climate change scenario.

The NLCD 2001 represents a land condition in the UCW that pre-dates the very significant burst of cantonment/residential and military training lands that resulted from Base Realignment and Closure (BRAC) in 2005. Accordingly, in referring to the baseline condition for the climate change demonstration component of this task, we refer to it as the "**pre-BRAC baseline condition**". The need for doing this will be made clear during the subsequent discussion of the land use change demonstration component in Section 5.2.

5.1.3 Demonstration Layout and Methodology

This demonstration of a BASINS.MIL application to assess climate non-stationarity entailed applying a down-scaled regional climate scenario to an installation-scale watershed for which a detailed baseline model, including representation of military land uses, had already been developed through a SERDP project. The endpoints on which the demonstration was focused were streamflow and suspended sediment. Selected metric values and comparison graphics were

produced both to express the impacts of climate change on flow and sediment, and to assess the reasonableness of the demonstration results.

We applied monthly precipitation ACF 'deltas' and intensity adjustments for the ACF WRFP climate scenario to the seven meteorological records used by the FB Model to simulate the UCW. We applied the monthly ACF Model WRFP scenario air temperature 'deltas' for the Columbus weather station to the FB period of record for the same station. The ACF simulation of the UCW utilized two PEVT time series (Columbus, Talbotton) for simulation of the UCW, and these times series were generated using the Penman-Monteith estimation method. To avoid extraneous deviations, we opted to preserve the original FB UCW Model approach of using a single PEVT time series (Columbus) for simulating the entire UCW; this time series was generated by applying the Hamon estimation method to the Columbus air temperature time series.

We produced results for annual stream flow; flood frequencies; mean annual sediment loss; and graphical representation of simulated timeseries values for flow, flow duration, and linear regression.

5.2 Land Use Change Demonstration

In addition to representation and simulation of changed climate, a parallel demonstration that focused on representation and simulation of changed future land use was performed.

As an initial reference point for the 2050 land use scenario that we eventually constructed for the FB UCW Model demonstration, we isolated and summarized the ACF Model WRFP representation of land use classes/areas in the UCW, specifically NLCD land use classes 21-24 and determined the % change from baseline for these classes. We also confirmed ACF WRFP scenario results for flow and sediment on a full-basin basis using the results shown in the Final Report (USEPA, 2013b).

In the November 2015 IPR, ESTCP suggested that comparison of impacts generated by USEPA's Year 2050 ACF Upatoi Watershed land use scenario to those generated by the Year 2050 scenario that we develop based on the FB Model may not be terribly useful. Subsequent review of EPA's Year 2050 land use scenario substantiated this concern. EPA's ACF Model land use projection was not sensitive to the burst of change that resulted from BRAC 2005. Consequently, when EPA applied their more generalized approach to the Upatoi Creek Watershed, a significantly smaller amount of development for the pre-BRAC baseline condition was represented in the Year 2050 scenario than had **already** occurred in 2010 due to BRAC.

In EPA's model scenario the total increase in developed area from the baseline in the Upper Upatoi segment was represented as **93 acres,** a **2%** increase to baseline developed areas (or a **0.08%** transition of the entire segment's land to developed status). Total increase in developed area from the baseline in the Lower Upatoi segment was represented as **582 acres**, a **5.4%** increase to baseline developed areas (or a **0.3%** transition of the entire segment's land to developed status).

We compared the increase in developed land within the two Upatoi segments from NLCD 2001 to NLCD 2011. Total increase in developed land in the Upper Upatoi from NLCD 2001 to NLCD 2011 was **121 acres** (i.e., **2.7%** increase in developed land by Year 2011 as compared to a **2%** increase projected by Year 2050 in the EPA ACF scenario), and the total increase in

developed land in the Lower Upatoi was **1688 acres** (i.e., **13.1%** increase in developed land by Year 2011 as compared to a **5.4%** increase projected by Year 2050 in the ACF scenario).

It should be noted in interpreting these numbers that both Fort Benning (most of the lower segment) and the non-military lands that comprise most of the upper segment are in a state of relatively low residential development. As a result the land use classification scheme that was developed for the FB Model justifiably limited its "developed" land use types to only five: urban/ cantonment open space, urban/cantonment low density, urban/cantonment high density and paved roads. This classification scheme essentially normalizes all types of off-base development to increases in residential growth in a manner that attempts to represent net hydrological alteration.

To provide an effective (and more easily interpreted) demonstration of land use change analysis for the UCW, we concluded that the Year 2050 scenario that is used should include a change to cantonment/residential areas that is at least as large as that documented in NLCD 2011. The changes that were eventually applied are described in the following section.

5.2.1 Conceptual Demonstration Design

The conceptual design is as follows:

1. Develop a post-BRAC baseline condition for UCW land use. Apply uniform increments to all cantonment areas represented in the sub-watersheds of each of the two pre-BRAC UCW model segments (Upper Upatoi, Lower Upatoi). Adjust UCW training areas as per documentation from Fort Benning that is available regarding the post-BRAC condition (Section 5.2.2). The result is a decrease in the training area that had been represented in the pre-BRAC baseline condition.
2. Perform simulation of streamflow and sediment transport for the post-BRAC baseline condition. With the goal of isolating the impacts of land use change from climate non-stationarity, apply the pre-BRAC baseline weather record to the simulation.
3. Develop two alternative Year 2050 land use change scenarios: one depicting changes to installation development responsive to a 'less aggressive' world political condition and the other corresponding to installation development in response to a world political condition of "heightened aggression". In recognition of Fort Benning's concerted efforts to move mechanized training activities out of the Upatoi Creek watershed to protect the Red Cockaded Woodpeckers, both future scenarios assume that there will be no change in the post-BRAC level of mechanized training in the UCW. The scenarios depict two significantly different increases in cantonment development in the UCW; the "heightened aggression" scenario corresponds to increased cantonment areas to reflect an increase in Installation population and training demands.
4. Perform simulation of streamflow and sediment transport for the two alternative Year 2050 land use change scenarios. With the goal of isolating the impacts of land use change from climate non-stationarity, apply the pre-BRAC baseline weather record to the simulation.
5. Compare and contrast scenario results.
6. Discuss effectiveness and limitations of the demonstration.

5.2.2 Baseline Characterization and Preparation

Development of the post-BRAC baseline condition was achieved by making adjustments to cantonment areas and training areas compared to the pre-BRAC baseline condition.

Cantonment Change

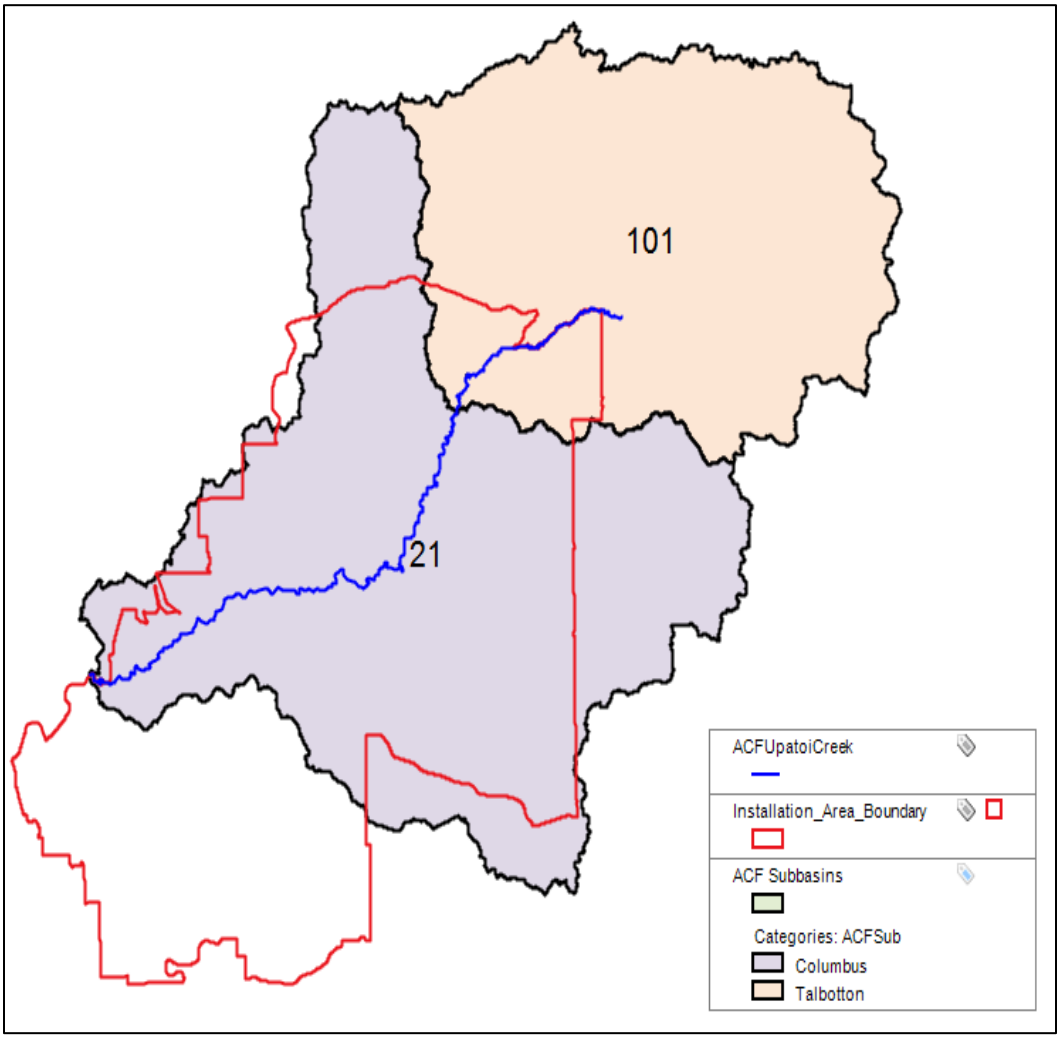


Figure 5.2 Upper and Lower Upatoi Watershed Boundaries w.r.t. Fort Benning Installation boundaries

Increments to cantonment from the pre-BRAC baseline to estimate the post-BRAC baseline were achieved by adding the changes in developed area between 2001 NLCD and 2011 NLCD (i.e., 2.7% increase in Upper Segment, 13.1% increase in Lower Segment) to an estimate of changes in developed area during the period from 2011 to 2013. (The lion's share of the growth during this period occurred during the period from 2008 to 2010 in response to BRAC). Columbus area reports document that rate of development tapered off during 2011-2013, and we propose assuming that another 50% of the previous increment due to BRAC occurred (i.e., 1.4% for Upper Segment, 6.7% for Lower Segment). Therefore, our proposed increments to achieve the post-BRAC baseline are **4.1%** for the Upper Segment and **19.8%** for the Lower Segment.

We applied uniform increments to all urban/cantonment and paved road areas in all sub-watersheds represented in each of the two pre-BRAC UCW model segments (Lower Upatoi, Upper Upatoi). For the purposes of this demonstration, particular land use types were first categorized as either available or unavailable for development; the unavailable land use types included water/wetlands, heavy maneuver areas, and tank trails, whose areas were assumed to be constant. Land areas from available land use categories were decreased by a corresponding equal percentage amount, such that there was no net gain/loss of land area within each sub-watershed. In other words, all land use types other than urban/cantonment, paved roads, water/wetlands, heavy maneuver areas, and tank trails were considered to be available for development, and these areas were converted to the expanded developed areas on an equal percentage basis.

Training land change

Our initial baseline (circa Year 2004 for the original FB model) land use representation included 241 acres of tank trails and 2290 acres of heavy maneuver areas for the pre-BRAC condition. While these two specialized military land use types comprise a relatively small percentage of the UCW, our previous simulation results suggested that these areas contribute between 15 and 20 times as much sediment erosion as the cantonment areas. As a result, we considered it a priority to 'fine tune' our representation of the current mechanized training activities/areas in the UCW.

Our approach to representing the **post-**BRAC tank training in Upatoi Creek Watershed is driven by the June 2015 "Enhanced Training Environmental Assessment Fort Benning, Georgia" document that indicates imminent and permanent re-location of all tank training to the Good Hope area outside of the Upatoi Creek Watershed that we will be modeling. This measure is being taken to protect the endangered Red Cockaded Woodpecker. One assumption we made is that it is unlikely that the installation will entirely decommission roads that have been used as tank trails in the past. In particular, we assume that the use of the DMPRC area will continue and require movement of tanks to and from the Good Hope area. (Repeated attempts to confirm this assumption with Fort Benning personnel were unsuccessful.) Accordingly, to represent the post-BRAC military training lands our approach has been to add the known acreage of the DMPRC (1876 acres) to the pre-BRAC HMA acreage and to preserve the 241 acres of tank trails that were represented in the pre-BRAC baseline. Because we had access to a GIS layer showing the DMPRC area as well as a GIS layer of the pre-BRAC land use, we were able to calculate a revised number of acres of each land use classification for those sub-watersheds affected by the construction of the DMPRC, through a straightforward GIS process.

5.2.3 Demonstration Layout and Methodology

The UCW is approximately evenly split between installation and non-installation lands, with the majority of the non-installation lands located in the upper extents of the watershed. We consulted with ESTCP to identify a land use change scenario for the Fort Benning lands in the UCW that they considered reasonable, interesting and insightful.

Cantonment Change

While doing a little more research to establish plausible cantonment/residential growth for the Year 2050 scenario, we became aware that Fort Benning has actually been experiencing some downsizing the last few years in terms of activities and manpower. This circumstance has led us to develop and simulate two Year 2050 scenarios in order to bracket different futures at Fort

Benning that might occur in a future world "with lessened aggression" versus a future world "with heightened aggression'.

We apply two pairs of 'composite' increments to cantonment for two different scenarios. An increment pair is merely different values for the Upper and Lower Upatoi Creek watershed segments. The scenarios are:

- Scenario 1: After Year 2017 the current downsizing of Fort Benning's operations and manpower comes to an end, and modest growth of operations and manpower is sustained from 2018 – 2050.
- Scenario 2: After Year 2017 the current downsizing of Fort Benning's operations and manpower is reversed to reflect the need to respond to greater military challenges/commitments throughout the world; residential/cantonment requirements experience another development event of equal magnitude to that resulting from BRAC 2005 sometime during the 2018 to 2050 period.

Accordingly, we incremented the cantonment/residential lands in the two UCW segments by two components, first an increment to reflect known development resulting from implementation of BRAC 2005 (i.e., the post-BRAC baseline), and then adding to this baseline the projected increments corresponding to the two scenarios defined above.

Future Scenario Increments from Post-BRAC baseline (circa 2013) until Year 2050

Scenario 1 (A Limited-Aggression World) assumes moderate growth for the period 2014-2050, with growth in the Upper Segment assumed to be encouraged by non-military as well as military factors. Accordingly, the same increments are assumed for both segments, i.e., both segments are assumed to experience a net **5.0%** increment. This assumption is consistent with intuitive positive correlations between development internal to an installation and concurrent urbanization of non-military lands directly adjacent to an installation. A more thorough discussion of this phenomenon is provided by Westervelt (2007).

Scenario 2 (A Heightened-Aggression World) assumes another development event of the same magnitude as that resulting from BRAC 2005 (i.e., another 2.7% increment for the Upper Segment and 13.1% increment for the Lower segment) prior to 2050, with additional low level increases (i.e., net 5% increase for both segments) for years not affected by this heightened development event.

Hence the Scenario 2 increments from the post-BRAC baseline to Year 2050 are **7.7%** for the Upper Segment and **18.1%** for the Lower Segment.

Note that we apply the same multiplier(s) to the pervious and impervious cantonment/residential land areas in the FB UCW Model, thereby assuming no change in Effective Impervious Area (EIA) %. Since EPA's method of projecting development considered movement of lands from a particular NLCD residential class to any one of the other three NLCD residential classes, their Year 2050 scenario did not represent the same percentage increments for pervious and impervious residential categories. Generally speaking, the increment to impervious lands was approximately 50% larger than that to pervious lands for both segments.

In summary, our increments in cantonment/residential areas from the **post-BRAC baseline** to Year 2050 are as follows:

- For the post-BRAC Baseline, we utilized a **4.1%** increment in the Upper Segment and a **19.8%** increment in the Lower Segment.
- For a 'limited-aggression' world (Scenario 1) we utilized a **5.3%** increment, from the new post-BRAC baseline, in the Upper Segment and a **6.3%** increment in the Lower Segment.
- For a 'heightened-aggression' world (Scenario 2) we utilized a **7.7 %** increment, from the new post-BRAC baseline, in the Upper Segment and a **18.1%** increment in the Lower Segment.

The approach to performing the land use change demonstration that is described above was presented to ESTCP for their comments; approval of the approach was received from Herb Nelson, Acting ESTCP RC Program Manager, on April 26, 2016. In granting approval, ESTCP noted that "not all choices available for specific simulations are worthy of detailed analysis prior to implementation of simulations. Baseline values adjusted to BRAC outcomes are important as are overall growth rates in the out-years. As the project results unfold using alternative simulations by adjusting imperviousness, erosion rates, etc. would seem a cost effective way to demonstrate sensitivity to climate change and land use change."

We produced results for annual stream flow; flood frequencies; mean annual sediment loss; and graphical representation of simulated timeseries values for flow, flow duration, and linear regression.

Training Land Representation

The role of the existing tank-training infrastructure (the DMPRC and related adjacent trails/roads) is not clearly understood vis-a-vis long term plans to move all tank infrastructure out of the UCW. It is very unlikely that the DMPRC nor the roads and trails that currently accommodate tanks will be decommissioned. Because flows and sediment are the focus of the Year 2050 simulations, we made the decision to leave their status at the current levels (i.e., those represented in the post-BRAC baseline condition).

SECTION 6.0
PERFORMANCE ASSESSMENT

6.1 Climate Non-Stationarity Demonstration

In the context of this demonstration, metrics and 'success criteria' take on a different role/meaning than they have for most ESTCP demonstration/validation efforts. While both can still play an important role, their interpretation is more suited to establishing 'reasonableness' and 'consistency' of simulation results, as opposed to 'success' or 'failure' of a tool or methodology. We note that demonstrations for model applications are essential as a means to identify the conceptual and task-level procedures that are required to effectively analyze questions and thereby produce meaningful results. In this sense the demonstration meets an important ESTCP program objective.

The reasonableness of the demonstration is measured in terms of similarity of annual stream flow and sediment loss modeling results predicted by a FB HSPF Model climate scenario simulation to a previously performed ACF HSPF simulation of the same climate scenario for the Columbus/FB region as per the 'success criteria'. Both quantitative and qualitative 'success criteria' are applied, as described in Section 3.4.

6.1.1 Simulation of Hydrological Change

Mean Annual Stream Flow

Success Criterion #1: "Annual stream flow results are within 15-20% of the change predicted by ACF climate scenario results for the Upatoi Creek Watershed."

The table below shows the mean annual runoff in acre-feet per year and mean annual streamflow in cfs, from the baseline and changed climate simulations, for both the ACF and the Fort Benning models.

Table 6.1 Comparison of ACF and FB Model Climate Change Simulation Results for Mean Annual Streamflow and Evaluation of Performance Success Criterion

Mean Annual Runoff (ac-ft/yr), Mean Annual Stream Flow (cfs/yr) and % Difference or Change in Mean Annual Streamflow

Mean Annual Runoff (ac-ft/yr) Baseline Simulation	
Runoff from Upper Upatoi Watershed Area	
ACF Model baseline scenario	165420
FB Model baseline scenario	189401
Runoff from Lower Upatoi Watershed Area	
ACF Model baseline scenario	184705
FB Model baseline scenario	249223
Runoff from Entire Upatoi Watershed Area	
ACF Model baseline scenario	350125
FB Model baseline scenario	438624

Mean Annual Runoff (ac-ft/yr) Changed Climate Simulation (Year 2050)	
Runoff from Upper Upatoi Watershed Area	
ACF Model 2050 WRFP scenario	133409
FB Model 2050 WRFP scenario	151767
Runoff from Lower Upatoi Watershed Area	
ACF Model 2050 WRFP scenario	147914
FB Model 2050 WRFP scenario	200865
Runoff from Entire Upatoi Watershed Area	
ACF Model 2050 WRFP scenario	281323
FB Model 2050 WRFP scenario	352632

Mean Annual Streamflow (cfs/yr) Baseline Simulation	
Flow from Upper Upatoi Pour Point	
ACF Model baseline scenario	228.47
FB Model baseline scenario	264.79
Flow from Lower Upatoi Pour Point	
ACF Model baseline scenario	482.63
FB Model baseline scenario	610.7

Mean Annual Streamflow (cfs/yr) Changed Climate Simulation (Year 2050)	
Flow from Upper Upatoi Pour Point	
ACF Model 2050 WRFP scenario	183.94
FB Model 2050 WRFP scenario	212.27
Flow from Lower Upatoi Pour Point	
ACF Model 2050 WRFP scenario	386.23
FB Model 2050 WRFP scenario	490.67

% Change in Mean Annual Streamflow Between Baseline & Changed Climate Simulation (Year 2050)	
% Change in Flow at Upper Upatoi Pour Point	
ACF	-19.5%
FB	-19.8%
% Change in Flow at Lower Upatoi Pour Point	
ACF	-20.0%
FB	-19.7%

Success Criterion #1 Change in FB annual stream flow is within 15-20% of the change predicted by the ACF UCW model	
Difference in predicted changes - Upper	-0.3%
Difference in predicted changes - Lower	0.3%
	SUCCESS!

The ACF model shows a decrease of 19.5 percent in mean annual streamflow at the upper Upatoi pour point, and a decrease of 20.0 percent at the lower Upatoi point. The Fort Benning model shows a nearly identical change, from 19.8 percent at the upper pour point to 19.7 percent at the lower pour point. The differences between these results, a decrease of -0.3 percent at the upper and an increase of 0.3 percent at the lower pour point, are well within the success criterion range of 15-20 percent. Thus, using simulated mean annual streamflow as a performance metric, the Fort Benning model successfully captures the effects of the climate change scenario shown in the ACF model. The simulation results expressed as mean annual streamflow are further interpreted and discussed in Section 6.3.1.

Flood Frequency

Success Criterion #2: "Flood frequencies are within 15-20% of the change predicted by ACF climate scenarios study results for the Upatoi Creek Watershed."

To assess this criterion, we used the SWSTAT Integrated Frequency Analysis feature of BASINS, using 100-, 50-, and 25-year flood events. The table below shows the flood event

magnitudes, expressed as cfs, from the baseline and changed climate simulations, for both the ACF and the Fort Benning models.

Table 6.2 Comparison of ACF and FB Model Climate Change Simulation Results for Magnitudes of 25-, 50- and 100-Year Flood Events and Evaluation of Performance Success Criterion

Flood frequency (100-, 50- and 25-year flood events) (cfs) and % Difference Between Model Estimations

Baseline Simulation (cfs) for ACF Model

Pour point from Upper Upatoi Watershed Area	
25-year flood event	13048
50-year flood event	19593
100-year flood event	28797
Pour point from Entire Upatoi Watershed Area	
25-year flood event	19040
50-year flood event	26420
100-year flood event	35808

Changed Climate Simulation - Year 2050 (cfs) for ACF Model

Pour point from Upper Upatoi Watershed Area	
25-year flood event	13874
50-year flood event	20316
100-year flood event	28998
Pour Point from Entire Upatoi Watershed Area	
25-year flood event	20709
50-year flood event	28737
100-year flood event	38839

Baseline Simulation (cfs) for FB Model

Outflow from Upper Upatoi Watershed Area	
25-year flood event	12855
50-year flood event	16975
100-year flood event	21971
Outflow from Entire Upatoi Watershed Area	
25-year flood event	25250
50-year flood event	32936
100-year flood event	42227

Changed Climate Simulation - Year 2050 (cfs) for FB Model

Outflow from Upper Upatoi Watershed Area	
25-year flood event	12373
50-year flood event	15739
100-year flood event	19563
Outflow from Entire Upatoi Watershed Area	
25-year flood event	26058
50-year flood event	35654
100-year flood event	48036

% Difference Between Baseline and Changed Climate (Year 2050) Flood Event Magnitudes

% Difference In Event at Pour Point from Upper UCW	
25-year flood event -- ACF	6.3%
25-year flood event -- FB	-3.7%
50-year flood event -- ACF	3.7%
50-year flood event -- FB	-7.3%
100-year flood event -- ACF	0.7%
100-year flood event -- FB	-11.0%
% Difference In Event at Pour Point from Entire UCW	
25-year flood event -- ACF	8.8%
25-year flood event -- FB	3.2%
50-year flood event -- ACF	8.8%
50-year flood event -- FB	8.3%
100-year flood event -- ACF	8.5%
100-year flood event -- FB	13.8%

Success Criterion #2

Change in FB flood frequencies is within 15-20% of the change predicted by the ACF UCW model

Difference in predicted changes - Upper	
25-year flood event	-10.1%
50-year flood event	-11.0%
100-year flood event	-11.7%
Difference in predicted changes - Lower	
25-year flood event	-5.6%
50-year flood event	-0.5%
100-year flood event	5.3%

SUCCESS!

From the above results we see that, at the upper Upatoi pour point, the ACF model predicts slight increases in flood event peak magnitudes while the Fort Benning model shows slight decreases. In contrast, at the pour point from the entire Upatoi, both the ACF and Fort Benning model simulations predict slight increases in flood event peak magnitudes. The fact that the models show a different result at the upper pour point can be attributed to a difference in spatial

resolution between the two models, where the ACF model consists of only one subbasin and stream reach at the pour point, while the Fort Benning model consists of 17 for each. The effect of the difference in spatial resolution is less pronounced further downstream. Regardless of that difference, the success criterion for flood frequency is met, as the differences in flood frequencies are all within the acceptable range of 15-20 percent. The simulation results expressed as flood event peak magnitudes are further interpreted and discussed in Section 6.3.1.

Graphical Comparisons of Flow

Success Criterion #3: "Graphical comparisons between FB simulated values and observed data for flow duration, daily flow timeseries, and flow linear regression are similar to ACF climate scenario results for the Upatoi Creek Watershed."

To address this success criterion, we present the following plots:

- Baseline and climate scenario (WRFP) daily flow duration curves (Figure 6.1) at the Upatoi pour point, for both the ACF model (top) and Fort Benning model (bottom).
- Baseline and climate scenario (WRFP) daily flow timeseries plots (Figure 6.2) at the Upatoi pour point, for both the ACF model (top) and the Fort Benning model (bottom).
- Baseline and climate scenario (WRFP) daily flow scatter plots (Figure 6.3) at the Upatoi pour point, for both the ACF model (top) and the Fort Benning model (bottom).
- And baseline and climate scenario (WRFP) flood peak frequency plots (Figure 6.4) at the Upatoi pour point, for both the ACF model (top) and the Fort Benning model (bottom).

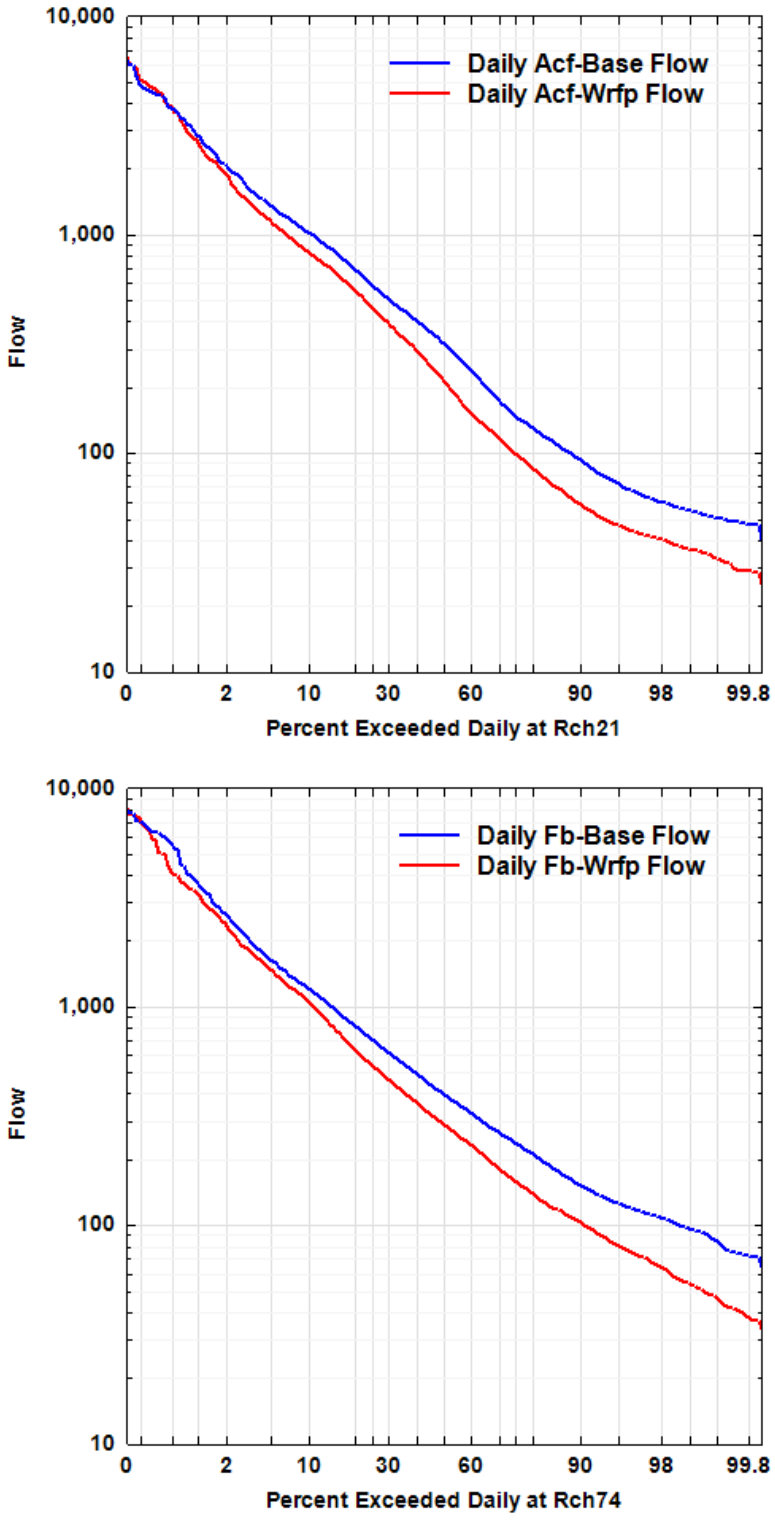


Figure 6.1 Comparison of simulated ACF and FB Model baseline/climate scenario daily flow duration curves at Upatoi pour point

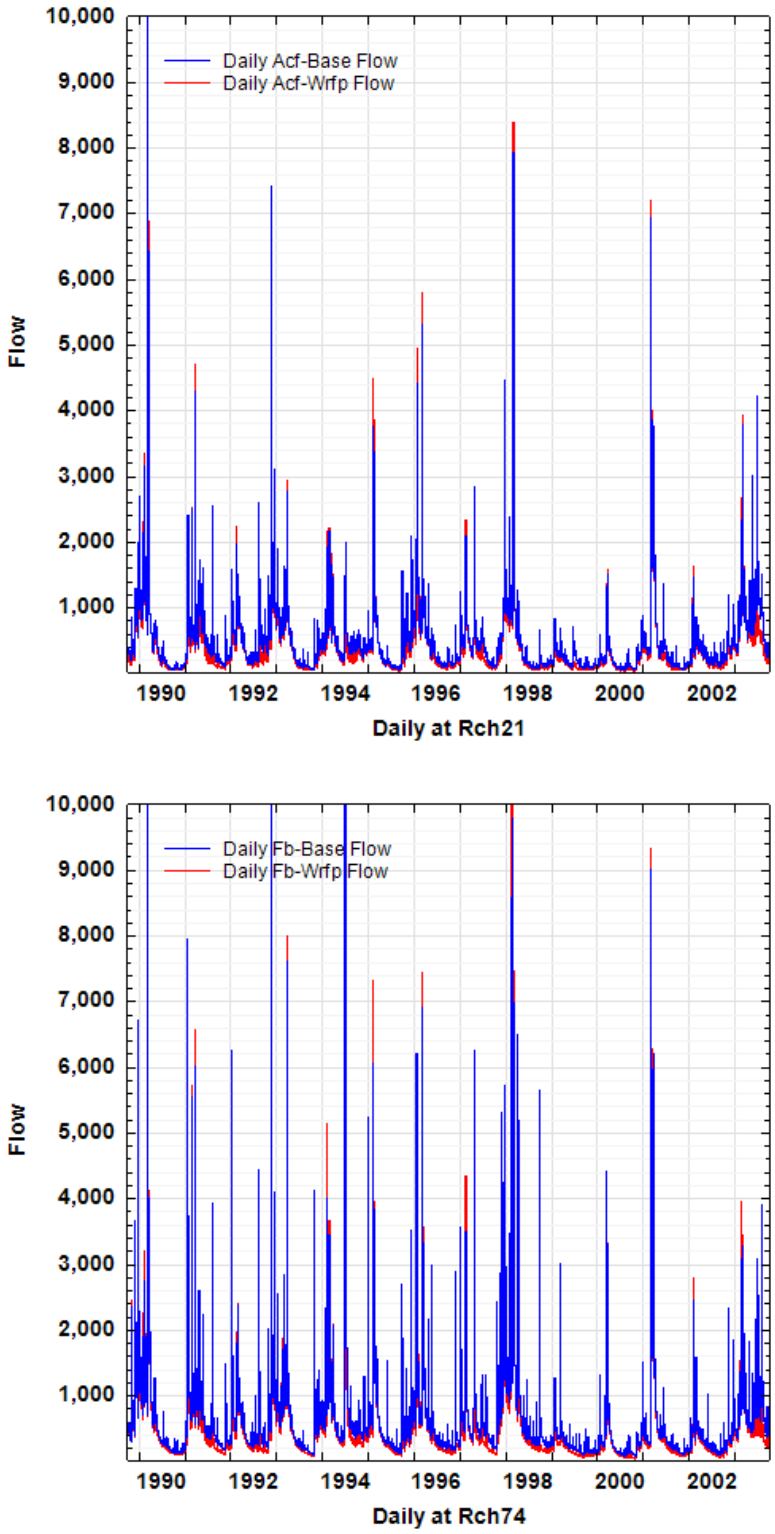


Figure 6.2 Comparison of simulated ACF and FB Model baseline/climate scenario daily flow timeseries plots at Upatoi pour point

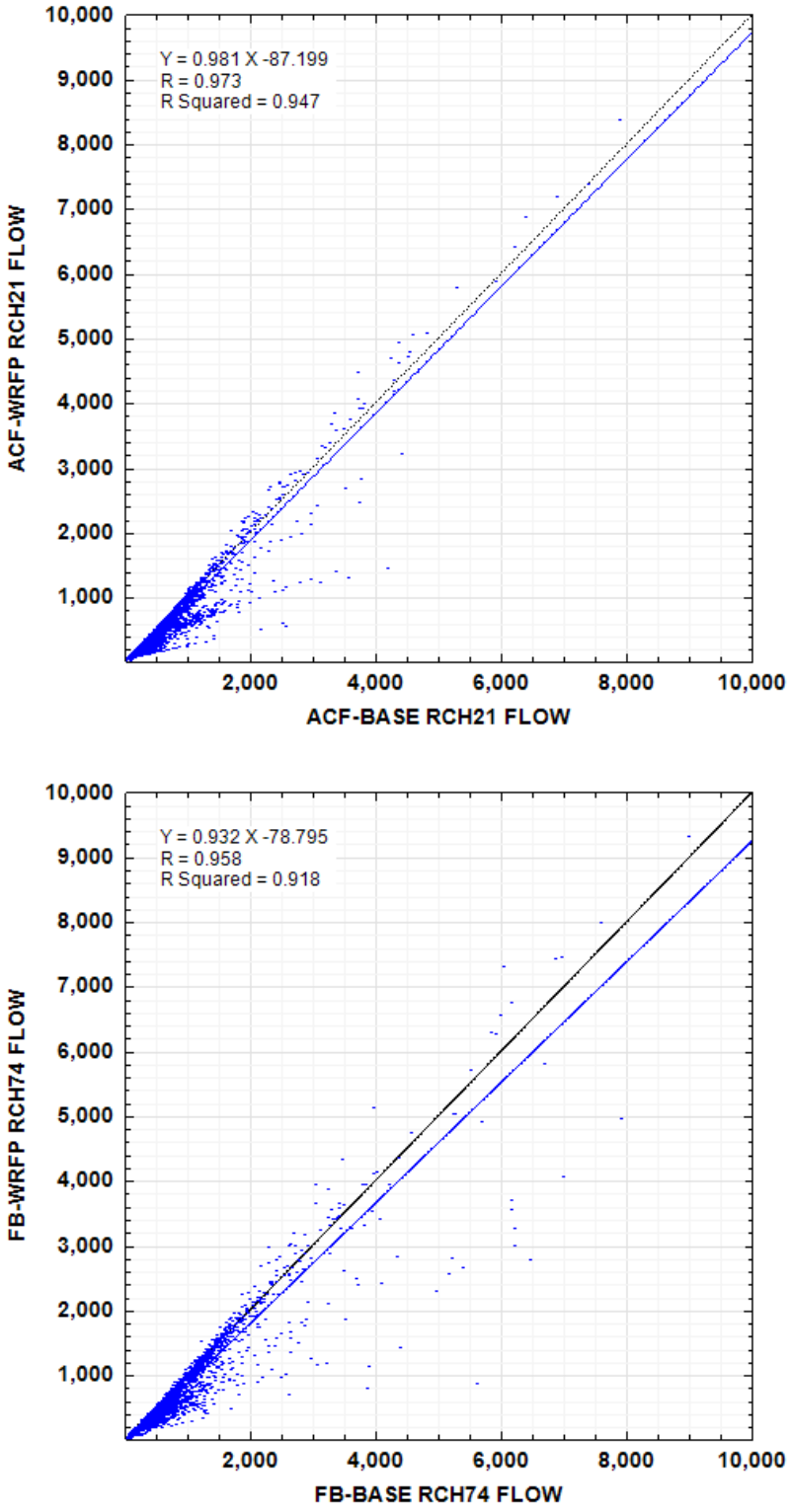


Figure 6.3 Comparison of simulated ACF and FB Model baseline/climate scenario scatter plots of daily flow at Upatoi pour point

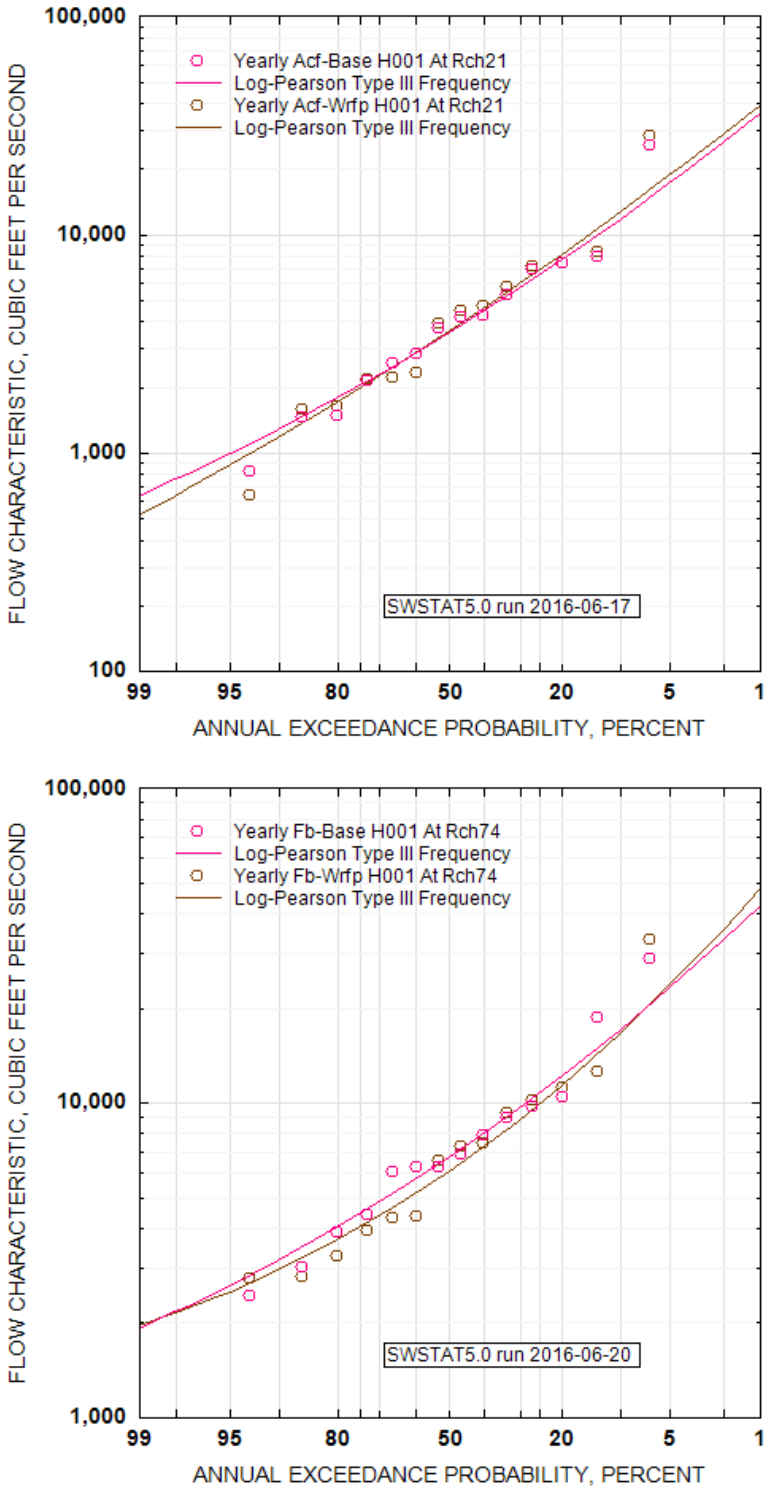


Figure 6.4 Comparison of simulated ACF and FB Model baseline/climate scenario flood peak frequency plots at Upatoi pour point

Each set of plots shows a similar trend when comparing the effects of the climate change scenario on the ACF and Fort Benning model results. The climate scenario shows higher peak flows for some storm events, but most often shows reduced flows overall. Since these results are qualitatively similar, we consider this criterion successfully met.

6.1.2 Simulation of Sediment Load Change

Success Criterion #4: "Mean annual sediment loss is within 20-35% of the change predicted by ACF climate scenario results for the Upatoi Creek Watershed."

The table below shows the mean annual erosion in tons per year and mean sediment transport/loss in tons of TSS per year, from the baseline and changed climate simulations, for both the ACF and the FB models. Mean annual erosion refers to the loss of sediment from the land surface and subsequent input to the channel system in each watershed model, whereas sediment transport/loss refers to the TSS discharge of sediment from the channel at the specified pour point, either upper or lower.

Table 6.3 Comparison of ACF and FB Model Climate Change Simulation Results for Mean Annual Erosion, Mean Annual Sediment Load and Evaluation of Performance Success Criterion

Mean Annual Erosion (tons/yr) Sediment Transport/Loss (tons TSS /yr) and % Change or Difference in Transport/Loss

Mean Annual Erosion (tons/yr) Baseline Simulation	
Erosion from Upper Upatoi Watershed Area	
ACF Model baseline scenario	12165
FB Model baseline scenario	24864
Erosion from Lower Upatoi Watershed Area	
ACF Model baseline scenario	13122
FB Model baseline scenario	36495
Ersosion from Entire Upatoi Watershed Area	
ACF Model baseline scenario	25287
FB Model baseline scenario	61359

Mean Annual Erosion (tons/yr) Changed Climate Simulation (Year 2050)	
Ersosion from Upper Upatoi Watershed Area	
ACF Model 2050 WRFP scenario	11561
FB Model 2050 WRFP scenario	18928
Erosion from Lower Upatoi Watershed Area	
ACF Model 2050 WRFP scenario	10144
FB Model 2050 WRFP scenario	28237
Erosion from Entire Upatoi Watershed Area	
ACF Model 2050 WRFP scenario	21705
FB Model 2050 WRFP scenario	47165

Mean Annual Sediment Transport/Loss (tons TSS /yr) Baseline Simulation	
Transport/Loss from Upper Upatoi Pour Point	
ACF Model baseline scenario	11794
FB Model baseline scenario	877.9
Transport/Loss from Lower Upatoi Pour Point	
ACF Model baseline scenario	23926
FB Model baseline scenario	2350.4

Mean Annual Sediment Transport/Loss (tons TSS/yr) Changed Climate Simulation (Year 2050)	
Transport/Loss from Upper Upatoi Pour Point	
ACF Model 2050 WRFP scenario	11178
FB Model 2050 WRFP scenario	672.6
Transport/Loss from Lower Upatoi Pour Point	
ACF Model 2050 WRFP scenario	20043
FB Model 2050 WRFP scenario	1812.6

% Change in Mean Annual Sediment Transport/Loss Between Baseline & Changed Climate Simulation (Year 2050)	
% Change in Sediment at Upper Upatoi Pour Point	
ACF	-5.2%
FB	-23.4%
% Change in Sediment at Lower Upatoi Pour Point	
ACF	-16.2%
FB	-22.9%

Success Criterion #4 Change in FB annual sediment loss is within 20-35% of the change predicted by the ACF UCW model	
Difference in predicted changes - Upper	-18.2%
Difference in predicted changes - Lower	-6.7%
	SUCCESS!

The above results show that the ACF model shows lower erosion amounts than the Fort Benning model, while the Fort Benning model shows lower sediment transport/loss than the ACF model. However, the percent changes are relatively similar, with the Fort Benning model within 18.2 percent of the ACF model change at the upper pour point, and a much closer 6.7 percent difference at the lower pour point. The fact that the models show significant difference in the amount of sediment transport/loss can be attributed to the apparent assumption in the ACF model that the stream channels are stable and are neither scouring nor depositing. In the Fort Benning Model, the sediment (silt and clay) scour and deposition parameters were calibrated to available TSS/sediment data, and the results demonstrated more dynamic changes to the channel through both scour and deposition. In spite of these differences, the success criterion for mean annual sediment transport/loss is met, as the differences in sediment loss are all well within the acceptable range of 20-35 percent.

6.2 Land Use Change Demonstration

Both the 'limited-agression' and 'heightened-agression' FB Model results were compared to the post-BRAC baseline model results. Looking at mean annual streamflow, shown below, neither scenario results in a very large increase in streamflow, with less than a one percent increase in both scenarios for both the upper and lower pour points.

Table 6.4 Comparison of ACF and FB Model Land Use Change Simulation Results for Mean Annual Streamflow

Mean Annual Stream Flow (cfs/yr) and % Difference in Mean Annual Streamflow

Mean Annual Streamflow (cfs/yr)	
Flow from Upper Upatoi Pour Point	
Post-BRAC Baseline scenario	265.4
'Limited-aggression' scenario	265.9
'Heightened-aggression' scenario	266.2
Flow from Lower Upatoi Pour Point	
Post-BRAC Baseline scenario	614.6
'Limited-aggression' scenario	616.1
'Heightened-aggression' scenario	618.2

% Difference in Mean Annual Streamflow Between Baseline & Future Land Use Scenarios	
% Difference in Flow at Upper Upatoi Pour Point	
'Limited-aggression' scenario	0.2%
'Heightened-aggression' scenario	0.3%
% Difference in Flow at Lower Upatoi Pour Point	
'Limited-aggression' scenario	0.3%
'Heightened-aggression' scenario	0.6%

This small increase is expected, since the increase in urbanized area (an increase of approximately 15 percent more urbanized acreage for the 'Heightened Aggression' scenario) is still relatively small. It only increased from 7.8 percent of the watershed in the Post-BRAC baseline to 9.0 percent of the watershed in the 'Heightened Aggression' scenario, a change of only 1.2% of the watershed.

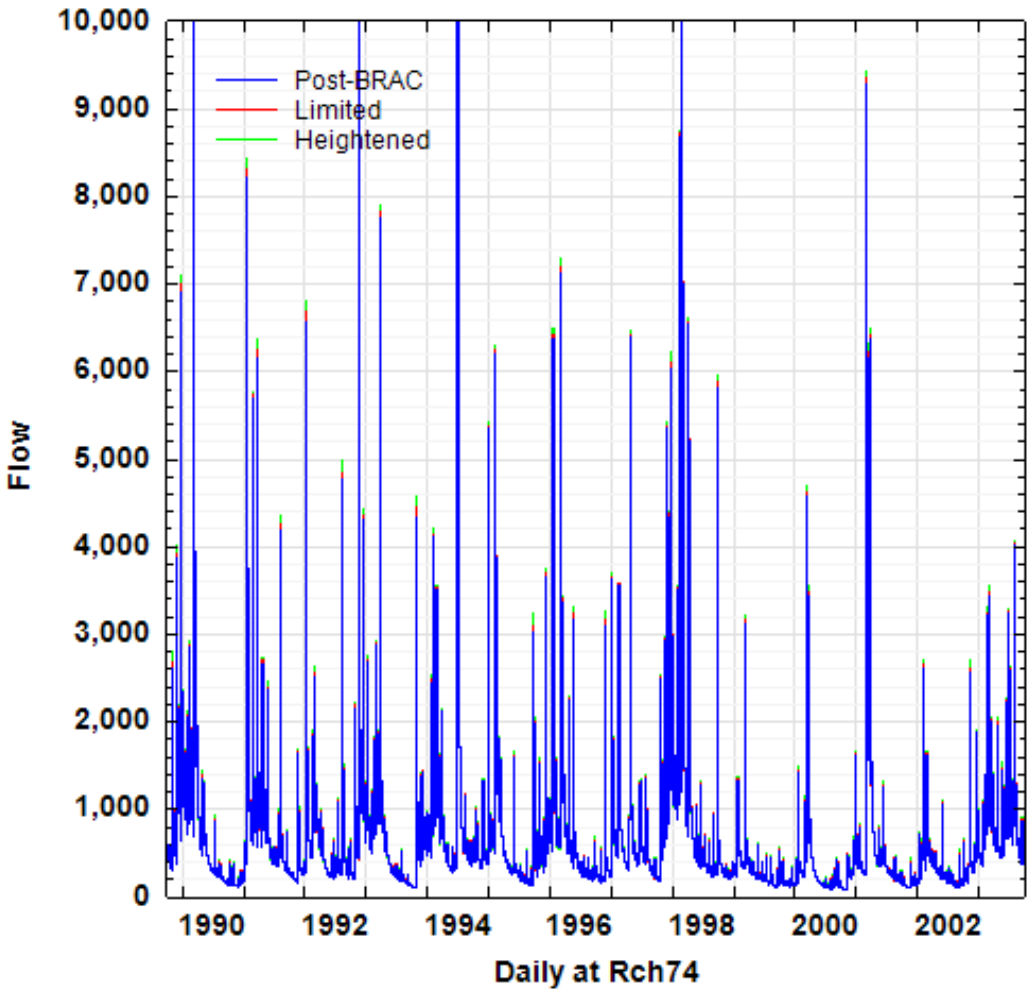


Figure 6.5 Timeseries plots of flow at Upatoi pour point for land use change scenarios w.r.t. post-BRAC baseline condition

The small increase in streamflow can hardly be discerned in the daily timeseries plot of flow at the Upatoi outlet, as shown above in Figure 6.5. The 'limited' and 'heightened' aggression scenarios show a slight increase in storm peaks due to the increase in urbanized area, as shown only at the very top of the storm peaks.

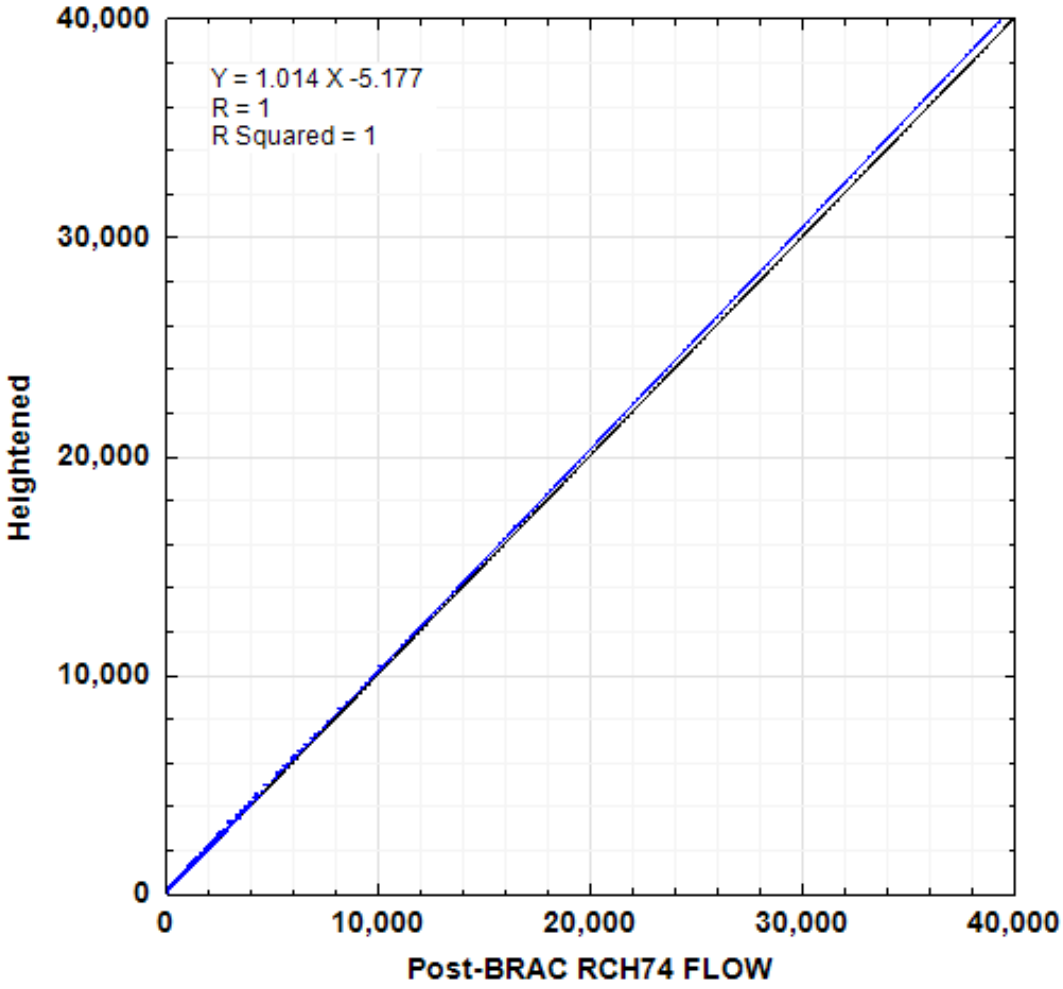


Figure 6.6 Scatter plot of flow at Upatoi pour point for land use change scenarios w.r.t. post-BRAC baseline condition.

The scatter plot of the Post-BRAC daily flows versus the flows in the 'heightened aggression' scenario shows a very strong correlation between the flows in the two scenarios, with the heightened-aggression scenario producing slightly higher flows.

Looking at flood peak frequency, shown below, again neither scenario results in a significant increase in 25-, 50-, or 100-year flood events, with only a greater than one percent increase in the flood peaks for the heightened-aggression scenario at the lower pour point.

Table 6.5 Comparison of ACF and FB Model Land Use Change Simulation Results for Magnitudes of 25-, 50- and 100-Year Flood Events

Flood frequency (100-, 50- and 25-year flood events) (cfs) and % Difference Between Model Estimations

25-year flood event (cfs)	
Flow from Upper Upatoi Pour Point	
Post-BRAC Baseline scenario	12,909
'Limited-aggression' scenario	12,967
'Heightened-aggression' scenario	12,993
Flow from Lower Upatoi Pour Point	
Post-BRAC Baseline scenario	25,600
'Limited-aggression' scenario	25,745
'Heightened-aggression' scenario	25,904
50-year flood event (cfs)	
Flow from Upper Upatoi Pour Point	
Post-BRAC Baseline scenario	17,039
'Limited-aggression' scenario	17,111
'Heightened-aggression' scenario	17,143
Flow from Lower Upatoi Pour Point	
Post-BRAC Baseline scenario	33,325
'Limited-aggression' scenario	33,509
'Heightened-aggression' scenario	33,691
100-year flood event (cfs)	
Flow from Upper Upatoi Pour Point	
Post-BRAC Baseline scenario	22,047
'Limited-aggression' scenario	22,137
'Heightened-aggression' scenario	22,178
Flow from Lower Upatoi Pour Point	
Post-BRAC Baseline scenario	42,657
'Limited-aggression' scenario	42,890
'Heightened-aggression' scenario	43,098
% Difference Between Baseline & Future Land Use Scenarios	
% Difference In Event at Pour Point from Upper UCW	
25-year flood event -- 'Limited-aggression'	0.4%
25-year flood event -- 'Heightened-aggression'	0.7%
50-year flood event -- 'Limited-aggression'	0.4%
50-year flood event -- 'Heightened-aggression'	0.6%
100-year flood event -- 'Limited-aggression'	0.4%
100-year flood event -- 'Heightened-aggression'	0.6%
% Difference In Event at Pour Point from Entire UCW	
25-year flood event -- 'Limited-aggression'	0.6%
25-year flood event -- 'Heightened-aggression'	1.2%
50-year flood event -- 'Limited-aggression'	0.6%
50-year flood event -- 'Heightened-aggression'	1.1%
100-year flood event -- 'Limited-aggression'	0.5%
100-year flood event -- 'Heightened-aggression'	1.0%

Results for sediment transport/loss are similar to those for flow. The simulation results for mean annual sediment transport/loss show only a small increase in sediment loss at the lower pour point.

Table 6.6 Comparison of ACF and FB Model Land Use Change Simulation Results for Mean Annual Sediment Load

Mean Annual Sediment Transport/Loss (tons TSS/yr) and % Difference in Mean Annual Sediment Transport/Loss

Mean Annual Sediment Transport/Loss (tons TSS /yr)

Transport/Loss from Upper Upatoi Pour Point	
Post-BRAC Baseline scenario	905.31
'Limited-aggression' scenario	905.30
'Heightened-aggression' scenario	905.35
Transport/Loss from Lower Upatoi Pour Point	
Post-BRAC Baseline scenario	2527.76
'Limited-aggression' scenario	2531.70
'Heightened-aggression' scenario	2539.01

% Difference in Mean Annual Sediment Transport/Loss Between Baseline & Future Land Use Scenarios

% Difference in Sediment at Upper Upatoi Pour Point	
'Limited-aggression' scenario	-0.001%
'Heightened-aggression' scenario	0.005%
% Difference in Sediment at Lower Upatoi Pour Point	
'Limited-aggression' scenario	0.2%
'Heightened-aggression' scenario	0.4%

6.3 Overall Assessment of This Demonstration's Success and Reasonableness

On the most fundamental level, this demonstration can be declared a success because all the success criteria that were established for the climate change assessment demonstration in conjunction with ESTCP were achieved. The land use change assessment demonstration had no success criteria associated with it for reasons explained in Section 5.2. The objective of the land use change assessment demonstration was achieving reasonable results, and we believe that this objective was also achieved.

A more thorough look at the successes and possible limitations of each of the change assessment demonstrations follows.

6.3.1 Assessment of the Climate Change Demonstration

The underlying assumption that is manifested in the success criteria for the climate change assessment demonstration was that the same *general* impacts on streamflow and sediment transport should be suggested by a less detailed regional model (ACF Model) and a more detailed localized model (FB Model) for the same test watershed (Upatoi Creek) and the same climate change scenario (WRFP). By using the term "the same general impacts" we mean that if

the ACF Model simulation results in reduced mean annual flow and reduced mean annual sediment transport, the FB Model simulation should result in the same. Simulations of Upatoi Creek Watershed by both models resulted in reduced mean annual streamflow and sediment transport when the WRFP scenario was imposed on the baseline weather.

Further, the relative magnitude of increase or decrease should be comparable. Again, this result was achieved. We consider the less than one percent relative difference in mean annual streamflow that the two models achieved favorable, but not indicative of the two models' true level of similarity, especially when comparing shorter time intervals. Again we consider the seven percent relative difference in mean annual sediment transport a favorable outcome.

Interpreting the flood event frequency results poses some problems. At the same time that overall rainfall amounts are reduced in the WRFP scenario (reduced approximately 5 inches per year from baseline rainfall), the largest storm events are intensified. In the absence of intensification it would be reasonable to expect that reduced rainfall will result in reduced 25-, 50- and 100-year flood event magnitudes. The process of surmising the expected net effect of adjustments in both rainfall amount (downward) and rainfall intensity (upward) on flood frequency is somewhat challenging. The water balance is further altered by variable monthly increases in evaporation. (Adjustments to potential evapotranspiration applied to the baseline PET time series to represent the WRFP scenario amount to a 17 percent annual increase (6.6 inches). The actual model results suggest that in the Upatoi the effects of intensification are outweighing the effects of reduced rainfall.

In Section 6.1.1 we noted that at the upper Upatoi pour point, the ACF model predicts slight increases in flood event magnitudes while the Fort Benning model shows slight decreases. In contrast, at the pour point from the entire Upatoi, both the ACF and Fort Benning model simulations predict slight increases in flood event magnitudes. The fact that the models show a different result at the upper pour point can be attributed to a difference in spatial resolution between the two models, where the ACF model consists of only one subbasin and stream reach at the pour point, while the Fort Benning model consists of 17 of each. The effect of the difference in spatial resolution is less pronounced further downstream. Regardless of that difference, the success criterion for flood frequency is met, as the differences in flood frequencies are all with the acceptable range of 15-20 percent.

The difference in scale and resolution between the ACF and FB models also provides important insight in the use of models for smaller scale assessments, such as might be needed for EISA 438 issues, hydromodification, local flooding, etc. It is clear from the model comparisons that when models are used for watershed planning and management, the scale of the modeling assessment (or decision to be made) should be as close as possible to the scale of the watershed change or BMP being evaluated, so that scale differences will not unduly impact the evaluation. Thus the FB model would be a much better choice for assessments on FB than the ACF model as its smaller scale and higher resolution provides a better and finer representation of the watershed and drainage processes that need to be accurately depicted.

6.3.2 Assessment of the Land Use Change Demonstration

As noted in Section 6.2, both land use change scenarios resulted in less than one percent change in both mean annual streamflow and mean annual sediment transport. This small increase is

expected, since the actual increase in urbanized area (an increase of approximately 15 percent more urbanized acreage for the 'Heightened Aggression' scenario) is relatively small on a watershed-wide basis, from 7.8 percent of the watershed in the post-BRAC baseline to 9.0 percent of the watershed in the 'Heightened Aggression' scenario.

With DoD's institutional commitment to further reducing stormwater by means of implementing green infrastructure practices, it is likely that the major focus of concern with impacting streamflow and sediment phenomena by land use change will focus on the training lands.

At the planning stage of our land use change assessment demonstration, we anticipated representing and assessing a major increase in Heavy Maneuver Areas (HMAs) in the Upatoi Creek Watershed (UCW) during the course of development from pre-BRAC to Year 2050. Instead we discovered that the development and use of HMAs in the UCW that had been planned as a component of BRAC 2006 had never really been implemented due to unresolved issues related to potential impact on the Red Cockaded Woodpecker population. Further, Fort Benning had resolved to permanently re-locate (by summer 2016) the majority of the tank training activities that had been planned for the UCW to the Good Hope Area outside of the watershed we had selected for our demonstration. As a result, we were unable to define and demonstrate a Year 2050 land use alternative in the UCW that addressed the potential impacts of high levels of vehicular training at this military installation. This was unfortunate.

SECTION 7.0
IMPLEMENTATION ISSUES

With respect to utilizing BASINS.MIL to investigate the potential impacts of climate change and land use change on streamflow and/or sediment erosion/transport, this demonstration suggested that technical implementation issues are minimal. As is often the case in watershed modeling perhaps the biggest challenge lies in defining useful and plausible change scenarios (e.g., see Section 5.2.2 and 6.3.2).

In the case of climate change, it was noted earlier in this report that common practice (due to model uncertainty) is to use weather changes projected by multiple RCM's to generate a suite of possible impacts on endpoints of concern in a regional watershed model (or, after further downscaling, to a smaller watershed model).

In the case of land use change, a different issue comes into play in defining changes that can be deemed reasonable. Changes in land use on military installations tend to be much more unpredictable than those to public land or private land. Management decisions related to training or cantonment development that are previously predicated on mitigating physical environmental impacts (streamflow, erosion) can be superseded by issues that are ancillary to water resources, such as mitigating impacts on endangered species (see Section 6.3.2). Decisions regarding base realignment and closure can effectively move major environmental disturbance from one installation to another. National budgetary decisions, as influenced by our nation's perspective on the need for military build-ups or reductions, can reverse the trajectory of change within short or sustained periods of time. This uncertainty again argues a need for defining and assessing a variety of possible futures and sustaining an operable model for this and other planning/design issues that encompasses the entire spatial extent of an installation.

Another issue related to defining reasonable land use scenarios that is somewhat unique to installations is the concurrent impact that a change in mission has on multiple land use categories. When a change in level or type of military training occurs at a base, changes to cantonment and training areas are interrelated and change scenarios must foresee and represent the interrelationships in a rationale manner.

Expressing change scenarios requires adjustment of information expressed in a baseline representation of the installation. For experienced or properly coached model users the mechanics of doing this are relatively straightforward. However, it is important to remember that typical change scenarios are expressed by applying adjustment factors (i.e. multipliers) to the land use distribution and spatial segmentation scheme that has been developed for the baseline condition. The land use categories that are the focus of a change scenario are adjusted uniformly within the model-defined subregions in which change is assumed to occur, and a scheme is used to make proportional increases or decreases to a collection of land use categories that can reasonably be assumed to be affected by conversion. The spatial resolution that can be achieved in defining a change scenario cannot achieve a finer resolution than that represented in the baseline model segmentation scheme. However, when it is deemed advantageous, BASINS.MIL model segmentation schemes can be refined selectively for subregions that require finer resolution.

Viewing the central objective of this demonstration (i.e., providing a means of assessing change alternatives) from the broader ESTCP perspective of "implementing a technology", it is also

warranted to consider possible *implementation issues* as they pertain to using this technology to assess possible environmental impacts and make adaptive planning decisions.

The use of the core watershed model in BASINS.MIL (HSPF) for assessing potential environmental impacts of land use change has been common practice in various non-military settings for decades. Military-centric land use change analysis has previously been successfully demonstrated as a component of the SERDP Project (RC-1547) that resulted in development of BASINS.MIL. The unique aspect of this ESTCP demonstration was development, assessment, and *comparison* of parallel climate and land use scenarios for a shared point in time, Year 2050. This objective was successfully met. Neither the SERDP nor the ESTCP land use change assessment demonstrations revealed any issues that suggest that model applications to a military-centric watershed would be expected to provide a less effective planning tool than has been commonly used to guide management practices in other mixed-use watersheds world-wide.

The use of the HSPF for assessing potential environmental impacts of climate change has evolved over the past decade. This ESTCP task is the first demonstration of utilizing the model to assess potential military-centric environmental impacts. The central need that was demonstrated was the marriage of a site-appropriate high end climate change scenario with a highly detailed characterization of an installation-scale watershed. As a result, a more tangible assessment of the impact of changed climate on specific military land use types and activities can be achieved. In performing this demonstration, we found nothing unique about military settings, or the necessary customization of mode development and assessment procedures, that imposes significant limitations on the utility of the modeling technology in a military setting. Rather, we find ample opportunity and utility for such model assessments.

SECTION 8.0
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APPENDICES

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APPENDIX A
CLIMATE CHANGE EMISSIONS STORYLINES, SCENARIOS, MODELS AND DOWNSCALING

The mechanics of modeling potential installation – scale runoff and erosion impacts attributable to future changes to climate follow a progression that includes emissions storylines, emissions scenarios, general circulation models (GCMs), regional climate models (RCMs), watershed-scale models and one or more downscaling efforts to accommodate the spatial scale(s) of interest. Each step along the progression offers many different assumptions, methods and models.

At least a high-level familiarity with the emissions storyline, emission scenario, GCM, RCM and downscaling strategies that provide the basis for the climate non-stationarity evaluations that were generated by the ACF and FB models is an essential prerequisite to understanding and comparing the simulation results that the two models generate for the Upatoi Basin.

The A2 Storyline

In 1996, the Intergovernmental Panel on Climate Change (IPCC) began the development of a set of emissions scenarios that are described in the IPCC Special Report on Emission Scenarios (SRES) (IPPC, 2000). Four different narrative 'storylines' were developed to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification. The IPPC developed 40 'scenarios' (35 of which contain data on the full range of gases required to force climate models) that cover a wide range of the main demographic, economic and technological driving forces of future greenhouse gas and sulphur emissions. Each scenario represents a specific quantification of one of the four storylines. All the scenarios based on the same storyline constitute a scenario 'family'.

The A2 storyline was investigated exclusively by EPA in the 20 Watersheds Study (USEPA, 2013b). The storyline and its scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than other storylines (http://www.ipcc.ch/ipccreports/tar/wg1/029.htm).

A2 Climate Scenarios

The modeling analyses that were performed by IPPC for the Third Assessment Report (IPCC, 2001) utilized one 'marker scenario' that was chosen from each of four of the scenario groups based directly on the four storylines. The choice of the markers was based on which of the initial quantifications best reflected the storyline and features of specific models. Marker scenarios are no more or less likely than any other scenarios, but are considered illustrative of a particular storyline. The gas emissions (CO_2, N_2O, CH_4, SO_2) that characterize the A2 scenario (brown line) as modeled in the GCMs are shown in the figures below (collectively labeled Figure 2-2).

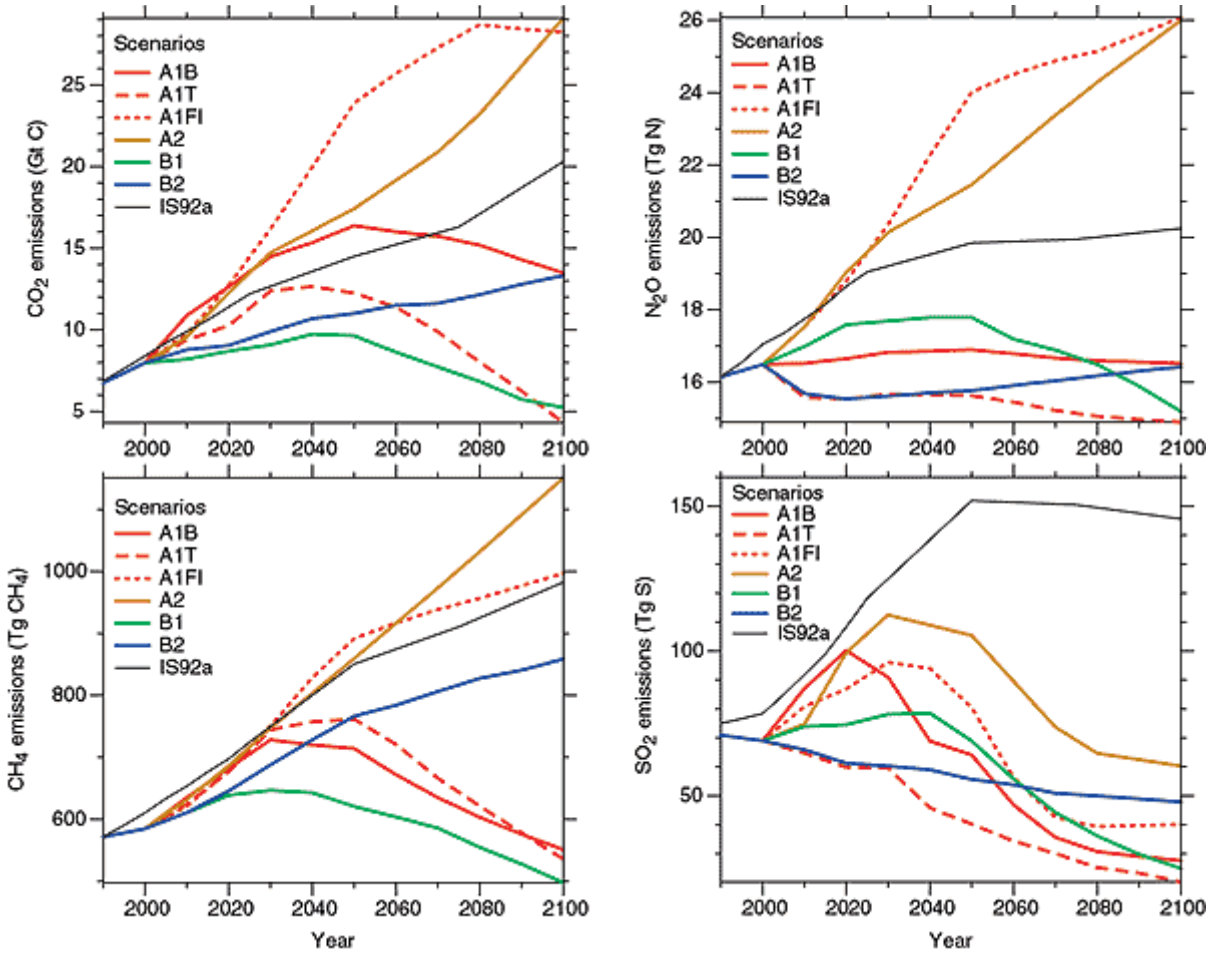


Figure A.1 Anthropogenic emissions of CO_2, CH_4, N_2O and sulphur SO_2 for the six illustrative SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T. For comparison the IS92a scenario is also shown. [Based on IPCC Special Report on Emissions Scenarios.]

EPA's 20 Watersheds Study Model Ensemble

In the 20 Watersheds Study (USEPA, 2013b), EPA used the term 'scenario' in a different context than does IPCC. All 14 'scenarios' EPA identifies use the A2 emissions scenario. The 14 'scenarios' are different combinations of General Circulation Models (GCMs) with and without dynamical or statistical downscaling, but all forced by IPPC's A2 greenhouse gas storyline, which portrays a relatively pessimistic scenario that assumes a very heterogenous world with high population growth, slow economic development and slow technological change.

Each of EPA's 14 scenarios relies on one of four GCMs:

- CGCM3 – Third Generation Coupled GCM
- HadCM3 – Hadley Centre Coupled Model v3
- GFDL – Geophysical Fluid Dynamics Lab GCM
- CCSM – Community Climate System Model

The 14 scenarios include three categories of scenarios:

- **6** scenarios that result from dynamical regional downscaling using RCMs. GCM/RCM pairings include:
    a. CGCM3/CRCM (Canadian Regional Climate Model)
    b. HadCM3/HRM3 (Hadley Region Model 3)
    c. GFDL/RCM3 (Regional Climate Model v3)
    d. GFDL/GFDL high res (Geophysical Fluid Dynamics Lab 50-km global atmospheric time slice)
    e. CGCM3/RCM3
    f. CCSM/WRFP (Weather Research and Forecasting Model)
- **4** scenarios that result from using statistical methods (BCSD, Bias-Corrected and Spatially Downscaled) for downscaling
- **4** scenarios that are derived directly from the GCMs and are not downscaled

The perceived credibility/utility of the three classes decreases in the order they are listed above. They are summarized in reverse order below in order to better present incremental improvements in capabilities.

The **non-downscaled** scenarios have a tendency to under-simulate the intensity of large events. Since intensity is a critical factor in watershed responses, this is a significant limitation in their application to estimate watershed-scale impacts that result from precipitation changes.

The **BCSD**-downscaling approach assumes that the relationship between large-scale precipitation and temperature and local precipitation and temperature in the future will be the same as in the past. The method can successfully account for orographic effects that are observed in current data, but not for impacts that might result from the interaction of changed wind direction and orographic effects in the future. The BCSD class of scenarios assumes that the solar radiation, dewpoint temperature and wind speed characteristics of a modeled area do not change with changed precipitation and temperature tendencies.

The **RCM**-downscaled scenarios are more capable than the other scenario classes to account for changes in precipitation intensity. They are supported by statistics/methods that enable representation of changed wind speed, solar radiation and dewpoint temperature, and hence are more sophisticated in their representation of PET and orographic effects on precipitation distribution.

The WRFP Downscaling and Modeling Approach

In a correspondence on 2 September 2014, ESTCP requested that the modeling ensemble member used for performing the ESTCP demonstration/validation feature the dynamical downscaling of the Community Climate System Model (CCSM) to a regional scale by pairing it with the Weather Research and Forecasting (WRF) Model (http://www.wrf-model.org/index.php).

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs. It features two dynamical cores, a data assimilation system, and a software

architecture facilitating parallel computation and system extensibility. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers. The effort to develop WRF began in the latter part of the 1990's and was a collaborative partnership principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (represented by the National Centers for Environmental Prediction (NCEP) and the (then) Forecast Systems Laboratory (FSL)), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA).

WRF allows researchers to generate atmospheric simulations based on real data (observations, analyses) or idealized conditions. WRF offers operational forecasting a flexible and computationally-efficient platform, while providing advances in physics, numerics, and data assimilation contributed by developers in the broader research community. WRF has a large worldwide community of registered users (over 25,000 in over 130 countries), and workshops and tutorials are held each year at NCAR.

The monthly 'deltas' estimated for air temperature, precipitation and potential evapotranspiration for each of the 14 ensemble models are summarized in Appendix B.

Precipitation Intensification

Relative changes in the *frequency* and *intensity* of precipitation events associated with climate change may prove to be more influential in determining future patterns of discharge than changes in overall (annual, seasonal) precipitation (USEPA, 2013). In the delta method, future climate time series are constructed by applying changes to observed precipitation time series that represent the relative differences between historical simulations and future climate scenarios from the climate models. Using the delta method alone, no modifications are made to the number of rainfall events in the observed record. Most of the climate scenarios utilized in the 20 Watersheds Study showed increases in precipitation volume in the larger events, while the smaller ones remained constant or decreased. The net effect of this was an increase in the proportion of annual precipitation occurring in larger events. EPA's analysis of the comprehensive (percentile, total volume) climate scenario data showed that, for most weather stations, the change in the lower percentiles of the intensity distribution appeared to be relatively small compared to the changes above the 70th percentile. To account for changes in intensity, EPA created climate change scenarios using the delta method by applying climate change adjustments separately to precipitation events > 70th percentile and events < 70th percentile, while maintaining the appropriate mass balance. A more detailed explanation of the intensification scheme that was applied to the scenarios (including the WRPF scenario) is provided in Appendix C.

APPENDIX B
DEVELOPMENT OF USEPA'S YEAR 2050 ACF LAND USE SCENARIO

The methods that can be used to represent/characterize land use change for HSPF evaluation scenarios are contingent on the land use categories that are used to characterize the baseline or current watershed condition.

In the case of the ACF HSPF model, 'current' conditions were derived from the 2001 National Land Cover Database or NLCD (Homer et al., 2004; Homer et al., 2007). The 2001 land use was chosen rather than a more recent coverage because it is closer in time to the calibration period of the model. The 2001 land use is assumed to apply throughout the baseline model application period. Some additional processing of the NLCD data was necessary by EPA. The developed land classes were aggregated. This is because HSPF explicitly separates developed pervious and impervious areas. The percent impervious area was specified for each developed land class from the NLCD Urban Impervious data coverage. The NLCD 2001 Urban Imperviousness coverage was mosaic-ed and clipped to the extent of the model watershed area (with 10-mile buffer) to calculate the impervious area. The percent impervious area was then specified by combining data from the 2001 NLCD Land Cover and Urban Impervious data products. Specifically, average percent impervious area was calculated over the whole basin for each of the four developed land use classes. These percentages were then used to separate out impervious land.

In the ACF study two land use scenarios were evaluated: a baseline scenario representing current (2001) conditions and a future scenario representing mid-21st century changes in urban and residential land. Projected changes in urban and residential development were acquired from EPA's Integrated Climate and Land Use Scenarios (ICLUS) project (USEPA, 2009). ICLUS has produced seamless, national-scale change scenarios for developed land that are compatible with the assumptions about population growth and migration that underlie the IPCC greenhouse gas emissions storylines. These scenarios were developed using a demographic model, consisting of a cohort-component model and gravity model, to estimate future population through 2100 for each county in the conterminous U.S. The resulting population is allocated to 1-hectare pixels, by county, using the spatial allocation model SERGoM (Spatially Explicit Regional Growth Model). The final spatial dataset provides decadal projections of housing density and impervious surface cover for the period 2000 through 2100.

Data from the ICLUS project are composed of grid-based housing density estimates with 100-m cells, whose values are set equal to *units/ha x 1,000*. Existing housing densities were estimated using a variety of sources and models, and future housing densities developed under various scenarios for each decade through 2100. For the existing housing density grid, two types of "undevelopable" area where residential developed was precluded were masked out during the production – a comprehensive spatial dataset of protected lands (including land placed in conservation easements), and land assumed to be commercial/industrial under current conditions. Undevelopable commercial/industrial land use was masked out according to the SERGoM method (USEPA, 2009) that eliminated commercial, industrial, and transportation areas that preclude residential development, identified as "locations (1 ha cells) that had >25% urban/built-up land cover but that also had lower than suburban levels of housing density."

The ICLUS projections used in this study thus do not account for potential growth in commercial/industrial land use. It is also important to note that the ICLUS projections do not explicitly account for changes in rural or agricultural land uses. These categories change only to the extent that they are predicted to convert to developed land.

B.1 Translating ICLUS Land Use Projections to Watershed Model Inputs

The ICLUS projections used in the ACF study are for changes in housing density and impervious cover. This data cannot be used directly with the HSPF watershed model which requires land use data consistent with the NLCD. It was therefore necessary to translate between ICLUS projections and NLCD land use classes.

Baseline land use, derived from the 2001 NLCD, contains four developed land classifications (NLCD classes 21 through 24), nominally representing "developed, open space" (less than 20 percent impervious), developed, low intensity (20 – 49 percent impervious), developed, medium intensity (50 – 79 percent impervious), and developed, high density (greater than 80 percent impervious). Impervious fractions within each developed NLCD land use class were estimated separately for each study area, using the 2001 NLCD Land Cover and Urban Impervious data products. ICLUS land use change projections were implemented by modifying the existing land use distribution in the watershed models.

ICLUS estimates housing density on a continuous scale. To process the data more efficiently, the data were reclassified into ten housing density ranges.

In the ACF Basin, the ICLUS housing density ranges were cross-tabulated with NLCD 2001 classes based on percent imperviousness. It was assumed that the number of housing units changes, but that the characteristic percent impervious values for each NLCD developed class remains constant. The change in land area needed to account for the change in impervious area was then back calculated.

ICLUS housing density class estimates and the NLCD developed classes do not have a one-to-one spatial relationship because they are constructed on different underlying scales. ICLUS represents housing density based largely on the scale of census block groups. As a result, it represents the overall density within a relatively large geographic area when compared to the 30x30 meter resolution of NLCD 2001 land cover and can represent a mix of different NLCD classes. Therefore, land use changes must be evaluated on a spatially aggregated basis at the scale of model subbasins.

The gains (and losses) in NLCD class interpreted from ICLUS were tabulated separately for each subbasin. In almost every case, the gains far exceeded the losses and a net increase was predicted in all four NLCD developed classes. However, there were a few cases where there was an overall loss of the lowest density NLCD class. This tended to occur when a subbasin was already built out, and ICLUS predicted redevelopment at a higher density.

To represent the net change in future land cover, the developed land use was added (or subtracted) from the existing totals in each subbasin. Land area was then removed from each undeveloped NLCD class (excluding water and wetlands) according to their relative ratios in each subbasin to account for increases in developed area. If the undeveloped land area was not sufficient to accommodate the projected growth, development on wetlands was allowed. The reductions in undeveloped land were distributed proportionately among hydrologic soil groups.

The new developed lands were then assumed to have the parameters of the most dominant soil and lowest HRU slope in the subbasin.

Even in areas of expected high growth, new development by 2050 is expected to constitute only a small fraction of the total watershed area at the large scale of EPA's 20 Watersheds Study. Therefore, effects of land use change proved to be relatively small at the scale of the ACF Basin, although greater impacts are evident at smaller spatial scales.

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APPENDIX C
CHANGES IN GEORGIA REGIONAL WEATHER REPRESENTED IN EPA'S WATERSHED MODEL ENSEMBLE

C.1 Air Temperature Changes

For each of EPA's fourteen change scenarios, 'deltas' for air temperature were calculated for each month of the year as the differences between simulated average monthly values for the 2041-2070 and 1971-2000 periods (Figure C-1). These change statistics were then used to perturb existing records using CAT.

C.2 Precipitation Changes

For each of EPA's fourteen change scenarios, 'deltas' for precipitation were calculated for each month of the year as the differences between simulated average monthly values for the 2041-2070 and 1971-2000 periods (Figure C-2). These change statistics were then used to perturb existing records using CAT. No changes were made to the number of precipitation events represented in scenarios. However to account for changes in storm intensity, concurrent with application of monthly precipitation 'deltas', methods were developed and applied to also shift a greater volume of the resulting monthly precipitation to largest 30% of events (see pages 85-86 of 20 Watersheds Study report). Because of differences in information availability, different methods of implementing intensity changes were applicable for the RCM-downscaled class of scenarios (including the WRFP Model) as opposed to the other two classes. The method applicable to this model is described as an appendix.

The results of performing the intensification computations were extracted from the input sequence that EPA developed for the ACF Basin.

C.3 Potential Evapotranspiration

The Penman-Monteith method of estimating PET was used for all EPA-generated scenarios. For the RCM-downscaled scenarios, a version of the SWAT weather generator was used in conjunction with NARCAPP statistics to generate changed solar radiation, dew point temperature and wind speed data for use in computing PET. For the ACF HSPF implementation a stand-alone version of the weather generator code was created and used to create time series for each of the needed variables at each BASINS meteorological station based on the nearest SWAT weather generator station after applying an elevation correction.

The SWAT weather generator database (.wgn) contains the statistical data needed to generate representative daily climate data for the different stations. Adjustments to the wgn file parameters were made using monthly change for the NARCCAP dynamically downscaled scenarios. Specifically, solar radiation, dew point temperature and wind speed were adjusted for each scenario.

The monthly deltas for temperature, precipitation and PET for all 14 members of the model ensemble are shown in Figure C-3. **The deltas for the WRFP model are labeled 'W6' and shown in red.** The temperature deltas for the WFRP model are not discernible on the figure, because they fall in the middle of the pack. The precipitation deltas for the WFRP model indicate the most significant monthly decreases of any of the ensemble's models. The PET deltas for the WRFP model appear to be in the middle of the pack for most of the year, but

among the highest increases during the summer months. The actual monthly deltas applied to the ACF WRFP scenario were obtained from alternative source.

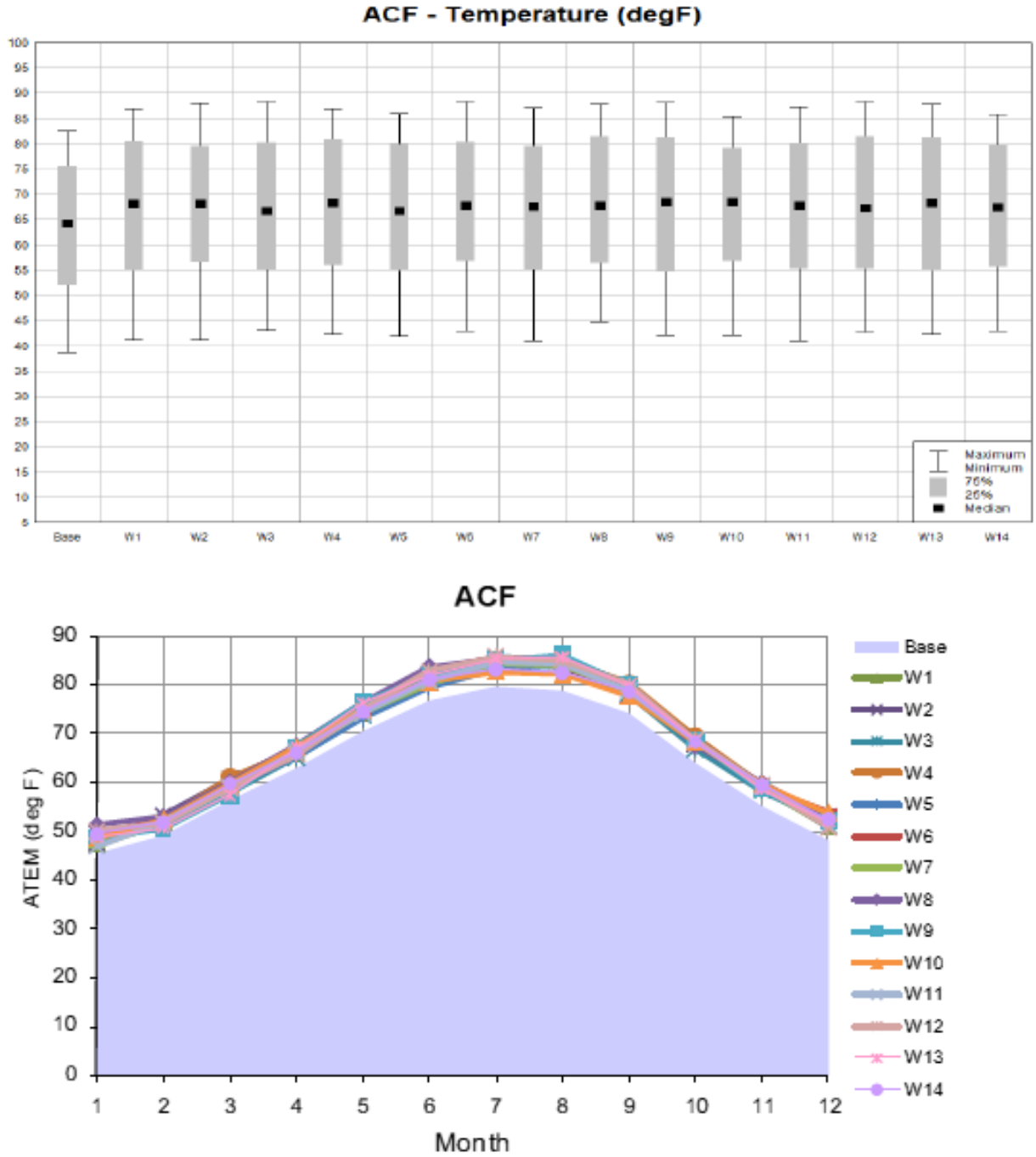


Figure C.1 Comparison of climate scenario air temperature results for the ACF Basin. 'W6' corresponds to the WRFP model results (USEPA, 2013b).

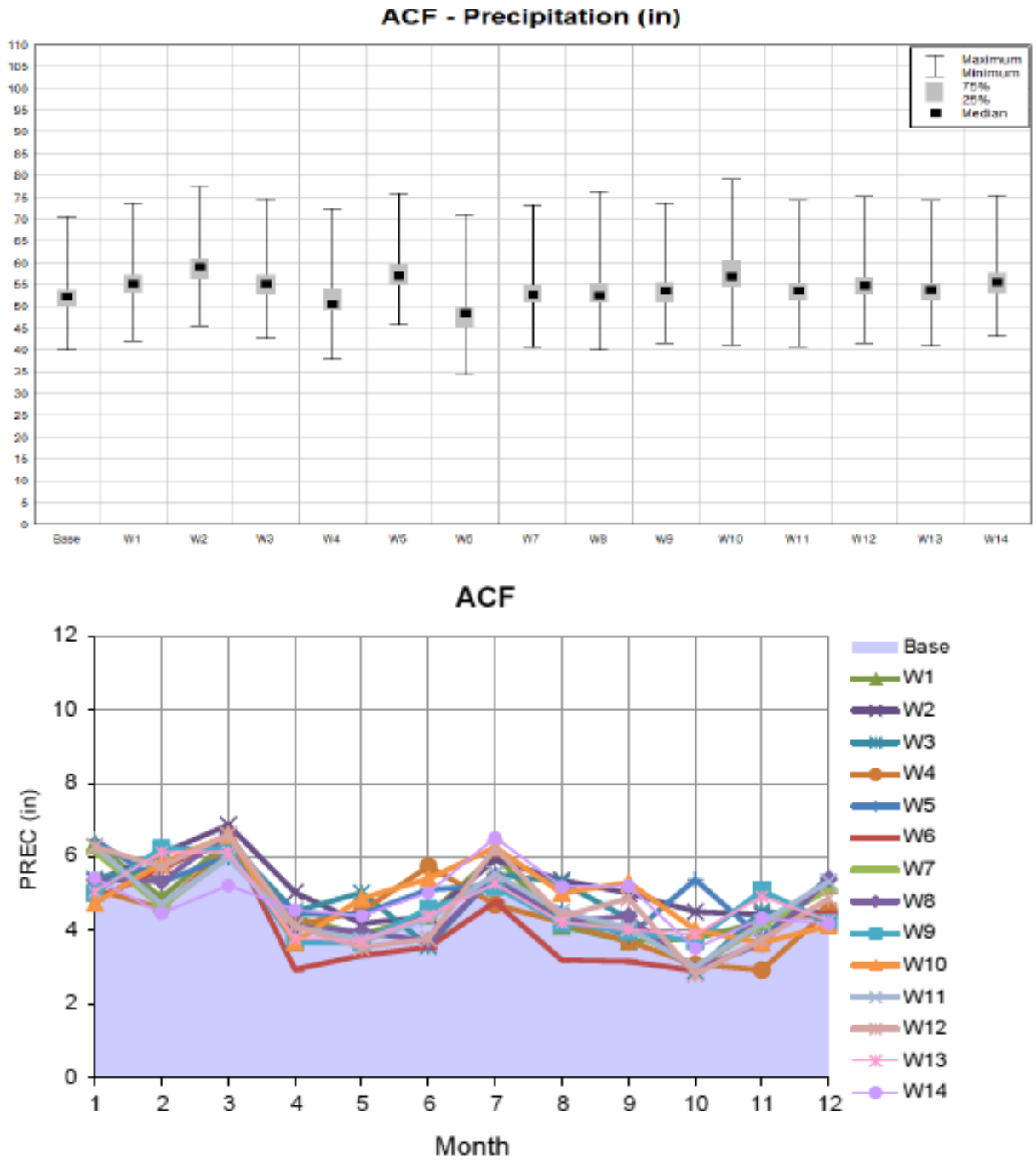


Figure C.2 Comparison of climate scenario precipitation results for the ACF Basin. 'W6' corresponds to the WRFP model results (USEPA, 2013b).

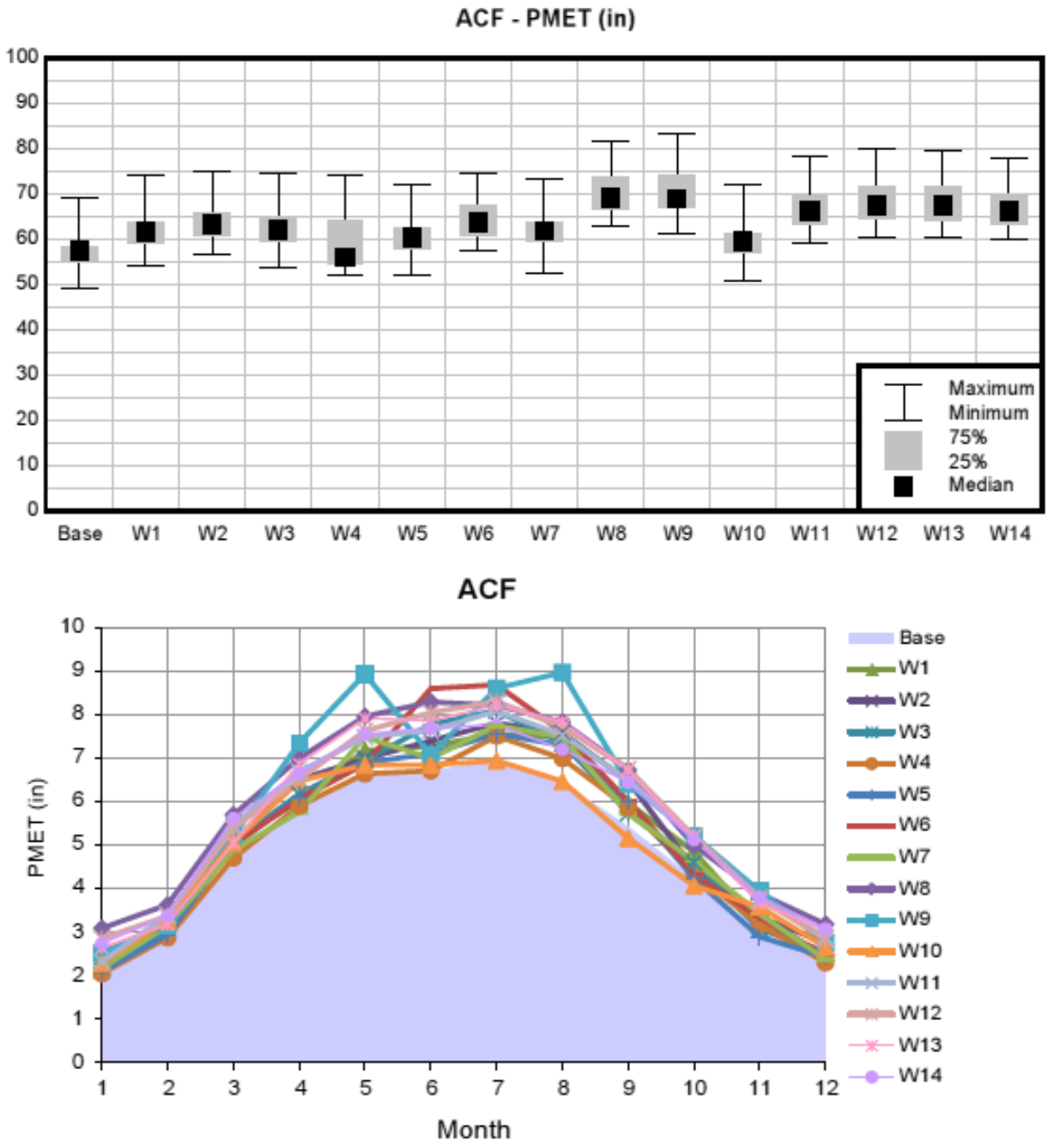


Figure C-3. Comparison of climate scenario monthly Penman-Monteith reference ET values for the ACF Basin. 'W6' corresponds to the WRFP model results (USEPA, 2013b).

APPENDIX D
APPROACH USED TO ACCOUNT FOR INTENSIFICATION FOR WRFP CLIMATE SCENARIO

This approach is applicable to scenarios 1 through 6 for which the total accumulated precipitation data for different percentile bins were provided by NARCCAP. For these data the change in the volume about the 70th percentile intensity can be taken as an *index* of the change in the top 30 percent of events. The change in the top 30 percent was selected based on the information on the percentile values of the 3-hr events. At the same time, it is necessary to honor the data on the relative change in total volume. This can be accomplished as follows:

Let the ratio of total volume in a climate scenario (V_2) relative to the baseline scenario volume (V_1) be given by $r = (V_2/V_1)$. Further assume that the total event volume (V) can be decomposed into the top 30 percent (V_H) and bottom 70 percent (V_L). These may be related by a ratio $s = V_H/V_L$. To conserve the total volume we must have

$$V_2 = rV_1.$$

This equation can be rewritten to account for intensification of the top 30 percent of events (V_H) by introducing an intensification parameter, q:

$$V_2 = rV_{L,1} + rV_{H,1} + \left(rqV_{H,1} - rqV_{H,1}\right) = \left[rV_{L,1} - rqV_{H,1}\right] + \left[r(1+q)V_{H,1}\right],$$

Substituting for the first instance of $V_{H,1} = s\,V_{L,1}$ yields:

$$V_2 = (r - rqs)V_{L,1} + (r + qr)V_{H,1}.$$

Here the first term represents the change in the volume of the lower 70 percent of events and the second term the change in the top 30 percent. This provides multiplicative factors that can be applied to event ranges using CAT's built-in capabilities on a month-by-month basis.

The intensification parameter, q, can be calculated by defining it relative to the lower 70 percentile values (i.e., from 0 to 70th percentile). Specifically (r-rqs) which represents the events below the 70th percentile can be written as the ratio of the sum of the volumes below the 70th percentile in a climate scenario relative to the sum of the volumes below the 70th percentile for the current condition:

$$(r - rqs) = \frac{(V_{70})_2}{(V_{70})_1} \approx \frac{(Q_{70})_2}{(Q_{70})_1}$$

where $(Q_{70})_1$ and $(Q_{70})_2$ are the sum of the volumes reported up to the 70th percentile for a month for the current condition and future condition respectively.

Solving this equation for q yields:

$$q = (1 - A/r)/s$$

where A is defined as $A = \frac{(Q_{70})_2}{(Q_{70})_1}$

In sum, for each month at each station the following were calculated:

$r = V_2 / V_1$ from the summary of the climate scenario output,

$s = V_H / (V - V_H)$ from the existing observed precipitation data for the station, sorted into events and post-processed to evaluate the top 30 percent (V_H) and bottom 70 percent (V_L) event volumes. The numerator is calculated as the difference between total volume and the top 30 percent volume, rather than directly from V_L to correct for analyses in which some scattered precipitation is not included within defined "events." The s value was calculated by month and percentile (for every station, every month) using the observed precipitation time-series data that forms the template for the delta method representation of future climate time series.

$q = (1 - A/r)/s$ from the summary of the percentile bin climate scenario output summary

The multiplicative adjustment factors for use in the CAT tool can then be assembled as:

$r\,(1 - qs)$, for the events below the 70th percentile, and
$r\,(1 + q)$, for the events above the 70th percentile.

In addition to the typical pattern of intensification of large events, this approach is also sufficient for the cases where there is a relative increase in the low-percentile intensities. In those cases the change in the 70th percentile intensity is relatively small and tends to be less than current conditions under the future scenario, resulting in q being a small negative number. Then, application of the method results in a decrease in the fraction of the total volume belonging to the larger events, with a shift to the smaller events – thus approximating observed increases in intensity for smaller events.

In general, it is necessary to have $-1 < q < 1/s$ to prevent negative solutions to the multipliers. The condition that $q < 1/s$ is guaranteed to be met by the definition of q (because A/r is always positive); however, the lower bound condition is not guaranteed to be met. Further, the calculation of q from the percentile bin data is at best an approximation of the actual intensification pattern. To address this problem a further constraint is placed on q requiring that some precipitation must remain in both the high and low ranges after adjustment by requiring $-0.8 < q < 0.8/s$. It should be noted that the cases in which negative solutions arose were rare and mainly occurred for stations located in Arizona in the summer months.

APPENDIX F

TASK 9 FINAL TECHNICAL MEMORANDUM

SENSITIVITY AND UNCERTAINTY ANALYSIS RESULTS OF THE UPATOI CREEK WATERSHED MODEL AT FORT BENNING, GA

EXTERNAL MEMORANDUM

To: Dr. Kurt Preston
Strategic Environmental Research and Development Program
Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 17D03
Alexandria, VA 22350

cc: Project Central File 2749 — Category A

From: Dr. Anurag Mishra
Mr. Anthony Donigian, Jr.
RESPEC
2685 Marine Way, Suite 1314
Mountain View, CA 94043

Date: October 19, 2017

Subject: Sensitivity and Uncertainty Analysis Results of the Upatoi Creek Watershed Model at Fort Benning, Georgia (Task 9 under RC-201307)

INTRODUCTION

When a natural system (e.g., a watershed) is modeled mathematically or physically, some degree of uncertainty is always present [Morgan and Henrion, 1990]. The primary reason for this uncertainty is that the models represent only an approximation of reality; i.e., the real watershed systems that exist in the nature. The US Environmental Protection Agency (EPA) [1999] noted that the model predictions cannot be any better than the accuracy of the observed data and the calibration and validation results and, therefore, will always have some uncertainty associated with the output. Uncertainty analysis is a procedure used to determine the confidence limits or reliability of model predictions with respect to the errors associated with observations and a model. Quantifying the uncertainty in modeling results is important to stakeholders and decision makers so that they may have additional information on the probability of achieving watershed management objectives. Stakeholders and decision makers can use the information about uncertainty in establishing a more accurate Margin of Safety (MOS) for the practices and procedures needed to achieve the watershed management objectives [Mishra, 2011].

Estimating uncertainty requires assessing the model parameters and inputs to which the model is sensitive to identify the primary parameters/inputs of concern, because of their critical impacts on watershed response and behavior. A sensitivity analysis is typically conducted to better understand how adjustments to the model parameters affect results. Sensitivity runs provide useful information regarding the physical, chemical, and biological processes represented in a model and identify the most influential parameters and inputs for

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improving model accuracy. This type of analysis provides insight into forcing factors in models and how adjustments made will affect results, both for historical conditions and potential management scenarios. A sensitivity analysis is usually conducted independent of uncertainty analysis, but often as a precursor as noted above.

A sensitivity analysis measures the variability of model outputs caused by perturbations in model parameter values and input data; i.e., how sensitive is the model to changes in the input forcing functions (e.g., precipitation) and parameters that describe its characteristics. Informal sensitivity analyses (iterative parameter adjustments) are generally performed during model calibration to ensure that reasonable values for model parameters will be obtained, thereby resulting in acceptable model results. The degree of allowable adjustment of any parameter is usually directly proportional to the uncertainty of its value and is limited to its expected range of realistic values. Knowledge about the model sensitivity to the model parameters and inputs can help direct model parameter selection for additional investigation, support data collection planning efforts, aid in model calibration, and ultimately serve as a precursor for the uncertainty analysis.

This technical memorandum presents the procedures used in the sensitivity and uncertainty analyses performed for the Upatoi Creek Watershed (UCW) model in Fort Benning, Georgia, along with the analyses results. For the sensitivity analyses, a sensitivity factor was calculated as the ratio of the percent change in model output to the percent change in input/parameter value (expressed as a percentage). These sensitivity factors allowed the input and parameters to be ranked in terms of the highest to lowest impacts on model outputs. This ranking method provided the means for selecting the most sensitive inputs and parameters for the subsequent uncertainty analyses. The uncertainty analyses were conducted with a Monte Carlo procedure whereby the most sensitive parameters were assigned probability distributions, random values were drawn from these distributions, the model was run for each parameter selection combination, 1,000 model runs were performed, and the model results were analyzed to produce the outputs with 90 percent confidence bounds to reflect and quantify the model uncertainty for each output variable of interest.

SENSITIVITY ANALYSIS

For the UCW sensitivity analysis effort, a methodology that was adapted from Donigian and Love [2007] was used to conduct a sensitivity analysis (SA) followed by uncertainty analysis (UA). These steps were performed following the completion of the calibration and validation of the UCW model using BASINS.mil (based on the EPA HSPF model) so that the SA results were focused on model performance when it is providing a reasonable representation of the watershed behavior and response. The steps involved in the SA were performed with the HSPEXP+ software (HSPEXP+1.40beta) [Mishra et al., 2017]. The specific steps for a SA are described in detail below, and depicted in the flowchart in Figure 1.

1. Critical model inputs and parameters were identified based on previous experience, literature review, and the specific calibration experience for the UCW model. Table 1 lists the selected model inputs and parameters, their definitions, and relevant values from the calibration and SA perturbations.
2. Reasonable percent perturbations of model parameters and inputs from the calibrated values in both positive and negative directions were established based on the same experience/sources as noted above in step 1.
3. Critical model output values of concern, at two sites within the UCW, were identified to provide the targets (or metrics) for the SA. These analysis sites were limited to the Upatoi Creek at McBride Bridge (Reach 46) and the UCW model outlet (Reach 74). For both hydrology and

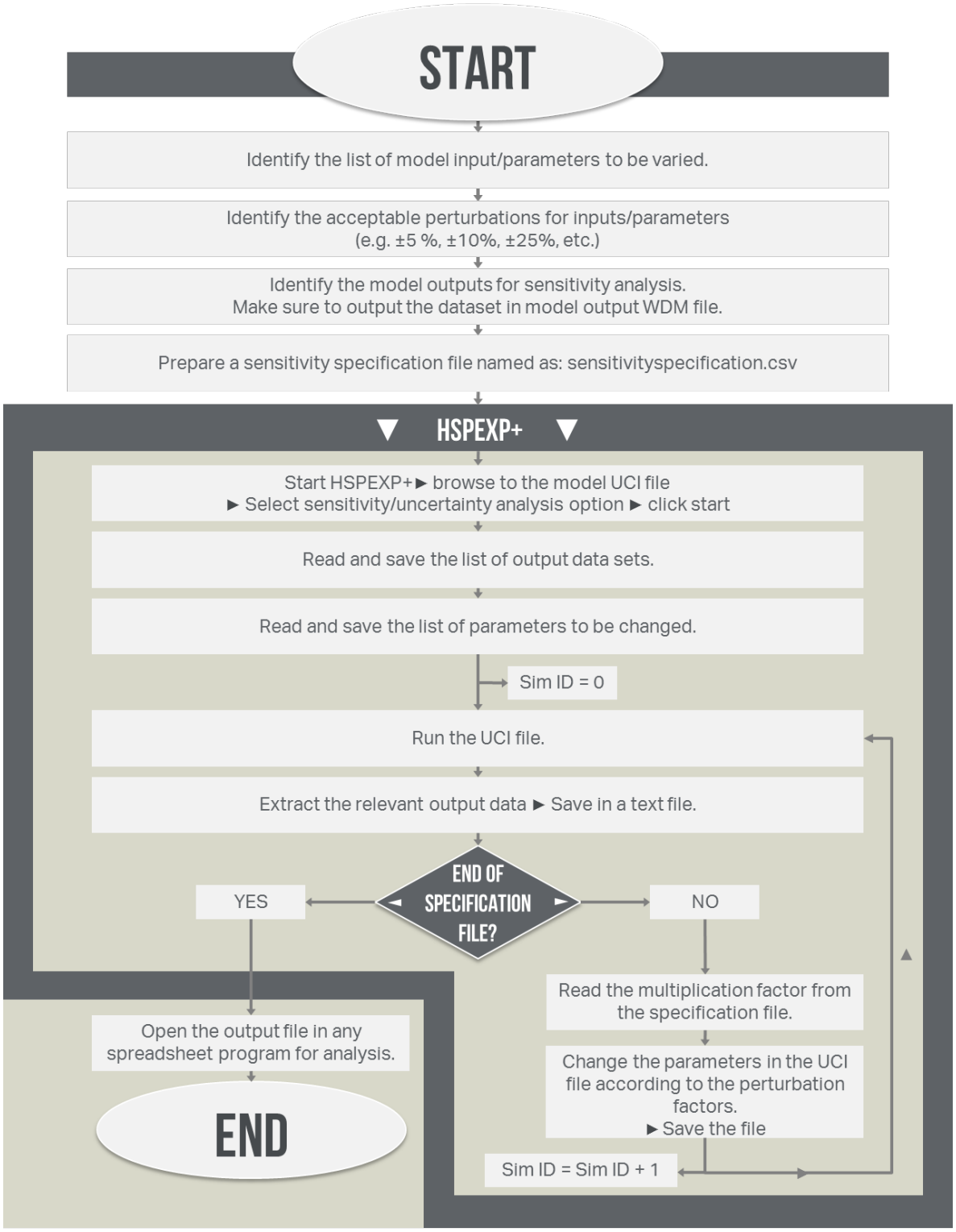


Figure 1. Steps for Conducting a Sensitivity Analysis With HSPEXP+1.40 beta.

sediment, the metrics were selected from those assessed as part of the "weight-of-evidence" approach to model calibration and included annual runoff volume, highest 10 percent flows, lowest 25 percent flows, annual and daily sediment (total suspended sediments [TSS]) loads and concentrations (see Table 2 for a list of the model outputs analyzed).

4. Model simulations for a 13-year period (October 1, 1999–September 30, 2012) were performed as a baseline run for the SA.
5. To conduct an SA, HSPEXP+ 1.40 beta [Mishra et al., 2017] was modified to read a specification file that contained information about the parameters to be varied, magnitude of variation, and the outputs to be analyzed. HSPEXP+ then used the values from the specification file to alter the parameter values, run the model, extract relevant output, save it in a text file, and repeat the process for the next simulation. A sample specification file for a SA is provided in Figure 2.
6. Following the completion of all of the simulations (i.e., 15 simulations, including 1 for baseline and 14 for input/parameter changes), the sensitivity factor was calculated as the ratio of percent change in model output to the percent change in input/parameter value (expressed as a percentage), as follows:

$$SF = \frac{\Delta y}{\Delta x} \times 100 \quad (1)$$

where:

Δy = percent change in output

Δx = percent change in input.

7. Model input and parameters were ranked according to the value of the sensitivity factor, as shown in Table 3.

Table 1. List of HSPF Parameters That Were Adjusted to Assess Model Sensitivity for the Upatoi Creek Watershed Model at Fort Benning

Category	Model Input Parameter	Input/Parameter Definition	Calibration Value			Percent Change to the Calibrated Value		Parameter Value Range	
			Weighted Mean	Minimum	Maximum	Decrease	Increase	Decrease	Increase
Meteorologic Time Series	Mean Precipitation (in/yr*)	Mean Annual Precipitation				15	15		
Hydrology	LZSN (in)	Lower Zone Nominal Soil Moisture Storage	9.00	3.5	15.2	50	50	1.75	22.8
	INFILT (in/hr**)	Index to Infiltration Capacity of the Soil	0.17	0.013	0.631	50	50	0.007	0.947
	INTFW	Interflow Inflow Parameter	4.49	0.4	7	30	30	0.28	9.1
	LZETP	Lower Zone Evapotranspiration	0.31	0.075	0.6	25	25	0.0563	0.75
	DEEPFR	Fraction of Groundwater Inflow to Deep Losses	0.20	0.1	0.4	50	50	0.05	0.6
	UZSN (in)	Upper Zone Nominal Soil Moisture Storage	1.15	0.16	3.38	50	150	0.08	8.45

*in/year – inches per year

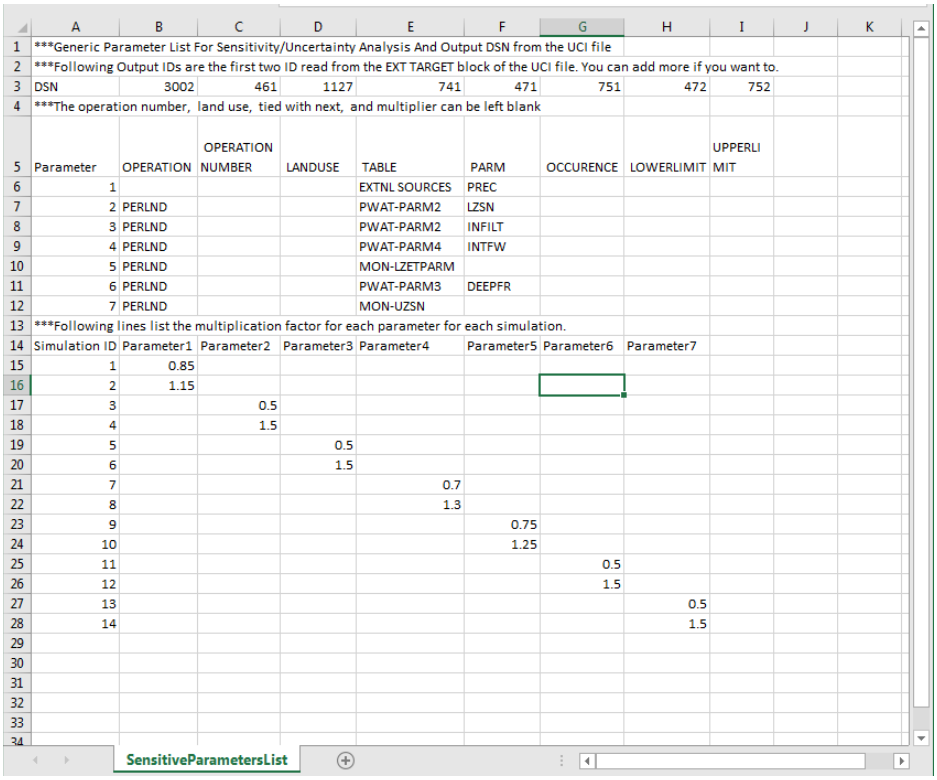
**in/hr – inches per hour

Table 2. List of Outputs of Interest at Reach 46 (McBride Bridge) and Reach 74 (Upatoi Creek Outlet) in the Upatoi Creek Watershed Model at Fort Benning

Hydrology	Water Quality
Mean Annual Flow (cfs*)	Mean Daily TSS Load (tons per day)
Annual Peak Daily Flow (cfs)	Mean TSS Conc. (mg/L**)
Mean Annual Runoff (in)	
10% High Runoff Volume (in)	
25% High Runoff Volume (in)	
50% High Runoff Volume (in)	
50% Low Runoff Volume (in)	
25% Low Runoff Volume (in)	
10% Low Runoff Volume (in)	

*cfs = cubic feet per second

**mg/L = milligrams per liter



	A	B	C	D	E	F	G	H	I	J	K
1	***Generic Parameter List For Sensitivity/Uncertainty Analysis And Output DSN from the UCI file										
2	***Following Output IDs are the first two ID read from the EXT TARGET block of the UCI file. You can add more if you want to.										
3	DSN	3002	461	1127	741	471	751	472	752		
4	***The operation number, land use, tied with next, and multiplier can be left blank										
5	Parameter	OPERATION	OPERATION NUMBER	LANDUSE	TABLE	PARM	OCCURENCE	LOWERLIMIT	UPPERLIMIT		
6	1				EXTNL SOURCES	PREC					
7	2	PERLND			PWAT-PARM2	LZSN					
8	3	PERLND			PWAT-PARM2	INFILT					
9	4	PERLND			PWAT-PARM4	INTFW					
10	5	PERLND			MON-LZETPARM						
11	6	PERLND			PWAT-PARM3	DEEPFR					
12	7	PERLND			MON-UZSN						
13	***Following lines list the multiplication factor for each parameter for each simulation.										
14	Simulation ID	Parameter1	Parameter2	Parameter3	Parameter4	Parameter5	Parameter6	Parameter7			
15	1	0.85									
16	2	1.15									
17	3		0.5								
18	4		1.5								
19	5			0.5							
20	6			1.5							
21	7				0.7						
22	8				1.3						
23	9					0.75					
24	10					1.25					
25	11						0.5				
26	12						1.5				
27	13							0.5			
28	14							1.5			
29											
30											
31											
32											
33											
34											

SensitiveParametersList

Figure 2. Example Specification File for Sensitivity Analysis With HSPEXP+1.40beta.

A sensitivity factor of 100 percent indicates that the model output changes in direct proportion; i.e., one to one, to the change of the parameter value; whereas, a value of 200 percent indicates a 2:1 response, and a 10 percent indicates a relatively insensitive 0.1:1 response (i.e., a 10 percent change produces only a 1 percent change in model output). The results are graphically depicted in a "tornado diagram" for each model output (e.g., Figures 3 and 4) for display and ease of interpretation. The tornado diagrams show the change in output for a certain change in the input parameter using a blue band.

Percent change in the input is shown as a legend in both sides of the band. When the signs of change in the input and the change in output are both on the same side, the sensitivity is positive and vice versa. For example, in Figure 3, sensitivity of average annual runoff volume is positive for PREC (precipitation), and negative for LZETP (Lower Zone Evapotranspiration); i.e., increasing PREC increases average annual runoff volume and vice versa; whereas, increasing LZETP decreases annual average runoff volume and vice versa.

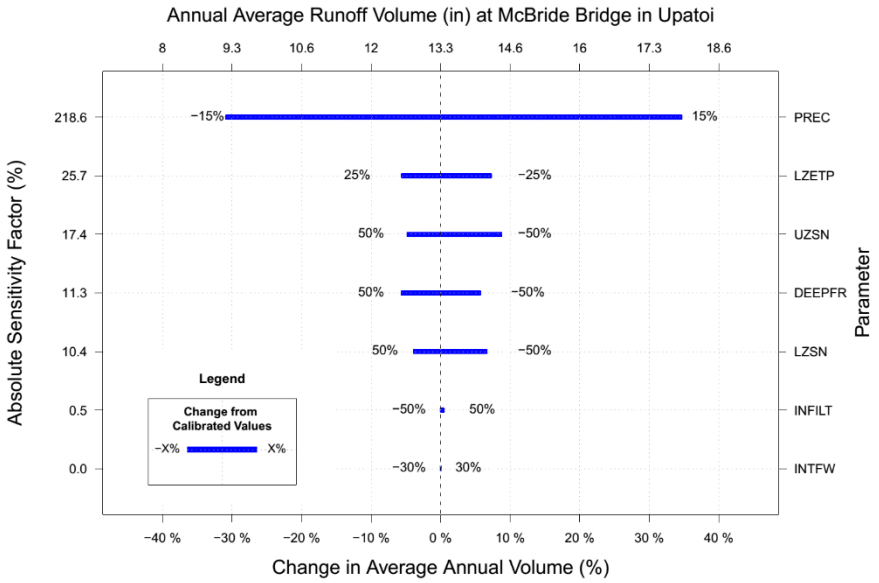


Figure 3. Tornado Diagram of Parameter Sensitivity for Annual Average Runoff Volume at Reach 46 in Upatoi Creek Watershed at Fort Benning (*y*-Axis Is Not to Scale). The blue bands show the change in output for the labeled change in input.

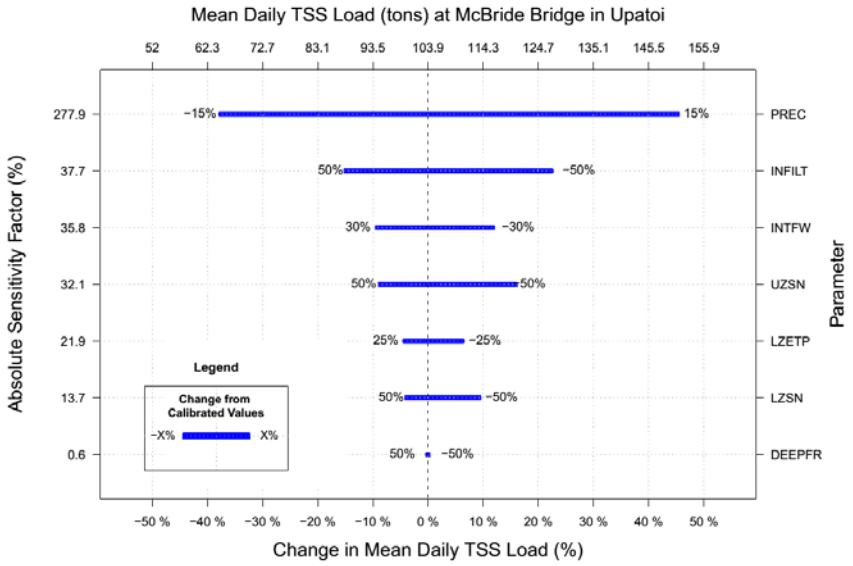


Figure 4. Tornado Diagram of Parameter Sensitivity for Daily Total Suspended Solids loading at Reach 46 in Upatoi Creek Watershed at Fort Benning (*y*-Axis Is Not to Scale).

Table 3 lists the sensitivity factors for different outputs of interest at McBride Bridge (Reach 46) and the Upatoi Creek outlet (Reach 74) to different inputs/parameters. The sensitivity factors at Reach 74 were

very close to the sensitivity factors at Reach 46. Tables list only the results where the sensitivity was greater than 20 percent. A complete set of tornado diagrams is provided in Appendix A for Reach 46.

Table 3. Sensitivity Factors for Hydrology and Water Quality Outputs of Interest at Reach 46 (McBride Bridge) for Selected Parameters (Only Factors Greater Than ± 20 percent are shown)

	Hydrology Outputs									Water Quality Outputs	
Parameter/ Input	Mean Annual Runoff	Annual Peak Flow	Mean Annual Flow Rate	10% High	25% High	50% High	50% Low	25% Low	10% Low	Mean TSS Concentration	Mean Daily TSS load
PREC	218.6	177.9	218.6	238.7	228.6	222.0	202.0	206.3	210.2	20.0	277.9
DEEPFR								–20.7	–20.8		
INFILT		–33.6		–21.7			24.1	25.9	28.2	–33.0	–37.7
INTFW		–27.5								–31.2	–35.8
LZETP	–25.7		–25.7	–20.2	–21.3	–22.8	–39.7	–48.3	–54.5		–21.9
LZSN											
UZSN		–23.4		–24.1	–21.9						–32.1

SENSITIVITY ANALYSIS CONCLUSIONS

Review of the SA results summarized in Table 3, along with the tornado diagrams provided in Appendices A and B, support the following conclusions:

1. As expected, the precipitation clearly dominates the SA results shown in Table 3 and the appendices, compared to all of the other inputs and parameters included in the SA, with Sensitivity Factors mostly in the range of 150 percent to over 250 percent for hydrology model outputs. The only cases when the precipitation sensitivity factor is less than 100 percent is for sediment concentration outputs, and this occurs because the precipitation impacts both the load (i.e., numerator) and the flow (i.e., denominator) of the concentration calculation—in the same direction.
2. Other than precipitation, the mean annual runoff volume was sensitive to LZETP because of its impact on the evapotranspiration component of the water balance; this is especially true during low flow conditions; e.g., 50 percent low, 25 percent low, and 10 percent low.
3. Peak flow rates are sensitive to more parameters, as shown in Table 3, with the greatest sensitivity after precipitation being INFILT (the infiltration index) in the model. The increase in INFILT causes reduction in peak flow and the direct surface runoff, but increases low flow. A decrease in INFILT causes increases in peak flow and the direct surface runoff and decreases low flow.
4. The hydrology parameters that impact the flow regime the most; e.g., precipitation, INFILT, INTFW, UZSN, and LZETP, also affected the sediment load.
5. An increase in INFILT and INTFW reduces the surface runoff without affecting total runoff (< 20 percent sensitivity factor); therefore, their reduction also reduces the sediment load and concentration.

The results of the SA for the UCW model are consistent with our experience in other watersheds, and they provide a sound basis for selecting parameters for the UA.

UNCERTAINTY ANALYSIS

The parameters and inputs that demonstrate the greatest sensitivity were then selected for further investigation in the UA. The sensitivity factor for precipitation was the highest for almost all the outputs of interest. Including precipitation in the SA demonstrated its importance in model performance. However, precipitation was not selected for UA because it is an input climate forcing time series, and its impact was included in the UA through the 10-year simulations using actual precipitation data. Additionally, including precipitation directly in the UA would have masked the model uncertainty for most all of the other parameters.

The UA involved Monte Carlo simulation of the UCW model with parameters randomly drawn from their respective statistical distributions. The parameters that resulted in greater than 30 percent sensitivity factors in all the outputs of interest were selected for the UA. Although LZSN was not as sensitive as other parameters, it was included in the UA because it is a major calibration parameter.

Each selected parameter was assigned a probability distribution. The distribution of parameters represents a modeler's expectations of the range, variability, and distribution of the parameter value in nature. For UAs conducted with watershed models such as HSPF, bounded probability distributions (both normal and lognormal) are frequently used [Donigian and Love, 2007; Mishra, 2011], so that the parameters are confined to physically realistic values and remain within the computational limits of the HSPF model. Some model parameters may be correlated and their correlation may be provided while sampling the parameters from their respective distributions. Correlations may be considered explicitly using a covariance matrix [Donigian and Love, 2007] or the distribution can be derived in such a way that correlation among parameters is implicit, using any of the Bayesian techniques [Mishra, 2011]. With the limited number and range of parameter values in the HSPF model, selected for the UA, the correlation among parameters was assumed to be not significant and therefore ignored in this UA. The steps for a UA are described below and in the flowchart in Figure 5.

1. The model parameters that result in sensitivity factors greater than 30 percent were selected. Additionally, LZSN was also selected for uncertainty analysis as noted above (see Table 4).
2. A probability distribution and value range limits were assigned to each model parameter. Assigning the probability distribution to the model parameters is based on the specific knowledge of the parameters, processes, and algorithms used in the HSPF model; calibration experience with the UCW model; and followed practices used by Donigian and Love [2007]. The correlation among the parameters was assumed to be insignificant for this application. The parameters that are a function of soil and/or climate were assigned a lognormal (LN) distribution and the parameters that are a function of vegetation were assigned a normal (NO) distribution.

   For the uncertainty analysis, the calibrated parameter range provided the basis for the range in which approximately 90 percent of these parameter values are expected. Based on this 90 percent range, standard deviation of these parameters was calculated as the range/3.3 (i.e., $\pm$ 1.65 standard deviation from the mean of the normal distributions). For the LN distributions, standard deviation and mean of the underlying normal distributions were calculated based on the range, as follows:

$$\text{std. dev} = \ln\left(\text{upper bound/lower bound}\right)\Big/3.3$$

$$\text{mean} = \ln\left(\text{lower bound}\right) + 1.645 \times \text{std. dev}$$

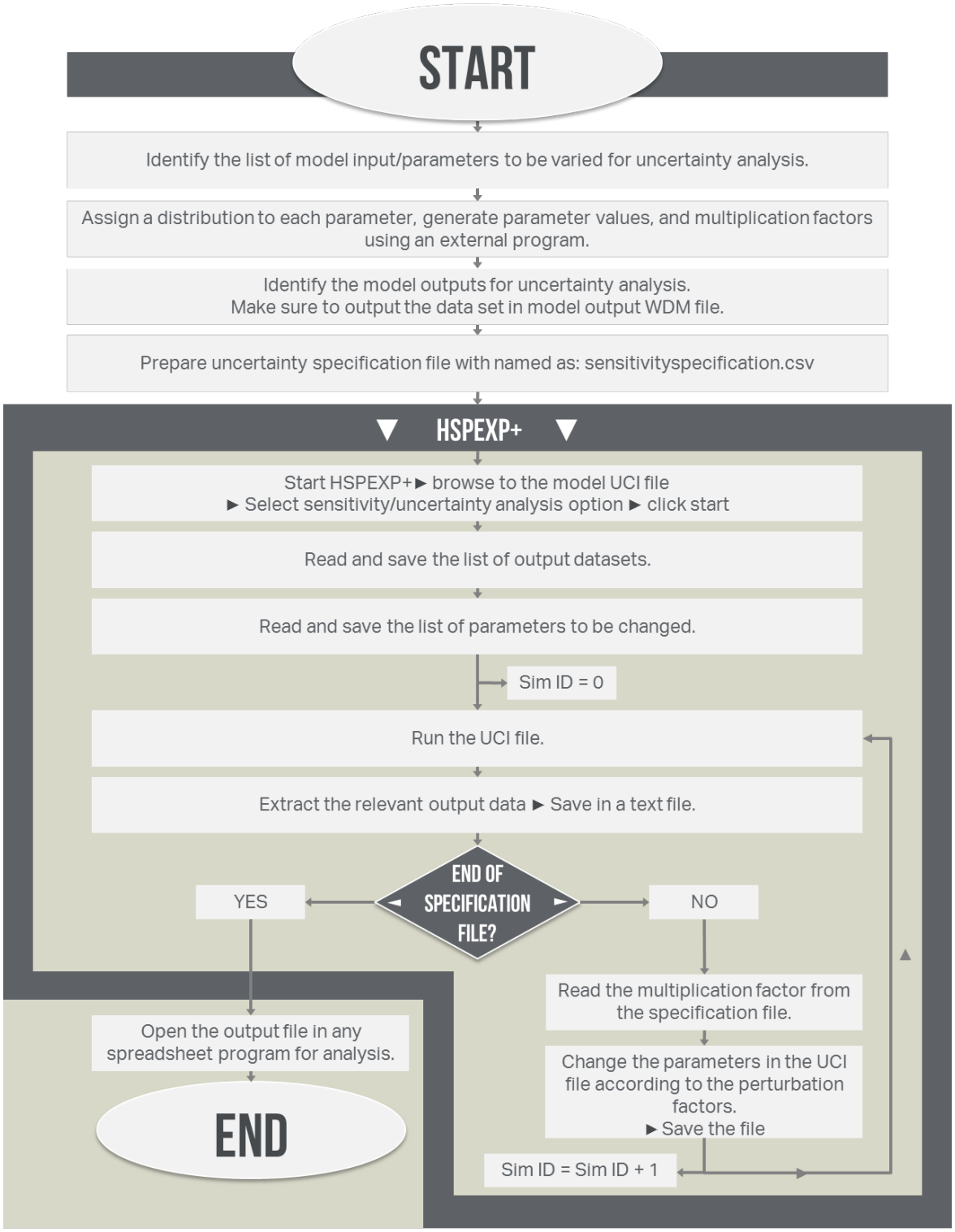


Figure 5. Steps for Conducting Uncertainty Analysis with HSPEXP+1.40beta.

Table 4. List of Parameters That Were Varied for the Uncertainty Analysis

Parameter Details					Calibrated Values					Distribution Parameters		
Category	Name	Definition	Type	Distribution Type	Minimum	Maximum	Mean	90% Range	Std. Dev. (90% Range/ 3.3)	Lower and Upper Limits	Std. Dev. For Underlying Normal Distribution	Mean for Underlying Normal Distribution
Hydrology	INFILT (in/hr)	Index to Infiltration Capacity of the Soil	Soil/ Climate	LN	0.01	0.63	0.17	0.01 – 0.63	0.19	0.005 – 0.7	1.18	–2.41
	INTFW	Interflow Inflow Parameter	Soil/ Climate	LN	0.40	7.00	4.50	0.40 – 7.00	2.00	0.3 – 7	0.87	0.51
	UZSN (in)	Upper Zone Nominal Soil Moisture Storage	Soil	LN	0.16	3.38	1.15	0.16 – 3.38	0.97	0.1 – 4	0.92	–0.31
	LZSN	Lower Zone Nominal Storage	Soil/ Climate	LN	3.50	15.20	9.00	3.50 – 15.2	3.55	2.5 – 6.0	0.45	1.98
	LZETP	Lower Zone Evapotranspiration	Vegetation	NO	0.16	0.38	0.31	0.16 – 0.38	0.07	0.05 – 0.9	NA	NA

To get the resulting LN distributions, the values from the normal distribution obtained with mean and standard deviation calculated above were individually exponentiated (i.e., assigned as exponent with base *e*). All of the distributions calculated above were truncated at their lower and upper limits (see Table 4) to avoid breaching physically realistic values and associated computational limits of HSPF. As examples, Figures 6 and 7 show the resulting NO and LN distributions of two parameters, LZETP and INTFW.

3. Random model parameter values were drawn based on their respective distributions and range limits, using the "pse" package [Chalom and Prado, 2017] in R [Venables et al., 2017]. The "pse" package provides the flexibility to draw samples from a distribution using a Latin Hypercube Sampling (LHS) scheme, which ensures that the entire parameter space is sampled efficiently.
4. In Monte Carlo simulations, the number of parameter draws should be enough to converge on an estimate of the probability distribution of the output variables [Gardner and O'Neill, 1983]. This number is generally achieved by trial and error and increases with the number of parameters and their variability. Mishra [2011] conducted Monte Carlo simulation with about 26 parameters and the number of simulations were 12,000. Donigian and Love [2007] performed a series of tests with the number of runs ranging from 150 to 1,500 and found that a stable output distribution could be obtained with about 500–600 runs; their subsequent uncertainty analyses for about 30 parameters/inputs was based on 600 runs.

   To ensure an adequate number of simulations, RESPEC started with a set of 1,000 parameter draws and calculated various output metrics (mean, standard deviation, 5 percentile, 95 percentile, and probability density function) after the end of 50, 100, 200, 500, and 1,000 simulations. The output metrics showed no significant difference after 500 and 1,000 simulations for all the outputs of interest, which indicated that a sufficient number of simulations had been conducted (see Figure 8).
5. In the UCW model, the parameters vary spatially and, therefore, a single value cannot be assigned to each individual parameter. The parameter sets generated in the previous steps were normalized by dividing them with their respective mean values to generate a multiplication factor for each parameter. For each HSPF simulation, the existing parameters were multiplied by these multiplication factors.
6. Using HSPEXP+, the User Control Input (UCI) file for each HSPF simulation of the UCW model was regenerated by using the multiplication factors for each parameter from the previous step, a model simulation was conducted, and the relevant output was saved in a text file for later processing.
7. Various statistics for the outputs of interest were calculated from all of the runs, including different percentiles, uncertainty, and probability density functions (see Tables 5 and 6).

UNCERTAINTY ANALYSIS RESULTS

Tables 5 and 6 show the primary UA results. The results are shown at both the Reach 46 (McBride Bridge) and Reach 74 (Upatoi Creek outlet). For each output metric, the table includes the mean value, the 5th and 95th percentile values, and the overall "Percent Uncertainty" which is calculated as the average deviation from the mean value; i.e., the sum of the 5th percentile minus the mean, and the 95th percentile minus the mean divided by 2. Percent uncertainty represents the average deviation from the mean value for the 90 percent confidence range.

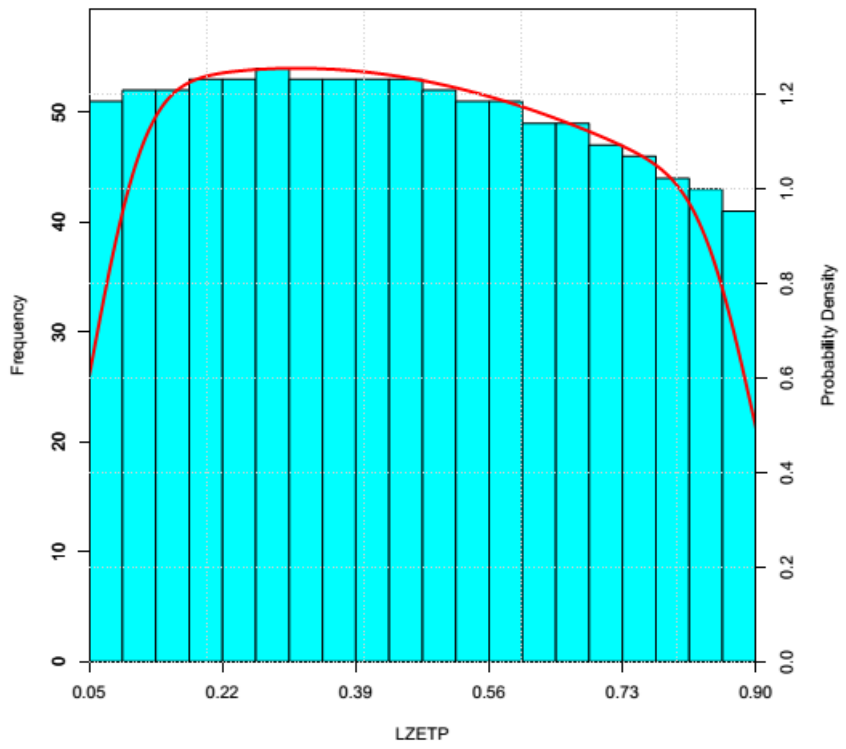


Figure 6. Histogram and Probability Density Function of Bounded and Normally Distributed Parameter, LZETP.

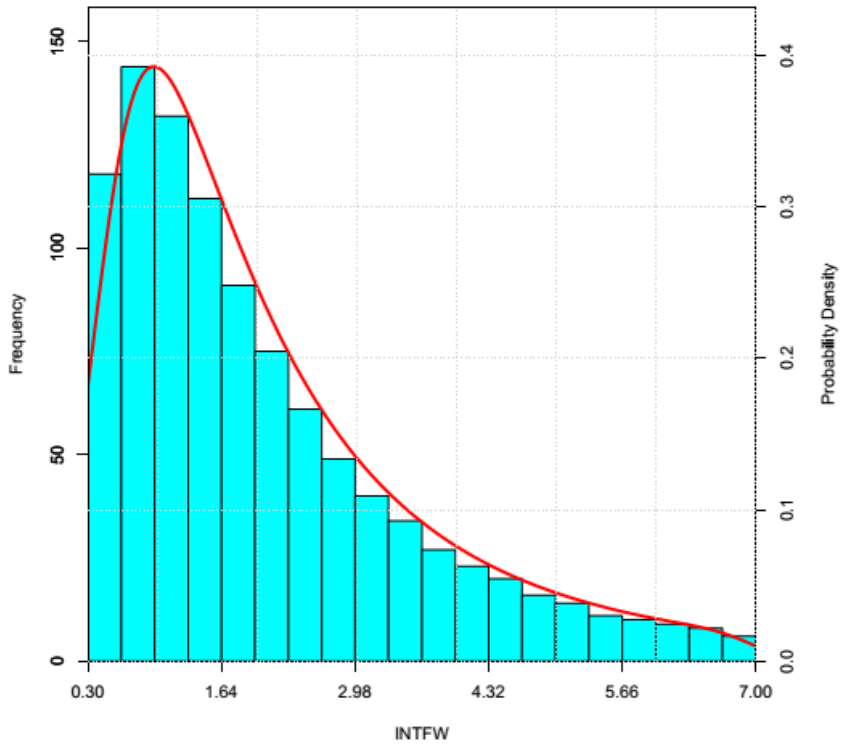


Figure 7. Histogram and Probability Density Function of Bounded and Log-Normally Distributed Parameter, INTFW.

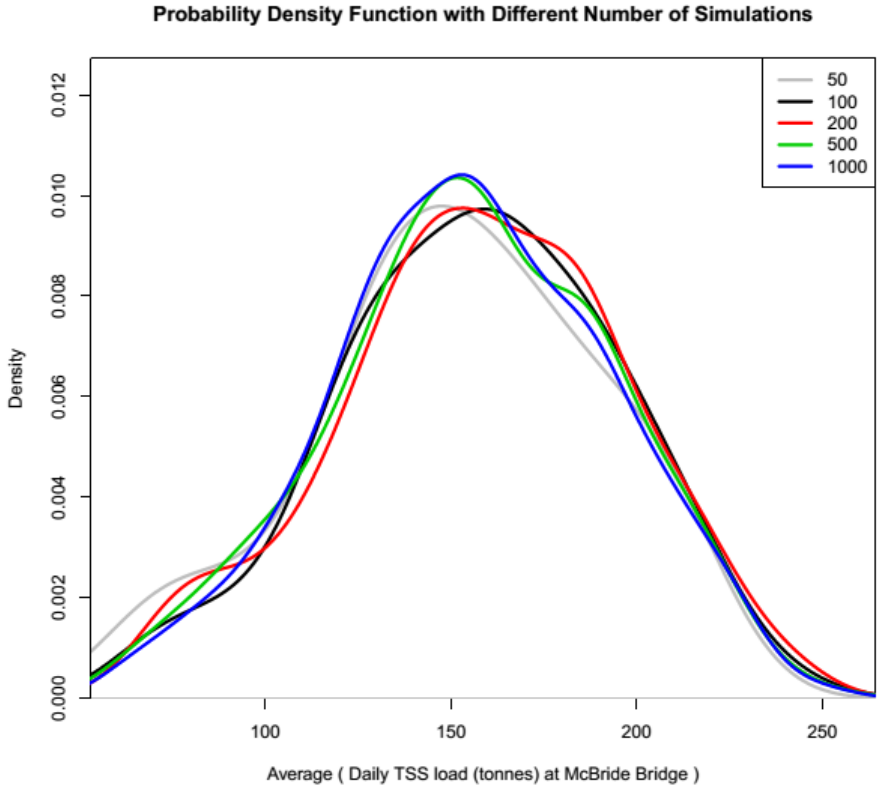


Figure 8. Probability Density Function of Mean Daily Total Suspended Solids (Tons/Day) in Reach 46 Generated With Different Number of Monte Carlo Simulations.

Table 5. Mean, 5th and 95th Percentiles, and Uncertainty of Hydrology Outputs of Interest at Reach 46, and Reach 74 in the Upatoi Creek Watershed Model at Fort Benning

	Mean Daily Flow Rate (cfs)	Annual Peak Flow (cfs)	Mean Annual Runoff (in)	10% High (in)	25% High (in)	50% High (in)	50% Low (in)	25% Low (in)	10% Low (in)	5% Low (in)
Reach 46 (McBride Bridge)										
5th Percentile	259.5	4,822.8	10.4	4.9	7.0	8.9	1.0	0.3	0.1	0.03
Mean	349.6	8,797.4	14.0	8.2	10.2	12.2	1.8	0.6	0.2	0.07
95th Percentile	457.7	12,330.0	18.3	11.9	13.8	15.9	3.1	1.2	0.4	0.14
% Uncertainty	28.3	42.70	28.3	43.0	33.2	28.5	59.5	68.0	74.1	77.2
Reach 74 (Upatoi Creek Outlet)										
5th Percentile	320.7	5,506.4	9.6	4.6	6.5	8.3	1.0	0.3	0.1	0.03
Mean	439.8	10,430.2	13.2	7.6	9.6	11.5	1.7	0.6	0.2	0.07
95th Percentile	583.4	14,998.7	17.5	11.1	13.1	15.1	3.0	1.1	0.3	0.14
% Uncertainty	29.9	45.5	29.9	43.0	34.5	29.7	58.6	67.3	73.0	76.3

Table 6. Mean, 5th and 95th Percentiles, and Uncertainty of Water Quality Outputs of Interest at Reach 46, and Reach 74 in the Upatoi Creek Watershed Model at Fort Benning

	Mean TSS Concentrations (mg/l)	Mean Daily TSS Load (tons/day)
Reach 46 (McBride Bridge)		
5th Percentile	25.9	90.7
Mean	39.9	155.2
95th Percentile	51.7	217.8
% Uncertainty	32.3	40.9
Reach 74 (Upatoi Creek Outlet)		
5th Percentile	33.6	109.0
Mean	49.6	190.7
95th Percentile	64.0	270.5
% Uncertainty	30.7	42.3

Thus, the overall uncertainty in hydrology outputs varied from 28 percent to 77 percent over the full range of flows, while mean flows showed uncertainties of about 28 to 30%. The uncertainty in the mean TSS concentration was observed to be between 28 and 32%; however, the uncertainty in mean TSS loading at the two locations was 40.9 and 42.3 percent. These ranges reflect the relative difficulties in calibrating the TSS loading compared to average flow rate and average TSS concentration.

Frequency duration curves of flow were also plotted to illustrate the uncertainty in flow simulation for the entire range of flows (see Figure 9). The curves were plotted with 5th and 95th percentile curves as is evident in Figure 9, the uncertainty increases for low flow conditions and high flow events, with the lowest uncertainty for the moderate flow ranges. The frequency duration curve of TSS concentration (Figure 10) illustrates the uncertainty in TSS concentration for entire range of TSS concentration. The uncertainty in TSS concentration is lower at higher concentrations and increases for lower values.

UNCERTAINTY ANALYSIS CONCLUSIONS

From the UA results shown in Tables 5 and 6, the following conclusions are derived:

1. Model uncertainty increases from median flow rate to and high flow rates and low flow rates (extremes).
2. Model uncertainty increases from median flow volume to high and low flow volumes.
3. Model uncertainty in mean TSS concentration are similar to the uncertainty in mean flow (around 30 percent); however, the uncertainty in daily TSS load is greater (about 40 percent).
4. Uncertainty estimates at Reach 46 (McBride Bridge) and Reach 74 (Upatoi Creek Outlet) are essentially the same; the differences in the Percent Uncertainty between these two sites is considered insignificant.

Based on the past experiences with UA in HSPF models in other watersheds, the results presented here are reasonable and realistic.

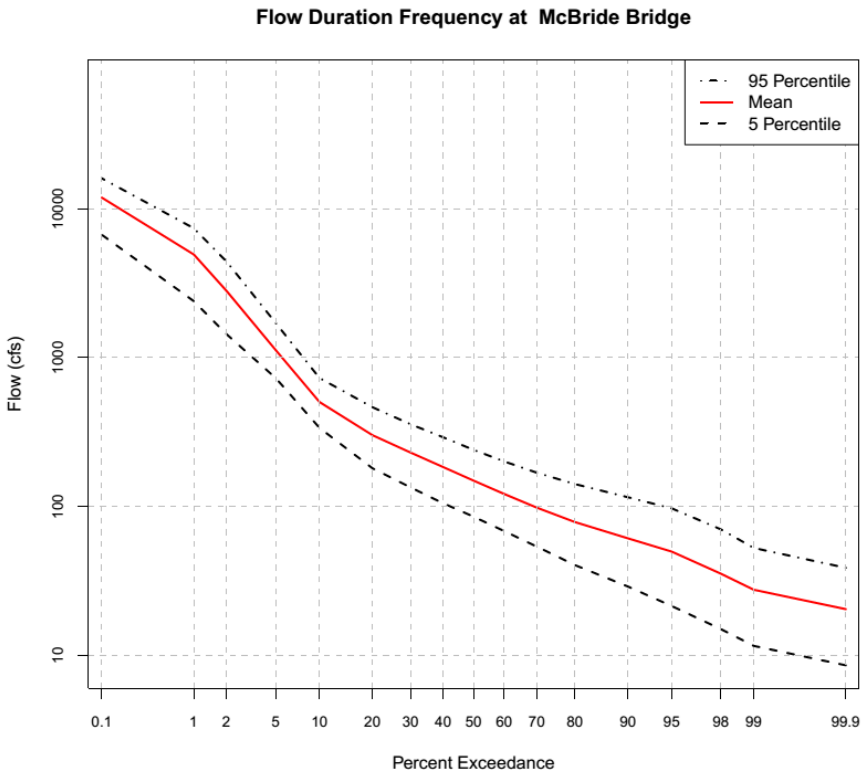


Figure 9. Flow Frequency Duration Curves at Reach 46 (McBride Bridge) With 5 and 95 Percentile Curves to Illustrate the Model Uncertainty.

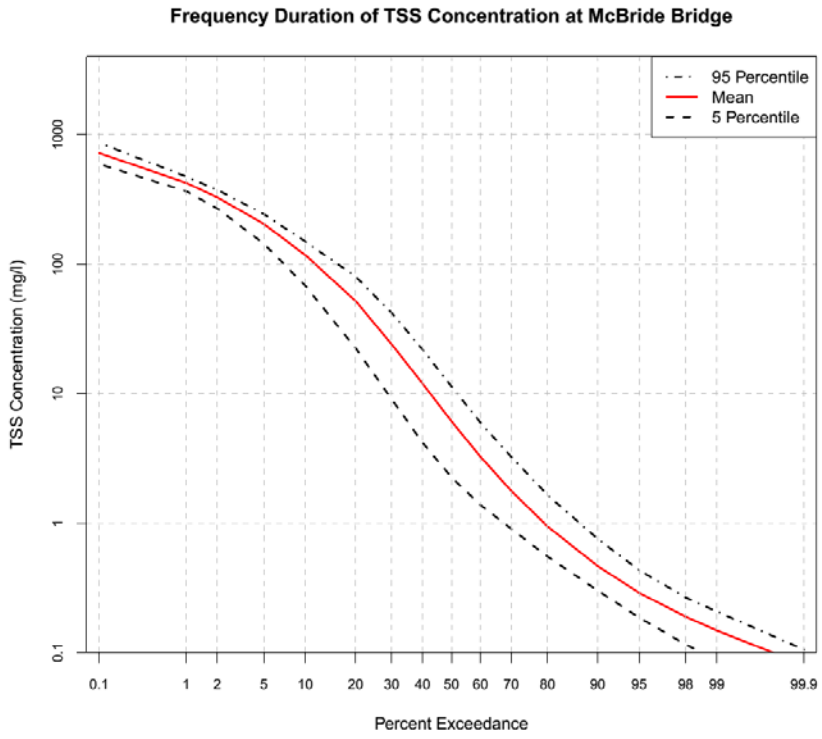


Figure 10. Total Suspended Solids Frequency Duration Curves at Reach 46 (McBride Bridge) With 5 and 95 Percentile Curves to Illustrate the Model Uncertainty.

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ATTACHMENT A

TORNADO DIAGRAM OF SOME KEY OUTPUTS OF INTEREST

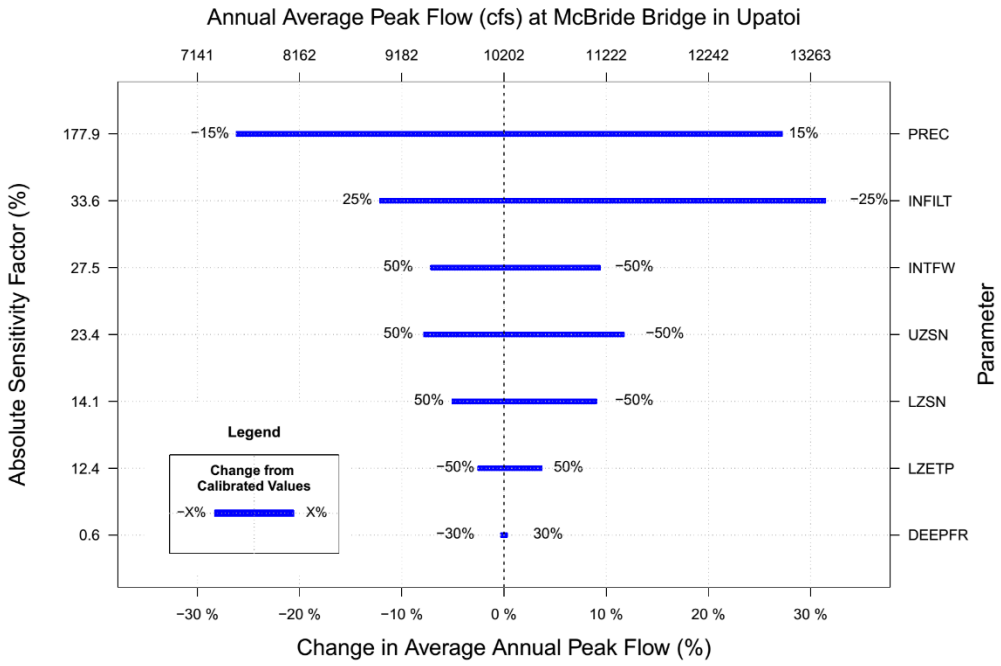


Figure A-1. Annual Average Peak Flow at McBride Bridge in Upatoi Creek Watershed.

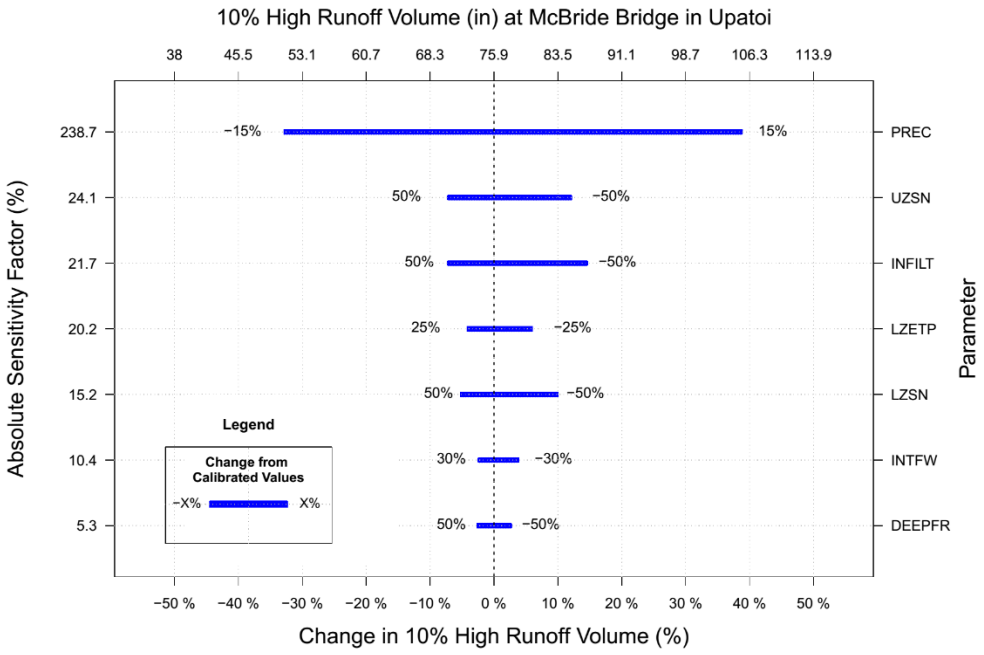


Figure A-2. 10 Percent High Runoff Volume at McBride Bridge in Upatoi Creek Watershed.

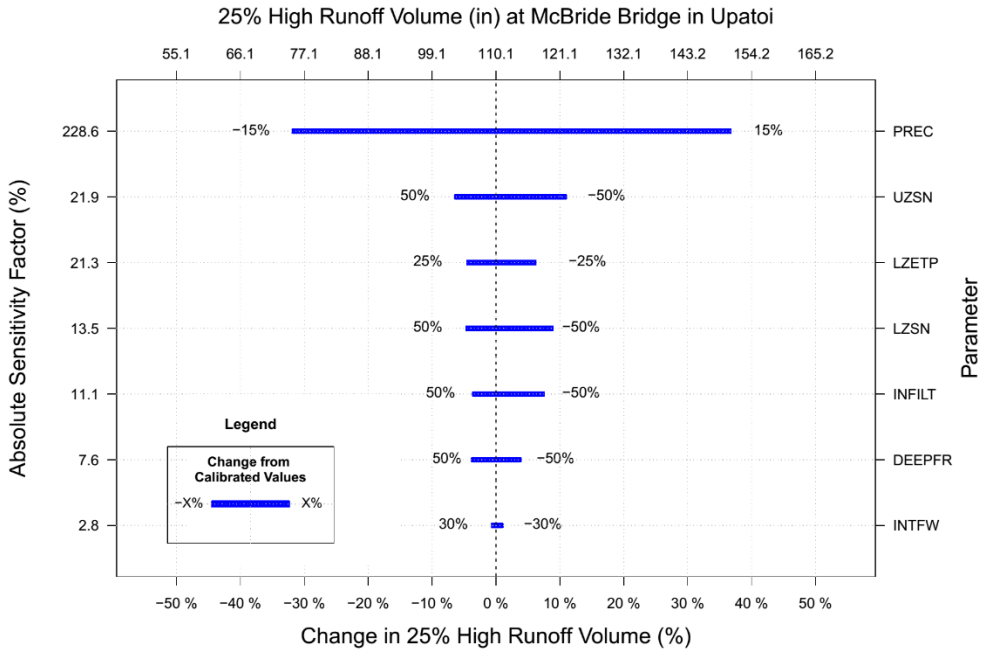


Figure A-3. 25 Percent High Runoff Volume at McBride Bridge in Upatoi Creek Watershed.

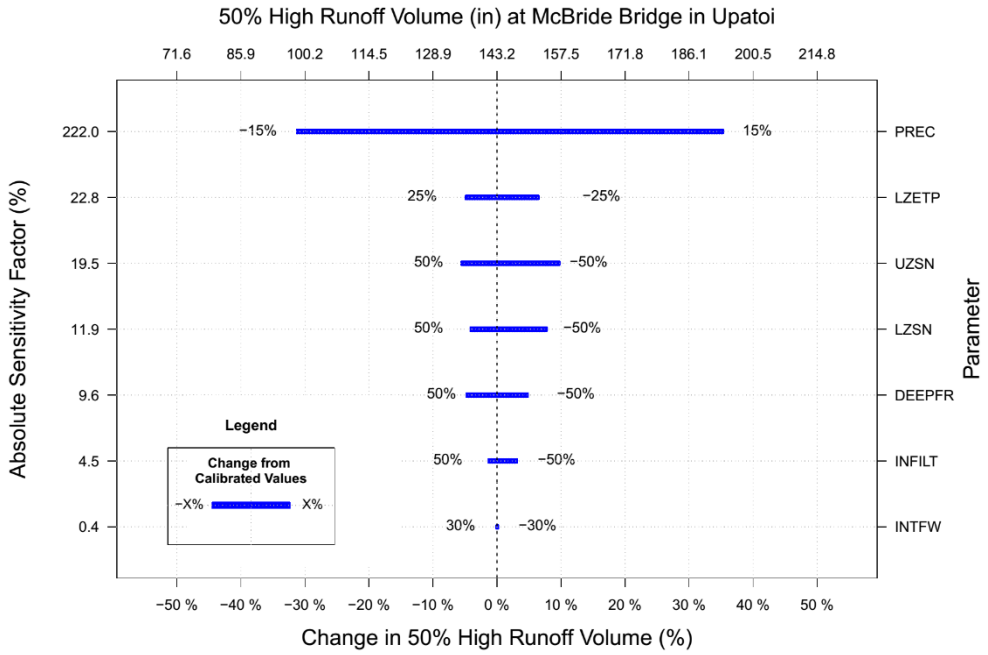


Figure A-4. 50 Percent High Runoff Volume at McBridge Bridge in Upatoi Creek Watershed.

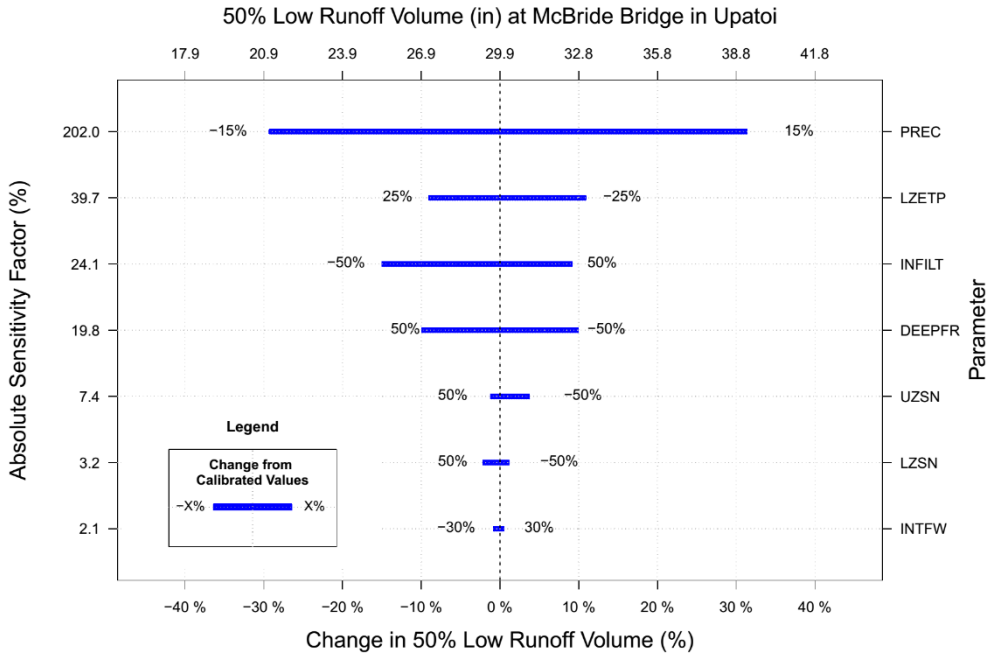


Figure A-5. 50 Percent Low Runoff Volume at McBride Bridge in Upatoi Creek Watershed.

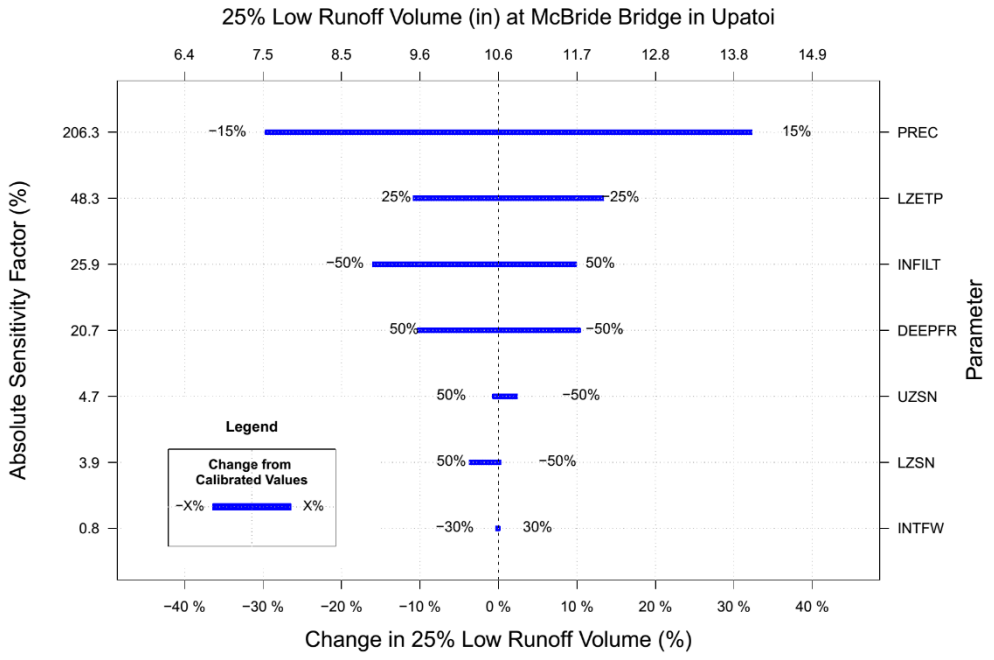


Figure A-6. 25 Percent Low Runoff Volume at McBride Bridge in Upatoi Creek Watershed.

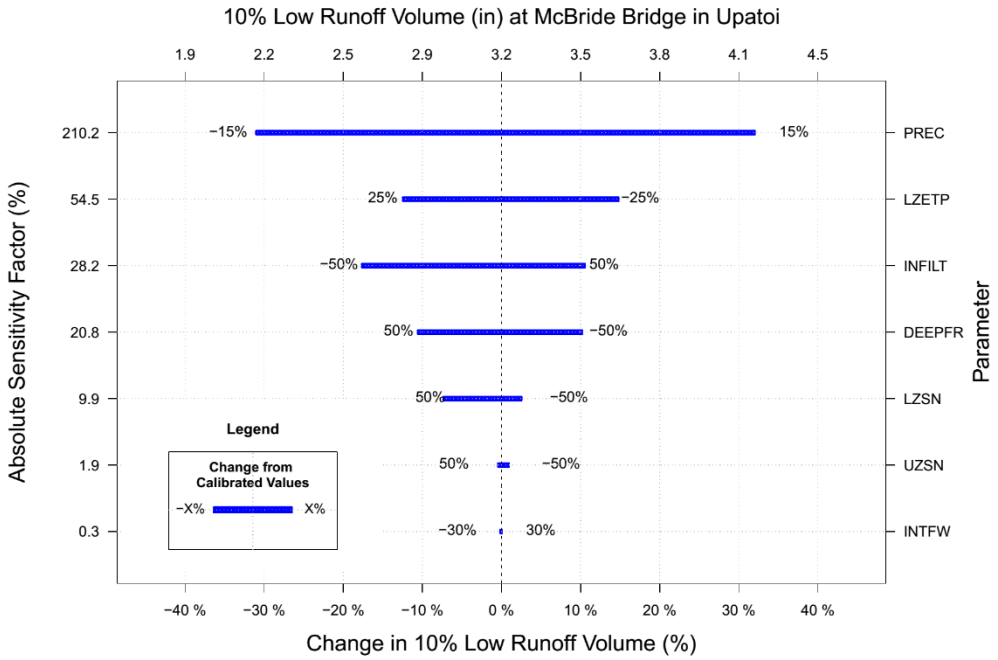


Figure A-7. 10 Percent Low Runoff Volume at McBride Bridge in Upatoi Creek Watershed.

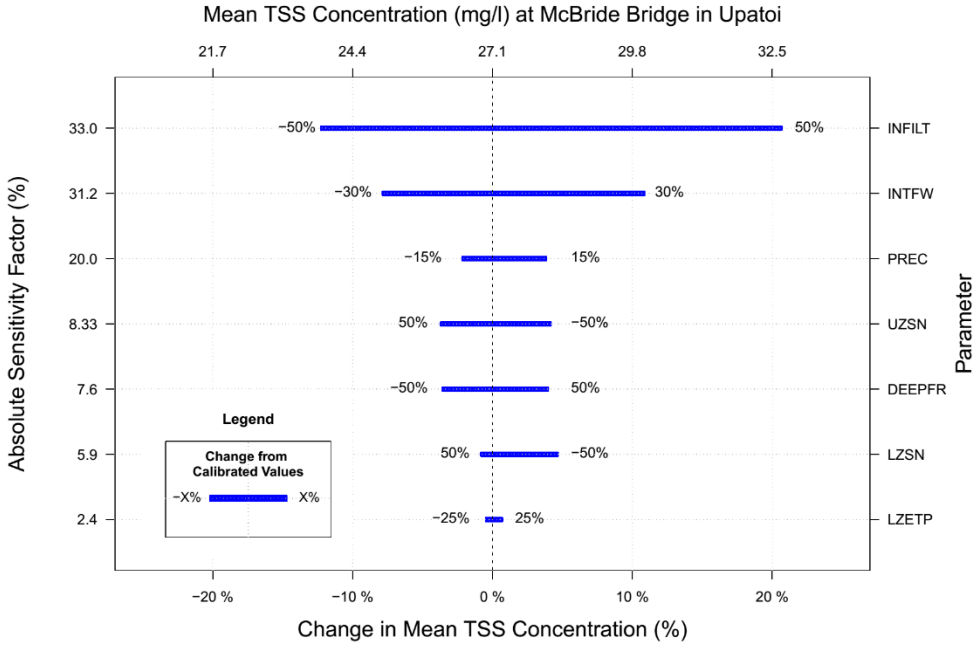


Figure A-8. Mean Total Suspended Solids Concentration at McBride Bridge in Upatoi Creek Watershed.