A Watershed Modeling Framework for Military Installations: A Preliminary Approach and Baseline Model Results

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ABSTRACT

The Strategic Environmental Research and Development Program (SERDP) identified the need to provide Fort Benning, Georgia (and eventually other military installations) with immediately usable and effective models that can be implemented for compliance and long-term watershed planning and management. The subject of this paper is a SERDP-funded project that focuses on the development of a watershed modeling system for Fort Benning using the U.S. EPA BASINS (BASINS) framework. The objective of this 4-year effort is to identify, adapt, and develop watershed management model(s) for Fort Benning that address impacts on watershed hydrology, sediment, water quality and related ecosystem processes and outcomes resulting from military activities and natural resources management. The 2005 Base Realignment and Closure (BRAC) decisions realigned thousands of additional troops and hundreds of military vehicles to Fort Benning and other military facilities, increasing the impact of military operations on the base watersheds. Soils within the Fort Benning watersheds, in general, are highly erodible, and a number of streams are currently listed as sediment impaired under the Federal Clean Water Act Section 303(d). Prudent planning is needed using analysis methods capable of linking land disturbance activities to sediment washoff, and instream impacts on water quality and ecological endpoints. This paper presents the preliminary Phase I results of this project which includes: 1) the initial calibrated baseline model to the Fort Benning watersheds, and 2) the recommended model enhancements identified as a result of investigating eight research areas. The Fort Benning baseline model application focuses on sediment impacts, sources and transport modeling and provides additional means for identifying improvements that are needed to address model limitations and improve the baseline model simulations of fate and transport processes, and land use characterization related to the military mission on Fort Benning.

KEYWORDS

Watershed modeling, BASINS, HSPF, military installation, sediment, water quality, hydrology

INTRODUCTION

Watershed modeling systems are becoming critical tools to support military readiness and advance the sustainability of testing and training lands. Sustainability involves balancing land use and resource protection within the carrying capacity of the watershed. This project (SERDP Project SI 1547) focuses on the development of a watershed modeling system for Fort Benning using the U.S. EPA BASINS (BASINS) framework (USEPA, 2007; Duda et al., 2006). The overarching objective of the project is to identify, adapt, and develop watershed management model(s) for Fort Benning that address impacts on watershed hydrology and water quality and related ecosystem processes and outcomes resulting from military activities and natural resources management.

BASINS is a multipurpose environmental analysis system designed for use by regional, state, and local agencies performing watershed and water quality-based studies. BASINS integrates environmental data, analytical tools, and modeling programs to support development of solutions to watershed management and environmental protection problems. Within BASINS are a suite of modeling packages and tools, ranging from simple to sophisticated. The U.S. EPA's Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell et al., 2005) is the primary watershed model included in the EPA BASINS modeling system. HSPF is the modeling package selected for this application.

HSPF is a comprehensive watershed model of hydrology and water quality that includes modeling of both land surface and subsurface hydrologic and water quality processes, linked and closely integrated with corresponding stream and reservoir processes. It is considered a premier, high-level model among those currently available for comprehensive watershed assessments. HSPF has enjoyed widespread usage and acceptance, since its initial release in 1980, as demonstrated through hundreds of applications across the U.S. and abroad. HSPF is jointly supported and maintained by both the U.S. EPA and the USGS. This widespread usage and support has helped to ensure the continuing availability and maintenance of the code for more than two decades, in spite of varying federal priorities and budget restrictions. HSPF is currently being used for watershed studies in more than 25 states, Canada, and Australia.

Fort Benning is a United States Army Installation, located mostly in west-central Georgia with portions in east-central Alabama. The Installation and surrounding area are shown in Figure 1. 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. Most of the Installation drains into the Upatoi Creek, a tributary to the Chattahoochee River just downstream of Columbus, GA.

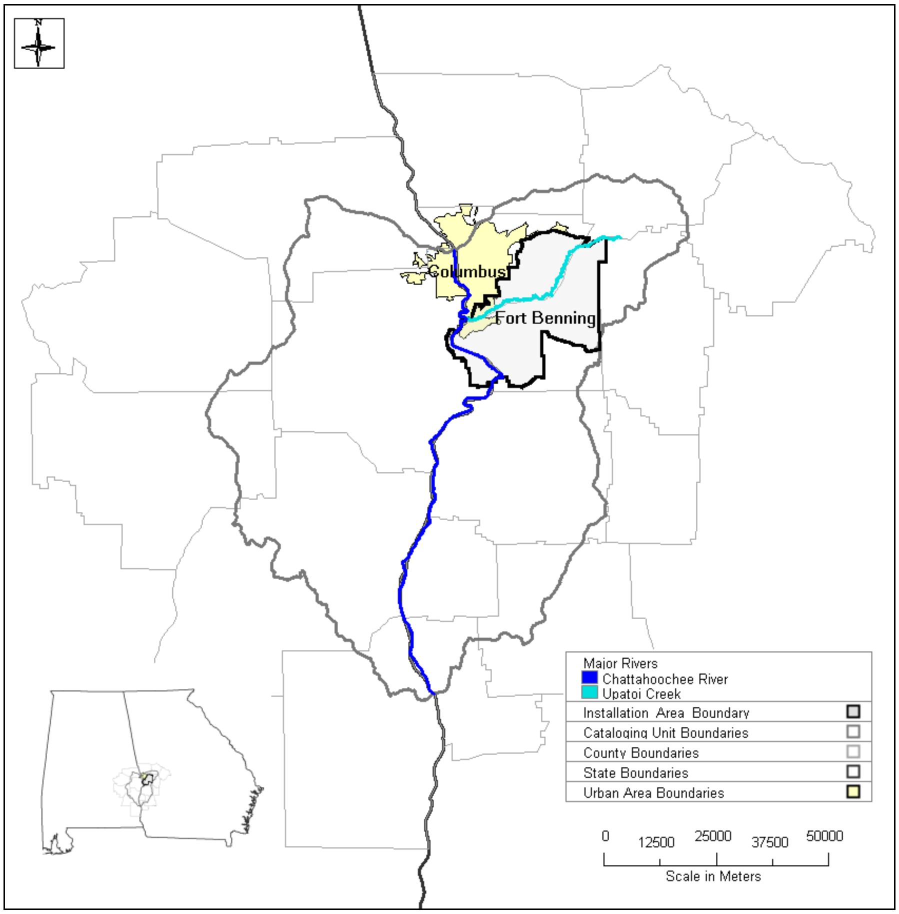


Figure 1 - Fort Benning Location, Municipalities, and Major Rivers

This modeling effort builds upon other SERDP projects that focus on assessing the health of ecosystems on Fort Benning lands with potential extensions to other government installations throughout the Southeast. Several of these are large multi-year research projects conducted by teams of nationally recognized scientists and represent many universities and multiple government laboratories. The Ecosystems Characterization and Monitoring Initiative (ECMI) was established to provide the Installation and researchers with baseline ecological data and to develop effective long-term monitoring techniques. These techniques include an automated, installation-wide meteorological and stream-monitoring network, and characterization of many streams on the Installation through the application of the EPA's Rapid Bio-assessment Protocol (RBP). To permanently record all research data collected by SERDP, the SERDP Ecosystem Management Project (SEMP) Data Repository was created. The SEMP Data Repository was designed to provide data access and exchange among the SERDP study partners and to act as an efficient, long-term data archive.

The SERDP ECMI established a set of Watershed Management Units (WMUs) for the area around and including Fort Benning. The Watershed Management Units and associated streams are shown in Figure 2. These WMUs contain about 682 square miles of area, and were used to define the study area and boundary of the model domain for this Fort Benning watershed model.

There are 28 unique Watershed Management Units, ranging in size from 175 square miles to about 4.4 square miles. Table 1 below shows each major stream of the study area, with its estimated total drainage area and percent of the entire study area.

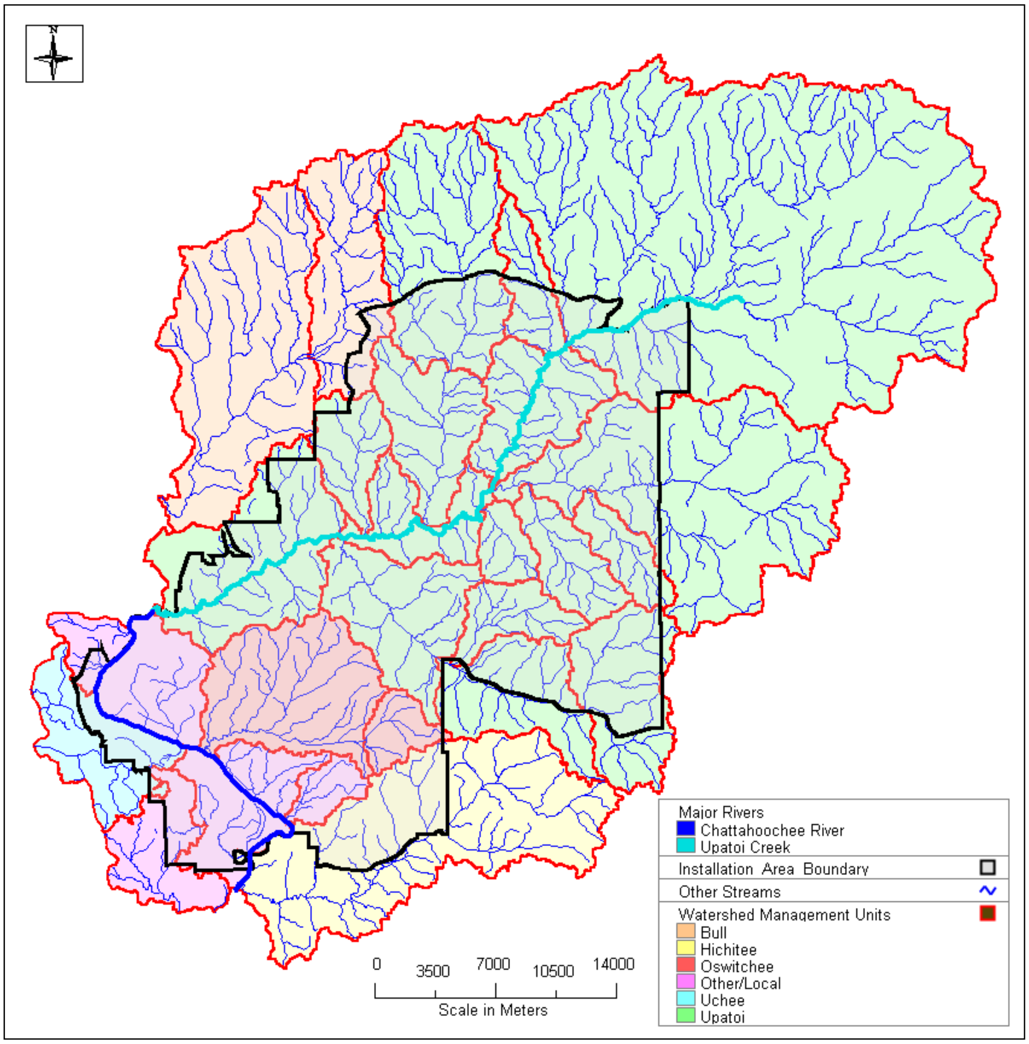


Figure 2 - Fort Benning Watershed Management Units

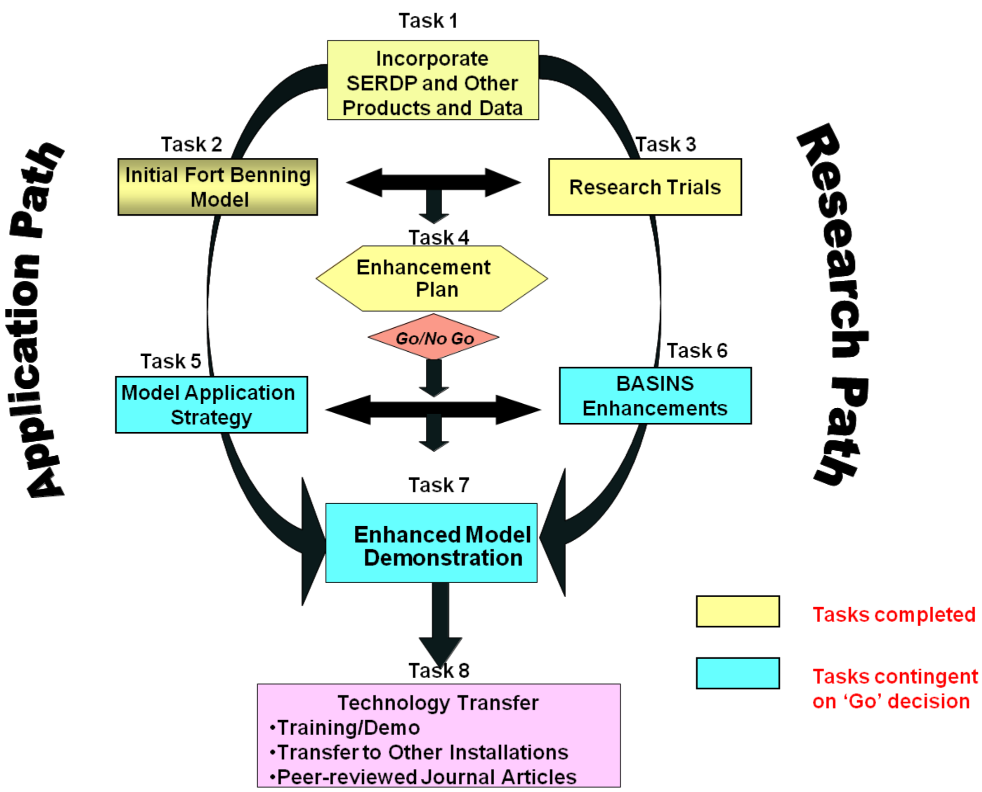
Table 1 - Major Streams of the Fort Benning watershed management units

Major Stream Name	Total Area (Sq Mi)	Percent of Total
Upatoi	452.8	66.44%
Bull	70.5	10.35%
Hichitee	57.7	8.46%
Oswitchee	32.4	4.75%
Uchee	16.6	2.44%
Other Local Inflows	51.5	7.56%
Grand Total	**681.5**	

METHODOLOGY

The project approach uses the BASINS modeling system as the toolkit for pursuing two interrelated 'paths', an application path and a research path (Figure 3). The application path is focused on integrating existing data and products into BASINS; development of an initial calibrated model of Fort Benning; and identification of apparent model/system limitations. The research path directs its focus on designing and implementing model enhancements that improve on recognized watershed model weaknesses, and more fully developing capabilities relevant to representing and evaluating military land uses and activities. This paper discusses Phase I of the project, as depicted in Figure 3. Phase I includes Tasks 1-4 and resulted in an initial calibrated baseline model of Fort Benning, and recommended modeling and model code enhancements.

Figure 3 - Dual Pathway Approach For Developing a Military BASINS Modeling System



Phase I Application Path: Fort Benning Baseline Model

The Fort Benning baseline model simulates the watershed and in-stream hydrology, as well as sediment, water temperature, and some water quality parameters. Figure 4 shows the components of the overall modeling process for the Fort Benning baseline model application.

The modeling, or model application, process can be described as comprised of three phases -- Phase I includes data collection, model input preparation, and parameter evaluation, i.e. all the steps needed to setup a model, characterize the watershed, and prepare for model executions.

Phase II is the model testing phase which involves calibration, validation, and, when possible, post-audit. This is the phase in which the model is evaluated to assess whether it can reasonably represent the watershed behavior, for the purposes of the study. Phase III includes the ultimate use of the model, as a decision support tool for management and regulatory purposes.

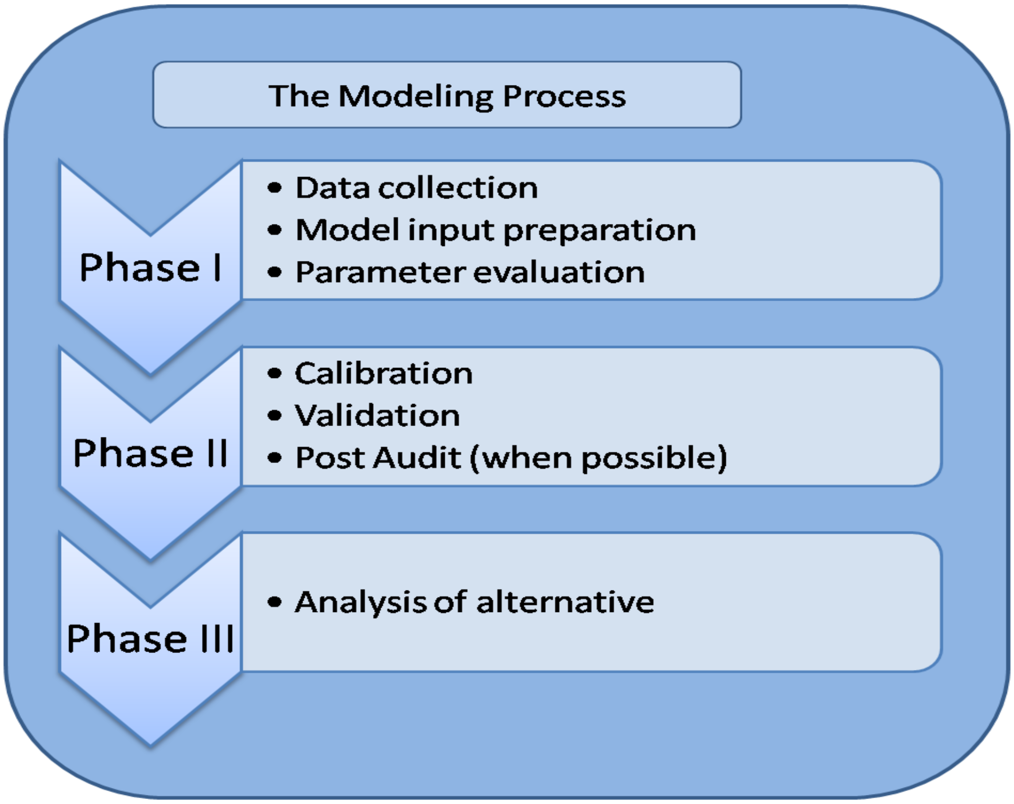


Figure 4 - The Modeling Process

Under Task 2 of our study, Phase I has been completed and Phase II is in process. The model setup process involves development and manipulation of a wide range of both time series and spatial data, including meteorologic, streamflow, topography/elevation, and land use data. The model setup process involves overlays of the spatial data (through GIS processing), along with geo-locating the meteorologic and streamflow (and water quality) as part of the Thiessen analyses and model segmentation tasks. Descriptions of data sources and methodologies for each of these components follow.

Meteorological Data
Long term precipitation data at 10 stations were collected at half hour intervals as part of the Ecosystems Characterization and Monitoring Initiative (ECMI) inside Fort Benning. BASINS provides a comprehensive database of precipitation records that included hourly precipitation data from Columbus Metro airport located in the northwestern part of the watershed, and daily precipitation data on the east side of watershed. These stations were used to fill any gaps in the 30 minute precipitation data in the 10 Ecosystem Characterization and Monitoring Initiative (ECMI) stations. The complete precipitation data from these stations were applied to different parts of the modeled watersheds as described later. The average annual precipitation recorded at

Columbus Metro airport, and Buena Vista was 48.50 inches, and 49.89 inches, respectively.

Pan evaporation data, used to estimate lake evaporation, were available from three US Surface airways monitoring stations located outside the watershed at distances of 37 km, 75 km, and 100 km from the nearest watershed boundary. BASINS also provided the potential evapotranspiration (PET) data calculated using the Hamon formula (Hamon, 1961), for the 10 active, computed PET stations near the study area, of which two were inside the watershed area. Pan evaporation and PET data were less variable and hence the PET data from only the stations located inside the watershed were used for the model simulation.

BASINS provided the source for other meteorological inputs including air temperature, cloud cover, dewpoint temperature, wind speed, and solar radiation at two stations within the study area. The ECMI stations also recorded wind and solar radiation data.

Stream Data

Long term streamflow data, critical for model hydrology calibration, were available from two stations: Upatoi Creek at Fort Benning, GA (drainage area 447 sq. mi), and Uchee Creek near Fort Mitchell, AL (drainage area 342 sq. mi). Much of the drainage area of Uchee Creek is outside the base, and therefore Upatoi Creek at Fort Benning was used as the primary location for hydrology calibration. Streamflow data were also available at six ECMI hydrological stations from August 1999 to July 2002. These data were used to supplement the overall hydrologic calibration effort.

Water quality data on Upatoi Creek are available from 1978 to 1984. Intermittent water quality data have been recorded elsewhere on the Installation, and additional data (both continuous and on a storm basis) continue to be collected by several current projects, including the SERDP SEMP.

Elevation Data

Elevation data in the form of National Elevation Datasets (NED) were obtained through the USGS seamless data distribution site (http://seamless.usgs.gov) and SEMP with a resolution of 30m and 10m, respectively. The SEMP layer was available for most of the watershed area except some portions in Alabama, in which case NED were used.

Segmentation

The study area was divided into individual land and channel segments, each representing relatively homogenous hydrologic/hydraulic and water quality behavior. This segmentation provided the basis for assigning similar or identical input and/or parameter values or functions to each segment (i.e., land area or channel length).

In addition to the WMUs, the NHDPlus (National Hydrography Dataset Plus) hydrography data that are accessible through the BASINS interface provided further delineation of catchments Catchment sizes were reduced to about one-half square mile including associated stream segments. The NHDPlus catchments were merged to provide 3rd order or smaller subwatersheds inside the Fort Benning installation area, and 4th order subwatersheds outside the installation area (Figure 2). Some of the northern upstream watersheds were divided approximately along the boundary of physiographic regions commonly referred to as the 'Fall Line'. Also, to further segregate the effect of activities within the base, some headwater watershed streams and areas were divided near the installation boundary. The segmentation efforts resulted in 129 subbasins, with an average size of about 3.5 sq. mi within the Installation and 8.1 sq. mi for the portion of the study area outside the Installation boundaries.

The river channel network in the Fort Benning study area is the major pathway by which flow, sediment and contaminants are transported from the watershed to the Chattahoochee River downstream. The river reach segmentation process requires consideration of river travel time, riverbed slope continuity, cross section and morphologic changes, and entry points of major tributaries. In addition, Section 303(d) reaches were represented as model reach boundaries so that flows, water balance, and volume information can be generated for use in TMDL assessments. The channel network in Fort Benning was divided into 127 stream reaches, corresponding to 129 subbasins (two subbasins do not have a reach and flow into the upstream end of the downstream subbasin).

The reach hydraulic behavior is defined in HSPF by a function table (FTABLE) for each stream reach, which contains the reach surface area, volume, and discharge as functions of depth, i.e. an expanded rating curve. Rating tables were used to generate FTABLES for gage sites. The rest were estimated using the regional curve equation and cross sections at the streams obtained by the digital elevation map. Manning's coefficient for different channel conditions was estimated from field surveys, photos and literature values.

Thiessen Network

The subbasins were overlaid with Thiessen network boundaries to define meteorological regions across the watershed, using the location of 11 ECMI meteorological stations. Meteorological stations were assigned to each subbasin based on their location and the polygon area derived from the Thiessen network (Figure 5). During the modeling, precipitation from each meteorological station was applied to the neighboring subbasins based on the Thiessen analysis.

Land Use Designation

Table 2 shows the acreage of aggregated land use categories including the military training categories designated within the study area. The National Land Cover Dataset (NLCD) 2001 provided the primary basis for characterizing land use. However, this land use coverage does not provide coverage for the extensive road network, tank trails, or other military activities on Fort Benning.

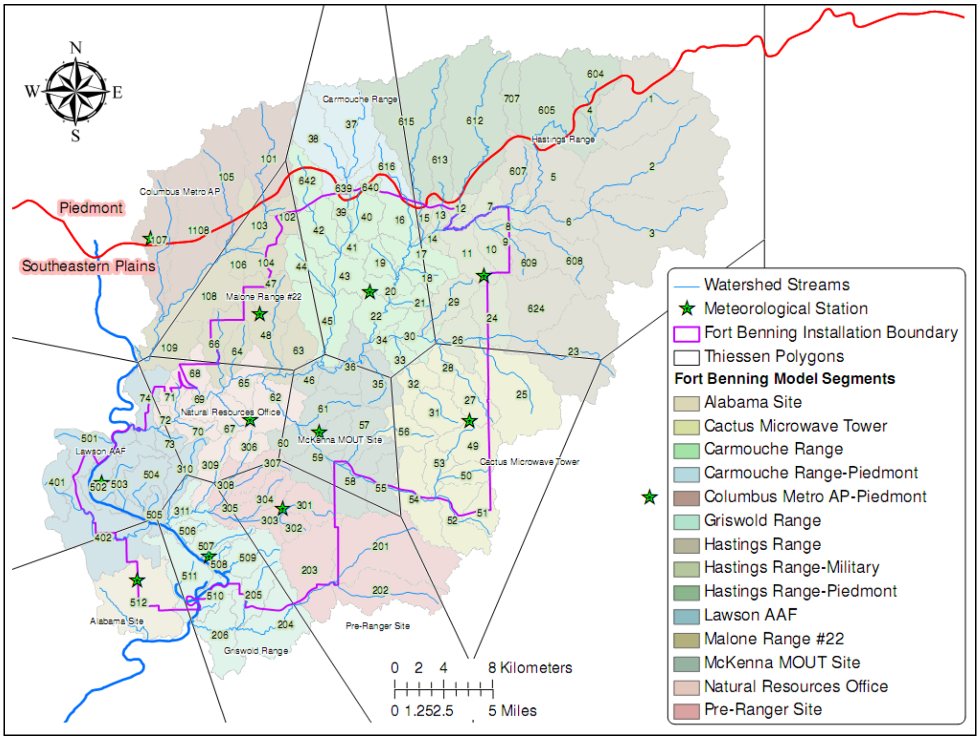


Figure 5 - Fort Benning watershed segmentation

Table 2 - Detailed land use distribution in the Fort Benning watershed

Landuse description	Area (ac.) in the complete watershed	Percent of area in complete watershed	Area (ac.) in the base	Percent of area in the base	Area (ac.) outside the base	Percent of landuse that is outside the base
Urban/Cantonment	40445.4	9.3	10410.7	5.7	30034.7	74.3
Evergreen Forest	99128.2	22.8	38840.6	21.3	60287.6	60.8
Deciduous Forest	134906.0	31.0	60304.8	33.1	74601.2	55.3
Mixed Forest	36816.3	8.5	22361.4	12.3	14454.9	39.3
Shrub/Scrub	12875.1	3.0	4784.4	2.6	8090.7	62.8
Grassland/Herbaceous	31638.7	7.3	13354.4	7.3	18284.2	57.8
Ag/Other	26566.2	6.1	0.0	0.0	26566.2	100.0
Paved Roads	10153.8	2.3	3000.4	1.6	7153.4	70.5
Tank Trails	241.0	0.1	241.0	0.1	0.0	0.0
Heavy Maneuver Areas	2289.6	0.5	2289.6	1.3	0.0	0.0
Water/Wetlands	28769.5	6.6	15204.8	8.3	13564.7	47.1
Unpaved Roads	11699.9	2.7	11640.8	6.4	59.2	0.5
Total	435529.6		182432.8		253096.9	

Data on roads within Fort Benning were obtained from the transportation page of the SEMP data repository which includes two categories of roads: unpaved roads and trails. Outside the Base, the roads layer was obtained from a seamless data distribution site. Location of tank trails was provided by Fort Benning (H. Westbury, personal communication, 2008). In addition, a military land use map developed by Dr. Virginia Dale (U.S. Army Fort Benning, 2006) which indicates tracked vehicle areas, wheeled vehicles areas, drop and landing zones, bivouac areas and other land use categories, was incorporated into our land use designations. The information on military land uses from these multiple sources was assimilated into a single land use GIS layer.

Imagery from Google EarthTM was consulted when discrepancies occurred between land use designations. Only line coverage was available for unpaved roads and tank trails. Therefore, tank trails were assumed to be 10m wide, and paved roads 30m wide (including ROW), with 85% impervious paved surface and 15% adjacent pervious buffer. The resulting comprehensive land use map for the entire watershed is illustrated in Figure 6.

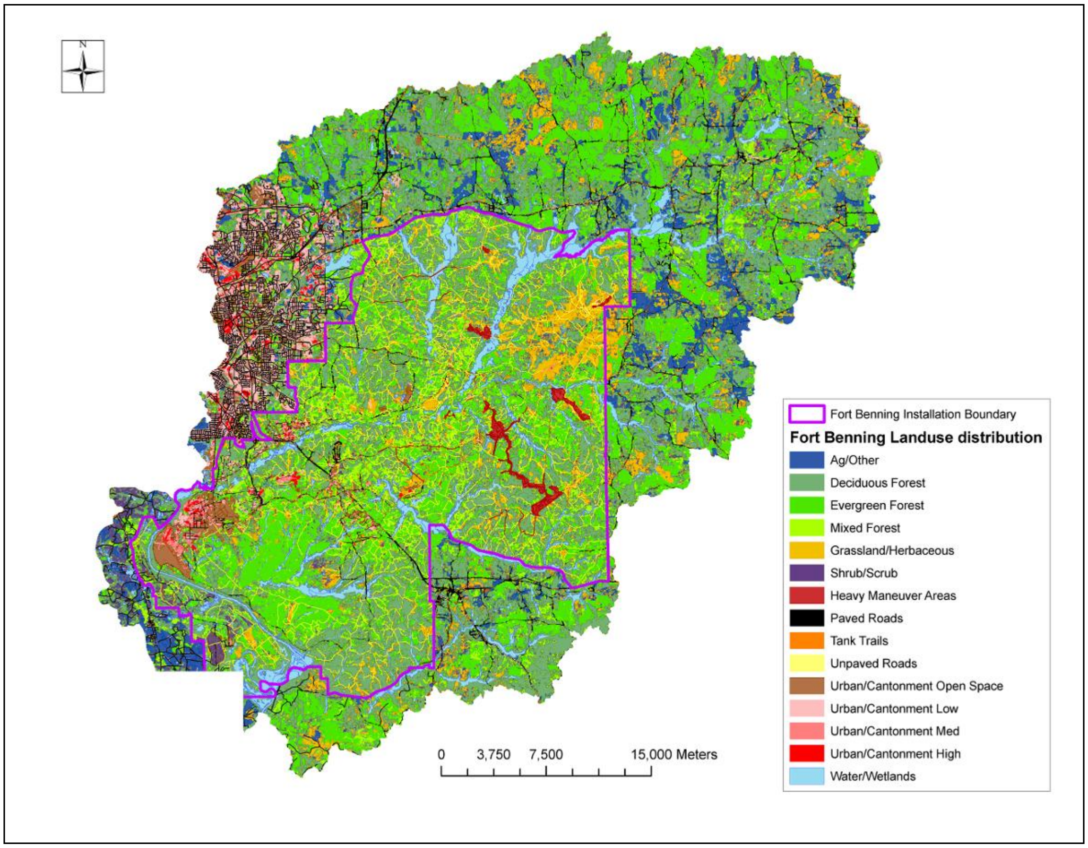


Figure 6 - Land use map of Fort Benning watershed

Prescribed Burning

Land management at Fort Benning, GA includes prescribed burning to promote healthy habitat for the Red-Cockaded Woodpecker (RCW) currently listed as an endangered species. Prescribed burning removes the herbaceous and woody shrubs beneath the forest stands that provide cover for the RCW predators; it also improves access for military training, timber management, and reduces fuel for wildfires. The land managers at Fort Benning follow a three year prescribed burn cycle, where about one-third of the forested areas in Fort Benning are burnt each year. Prescribed burn data for 7 FYs from 1999 to 2006 were compiled to estimate the areas that are burnt at regular intervals. All the areas that were subjected to at least one prescribed burn 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 obtain the type of forest burnt in each cycle.

PRELIMINARY RESULTS

Calibrated Baseline Model

Water years 2000 to 2006 offered the most meteorological and streamflow data and served as an appropriate time period for calibration. Hydrologic calibration was conducted by comparing the observed daily streamflow at Upatoi Creek at Fort Benning to simulated streamflow and adjusting the relevant model parameters. Tables 3 and 4 show the comparison of observed and simulated data for the hydrology calibration which are illustrated in Figure 7.

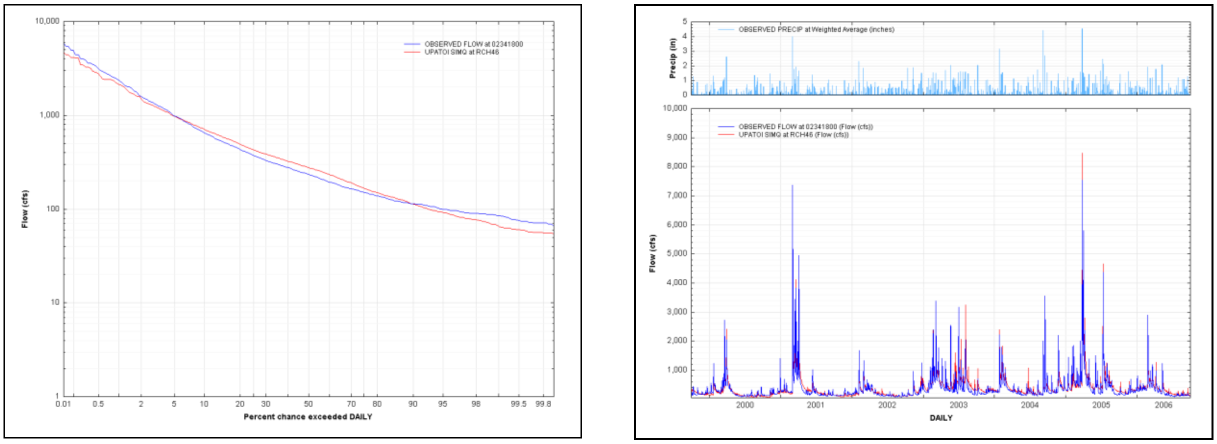
Table 3 - Comparison of observed and simulated flow annually for the simulation period

Year	Precipitation	Simulated	Observed	Residual	%Error
2000	31.37	9.24	9.99	-0.74	-7.44
2001	41.11	15.39	15.25	0.13	0.86
2002	32.51	7.45	7.88	-0.43	-5.46
2003	58.11	21.53	19.00	2.54	13.35
2004	44.04	15.05	12.91	2.14	16.59
2005	53.49	24.66	23.82	0.84	3.54
2006	37.37	12.67	10.82	1.85	17.14
Mean	41.57	15.14	13.36	0.90	5.51

Table 4 - Daily and monthly flow statistics for the simulation period

	Daily	Monthly
Correlation Coefficient, R	0.91	0.96
Coefficient of Determination, R^2	0.83	0.91
Mean Error, cfs	22.62	22.22
Mean absolute Error, cfs	107.89	67.75
RMS Error, cfs	200.64	87.58
Model Fit Efficiency	0.83	0.90

Model calibration involves a “weight-of-evidence’ approach comprised of multiple graphical and statistical comparisons of observed data and simulated values. Tables 3 and 4 and Figure 7 demonstrate some of these types of comparisons and the common statistical measures that are used. These results demonstrate a good to Very Good calibration, with a mean % error of 5.5% for annual volumes, R^2 values of 0.83 to 0.91 for daily and monthly comparisons, and corresponding model-fit efficiencies of 0.83 and 0.90. Figure 7 shows a good representation for both the daily flow timeseries and the flow duration curves, for the full range of expected flow regime.



(a) (b)

Figure 7 - Comparison Of Observed and Simulated (A) Flow Duration Frequency Curve, and (B) Daily Flow

Data for total suspended solids (TSS) were available for only a few storms during this calibration period at selected locations including the Upatoi Creek gage. The sediment calibration process involved establishing reasonable initial values for the parameters in HSPF surface sediment washoff formulations, and then adjusting them to gain agreement between computed loading rates and sediment loading targets that were established as a function of topography, soils, land use, and management practices using USLE and literature review. For details on sediment calibration on a HSPF model, please refer to Donigian and Love (2003). The preliminary sediment calibration results are illustrated in Table 5.

Table 5 - Sediment loading rates and percent contributions at Upatoi Creek at Fort Benning*

Land use	Washoff (tons/acre/year)	Total (tons/year)	Percent of Total Load	Land use Groups	Land use group percent
Urban/Cantonment	0.29	1514.73	1.74	Urban	1.74
E Forest	0.10	5567.86	6.38		
D Forest	0.11	7596.21	8.71		
M Forest	0.10	1584.00	1.82	Forest	16.90
Shrub/Scrub	0.27	1460.47	1.67	Shrub/Scrub	1.67
Grass/Herb	0.27	5663.86	6.49	Grass/Herb	6.49
Ag/Other	1.48	25644.20	29.39	Ag/Other	29.39
Paved Roads	0.22	179.51	0.21	Paved Roads	0.21
Tank Trails	7.02	1000.22	1.15		
Heavy Maneuver	12.12	19596.86	22.46		
Unpaved Roads	3.31	17320.89	19.85	Military	43.46
Water/Wetlands	0.01	127.33	0.15	Water/Wetlands	0.15
Total/WtdAvg	0.41	87195.95	100.00		

*These results are from preliminary sediment calibration after setting up the baseline watershed model. Please contact the authors before referencing these values.

Sediment and water quality calibration is continuing, but the preliminary model results indicate that military activities and land uses, as shown in Table 5 can possibly contribute more than 40% of the total sediment load while occupying less than 2% of the land area. Clearly, military activities are having a major impact on the stream system at Fort Benning.

Recommended Research Enhancements

Phase I of the research path assessed watershed model limitations of a general nature and modeling limitations unique to the representation of activities common to military installations. Each research area was assessed in terms of the nature of the enhancements needed, available supporting resources and methodologies, viable enhancement alternatives, and a recommended path forward. A systematic investigation of the initial list of research areas, a literature review, and assessment of the baseline model results and limitations resulted in the identification and evaluation of eight research areas.

1. **Multiple spatial scales:** Techniques and model capabilities that improve a modeler's ability to represent and evaluate combinations of sources and endpoints that have significantly different spatial scales.

2. **Sediment washoff/erosion related to military training activities:** Enhanced sediment washoff/erosion model science to accommodate impacts from military maneuvers and associated equipment.

3. **Sediment washoff/erosion related to forest road construction and maintenance activities:** Enhanced sediment washoff/erosion model science to accommodate impacts from unpaved roads.

4. **Channel phenomena.** This research topic includes three components: (1) channel flow: improved methods for modeling dynamic channel flows (particularly low and high flow events); (2) sediment transport: improved methods for modeling channel sediment transport (particularly for coarse sediments) and (3) stream bank erosion: integration of methods that enable representation of sediment loads introduced to streams by bank erosion or failure phenomena.

5. **Linkages to ecological indicators:** Development/integration of methods and tools that enable modelers to link watershed management practices to indicators of aquatic and terrestrial ecosystem impacts.

6. **Representation of forest canopy compartment and fire:** Improved representation of hydrologic and water quality processes for above-ground vegetation and forest canopy compartments. Improved methods/capabilities for representing the watershed effects of prescribed burning or wildfires.

7. **Diagnostic mode capabilities:** Improved methods/capabilities for using watershed models in a diagnostic mode, to assess and quantify source-effect relationships.

8. **Rating curve development and integration:** Investigate the value to the overall watershed simulation of having/using more or fewer flow rating curves at Fort Benning, to provide a basis for calibration of component sub-watersheds and potential for technology transfer to other military installations.

Investigations for five out of the eight research topics resulted in either (1) no recommended model code enhancements, due to current model capabilities and flexibility, (2) lack of detailed data on process impacts for formulations to be developed, or (3) recommended code enhancements that are sufficiently minimal that they will be achieved during and as part of the model application efforts. These were:

1. Military training (Lack of detailed investigation on process impacts, along with data on the location, intensity, duration, and frequency of activities limited the potential code/algorithm enhancements. Work is continuing)
2. Roads (coding requirements will be performed as an element of developing the generalized capability for hybrid modeling)
3. Ecological indicators (some enhancements were implemented during Phase 1)
4. Diagnostic mode capabilities
5. Rating curves

Investigations for the remaining three research topics did result in the recommendation of significant model code enhancements. These were: multiple spatial scales, channel phenomena, forest canopy compartment and canopy management.

1. **Multiple Spatial Scales.** A need is shared by many watershed managers, including the managers of military installations such as Fort Benning, for techniques and model capabilities that improve the ability to represent and evaluate combinations of sources and endpoints that have significantly different spatial scales. Watershed models and modeling efforts need improved ability to assess management-scale impacts within a larger watershed-scale context. To address this issue, a general capability to perform hybrid model applications will be implemented in which HSPF is used for modeling catchment-scale phenomena, while one or more field- or hillslope-scale models featuring more detailed process formulations for specific activities or land uses are run in parallel to HSPF to provide time series flow and loadings for smaller areas with large runoff or water quality impacts. The output from the small scale models will be linked to HSPF in the form of discrete point sources to targeted land segments or channel reaches.

2. **Forest Roads.** It is a repeated message throughout forestry literature that road erosion is commonly the largest contributor to sediment production within forest watersheds. Proper understanding, design, construction and management of unpaved roads at Fort Benning requires the use of credible methods and models for estimating sediment erosion and its impacts, and these models require a level of smaller-scale detail that surpasses the capabilities currently provided by HSPF. The forestry community considers USDA's WEPP:Road model as the state-of-the art model for estimating sediment yield from

unpaved forest roads. To make available a more robust set of formulations for simulating sediment washoff from Fort Benning's unpaved forest roads, the WEPP:Road will be used as a demonstration application of the hybrid modeling capability that will be developed for HSPF.

3. **Channel phenomena.** Improvements to three aspects of HSPF will provide significant benefit to model applications at Fort Benning and at other installations. These enhancements relate to simulation methods for instream flow, instream sediment transport, and bank erosion. Previous observations and studies have identified the vulnerability of Fort Benning's stream banks to erosion and failure under both wet and dry weather conditions. Representing the additional stream load caused by these sediment-generating phenomena requires improved algorithms for bank erosion, as well as instream sediment erosion and deposition of multiple size classes of sediment. Appropriate representation of high flow events is particularly critical to sediment transport simulations and provides the starting point for representing channel scour and deposition.

   To improve the flow module in HSPF, a hydrodynamic model needs to be added. A hydrodynamic model will provide a more accurate calculation of the flow field and resulting bed shear stresses (particularly during runoff events when the flow is unsteady and typically accelerates rapidly during the rising limb of the flow hydrograph) than is achievable with the flow routing routine currently in HSPF. To meet this need, the Environmental Fluids Dynamics Code (EFDC) will be integrated into HSPF.

   The sediment transport module in HSPF needs to be upgraded to add the improved capabilities for simulating scour and deposition. The SEDZLJ sediment transport model developed by Jones and Lick (2001) will be added to HSPF. SEDZLJ has all the capabilities identified as necessary improvements to the sediment transport model in HSPF. SEDZLJ is an advanced, state-of-the science sediment transport model that represents the dynamic processes of erosion, bedload transport, settling, bed sorting, armoring, consolidation of fine-grain sediment dominated sediment beds, and deposition. Multiple size classes of both fine-grain (i.e., cohesive) and noncohesive sediments can be represented in the sediment bed that is divided into a user specified number of bed layers.

   Currently the Fort Benning HSPF watershed model lacks a method for representing the generation of sediment loads due to events of bank erosion/failure. An empirical-based bank erosion model to HSPF will be added such that the estimated sediment mass from the eroding bank is added to the sediment bed for the channel reach where the eroding bank is located. This empirical model will calculate the lateral bank erosion rate (in units of bank length/day) as a linear function of the difference between the near-bank, depth-averaged velocity and the reach-averaged velocity at bank-full flow.

4. **Forest canopy and fire.** In a comprehensive environmental assessment of military training facilities such as Fort Benning, watershed modeling needs to take into account many aspects of the environment, most notably the plant community, as impacted by

forest management and prescribed burning treatment, in order to fully evaluate the hydrological consequences and ecological outcomes. Currently, HSPF represents the plant community via simple expressions of its functional relationship with other components of the hydrologic cycle and the nutrient cycle. This approach generally suffices in a hydrologic and water quality study; however, intensively disruptive events, such as prescribed burning, timber harvesting, etc., call for more complete representation of the plant community in terms of temporal dynamics of plant growth, related physical presence (e.g. canopy) for both overstory and understory vegetation, and substrate fluxes between the plant community and its soil environment. Increasing the level of explicit representation of these dynamic processes will provide HSPF with an ability to comprehensively evaluate the impact of prescribed burning and forest management, and also the potential ability to quantitatively evaluate ecological performance of a given landscape from a vegetation perspective. The following two enhancements will be implemented:

(1) Refine canopy processes in HSPF to accommodate multi-level forest conditions consistent and compatible with the current representation, and based on relatively simple model inputs comparable to the current HSPF formulations, i.e., adding another canopy (or multiple) layer for understory vegetation.

(2) Refine the model's ability to accommodate fire impacts, either through refined model capabilities or development of a separate 'fire' module to oversee and impose adjustments to reflect fire occurrence, intensity, and areal distribution within the watershed. A 'Fire' module would provide users with the flexibility to define the rate of return, parameter adjustments, and fire intensities, along with other needed information.

The other research areas, although significant model code enhancements are not recommended, remain high priorities areas for enhancing the Fort Benning baseline model. These areas have been addressed in part by the Phase I application path and/or other methods were recommended for incorporating new science and/or data into the baseline model. For instance, not enough data are available to characterize the impact of military training on watershed processes to allow for a justifiable code enhancement. However, this issue will be addressed by parameterization and use of current model capabilities to approximate the frequency, intensity, and timing of military training activities.

DISCUSSION

It is useful to re-visit the project flow schematic (Figure 3) in order to better understand how the results of Phase I facilitate the implementation of Phase II. The Fort Benning baseline model and the recommendations for research enhancements provide the input to refine modeling strategies and model scenarios to better represent and evaluate activities and management issues at Fort Benning, and the endpoints, indicators, and thresholds that were used for the preliminary model applications.

Phase II will involve the formulation of approaches to compare original model capabilities directly to enhanced model capabilities. Model code enhancements will be designed in detail, implemented and tested. An enhanced comprehensive watershed management model for Fort Benning will be developed and re-calibrated. The Fort Benning baseline model will be refined to test/demonstrate the operation and significance of enhancements. Simulations performed using the pre-project BASINS capabilities will be repeated using the enhanced capabilities to demonstrate the impact of the code improvements and extensions. The resulting watershed modeling results will be suitable for input to the aquatic ecosystem models, AQUATOX, and will enable installation managers to evaluate ecological endpoints.

AQUATOX predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants. AQUATOX can be used in conjunction with HSPF to evaluate impacts of land-based activities and management practices on aquatic ecosystems by means of either indicators (e.g., chlorophyll a, clarity) or ecological endpoints (e.g., fish). BASINS provides a direct linkage between HSPF results and AQUATOX.

Challenges remain for Phase II implementation, for example, some of these include consideration of the following:

1. Alternative land use coverages representing expected, or alternative, conditions to be evaluated for impacts on hydrology, water quality, and the aquatic ecosystem.
2. Focusing the future scenarios that might be simulated would help to identify other data needs, such as whether new model land uses/conditions will be needed to represent expected future conditions.
3. Translation of expected future training levels and activities into model representations and parameterization, e.g how will the new amour vehicles expected to be deployed at Fort Benning impact current conditions.
4. Discussion of whether areas outside the Fort Benning boundaries, i.e. neighboring areas, will be included in the future scenario simulations along with projected changes such as increased urbanization due to BRAC deployment levels.

CONCLUSIONS

The preliminary application of BASINS/HSPF to the Fort Benning watersheds to develop a baseline model required utilization of existing data provided by BASINS, and ECMI. The hydrologic and sediment concentration data, and sediment detachment targets were used to calibrate the model. The correlation coefficient of daily and monthly flow was greater than 0.9, and model fit efficiency for daily and monthly flow was greater than 0.8. Early calibration results indicate that although the military land use is only 3.3% of entire watershed, it is responsible for as much as 43.5% of sediment loading at the outlet. As the calibration is continuing, the preliminary results shown here were deemed acceptable for the initial model application. As the baseline model is refined and enhanced, these results are expected to greater insight into the source contributions of both military and non-military sources, as well as onsite and off-site (i.e., non-installation) contributions.

This model application presented unique challenges and provided an opportunity to identify necessary refinements and code enhancements for the comprehensive watershed management model for Fort Benning. Three significant enhancements to the HSPF code are planned:

1. **Multiple spatial scales:** As noted in the early stages of model calibration, sediment washoff resulting from military activities can be very important even though these activities occur on relatively small areas of the Installation. To simulate the processes occurring at smaller scales in an overall watershed modeling project, an ability to conduct model simulations at multiple spatial scales is sought. In this hybrid approach, a watershed scale model can be used to model the overall watershed, whereas a field- or hillslope-scale model featuring more detailed process formulations for specific activities, sources, or land uses can be run in tandem and provide time series and pollutant loadings that are then represented as point sources within the overall watershed scale model. Examples of activities in Fort Benning that occur in localized areas but have the potential to significantly affect the overall sediment loading are unpaved roads, tank trails and heavy maneuver areas.

2. **Enhanced channel flow and sediment simulation capabilities:** Improvements to three aspects of HSPF will provide significant benefit to model applications at Fort Benning and at other installations. Relevant capabilities of the Environmental Fluids Dynamics Code (EFDC) (Hamrick, 2007) will be integrated into HSPF to provide a more accurate calculation of the flow field and resulting bed shear stresses than is achievable with the hydraulics-based, flow routing routine currently in HSPF. The SEDZLJ sediment transport model developed by Jones and Lick (2001) will be added to HSPF to enable simulation of multiple size classes of both fine-grain and noncohesive sediments, thereby enabling improved capabilities for simulating channel scour and deposition. An empirical-based bank erosion model (Ikeda et al., 1981) will be added to HSPF since bank erosion is a significant contributor to stream sediment loadings at the Installation and the current model lacks a method for representing the generation of sediment loads due to events of bank erosion/failure.

3. **Vegetation growth and management:** HSPF does not have the capability to simulate the dynamic nature of watershed-specific management activities like prescribed burning, harvesting, clear cutting etc. on watershed hydrology. HSPF represents vegetation via simple expressions of its functional relationship with other components of the hydrologic cycle and the nutrient cycle. Preliminary model results suggest that significant benefits can be achieved by representing additional dynamic processes (e.g., plant growth) in HSPF, additional model compartments for both overstory and understory vegetation, and substrate fluxes between the plant community and its soil environment.

The enhancements that proposed will result in a significant improvement in the watershed models and modeling, in general, and specifically facilitate Fort Bennings understanding and management of its watersheds simulation capabilities and performance of HSPF. Phase II of this project will develop modeling strategies for the Fort Benning watershed that take full advantage of the new capabilities to provide a better planning tool to support land management decisions.

Demonstration studies designed and performed as part of Phase II will serve as a catalyst for application of the Military-Enhanced BASINS modeling system at other installations.

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