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Environmental Security Technology Certification Program

The Demonstration and Validation of a Linked Watershed-Riverine Modeling System for DoD Installations

User Guidance Report Version 2.0

Billy E. Johnson and Zhonglong Zhang

April 2021

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Final report

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Abstract

A linked watershed model was evaluated on three watersheds within the U.S.: (1) House Creek Watershed, Fort Hood, TX; (2) Calleguas Creek Watershed, Ventura County, CA; and (3) Patuxent River Watershed, MD. The goal of this demonstration study was to show the utility of such a model in addressing water quality issues facing DoD installations across a variety of climate zones.

In performing the demonstration study, evaluations of model output with regards to accuracy, predictability and meeting regulatory drivers were completed. Data availability, level of modeling expertise, and costs for model setup, validation, scenario analysis, and maintenance were evaluated in order to inform installation managers on the time and cost investment needed to use a linked watershed modeling system.

Final conclusions were that the system evaluated in this study would be useful for answering a variety of questions posed by installation managers and could be useful in developing management scenarios to better control pollutant runoff from installations.

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Acronyms

ASCE	American Society of Civil Engineers
BASINS	Better Assessment Science Integrating point and Non-point Sources
CBOD	Carbonaceous Biochemical Oxygen Demand
CEQ	Council on Environmental Quality
CSM	Contaminant Simulation Module
CTT&F	Contaminant Transport, Transformation, and Fate
CWA	Clean Water Act
DEM	Digital Elevation Map
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DOD	Department of Defense
EPA	Environmental Protection Agency
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FTABLE	Hydraulic Function Table
HEC-DSS	Hydrologic Engineer Center – Data Storage System
HEC-RAS	Hydrologic Engineer Center – River Analysis System
HSPF	Hydrological Simulation Program Fortran
IMPLND	Impervious Land Segment
LIDAR	Light Detection and Ranging
MV	Modeled Value
NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
NSE	Nash-Sutcliffe Efficiency
NSM	Nutrient Simulation Module
OV	Observed Value
PBIAS	Percent Bias
PERLND	Pervious Land Segment
QA/QC	Quality Assurance / Quality Control
RCHRES	Reach Reservoir
RMSE	Root Mean Square Error
RSR	RMSE-observations standard deviation ratio
TMDL	Total Maximum Daily Load
UNET	Unsteady Network
U.S.	United States
USGS	United States Geological Survey
WDM	Water Data Management

Preface

This study was conducted for the Department of Defense, Environmental Security Technology Certification Program (ESTCP) under MIPR number W74RDV70534593. The technical monitor was Dr. Kurt T. Preston.

The work was performed by the Water Quality and Contaminant Branch (WQCMB) of the Environmental Processes and Effects Division (EPED), U.S. Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Mr. Mark R. Noel was Chief; Mr. Warren P. Lorentz was Chief; and Dr. Elizabeth A. Ferguson was the Technical Director for Environmental Quality and Installations (EQ/I). The Deputy Director of ERDC-EL was Dr. Jack E. Davis and the Director was Dr. Edmond J. Russo.

The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

1 Introduction

1.1 Need for a linked watershed modeling system

This User Guidance Report discusses the background and drivers behind installations needing a linked watershed modeling system, a general description of the technology, standard performance measures that one must meet in order to have confidence in model results, and time and cost estimates associated with required tasks and various levels of expertise in gathering necessary data, setting up models, calibrating and validating models, and performing management scenarios based on questions that might be asked by installation managers.

1.2 Objective

The objective of this report is to inform the reader on how a linked watershed modeling system answers regulatory questions; data availability for model setup, calibration, and validation; and costs associated with personnel needed for the analysis.

1.3 Background

The National Environmental Policy Act (NEPA) requires all federal agencies to evaluate the environmental implications of their plans, policies, programs, and projects. In addition, Clean Water Act (CWA) regulations concerning water quality and effluent standards have grown exponentially in the past 20 years. Military impacts on training lands are well documented and understood (Milchunas, et al. 1999; Shaw and Diersing 1989). These impacts include soil compaction, complete loss of vegetative cover, increased erosion rates, and shifts from native vegetation communities. Consequently, since streams and rivers are functionally linked to the watershed, training can degrade water quality in the form of sediment, nutrient, and contaminant loading and general decline in aquatic ecosystem health (Quist, et al. 2003).

In addition to impacts from military training, deficient land use management practices outside of military installations can also pose a threat to installation natural resources and mission readiness. DoD installation missions and assets are increasingly threatened by encroachment which can include watersheds traversing both public/private and DoD property.

Encroachment is often caused by a lack of upstream land management practices that contribute to sediment loading, erosion, trash disposal, invasive plant species, and other environmental and biological stressors that ultimately impact the watershed at the DoD installation and the training mission. Erosion and sediment loading is exacerbated when there is an absence of flood control measures, and the river system at the installation is located within a flood plain. In some cases, DoD installations are located within a Tsunami inundation zone, and installation contained rivers are listed on the 303(d) list of impaired waters. These conditions, coupled with a lack of land management practices, create an unbalanced system that threatens installation assets, resources, and operational capabilities.

Quantitative assessments of past, current and future mission impacts on wetland and surface water ecosystems is often a difficult task requiring expensive monitoring efforts. Changing and/or extreme weather events and improper loading of a river with a variety of contaminants adds a high level of variability and uncertainty to preserving installation habitat(s), operation and maintenance of facilities, and conducting night/day military training exercises. As such, watershed modeling systems are becoming increasingly critical in assessing mission impact and managing military training lands.

Installation decision makers require a system that enables proactive decision making and strategic investments that support erosion and flood control measures, prevention of pollutant loading, preservation of critical habitat, mission readiness enabled by unhindered military training exercises and promotes buy in from a variety of stakeholders. The linked Hydrological Simulation Program –Fortran [HSPF]-Hydrologic Engineering Center- River Analysis System [HEC-RAS] (HSPF/HEC-RAS) model provides predictions so that managers can determine optimum times for training in addition to being used to evaluate mitigation scenarios supporting issues with flow, sediment, and/or constituent runoff. HSPF and HEC-RAS are mechanistic models with a track record of performing military as well as non-military analyses. They all are able to use available national databases and cover all climatic regions, hence making them transferrable to all military installations.

1.4 Regulatory drivers

The two major national regulatory drivers at military installations are: 1) NEPA; and 2) CWA. These acts are intended to ensure that surface runoff into our nation’s waterways meet minimum water quality criteria. The linked watershed modeling system simulates flow, sediment, nutrient, and contaminant runoff. Model results can be compared to human and ecosystem health benchmarks in order to assess whether or not a site is compliant. If a site is not compliant then the modeling system can incorporate best management practices (BMP) to show load reductions and concentrations that do meet the regulatory guidelines.

1.4.1 National Environmental Policy Act (NEPA)

NEPA was signed into law by President Richard Nixon on January 1, 1970. Acknowledging the decades of environmental neglect that had significantly degraded the nation's landscape and damaged the human environment, the law was established to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and to fulfill the social, economic, and other requirements of present and future generations of Americans.

NEPA advanced an interdisciplinary approach to Federal project planning and decision-making through environmental impact assessment. This approach requires Federal officials to consider environmental values alongside the technical and economic considerations that are inherent factors in Federal decision making. Environmental impact assessment also calls for the evaluation of reasonable alternatives to a proposed Federal action; the solicitation of input from organizations and individuals that could potentially be affected; and the unbiased presentation of direct, indirect, and cumulative environmental impacts. This information is used by a Federal official before a decision is made. Doing so results in informed, and ultimately, improved Federal decision making.

CEQ’s regulations (40 C.F.R. Parts 1500-1508) set the standard for NEPA compliance. They also require agencies to create their own NEPA implementing procedures. These procedures must meet the CEQ standard while reflecting each agency's unique mandate and mission.

1.4.2 Clean Water Act

The Clean Water Act (CWA) establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. The basis of the CWA was enacted in 1948 and was called the Federal Water Pollution Control Act, but the Act was significantly reorganized and expanded in 1972. "Clean Water Act" became the Act's common name with amendments in 1972.

Under the CWA, EPA has implemented pollution control programs such as setting wastewater standards for industry. EPA also sets water quality standards for all contaminants in surface waters. The CWA made it unlawful to discharge any pollutant from a point source into navigable waters, unless a permit was obtained. EPA's National Pollutant Discharge Elimination System (NPDES) permit program controls discharges.

2 Technology/Methodology Description

2.1 Technology/Methodology overview

The linked modeling system provides predictions so that training range managers can determine optimum times for training, in addition to being used to evaluate mitigation scenarios supporting issues with flow, sediment, and/or constituent runoff. This linked modeling system has been applied for multiple installations to demonstrate application of the methodology (Johnson, et al. 2015, 2017; Johnson and Zhang 2018).

The modeling systems are available for download along with detailed documentation describing the model theory and user's manuals to help in training people on their use. These modeling systems have been used across broad spatial (acres to many square miles) and temporal scales (seconds to years) which allows one the flexibility to solve a host of environmental modeling problems associated with military installations. These modeling systems require the user to have a working knowledge of hydraulics, hydrology, erosion and sedimentation, and water quality. Based on previous experience, a person with a Bachelor of Science degree in the Water Resources and Land Management technical areas along with two to five years of work experience should be able to set up, use, and interpret model results. One of the goals of this demonstration study is to verify that this is the case for the linked watershed modeling approach.

Computationally, both of the proposed models (HSPF and HEC-RAS) are able to simulate years to decades in a matter of minutes to a few hours of computer time. These models are mature systems that have excellent documentation and training opportunities. For each system, a user should be able to take a one to two week training session, per model, and be able to setup, parameterize, and run the respective model.

As with any numerical model, these models do need to be calibrated and validated for each new application site. If these models are used over a long period of time, then it may be necessary to recalibrate them as more data becomes available. In calibrating either model, a sufficiently long data set needs to be gathered whereby model results can be compared with field observations. One portion of the data set is used for the calibration phase and the remainder of the period of record is used to validate the model parameters. In the calibration phase, those parameters that are deemed most sensitive to the simulations are allowed to vary within acceptable ranges until the model results best fit the field observations. Once this has been accomplished then the remainder of the period of record is used to simulate model results with the parameters unadjusted. If the model results are able to reproduce the field observations within acceptable error criteria, then the model is said to be validated and useful for making predictions. This process, while not difficult, can be time consuming due to having to make many model runs and parameter adjustments.

HSPF was used to compute watershed processes while HEC-RAS was used for the riverine environment. HSPF simulates for extended periods of time the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. HSPF is a valuable tool to land managers. Because it is more comprehensive than most systems, it permits effective planning. Benefits to the user include:

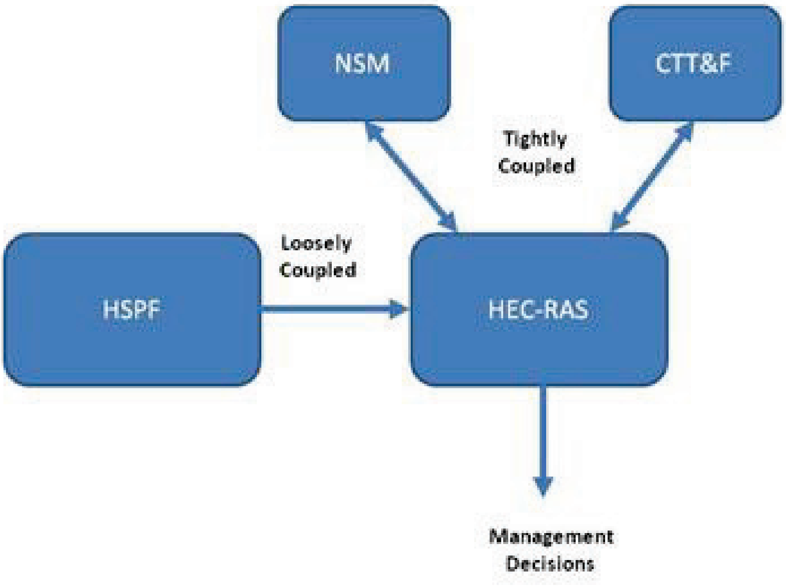
- Flexibility in solving a wide range of water quantity and quality problems using a single model

- Convenient data management features that save time and money

- Modular program structure which facilitates program changes and additions for special applications

While HSPF encompasses flow, sediment, nutrients, and contaminants within its model formulations, HEC-RAS has been integrated with the Nutrient Simulation Module (NSM) and the Contaminant Transport, Transformation, and Fate (CTT&F) sub-model, thus providing flow, sediment, nutrient, and contaminant fate and transport within the riverine environment, Figure 2.1.

Figure 2-1. Model integration strategy.’



2.1.1 HSPF (Hydrological Simulation Program—Fortran)

HSPF simulates for extended periods of time the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. The model uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs (Bicknell et al, 2005). HSPF simulates 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, and zooplankton. 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 done for any time series. Any time step, from one minute to one day, into which one day can be equally divided, 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 Water Data Management (WDM) file.

2.1.1.1 Pervious land segments

A land segment (polygon) 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 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.

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 for estimating the outflow temperatures and influencing reaction rates in the agri-chemical sections, and determining outflow temperatures which influence the solubility of oxygen and carbon dioxide.

2.1.1.2 Impervious land segments

In an impervious land segment (polygon), 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 snow and air temperature components perform functions that can be applied to pervious or impervious segments, they are shared by both modules.

2.1.1.3 Streams and reservoirs

This module simulates the processes which occur in a single reach of open or closed channel or a completely mixed lake. 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.

2.1.2 HEC-RAS (Hydrologic Engineering Center - River Analysis System)

The HEC-RAS system contains four one-dimensional river analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; (3) movable boundary sediment transport computations; and (4) water quality analysis (via NSM and CTT&F). A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

2.1.2.1 Steady flow water surface profiles

This component of the modeling system is intended for calculating water surface profiles for steady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regimes water surface profiles.

The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning’s equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation may be used in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e. hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions).

The effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain may be considered in the computations. The steady flow system is designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. Also, capabilities are available for assessing the change in water surface profiles due to channel improvements, and levees.

Special features of the steady flow component include multiple plan analyses; multiple profile computations; multiple bridge and/or culvert opening analyses; and split flow optimization.

2.1.2.2 Unsteady flow simulation

This component of the HEC-RAS modeling system is capable of simulating one-dimensional unsteady flow through a full network of open channels. The unsteady flow equation solver was adapted from the UNET model (Barkau 1992 and HEC 1997). The unsteady flow component was developed primarily for subcritical flow regime calculations. However, with the latest release of HEC-RAS, the model can now perform mixed flow regime (subcritical, supercritical, hydraulic jumps, and drawdowns) calculations in the unsteady flow computations module.

HEC-RAS solves the complete one-dimensional Saint-Venant equations of unsteady flow. The model is able to simulate back water flow effects and a variety of hydraulic structures, thus allowing one to model tidally influenced streams and rivers. As an example, the National Weather Service used HEC-RAS to model the Potomac River under tidal influence (Mashriqui, et al. 2010) using observed time series as the tidal boundary conditions.

The hydraulic calculations for cross-sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow module.

Special features of the unsteady flow component include: dam break analysis; levee breaching and overtopping; pumping stations; navigation dam operations; and pressurized pipe systems.

2.1.2.3 Sediment transport/Movable boundary computations

This component of the modeling system is intended for the simulation of one-dimensional sediment transport/movable boundary calculations resulting from scour and deposition over moderate time periods (typically years, although applications to single flood events are possible).

The sediment transport potential is computed by grain size fraction, thereby allowing the simulation of hydraulic sorting and armoring. Major features include the ability to model a full network of streams, channel dredging, various levee and encroachment alternatives, and the use of several different equations for the computation of sediment transport.

The model is designed to simulate long-term trends of scour and deposition in a stream channel that might result from modifying the frequency and duration of the water discharge and stage or modifying the channel geometry. This system can be used to evaluate deposition in reservoirs, design channel contractions required to maintain navigation depths, predict the influence of dredging on the rate of deposition, estimate maximum possible scour during large flood events, and evaluate sedimentation in fixed channels.

2.1.2.4 NSM (Nutrient Simulation Module)

The NSM includes two kinetics: NSMI, NSMII. The levels of NSM are determined by the number of interacting state variables involved in water quality simulation and the degree of their interactions. NSMI simulates nutrients and eutrophication processes using 16 state variables. Water quality state variables may be individually activated or deactivated. Using 24 state variables, NSMII simulates nutrients and eutrophication processes in the water column. Sediment oxygen demand and nutrient release can be simulated using zero-order approach or a sediment diagenesis module. Carbon, nitrogen and phosphorus have complex cycles that are mediated by physical, chemical, and biotic processes in the water and in the bed sediment. The NSMI consists of three nitrogen species, two phosphorus species, three carbon species (particulate organic carbon, dissolved organic carbon, and dissolved inorganic carbon). Algae, benthic algae, DO, CBOD, pathogen, and alkalinity are also simulated in NSMI. The incorporation of NSM water quality capabilities in HEC-RAS provides a fully integrated riverine hydraulic, sediment and water quality model that encompasses diagnostic, predictive, and operational applications that greatly aid in Total Maximum Daily Load (TMDL) development and implementation required by the Clear Water Act.

2.1.2.5 CTT&F (Contaminant Transport, Transformation and Fate)

Contaminant Transport, Transformation, and Fate [CTT&F] sub-model was renamed as the Contaminant Simulation Module (CSM) in HEC-RAS.

The CSM is capable of modeling contaminants in an aquatic system as influenced by the following processes: ionization, multi-phase partitioning, degradation, photolysis, hydrolysis, volatilization, generalized second-order reaction, and transformations where one chemical undergoes a reaction and is transformed to a daughter product. Any process in CSM can be ignored by use of switches where such processes are not applicable. Each contaminant in the water column is subject to adsorption and desorption with dissolved organic carbon (DOC) and solids. The dissolved phase in the bulk water (aqueous phase), the adsorbed phase to DOC in the bulk water, and the adsorbed phases to organic and inorganic solids are simulated in CSM. Two types of contaminant partitioning options are included for algae and solid particulates; equilibrium and non-equilibrium, in which adsorption/desorption can be affected by rate limiting processes. The water column exchange with underlying sediments and exchange with the atmosphere are also simulated in CSM. The CSM can model multiple contaminants in one simulation. The contaminants themselves are arbitrary, in that the specific contaminant to be simulated is defined through the specification of processes and kinetic rates.

2.2 Advantages and limitations of the technology/methodology

HSPF simulates the hydraulics in the river channel network by using a simplified hydraulic function table (FTABLE) of water depth, surface area, water volume, and outflow of a reach. The FTABLE in the HSPF model is the essential component for flow routing in reaches. It describes a fixed functional relationship between water depth, surface area, water volume, and outflow in the river reach. Under the assumption of a fixed depth, area, volume, and outflow relationship, the HSPF model cannot account for reverse flow and backwater effects to the upstream reaches in a time-dependent way. It is very important to perform the flow routing process accurately because routed results affect sediment routing and the in-stream contaminant process, both of which are strongly tied to water routing. The limitations of a standalone HSPF model (HSPF-Only) and the demands of assessing the attainability of contaminant standards derived from the model-based results require additional capabilities not available within HSPF. These needed capabilities can be accomplished through the linked HSPF/HEC-RAS system. For the HEC-RAS boundary requirements, HSPF provides discharge, sediment and contaminant loads from the major streams and drainages tributary to the HEC-RAS model segments. HSPF is used to estimate flow, sediment, and water quality loadings based on watershed characteristics and land use practices for all demonstration sites. HEC-RAS is used to estimate in-stream aquatic sediment and contaminant concentrations and to relate these concentrations to the contaminant criteria. Therefore, a linked modeling system, HSPF/HEC-RAS, should better address regulatory compliance and the range of environmental migration pathways and potential exposures.

The overall ESTCP project calls for sequential demonstrations at Fort Hood (House Creek watershed), Naval Base Ventura County Point Mugu (Calleguas Creek watershed), and Fort Meade (Patuxent River watershed). Application of the linked models for the three demonstration installations was conducted and is described elsewhere (Johnson, et al. 2015, 2017; Johnson and Zhang 2018). In order to demonstrate the improvements HSPF/HEC-RAS may have over HSPF-Only, the Performance Objectives and Assessments (PO 1 through PO 7) discussed in Chapters 3 and 6 of the demonstration reports (Johnson et al, 2015, 2017; Johnson and Zhang 2018) were assessed for HSPF-Only and HSPF/HEC-RAS. In cases where no improvement was observed between HSPF-Only and HSPF/HEC-RAS, we discuss the factors that contribute to no improvement and make recommendations for the cases where a linked modeling system may not be advantageous to an installation.

Given that HSPF/HEC-RAS computes more state variables than HSPF-Only, one limitation may be the availability of field data sufficient to calibrate and validate the system for all the required model state variables. As a part of this demonstration, we have assessed existing data being collected at the various sites to see if sufficient data is being collected; if not, then we have made recommendations on additional sampling efforts that could improve the models.

Model linkage procedures must consider spatial and temporal characteristics of the systems being linked, correspondence and transference of the state variables between the models, and file format specifics for proper communications between two models. All of these issues must be adequately investigated and analyzed to ensure proper representation of the watershed and riverine system.

3 Discussion of Performance Objectives

Performance metrics include qualitative and quantitative parameters. Quantitative parameter threshold values are based on the recommended model performance evaluation statistics from literature review (ASCE, 1993; Moriasi, et al. 2007). Qualitative parameters are based on visual comparison of modeled and observed data and previous modeling experience. According to Legates and McCabe (1999), graphical techniques are essential to appropriate model evaluation. A graph is defined as a time series plot of modeled results and observed data throughout the calibration and validation periods. Time series graphs, for example Figure 3-1 and 3-2, help identify model bias and can identify differences in timing and magnitude of peak flows. Performance metrics are organized by demonstration/validation study component and methodology component.

Figure 3-1. Example Time Series Plot: monthly streamflow volume time series for Patuxent River near Bowie, MD (Segment: XU3_4650_0001).

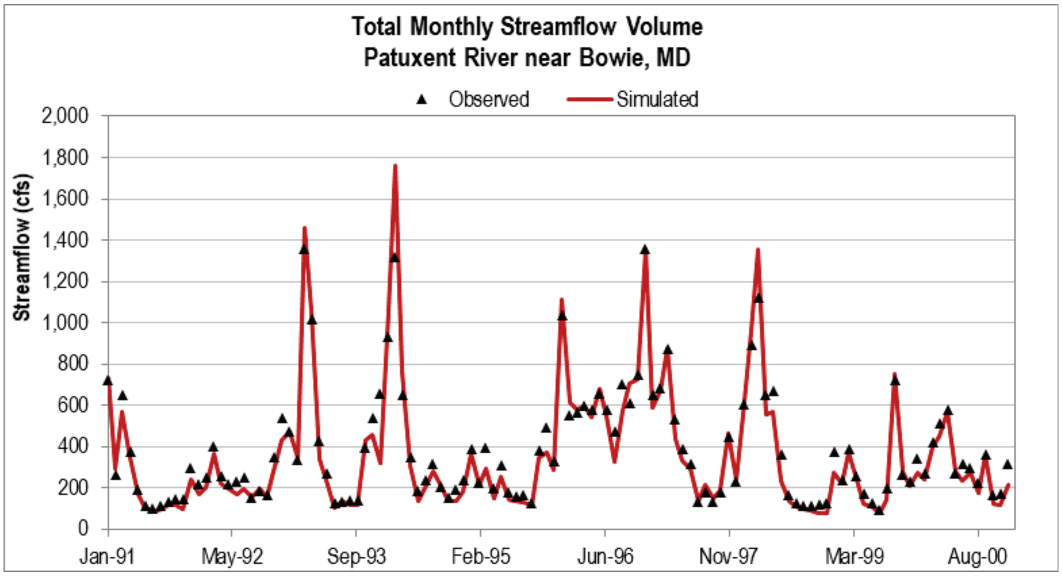
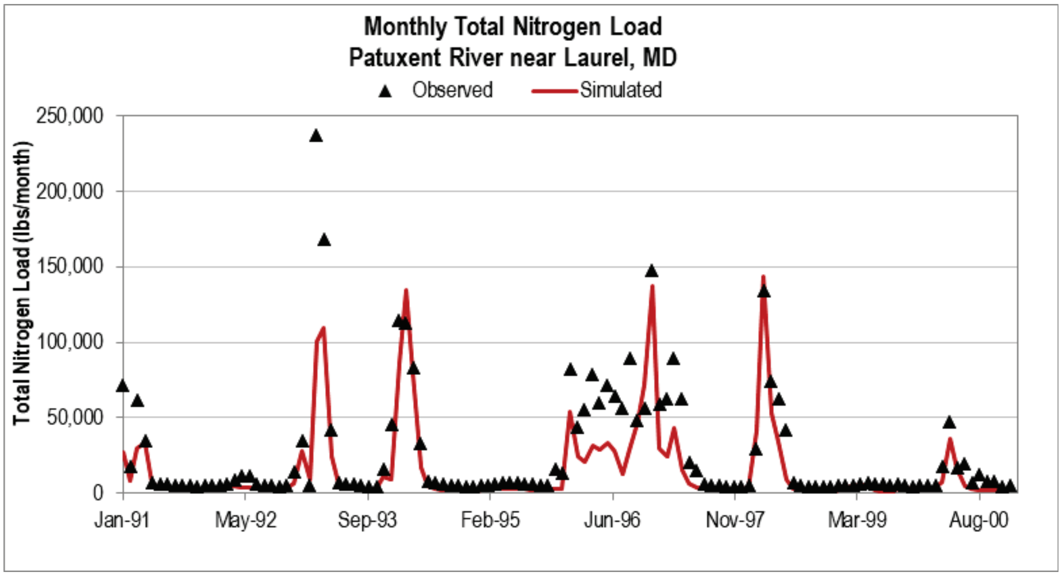


Figure 3-2. Example Time Series Plot: monthly total nitrogen load time series for Patuxent River near Laurel, MD (Segment: XU2_4330_4480)



Three statistical measures were used to assess how well the linked modeling system performed when compared to observed data: 1) Nash-Sutcliffe Efficiency (NSE); 2) Percent Bias (PBIAS); and 3) RMSE-observations standard deviation ratio (RSR). Table 3.2 indicates the general performance ratings for recommended statistics for a monthly time step.

3.1 Nash-Sutcliffe Efficiency (NSE)

NSE is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the observed data variance (“information”). NSE indicates how well the plot of observed versus modeled data fits the 1:1 line. NSE ranges between -∞ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicate that the mean observed value is a better predictor than the modeled value, which indicates unacceptable performance.

$$NSE = 1.0 - \frac{\sum_i (OV_i - MV_i)^2}{\sum_i (OV_i - \overline{OV})^2} \qquad (3.1)$$

Based on Moriasi et al., 2007, a “successful” NSE for flow, sediment, contaminants, and nutrients will be greater than 0.5.

NSE is the best objective function for reflecting the overall fit of a hydrograph (shape, peak, timing, etc.).

3.2 Percent Bias (PBIAS)

PBIAS measures the average tendency of the modeled data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. PBIAS has the ability to clearly indicate poor model performance.

$$PBIAS = \frac{\sum_i \left(OV_i - MV_i\right)}{\sum_i OV_i} * 100 \qquad (3.2)$$

Based on Moriasi, et al. 2007, a “successful” PBIAS for monthly and peak flows will be less than 25 percent; for monthly sediment, less than 55 percent; for peak sediment, less than 70 percent; and for monthly and peak contaminants and nutrients it will be less than 70 percent.

PBIAS is commonly used to quantify water balance (streamflow volume) errors and can be easily extended to evaluate load (mass load) errors.

3.3 RMSE-Observations Standard Deviation Ratio (RSR)

RSR standardizes root mean square error (RMSE) using the observations’ standard deviation. RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor so that resulting statistics and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower the RSR, the lower the RMSE, and the better the model simulation performance.

$$RSR = \frac{RMSE}{OV_{STDEV}} = \frac{\sqrt{\frac{1}{n}\sum_i (OV_i - MV_i)^2}}{\sqrt{\frac{1}{n}\sum_i (OV_i - \overline{OV})^2}} \qquad (3.3)$$

where n is the number of observations during the simulation period, OV_i =

observed value, = mean observed value, MV_i = modeled value, $\overline{MV}$ = mean modeled value.

Table 3-1. General performance ratings for recommended statistics.

Stream Flow			
Statistical Modeling Metrics	**Performance Rating**	**Daily Average**	**Monthly Average**
Nash-Sutcliffe (NSE)	Very Good Good Satisfactory Unsatisfactory	NSE>=0.5	0.75<=NSE<=1.0 0.65<NSE<=0.75 0.5<=NSE<=0.65 NSE<0.5
RMSE-observation standard deviation ratio (RSR)	Very Good Good Satisfactory Unsatisfactory	RSR<0.8	0.0<=RSR<=0.5 0.5<RSR<=0.6 0.6<RSR<=0.7 RSR>0.7
Percent Bias (PBIAS %)	Very Good Good Satisfactory Unsatisfactory	PBIAS<=|35|	PBIAS<|10| |10|<=PBIAS<|15| |15|<=PBIAS<|25| PBIAS<=|25|
Sediment load discharging			
Statistical Modeling Metrics	**Performance Rating**	**Daily Average**	**Monthly Average**
Nash-Sutcliffe (NSE)	Very Good Good Satisfactory Unsatisfactory	NSE>=0.25	NSE>0.4
RMSE-observation standard deviation ratio (RSR)	Very Good Good Satisfactory Unsatisfactory	RSR<0.9	RSR<0.75
Percent Bias (PBIAS %)	Very Good Good Satisfactory Unsatisfactory	PBIAS<=|75|	PBIAS<|15| |15|<=PBIAS<|30| |30|<=PBIAS<|55| PBIAS<=|55|
Water Quality/Nutrients			
Statistical Modeling Metrics	**Performance Rating**	**Daily Average**	**Monthly Average**
Nash-Sutcliffe (NSE)	Very Good Good Satisfactory Unsatisfactory	NSE>=0.35	NSE>0.5
RMSE-observation standard deviation ratio (RSR)	Very Good Good Satisfactory Unsatisfactory	RSR<0.85	RSR<0.7
Percent Bias (PBIAS %)	Very Good Good Satisfactory Unsatisfactory	PBIAS<=|85|	PBIAS<|25| |25|<=PBIAS<|40| |40|<=PBIAS<|70| PBIAS<=|70|

4 Cost Assessment

A main objective of this demonstration study was to provide accurate estimates of HEC-RAS and HSPF implementation time and costs associated with land management activities.

4.1 Time and cost for initial model development, calibration, and validation

Time and Cost associated with various study activities are summarized in Table 4.1. In estimating costs, the following expertise and associated labor rates were used:

B.S. Engineer	\$100/hr
M.S. Engineer	\$135/hr
Ph.D. Engineer	\$170/hr

Table 4-1. Cost model.

Cost Element	Cost Sub-element	Data Tracked
Data Processing		Data needed for building model input for HSPF and HEC-RAS
B.S. \$100/hr	Topography 16 hrs \$1,600	USGS Digital Elevation Maps (DEM) and Light Detection and Ranging (LIDAR), where applicable, for developing topographic delineations.
B.S. \$100/hr	Channel Cross-sections 80 hrs \$8,000	Existing surveyed channel cross-sections and LIDAR data sets, collected and processed into FTABLES for HSPF and Irregular shaped cross-sections for HEC-RAS.
B.S. \$100/hr	Land use 40 hrs \$4,000	Land use/Land cover data, gathered from installation sources to create surface roughness, conservation practice, soil erosion, and constituent loadings for HSPF.
B.S. \$100/hr	Soil Texture 16 hrs \$1,600	Soil texture maps, gathered from the U.S. Department of Agriculture in order to compute soil erosion and infiltration for HSPF.

Cost Element	Cost Sub-element	Data Tracked
B.S. $100/hr	Precipitation/Meteorological 80 hrs $8,000	Precipitation/Meteorological data collected from local sources and the National Climatic Data Center (NCDC) in order to compute rainfall and evaporation. In addition to precipitation, the following meteorological data need to be collected: • barometric pressure, • relative humidity, • total sky cover, • wind speed, • dry bulb temperature, • direct radiation, • global radiation.
B.S. $100/hr	Flow 80 hrs $8,000	Local and USGS sources of flow data, to calibrate the HSPF and HEC-RAS models.
B.S. $100/hr	Sediment 80 hrs $8,000	Local and USGS sources of sediment data, to calibrate the HSPF and HEC-RAS models.
B.S. $100/hr	Nutrient 80 hrs $8,000	Local sources of nutrient data, to calibrate the HSPF and HEC-RAS models. Local sources include local universities, storm water districts, and on-going projects within the project boundaries.
B.S. $100/hr	Contaminant 80 hrs $8,000	Local sources of contaminant data to calibrate the HSPF and HEC-RAS models. Local sources include local universities, storm water districts, and on-going projects within the project boundaries.
Cost Element	**Cost Sub-element**	**Data Tracked**
Model Setup - HSPF		The following is a discussion of the tasks to be tracked in setting up the HSPF models.
M.S. $135/hr	Overland 40 hrs $5,400	Using gathered land use data, pervious (PERLND) and impervious land (IMPLND) segments need to be determined for each HSPF subarea. Associated model parameters and contaminant loading can then be estimated based on PERLND and IMPLND designations.
M.S. $135/hr	Channel 40 hrs $5,400	Using gathered channel cross-sections and LIDAR information, develop FTABLES for each river segment (RCHRES).

Cost Element	Cost Sub-element	Data Tracked
B.S. $100/hr	Precipitation/Meteorological 40 hrs $4,000	Process all precipitation and meteorological data such that they can be imported into the Water Data Management (WDM) system. WDM controls the input and output time series data for HSFP.
B.S. $100/hr	Flow 40 hrs $4,000	Process all flow monitoring data such that they can be imported into WDM.
B.S. $100/hr	Sediment 16 hrs $1,600	Process all sediment monitoring data such that they can be imported into WDM.
B.S. $100/hr	Nutrients 16 hrs $1,600	Process all nutrient monitoring data such that they can be imported into WDM.
B.S. $100/hr	Contaminants 16 hrs $1,600	Process all contaminant monitoring data such that they can be imported into WDM.

Cost Element	Cost Sub-element	Data Tracked
Model Setup – HEC-RAS		The following is a discussion of the tasks to be tracked in setting up the HEC-RAS models.
B.S. $100/hr	Channel 40 hrs $4,000	Using gathered channel cross-sections and LIDAR information, develop irregular shaped channel cross-sections for each river segment.
B.S. $100/hr	Boundary Conditions 8 hrs $800	Transition HSPF output from WDM into the Data Storage System (HEC-DSS). HEC-DSS controls the input and output time series data for HEC-RAS.
B.S. $100/hr	Flow 8 hrs $800	Process all input and calibration/validation flow data, not imported from WDM, such that they can be imported into the DSS.
B.S. $100/hr	Sediment 8 hrs $800	Process all input and calibration/validation sediment data, not imported from WDM, such that they can be imported into the DSS.
B.S. $100/hr	Nutrients 8 hrs $800	Process all input and calibration/validation nutrient data, not imported from WDM, such that they can be imported into the DSS.
B.S. $100/hr	Contaminants 8 hrs $800	Process all input and calibration/validation contaminant data, not imported from WDM, such that they can be imported into the DSS.

Cost Element	Cost Sub-element	Data Tracked
Model Calibration and Result Analysis - HSPF		The following is a discussion of the tasks associated with analyzing HSPF output.
M.S. $135/hr	Flow 160 hrs $21,600	Compare observed flow data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
M.S. $135/hr	Sediment 80 hrs $10,800	Compare observed sediment data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
Ph.D. $170/hr	Nutrients 160 hrs $27,200	Compare observed nutrient data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
Ph.D. $170/hr	Contaminants 80 hrs $13,600	Compare observed contaminant data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
Cost Element	**Cost Sub-element**	**Data Tracked**
Model Calibration and Result Analysis – HEC-RAS		The following is a discussion of the tasks associated with analyzing HEC-RAS output.
M.S. $135/hr	Flow 160 hrs $21,600	Compare observed flow data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
M.S. $135/hr	Sediment 80 hrs $10,800	Compare observed sediment data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
Ph.D. $170/hr	Nutrients 160 hrs $27,200	Compare observed nutrient data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.
Ph.D. $170/hr	Contaminants 80 hrs $13,600	Compare observed contaminant data to model simulations. Compute the appropriate model statistics and adjust model parameters until successful model statistics are computed.

Cost Element	Cost Sub-element	Data Tracked
Training		Cost of labor for person to learn how to develop and apply the linked watershed riverine modeling system. Costs based on number of hours of training per person trained and average employee cost/hour. Cost data is collected during single training event activities. Costs scaled by multiplying number of people trained by cost per person. Generally, training costs are cost per responsible employee.
B.S. $100/hr	Data processing 40 hrs $4,000	Cost of labor for person to learn data processing and data QA/QC procedures. Cost is based on number of hours of training per person trained.
M.S. $135/hr	Model Setup 80 hrs $10,800	Cost of labor for person to learn how to set up a HEC-RAS and an HSPF model. Cost is based on number of hours of training per person trained.
Ph.D. $170/hr	Model Result Analysis 160 hrs $27,200	Cost of labor for person to learn data analysis procedures. Cost is based on number of hours of training per person trained.

The total cost for gathering data, setting up the models, calibrating and validating the models, and analyzing model results is the following for each technical level: B.S. Engineer is $76,000, M.S. Engineer is $75,600, and Ph.D. Engineer is $81,600, for a total project cost of $233,200. The total training cost for each technical level is $4,000, $10,800, and $27,200 for B.S., M.S., and Ph.D. levels, respectively. In order to keep the models updated on an annual basis with new data, calibration, and validation, it is estimated that an installation would need to provide $30,000/yr in model maintenance cost.

4.2 Management Scenarios

Estimating lifecycle costs required assumptions about technology use. This is because the different cost elements are associated with different management scenarios and periodic updates of model information necessary to keep the linked system current. Data analysis costs are generally a cost per question asked, since the question could require multiple model simulations. These estimates are made assuming that calibrated and validated models exist from section 4.1 and only require some level of updating for use in answering the management questions.

The following Management Scenarios were selected based on being typical scenarios that might be assessed on a DoD installation. They cover flooding, sediment, contaminant allocation, and evaluation of BMP to reduce pollutant loads from an installation.

1. Scenario 1: An installation that needs to estimate flooding effects on cantonment or training areas and the impact on installation operations, Table 4-2.
2. Scenario 2: An installation that needs to estimate sediment runoff due to land use changes made by military operations, Table 4-3.
3. Scenario 3: An installation needs to estimate contaminant runoff due to military operations. In addition, an installation may also be interested in how much contaminant at an off-site decision point is due strictly to military operations as opposed to off-site commercial activities, Table 4-4.
4. Scenario 4: An installation may be interested in investigating best management practices (BMP) to mitigate sediment and/or contaminant runoff due to military activities, Table 4-5.

Table 4-2. Lifecycle Cost – Management Scenario 1.

Task	Time (hrs)	Cost ($)
Simulate models for flood frequency storm (M.S. $135/hr)	40	5,400
Map Flood Extent (B.S. $100/hr)	16	1,600
Determine duration of flood inundation and how that affects installation operations (M.S. $135/hr)	40	5,400

Task	Time (hrs)	Cost ($)
Reporting and Documentation (M.S. $135/hr)	40	5,400
Total	136	17,800

Table 4-3. Lifecycle Cost – Management Scenario 2.

Task	Time (hrs)	Cost ($)
Update land use map (B.S. $100/hr)	16	1,600
Incorporate updated land use map into HSPF model (M.S. $135/hr)	16	2,160
Simulate and Analyze model results (M.S. $135/hr)	40	5,400
Reporting and Documentation (M.S. $135/hr)	40	5,400
Total	112	14,560

Table 4-4. Lifecycle Cost – Management Scenario 3.

Task	Time (hrs)	Cost ($)
Estimate contaminant loading due to military operations (M.S. $135/hr)	40	5,400
Estimate contaminant loading due to off-site commercial activities (M.S. $135/hr)	40	5,400
Perform model simulations and analysis (Ph.D. $170/hr)	80	13,600
Reporting and Documentation (M.S. $135/hr)	40	5,400
Total	200	29,800

Table 4-5. Lifecycle Cost – Management Scenario 4.

Task	Time (hrs)	Cost ($)
Determine which BMP are most applicable to the installation (M.S. $135/hr)	40	5,400
Implement the BMP into the models (M.S. $135/hr)	80	10,800
Perform model simulations and analysis (Ph.D. $170/hr)	160	27,800
Reporting and Documentation (M.S. $135/hr)	40	5,400
Total	320	49,400

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14. ABSTRACT

A linked watershed model was evaluated on three watersheds within the U.S.: (1) House Creek Watershed, Fort Hood, TX; (2) Calleguas Creek Watershed, Ventura County, CA; and (3) Patuxent River Watershed, MD. The goal of this demonstration study was to show the utility of such a model in addressing water quality issues facing DoD installations across a variety of climate zones.

In performing the demonstration study, evaluations of model output with regards to accuracy, predictability and meeting regulatory drivers were completed. Data availability, level of modeling expertise, and costs for model setup, validation, scenario analysis, and maintenance were evaluated in order to inform installation managers on the time and cost in-vestment needed to use a linked watershed modeling system.

Final conclusions were that the system evaluated in this study would be useful for answering a variety of questions posed by installation managers, and could be useful in developing management scenarios to better control pollutant runoff from installations

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