The Housatonic River Watershed Model: Model Application and Sensitivity/Uncertainty Analyses

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Abstract
The Housatonic River, its sediment, and associated floodplain have been contaminated with polychlorinated biphenyls (PCBs) and other hazardous substances released from the General Electric Company facility in Pittsfield, Massachusetts. Evaluation of risks posed to human health and the environment from contaminated sediment often requires the application of watershed/hydrodynamic/ water-quality models and contaminant fate and bioaccumulation models to address the range of environmental migration pathways and potential exposures. For this study, a linked modeling system was developed and applied to the Housatonic River and surrounding watershed using the following modeling components:

- Watershed Model (**Hydrological Simulation Program – FORTRAN** (**HSPF**))
- Hydrodynamic and Sediment/Contaminant Transport and Fate Model (**Environmental Fluid Dynamics Code** (**EFDC**)).
- Bioaccumulation Model (**Food Chain Model** (**FCM**)), derived from **QEAFDCHN** Version 1.0.

This paper describes the sensitivity and uncertainty analyses performed on the calibrated and validated **HSPF** model application.

Keywords
HSPF; sensitivity; uncertainty; watershed model; streamflow; sediment; water temperature

INTRODUCTION

The Housatonic River, its sediment, and associated floodplain have been contaminated with polychlorinated biphenyls (PCBs) and other hazardous substances released from the General Electric (GE) Company facility in Pittsfield, Massachusetts. The GE/Housatonic River site has been subject to regulatory investigations dating back to the early 1980s. The Consent Decree entered by U.S. District Court in October 2000 provides for, among other things, the cleanup and environmental restoration of the Housatonic River and its floodplains extending downstream of the Pittsfield facility located in western Massachusetts.

Evaluation of risks posed to human health and the environment from contaminated sediment often requires the application of watershed/hydrodynamic/water-quality models and contaminant fate and bioaccumulation models to address the range of environmental migration pathways and potential exposures. For this study, a linked modeling system was developed and applied to the Housatonic site and the surrounding watershed using the following modeling components (Figure 1):

- Watershed Model (**Hydrological Simulation Program – FORTRAN** (**HSPF**) (Bicknell et al, 2005)).
- Hydrodynamic and Sediment/Contaminant Transport and Fate Model (**Environmental Fluid Dynamics Code** (**EFDC**)).
- Bioaccumulation Model (**Food Chain Model** (**FCM**)), derived from **QEAFDCHN** Version 1.0.

The primary goal of this work was to evaluate alternative remediation scenarios for a 12-mile segment of the Housatonic River, referred to as the primary study area (PSA), using the linked system of models and to

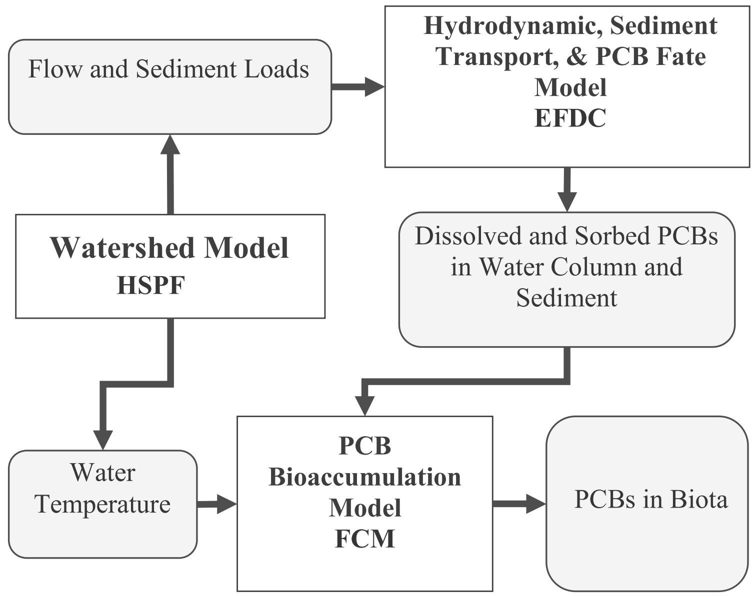

Figure 1. Housatonic River Watershed Integrated Modeling Framework.

calculate the uncertainty in model predictions. This paper describes the sensitivity analysis (SA) and uncertainty analysis (UA) performed on the calibrated and validated **HSPF** model application. Details and reference citations can be found in the study reports (Weston Solutions, Inc., 2004, 2006).

METHODS

Before performing the sensitivity and uncertainty analyses, the **HSPF** model application was calibrated and validated. Model calibration was performed for an 11-year period, 1990–2000, while validation was performed with both a split sample procedure for 1979–1989 and 2001–2004 and the entire 1979–2004 period of record. The model calibration used a "weight-of-evidence" approach to model performance assessment and is described in the Quality Assurance Project Plan (QAPP) for the Housatonic Modeling Study (Beach *et al.*, 2000). Based on the discussion and the "weight-of-evidence" results presented in Weston Solutions, Inc. (2004, 2006), the watershed model was determined to provide a very good representation of flow and water temperature and a reasonable representation of sediment loadings within the Housatonic River Watershed.

Sensitivity Analysis

Almost 4 decades of experience with the **HSPF** model and predecessor models has provided a strong foundation for identifying the most sensitive model parameters for most climatic, edaphic, and physiographic watershed settings. However, sensitivity of model results to parameters in a specific watershed, like the Housatonic, depends on the combined impacts of climate and watershed conditions as reflected in the parameter values produced during the calibration phase. In other words, sensitivity for a specific watershed is a function of the specific combination of parameter values that reflect climate and watershed characteristics which control the hydrologic response, along with the sediment and water temperature behavior. To assess the sensitivity of the Housatonic Watershed model, the following steps were performed:

1. Identify the critical model input and parameters, based on past experience and the specific calibration experience for the Housatonic Watershed.
2. Identify reasonable percent perturbations from the calibration values, increases and decreases, for each model input and parameter.

3. Assess the resulting changes to ensure the absolute differences in input and parameters are reasonable and appropriate.
4. Perform a 25-year model run using the calibration parameters as a baseline simulation.
5. Perform model runs for the entire 25-year period, with each run representing a single input/parameter change.
6. Process the model sensitivity run results to calculate the percent difference from the baseline and the sensitivity factor, defined as the percent change in model output divided by the percent change in input/parameter value.
7. Rank the model input and parameters by the sensitivity metric to establish those with the greatest impact on model results.

The specific model output values for each model run which provide the basis for the sensitivity analyses include: (1) mean annual streamflow, cubic feet per second (cfs); (2) mean annual runoff, inches; (3) 10 percent highest flows (i.e., mean flow exceeded 10 percent of the time), cfs; (4) 25 percent lowest flows (i.e., mean flow exceeded 75 percent of the time), cfs; (5) average peak flow (average of 62 selected storms), cfs; (6) mean annual total suspended solids (TSS) loadings, tons/year; (7) mean annual water temperature, °F; and (8) mean summer water temperature (June – August), °F. All of these quantities were produced by the model at six stream site locations throughout the Housatonic Watershed; additional details are provided in (Weston Solutions, Inc., 2004; 2006).

Uncertainty Analysis

A Monte Carlo approach to UA was performed for the watershed model involving execution of 600 model runs, each for the 11-year time period of water years 1990–2000, with selected model parameters being randomly chosen from assigned Bounded Normal (NO) or Bounded Lognormal (LN) probability distributions. The parameters that were randomly varied were determined based on the results from the SA, i.e., those with high sensitivity factors. Bounded distributions were used for two reasons: to ensure parameter values stayed within physically realistic limits for the Housatonic Watershed and within computational limits imposed by **HSPF**. In assigning distributions, each parameter was first characterized in terms of whether it reflected soil, climate, vegetation, sediment, or general site characteristic, or some combination of these. Then an LN distribution was assigned for the soil- and sediment-related parameters and NO distributions were assigned for the others. A number of articles on soil hydrologic and hydraulic characteristics (see Weston Solutions Inc., (2006) for citations) clearly confirm a general consensus that soil properties more often demonstrate LN distributions, and the LN generally is preferred over an NO distribution. To address the issue of parameter correlation, major parameters were identified and grouped that were clearly related because they represented similar soil, sediment, or vegetation characteristics of the watershed. Consequently, these parameters were correlated in terms of any perturbation performed as part of the UA, and an appropriate correlation structure was incorporated into the parameter perturbations generated for each model run. Fortunately, the **Sandia Latin Hypercube Sampling** (**LHS**) software (Wyss and Jorgensen, 1998) used in this effort implements a nonparametric technique known as rank correlation that allows the user to specify which model parameters to correlate within a sample. The method preserves the sampling scheme; i.e., the same numbers originally selected as input values are retained; only their pairing is affected to achieve the desired rank correlations (Iman and Conover, 1982). Thus for each correlated group, the parameters perturbations were correlated so that their values changed in the same direction and with similar magnitudes; i.e., they each increased or decreased together for each model run.

The model results were processed for the same output variables and locations as used in the SA to analyze and quantify the expected uncertainty in the model predictions. Quality assurance efforts focused on assessing both the plausibility of parameter distributions and model results and the stability of the Monte Carlo procedures. Model parameters generated for the Monte Carlo runs were plotted and checked for adherence to their assigned distributions and bounds, and model results were checked in comparison to the full range of calibration/validation results. Stability refers to the sensitivity of the outcome of interest to the sample size (i.e., number of runs) and was checked by analyzing the convergence behavior of the expected result as model runs were performed. After confidence was gained in the Monte Carlo methodology and procedures, uncertainty in the model predictions was expressed by calculating the 5th and 95th percentiles of the ranked output, representing the range for 90 percent of the model results. The differences between the mean value and the 5th and 95th percentiles values were calculated, divided by the mean and expressed as percentages, and averaged to express uncertainty as the percent deviation from the mean. Normalizing to the mean allowed for uncertainty comparisons to be made between the output variables (i.e., flow, TSS, temperature) and within specific percentiles of output variables; e.g., uncertainty in the 10 percent highest flows, 25 percent lowest flows, and throughout the flow duration curve.

Operationally, a number of different codes and software components were used to generate the parameter distributions, update the **HSPF** input file (UCI file), execute the run, and process the output. The overall process is organized within a Matlab© framework and uses Sandia **LHS** software to generate the parameter values for the NO and LN distributions, in-house scripts to revise the UCIs, and Matlab© again to execute **HSPF** and process the output.

RESULTS AND DISCUSSION

Sensitivity Analysis

The sensitivity factor previously discussed was calculated as the ratio (expressed as a percentage) of the average absolute percent change in model output for the two model runs to the average absolute percent change in input/parameters. Values near 100 percent indicate a 1:1 sensitivity with the model producing a result in direct proportion to the input/parameter change; e.g., a 10-percent change in input/parameter produces a 10 percent change in model results. In a similar fashion, values of the sensitivity factor near 200 percent indicate a highly sensitive response of 2:1, whereas a value of 10-percent indicates relative model insensitivity of 0.1:1, where a 10-percent input/parameter change produces only a 1 percent model response.

The sensitivity results were displayed in graphics such as Figure 2, referred to as “tornado diagrams.” Within each diagram, the input/parameters are shown on the left ordinate, ranked by the sensitivity factor (highest to lowest) which is listed on the right ordinate. The bottom horizontal scale shows the “percent difference” from the baseline values, while the top horizontal scale shows the absolute values of the model results. Within the figures, the vertical center line is the mean value from the baseline run, with the width of the horizontal line for each model input/parameter representing the model results from the parameter perturbations. Of the 30 model input/parameters that were analyzed, only a subset have significant impacts and show high sensitivity to each of the model output quantities; thus, each figure ranks and displays only the input/parameters with sensitivity factors greater than 2–3 percent .

Review of these model sensitivity results provides the following observations:

- All model results are the most sensitive to the input of precipitation and air temperature, reflecting the importance of accurately representing climate conditions for the watershed.
- Precipitation, as expected, dominates all the model output related to flow and sediment loads, with air temperature occupying the top spot for the water temperature results. Precipitation sensitivity factors approach or exceed 200 percent for all the flow output and are in the range of 300–500 percent for annual TSS loads.

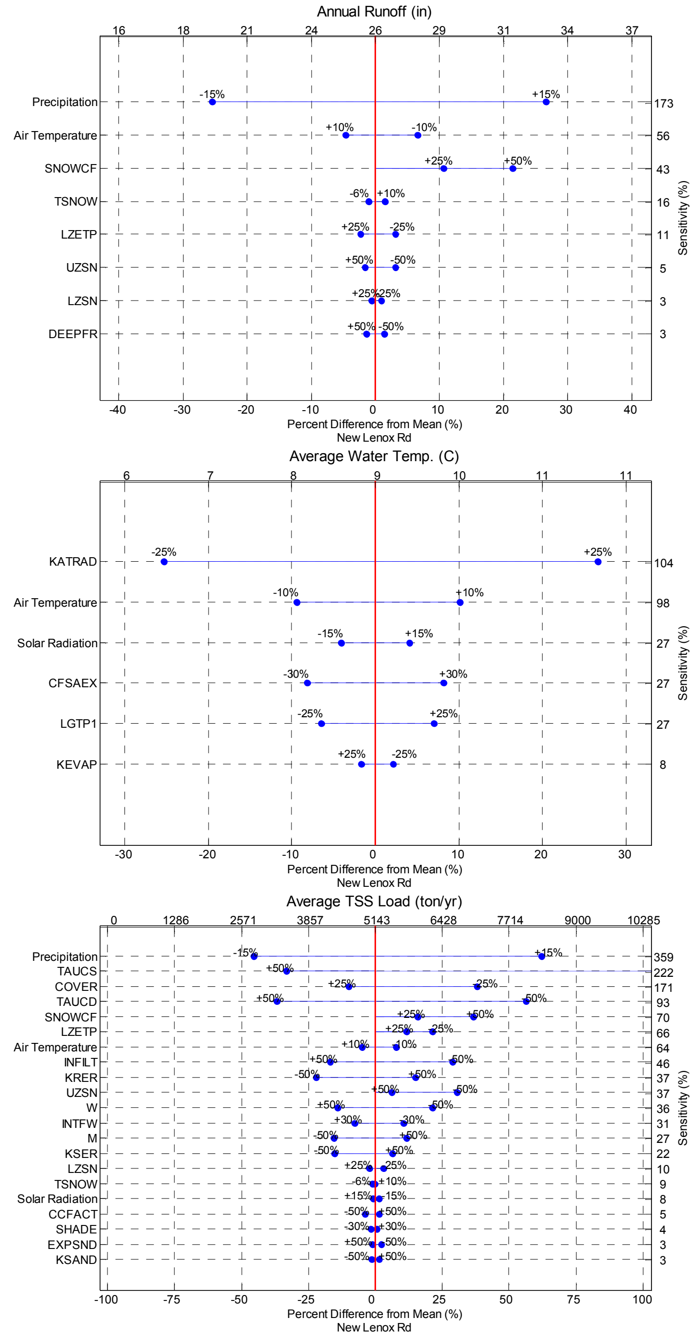

Figure 2. Example Tornado Diagrams at New Lenox Road.
(Conversion Factors: 1 in = 2.54 cm; 35.3 cfs = 1 cms; 1 short ton = 0.907 metric tons)

- For flow results, the next most sensitive parameters are related to the snow simulation, SNOWCF and TSNOW, reflecting the impact of snow accumulation and melt on the hydrology of the Housatonic River Watershed. SNOWCF increases the recorded gage precipitation for deficiencies in accurately recording snowfall amounts; thus, it has a direct impact on input precipitation during the winter months. TSNOW, which is the threshold temperature between rain and snow, only affects the form of precipitation and not the amount.
- Soils-related parameters are next in importance, followed by sensitivity, including infiltration (INFILT), soil/plant evapotranspiration (LZETP), and soil moisture storages (UZSN, LZSN). These parameters

show greater sensitivity for high and low flows values and for average storm peaks than for the mean annual runoff and flow.
- Average TSS loads are also sensitive to the forcing functions of precipitation and air temperature since they control the runoff and streamflow that supplies the source and transport mechanisms for TSS. However a larger number of parameters show some degree of sensitivity for TSS since both hydraulic and sediment processes are important.
- For water temperature sensitivity, the forcing functions of air temperature and solar radiation are high on the list at all sites, along with instream heat exchange (KATRAD) and surface exposure (CFSAEX) parameters.

Uncertainty Analysis

Following the quality assurance and stability checks indicating that the Monte Carlo simulation was stable and reasonable, the results of the model runs were analyzed to determine the 90 percent range representing the values between the 5th and 95th percentiles. These were determined using Matlab©, by rank ordering the 600 values, high to low, to identify the 30th value and the 571st value regions. For the majority of the output variables, the percentiles were calculated based on the annual mean values that resulted from each of the runs. For each of the six sites, the 5th and 95th percentile values were determined for each of the output variables; the results of this analysis are presented in Table 1. These values represent the range that encompasses 90 percent of the values produced by the 600 runs.

In addition, a flow duration curve was generated for each of the model runs at each site. This information was processed in the same manner as noted above, allowing us to generate a mean along with the 5th and 95th percentile for selected flow-interval durations. Ultimately, this resulted in flow duration graphics for each site with three curves that show the mean bounded by the 5th and 95th percentile flow durations. An example flow duration curve for each site is shown in Figure 3.

A summary uncertainty statistic, referred to as "Percent Uncertainty" in the tables, was calculated as:

$$\text{Percent Uncertainty} = ((\text{95th Percentile} - \text{5th Percentile}) / \text{Mean}\ ) / 2 \times 100 \qquad (1)$$

This allows comparison of uncertainty among the different variables analyzed in this effort, as follows:

- As shown in Table 1, the overall level of uncertainty is lowest for all the flow metrics, slightly higher for the water temperature metrics, and as expected, highest for the sediment metrics.
- The mean annual streamflow and runoff show identical "percent uncertainty" values in the range of 10–11 percent, with high flows in the range of 17–20 percent, and low flows in the range of 27-31 percent. Greater uncertainty at the extreme flows–both high and low–is expected, and is demonstrated in the flow duration uncertainty results in Figure 3.
- The "Percent Uncertainty" for the output variables analyzed, as shown in Table 1, is very consistent among all the sites analyzed. The mean annual sediment load is an exception; it shows the largest variation and increases with increasing drainage area.
- The uncertainty levels for water temperature are low and similar for both the mean summer and mean annual values, in the range of 10–15 percent.

CONCLUSIONS

Formal uncertainty analyses with **HSPF** applications have not historically been done, largely due to the complexity and computational demands of most watersheds modeled with **HSPF**. To address the need for uncertainty analyses for this project while recognizing such restrictions when complex codes are involved,

Table 1. 5th to 95th Percentile Ranges and Percent Uncertainty of Output Variables

	Mean Streamflow (cfs)	Mean Annual Runoff (in/yr)	10% High Flow (cfs)	25% Low Flow (cfs)	Mean Summer Water Temperature (C)	Mean Annual Water Temperature (C)	Mean Annual Sediment Load (ton/yr)
Coltsville - Reach 110							
5th Percentile	105	27	220	27	13.9	6.1	448
Mean	116	30	267	37	18.9	8.9	4,599
95th Percentile	129	33	311	49	23.3	12.2	9,785
Percent Uncertainty	10%	10%	17%	29%	13%	11%	102%
New Lenox–Reach 540							
5th Percentile	272	27	533	88	14.4	6.1	77
Mean	300	30	638	118	18.9	8.9	13,870
95th Percentile	332	34	738	152	22.8	11.7	47,654
Percent Uncertainty	10%	10%	16%	27%	12%	10%	172%
Great Barrington–Reach 900							
5th Percentile	519	27	1,040	149	15.0	6.1	165
Mean	576	30	1,273	211	21.1	10.0	15,522
95th Percentile	640	34	1,558	281	26.7	13.3	72,223
Percent Uncertainty	11%	11%	20%	31%	15%	13%	232%

(Conversion Factors: 1 in = 2.54 cm; 35.3 cfs = 1 cms; 1 short ton = 0.907 metric tons)

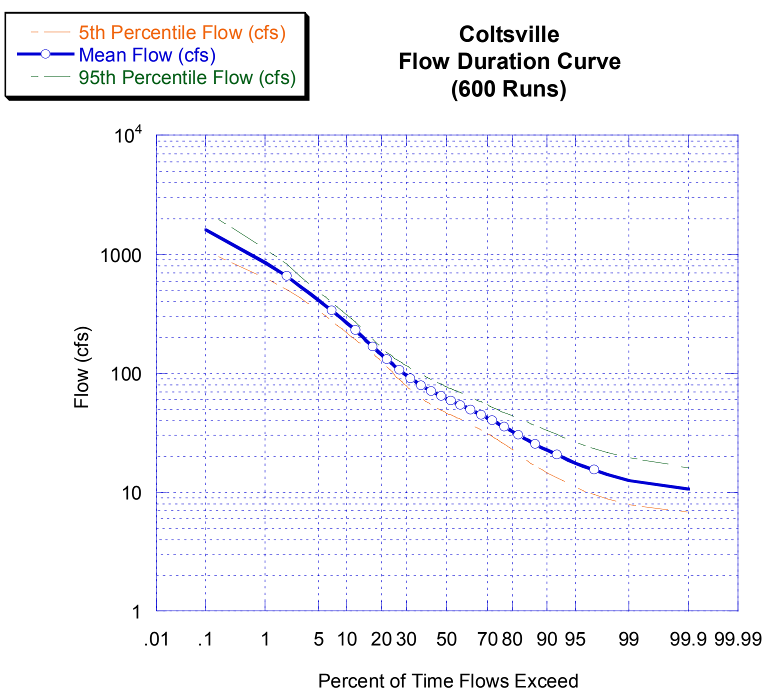

Figure 3. Flow Duration Curves Showing Mean, 5th, and 95th Percentile Flows.

the approach was to identify key parameters using a SA and then to focus on the model uncertainty associated with those **HSPF** parameters identified as most "sensitive."

The SA results demonstrated the critical importance of accurate and representative climate forcing data to adequately perform watershed modeling for the Housatonic River. The results also expose the significant impact of snow-related parameters and processes, the effects of instream scour and heat exchange parameters, and less sensitive impacts of soil parameters. However, it should be noted that climate data are not adjusted during model calibration, so the model parameters noted above are the primary tools by which the model must be calibrated to achieve performance and accuracy targets. Furthermore, the sensitivity results also support the need to consider, and help to identify, those parameters that impact each of the various model-data comparisons performed as part of the weight-of-evidence approach to model calibration and validation.

The subsequent UA results showed that the uncertainty associated with flow and water temperature where similar to the level of agreement with available data for an acceptable calibration. Thus a high level of confidence can be placed in the representative nature of the **HSPF** boundary conditions for flow and water temperature. However, the uncertainty for the boundary watershed sediment loads provided to **EFDC** can contain significantly higher levels of uncertainty.

This project provided an opportunity to develop a new and inventive methodology for performing an uncertainty analysis with **HSPF** that future projects can continue to emulate and refine.

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