Watershed and Receiving Water Model Linkage With HSPF: Issues and Example Applications

Anthony S. Donigian, Jr., P.E., AQUA TERRA Consultants, Mountain View, CA 94043
Brian R. Bicknell, AQUA TERRA Consultants, Mountain View, CA 94043
Jason T. Love, P.E., RESPEC, Rapid City, SD 57703

ABSTRACT

Capabilities of watershed models have continued to evolve over the past decade, with advances in computing power and scientific knowledge to greatly improve the ability to represent complex watersheds and water systems with increasing detail, both spatially and temporally. In many cases, watershed models must be linked to lake, estuary, or other detailed receiving water models in order to adequately represent the intricacies of the physical system under study. Watershed models are often called upon to provide “boundary conditions,” both hydrologic/hydraulic and nonpoint source loading fluxes, to the receiving water 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 the computer codes. All of these issues must be adequately investigated and analyzed to ensure proper and appropriate representation of the complex water system.

The United States Environmental Protection Agency (US EPA) Hydrologic Simulation Program – FORTRAN (HSPF) has been applied to hundreds of watersheds within the United States and abroad over the past 2 decades. In recent years, a number of these studies have required linkage with more detailed hydrodynamic and water-quality receiving water models in order to adequately represent complex watersheds and water systems. This paper describes a few recent model linkage efforts to demonstrate the temporal, spatial, and state variable issues that arise when such complex water modeling systems must be linked.

KEYWORDS

Simulation, watershed, waterbodies, water quality, nonpoint loads, boundary conditions

INTRODUCTION

Over the past decade, the United States Environmental Protection Agency (US EPA) Hydrologic Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 2001) has been applied to numerous water systems that require linkage to other receiving water models as part of total maximum daily loads (TMDLs), watershed and water quality management, and environmental impact assessment. These linkage efforts have included the following:

- Assessment of polychlorinated biphenyls (PCB) contamination in the Upper Housatonic River with HSPF linked to the Environmental Fluid Dynamics Code (EFDC) (Hamrick,
• Investigation of nutrient criteria for the Minnesota River with HSPF linked to the AQUATOX (Park and Clough, 2004) aquatic ecosystem model.
• Comprehensive watershed and water quality assessment in King County, Washington, with HSPF linked to EFDC and the US Army COE CE-QUAL-W2 (Cole and Buchak, 1995) and CH3D-ICM (Cerco and Cole, 1995) models

Although HSPF includes detailed receiving water hydraulic and water quality capabilities, in each of these examples, the demands of the study objectives and/or the specific characteristics of the receiving water system required additional capabilities not available within HSPF.

This paper reports on each of these studies to explore and demonstrate model linkage issues that arise, and methods of resolution, when complex models such as those noted above must be interfaced in order to address real-world water management concerns. Although linkage procedures must be specific to the models being linked and the physical systems being represented, this paper helps to identify and demonstrate appropriate linkage procedures for these examples considering spatial and temporal differences, model state variables, and linkage mechanics.

UPPER HOUSATONIC RIVER HSPF-EFDC LINKAGE

The Housatonic River, its sediment, and associated floodplain have been contaminated with PCBs and other hazardous substances released from the General Electric Company (GE) facility in Pittsfield, Massachusetts (Figure 1). 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 (Figure 2) was developed and applied to the Housatonic site and surrounding watershed using the following modeling components:

• Watershed Model (HSPF)
• Hydrodynamic and Sediment/Contaminant Transport and Fate Model (EFDC)
• Bioaccumulation Model (FCM), derived from QEAFDCHN Version 1.0.

The modeling effort involved model development, calibration, and validation of the U.S. EPA HSPF model to the 282-square-mile Housatonic River Watershed as the watershed model component of the integrated model system. HSPF was calibrated and validated for flow, sediment loadings, and water temperature to provide watershed boundary conditions to the other models for a 12-mile segment of the Housatonic River, which was the Primary Study Area (PSA) and focus of the investigation (Weston Solutions, Inc., 2004a; 2004b).
An extensive database was developed, from both historic data and recent data collection, to support the watershed modeling efforts. 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. A “weight-of-evidence” approach to calibration and validation was applied with multiple graphical and statistical comparisons of measured and simulated values (Weston Solutions Inc., 2004b).
Figure 2. Modeling Framework for PCB Modeling of the Housatonic River Watershed.

Model Linkage
As shown in the modeling framework in Figure 2, HSPF is linked to the other models providing tributary discharge and sediment loads to the EFDC model and water temperature conditions for use in the FCM. The linkages of HSPF to the EFDC model and to the FCM are discussed below.

Spatial Linkage
For the EFDC model, HSPF provides discharge and sediment loads from the major streams and drainages tributary to the EFDC model’s domain, i.e., the Primary Study Area (PSA in Figure 1 and 3). The streams include the East Branch, West Branch, Sackett Brook, Yokun Brook, and Roaring Brook and represent a combined drainage area of approximately 150 square miles. Local drainages to the EFDC model correspond to areas within HSPF PSA segments 500-600 which lie outside of the EFDC model’s main channel. These local drainages have an area of approximately 15 square miles.
For the FCM, HSPF provides water temperature conditions for the reaches within the FCM’s domain (i.e., HSPF PSA reaches 500–600). The HSPF reach boundaries were established to coincide with the FCM reach endpoints. However, since HSPF requires smaller reach segments to adequately represent dynamic flow conditions, each FCM reach included multiple HSPF reaches and the HSPF temperature results were averaged to provide values for each FCM reach domain.

**State Variables**
Table 1 describes the state variables that HSPF passes to the EFDC model and the FCM. The state variables required for EFDC and FCM input are passed from HSPF using ASCII text files. The files are composed of 10 files that represent the instream water temperature for HSPF reaches 500–600, 20 files that represent the runoff from local drainages that lie east or west of the EFDC main channel, and 5 files from the stream channels tributary to the EFDC model.

As shown in Table 1, HSPF provides hourly time-series for flow and sediment concentrations for EFDC and daily temperature values for FCM.

The flows that originate from local drainages are distributed into an overland and subsurface (interflow+baseflow) component to better represent their input location to the EFDC grid; i.e., EFDC can accommodate overland flow into a surface grid cell and subsurface flow into a subsurface cell. The sediment concentration from local drainages represents the concentration of the overland flows. Sediment concentrations are distributed into noncohesive (sand) and cohesive (silt+clay) classes to be consistent with EFDC.
EPA guidance documents encourage states and tribes to develop nutrient criteria that recognize the ecoregion-based criteria as a starting point and, subsequently, to refine the values by using additional scientifically defensible methods and data. This paper describes an approach that incorporates three of EPA’s recommended elements for refining nutrient criteria (i.e., historical data, use of predictive models, expert judgment). The demonstration methodology uses readily available types of data (e.g., meteorological, land use, topography, streamflow) in conjunction with a linked mechanistic modeling system that includes a watershed model and an ecological effects model.

The demonstration was performed using the watershed model HSPF and the aquatic ecosystem model AQUATOX, which are both components of EPA’s BASINS watershed and waterbody assessment package. To provide the foundation of the demonstration study, the linked watershed/ecological effects modeling system was applied to two large Minnesota watersheds (Blue Earth River, Crow Wing River), each of which is representative of a different nutrient ecoregion (Figure 4). HSPF was used to estimate sediment, nutrient, dissolved oxygen, and BOD loadings based on watershed characteristics and land use practices. AQUATOX was used to estimate instream aquatic nutrient concentrations and to relate these concentrations to the concentrations of “response variables” (e.g., chlorophyll-a).

A second objective of the demonstration study was to use the linked system to assess the attainability of standards derived from the model-based nutrient criteria. This was accomplished by modeling selected permit and land management scenarios with HSPF to estimate modified nutrient loadings, then using AQUATOX to estimate the effects on nutrient concentrations and other response parameters which might be used to define standards. This study involved watershed model development

**Table 1. HSPF State Variables Passed to EFDC and FCM**

<table>
<thead>
<tr>
<th>HSPF SOURCE</th>
<th></th>
<th>LOCAL DRAINAGES</th>
<th>UNITS</th>
<th>TIME STEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIBUTARY REACHES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EFDC INPUT</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Flow</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Overland Flow</td>
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<td>cfs</td>
<td>hr</td>
</tr>
<tr>
<td></td>
<td>Subsurface Flow</td>
<td></td>
<td>cfs</td>
<td>hr</td>
</tr>
<tr>
<td></td>
<td>(interflow + baseflow)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-Cohesive Sediments (Sand)</td>
<td></td>
<td>mg/L</td>
<td>hr</td>
</tr>
<tr>
<td></td>
<td>Cohesive Sediments (Silt + Clay)</td>
<td></td>
<td>mg/L</td>
<td>hr</td>
</tr>
<tr>
<td>PSA REACHES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCM INPUT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water Temperature</td>
<td></td>
<td>F</td>
<td>day</td>
</tr>
</tbody>
</table>

1. The concentration from the local drainages is that of the overland flow.

**MINNESOTA RIVER HSPF-AQUATOX LINKAGE**

Figure 4. Blue Earth and Crow Wing Rivers.
and application efforts for both the Blue Earth (Figure 5) and Crow Wing watersheds, along with the development of linkage procedures and transfer of model results to AQUATOX. Recent papers have presented the overall project methodology and demonstration study results (Carleton et al., 2005), Watershed Model calibration and validation (Donigian et al., 2005), and the calibration and validation efforts for AQUATOX under alternative nutrient conditions (Park et al., 2005).

**HSPF-AQUATOX MODEL LINKAGE**

As noted above, both HSPF and AQUATOX are components of the BASINS modeling system. As a result, an automated linkage already exists between HSPF state variables and various AQUATOX compartments (Clough, 2004). The model linkage is designed so that a single HSPF stream reach is selected to be the same as the physical/spatial location as the corresponding AQUATOX river reach. AQUATOX then assumes that this single HSPF river reach is “equivalent” to a single AQUATOX reach. WinHSPF, the user interface within BASINS (Duda et al., 2002) provides AQUATOX with the needed time-series of flow volumes and loadings for sediment and nutrients (and other constituents) from that single HSPF reach.

![Figure 5. Blue Earth Watershed and Data Stations in Southern Minnesota.](image)

The HSPF-AQUATOX linkage in BASINS was designed to accommodate a distinction between *inflows* to the reach versus HSPF-calculated conditions *within* the reach, as follows:

- WinHSPF passes inflow loads into that reach whenever AQUATOX will be doing the processing (i.e., process/compartment simulations).
WinHSPF passes HSPF-calculated concentrations/temperatures within the equivalent reach whenever AQUATOX is using values predicted by HSPF in lieu of performing internal/repetitive calculations. The linkage can also provide AQUATOX with time-varying channel hydraulic information; e.g., average depth, surface area, and volume.

Thus HSPF performs the flow routing, water temperature, and sediment transport simulations within the equivalent AQUATOX reach, and then passes the needed state variables, along with the inflow loads of nutrients (e.g., BOD, DO), to AQUATOX (Figure 6).

Although the state variable and time-step issues of model linkage have been predefined in the BASINS system (i.e., for each of the time-series that are linked, the linkage automatically converts units and integrates the average daily HSPF results to the appropriate AQUATOX time-step), the spatial issues for the Minnesota Watersheds required further consideration. The previous HSPF model of the Blue Earth watershed included relatively long stream reaches, ranging from 20 to 60 miles for the mainstem river, where the upstream sites (BE-100, BE-94, BE-73, and BE-54 in Figure 5) are located. To implement a more representative model linkage at these sites, the long reaches were subdivided and shorter HSPF reaches were inserted immediately above the gage, on the order of 1 mile long, which would correspond to the “equivalent” AQUATOX reach. For the Crow Wing Watershed, a similar spatial scale for reaches was implemented.

![Figure 6. AQUATOX State Variables Used in the Minnesota Rivers Study.](image)

Use of shorter AQUATOX reaches also allowed us to circumvent a limitation in the current BASINS model linkage that does not allow a direct input of local, direct drainage (i.e., local...
runoff and loads) into the AQUATOX reach; the current linkage allows only an HSPF reach to be linked with AQUATOX, not adjacent land areas (PERLNDs and IMPLNDs in HSPF) which contribute to the stream. With a short AQUATOX reach, local contributions could be ignored since they are only a few percent of the total inflows to the reach; i.e., the inflows will be dominated by the upstream contributions; however, these local areas were routed into the reach immediately upstream in order to account for the entire drainage area.

**KING COUNTY WASHINGTON HSPF-CEQUAL W2/ICM LINKAGE**

King County (Washington) Department of Natural Resources and Parks, Water and Land Resources is currently spearheading a comprehensive effort to model hydrology and water quality within the Sammamish-Washington and Green-Duwamish Watersheds, which include all of metropolitan Seattle except areas that drain directly to Puget Sound. The Department’s mission is to protect and restore the ecosystem to be beneficial to both the public and the environment within King County while, where reasonable, supporting similar efforts around the Puget Sound region.

With increasing pressure from population growth and diminishing natural resources, it has become necessary for King County to develop a methodology for evaluating current and potential future conditions in the landscape. The methodology being constructed consists of a suite of numerical models capable of characterizing land use (UrbanSim) (Waddell et al., 2003); land cover (LCCM) (Alberti and Waddell, 2000); watershed processes (HSPF); rivers (CE-QUAL-W2); lakes (CH3D-ICM); estuaries (EFDC); and, if further funding is procured, climatic conditions. The goal, however, is not only to characterize each of those features but sequentially to link them together as part of a holistic evaluation of the environment based on a defined set of conditions. This integrated approach, called Integrated Water Resource Modeling System (IWRMS) (King County, 2004), is based partially on the U.S. Department of Energy – Pacific Northwest National Laboratory’s Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES) (Whelan et al., 1997).

Given that most of the King County population is located within the Lake Washington and Green River Watersheds, two initial programs were created to address these areas: (1) Sammamish-Washington Analysis and Modeling Program (SWAMP), and (2) the Green Water Quality Assessment (Green WQA). The SWAMP study area encompasses approximately 670 square miles from its mouth at the Chittenden Locks by the Puget Sound outlet; east to Lakes Union, Washington, and Sammamish; north into the Snohomish County headwaters; and south along the Cedar River as far as the Chester Morse Lake Basin. There are five primary water bodies of concern in the study area: Lake Washington; Lake Sammamish; Lake Union; the Sammamish River, which connects Lakes Sammamish and Washington; and the lower reaches of the Cedar River from its mouth at Lake Washington to Landsburg Dam, the site of drinking water intake and treatment facilities for the Seattle Public Utility.

The Green WQA study area encompasses approximately 265 square miles of the Green-Duwamish Watershed that extends from Howard Hanson Dam to the mouth of the Duwamish River. The Upper Green River sub-watershed (220 square miles) above Howard Hanson Dam is not included in this study nor are the Puget Sound shoreline drainages. The one primary
waterbody of concern in the study area is the Green River.

This study is ongoing with the watershed modeling completed in 2005 and the linkage to the receiving water models currently in progress; a discussion of the modeling effort has been presented by Bicknell et al. (2005). Below we discuss the model linkage issues for the Lake Sammamish and Sammamish River that connects to Lake Washington.

**Sammamish Watershed Domain**

The physical domain of the HSPF model for this portion of the overall SWAMP effort is the Sammamish Watershed (Figure 7) above the confluence with Lake Washington and excluding the calibrated watersheds of Little Bear, North, Swamp, and Issaquah. Each of these calibrated watersheds has previously generated loads that enter the system at specific nodes/cells of the lake and river models. The remaining drainage area has been divided into five major watersheds: Bear Creek, Evans Creek, West Lake Sammamish drainages, East Lake Sammamish drainages, and Sammamish River drainages, as shown in Figure 8. These five watersheds were not calibrated due to budget/resource limitations, so their parameters were extended from the previous calibrated watersheds and subsequent consistency checks were performed to ensure predicted values were reasonable. Together, these five watersheds comprise an area of approximately 103 square miles.

*Figure 7. SWAMP and Green WQA Areas of Puget Sound Region, Seattle Washington.*
**Figure 8.** Sammamish Watershed Drainage Tributary to Lake Washington.

**Model Linkages**

The Sammamish River and Sammamish Lake Models requires a subset of the quantities/constituents shown in Table 2. The HSPF model applications of the watersheds (shown in Figure 8) explicitly simulate (or can simulate) all of these quantities/constituents except for the organic N, P, and C quantities; i.e., LDOM, RDOM, LPOM, AND RPOM/C for CE-QUAL-W2; DON, LPON, and RPON for CE-QUAL-ICM. Note that at the current time, the HSPF model applications do not simulate the TDS constituent. The correspondence between HSPF constituents refractory organic N, P, and C and the W2 organic matter constituents is being further investigated to identify appropriate fractionation procedures; a schematic of the linkage for all constituents is shown in Figure 9.
Table 2. CE-QUAL-W2 and CE-QUAL-ICM Quantities/Constituents

<table>
<thead>
<tr>
<th>Sammamish River Model (CE-QUAL-W2)</th>
<th>Sammamish Lake Model (CE-QUAL-ICM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Flow (m$^3$/s)</td>
<td>• Flow (m$^3$/s)</td>
</tr>
<tr>
<td>• Temperature (deg C)</td>
<td>• Temperature (deg C)</td>
</tr>
<tr>
<td>• Sand (g/m$^3$)</td>
<td>• Sand (g/m$^3$)</td>
</tr>
<tr>
<td>• Silt (g/m$^3$)</td>
<td>• Silt (g/m$^3$)</td>
</tr>
<tr>
<td>• Clay (g/m$^3$)</td>
<td>• Clay (g/m$^3$)</td>
</tr>
<tr>
<td>• NO3-N (g/m$^3$)</td>
<td>• NO3-N (g/m$^3$)</td>
</tr>
<tr>
<td>• NH3-N (g/m$^3$)</td>
<td>• NH4-N (g/m$^3$)</td>
</tr>
<tr>
<td>• PO4-P (g/m$^3$)</td>
<td>• DON (g/m$^3$)</td>
</tr>
<tr>
<td>• TDS (g/m$^3$)</td>
<td>• LPON (g/m$^3$)</td>
</tr>
<tr>
<td>• Silica-Si (g/m$^3$)</td>
<td>• RPON (g/m$^3$)</td>
</tr>
<tr>
<td>• Alkalinity as CaCO3 (g/m$^3$)</td>
<td>• Total PO4-P (g/m$^3$)</td>
</tr>
<tr>
<td>• Dissolved Oxygen (g/m$^3$)</td>
<td>• DOP (g/m$^3$)</td>
</tr>
<tr>
<td>• LDOM (g/m$^3$)</td>
<td>• LPOP (g/m$^3$)</td>
</tr>
<tr>
<td>• RDOM (g/m$^3$)</td>
<td>• Silica-Si (g/m$^3$)</td>
</tr>
<tr>
<td>• LPOM (g/m$^3$)</td>
<td>• DOC (g/m$^3$)</td>
</tr>
<tr>
<td>• RPOM (g/m$^3$)</td>
<td>• LPOC (g/m$^3$)</td>
</tr>
<tr>
<td>• Indicator Bacteria (E-Coli) (E6/m$^3$ $=$ #/mL $=$ 100/100mL, etc.)</td>
<td>• Dissolved Oxygen (g/m$^3$)</td>
</tr>
<tr>
<td></td>
<td>• Indicator Bacteria (E-Coli) (E6/m$^3$ $=$ #/mL $=$ 100/100mL, etc.)</td>
</tr>
</tbody>
</table>

Spatial Linkage
Loadings to the Sammamish River and Lake Sammamish originate from multiple sources; i.e., tributaries and local drainage. Time-series predicted by HSPF for all of the required constituents and drainage sources to the lake and river will provide the necessary boundary conditions to exercise CE-QUAL-W2 (Sammamish River) and CE-QUAL-ICM (Lake Sammamish).

Temporal Linkage
HSPF can generate results at any time-step which is a multiple of the simulation time-step, which was 15 minutes in this application. According to C. DeGasperi (2003, personal communication), the appropriate time-step for the CE-QUAL-W2 model is 1 hour. Therefore, the HSPF model results (flows, temperatures, concentrations) will be generated as 1-hour averages. The appropriate time-step for the CE-QUAL-ICM model is 1 day. Therefore, the model results (flows, temperatures, concentrations) will be provided as 1-day averages.
Figure 9. Correspondence Between HSPF and CE-QUAL-W2 State Variables for Model Linkage.
Linkage Formats
The model linkage output from HSPF has been generated in sequential text-file formats in multiple columns, for each time-step, which is easy to generate and understand. Each sequential text file can contain up to 20 time-series, so all of the results produced at a boundary location (e.g., a tributary stream node) contributing to CE-QUAL-W2 are stored in a single file. It is also easy to control the time-step, aggregation, and units of the results. Flow is in units of m$^3$/s, temperature is in degrees C, and all water-quality constituents are generated in the form of concentrations (g/m$^3$ or mg/l) with the possible exception of the indicator bacteria.

CLOSURE AND LESSONS LEARNED

The studies presented here provide a range of examples of alternative receiving water models linked to HSPF for watershed and water quality issues. The discussion focused on linkage issues related to temporal scales, spatial domains and scales, and state variables represented by each model. In addition to, and complementary to, these technical issues, a number of “Lessons Learned” have become evident through the course of these modeling efforts. A few of these are presented below to help readers who may be faced with model linkage issues of their own.

- **Resources devoted to model linkage are often limited and inadequate.**
  Model linkage issues are often added as an after-thought and, therefore, often receive little attention and resources until one modeling effort ends and the other begins. This can cause significant problems to both modeling efforts and should be avoided at all costs.

- **Models to be linked are often applied by different groups, with little interaction.**
  The separate models to be linked are often applied by different groups, either contractors or groups within the same agency but with different capabilities. This is often necessary, due to the different knowledge and expertise needed, but it can often lead to a lack of communication between the groups. This lack of communication can cause significant model linkage issues and problems that may not be evident until model results are analyzed and investigated. For example, in the AQUATOX linkage discussed above, dynamic water depth (daily values) was being passed from HSPF to AQUATOX for use in light extinction, algal growth, and settling processes. Problems in the algal simulation led to an examination of the light extinction algorithm and inputs, and it was discovered that AQUATOX (traditionally applied to lake/waterbody conditions) averaged the depth values and used a constant depth in its calculations. This was discovered during a conference call among all the modelers, and a simple code change in AQUATOX to use daily values corrected the problem.

- **Frequent and detailed communications are important between modeling groups.**
  The example above illustrates the need for frequent and detailed technical discussions among the modeling groups as the study progresses.

- **A Strategy for model linkage should be developed early in the study.**
  As part of the modeling efforts, a detailed written Model Linkage Strategy document should be developed as a joint effort among all the modeling groups. This will serve as
both a guide and planning document and ultimately, as model documentation upon completion of the study. The document should address:

- Temporal scales of each model and appropriate conversion (distribution or aggregation) for a mismatch in time-steps, along with any unit conversions required.
- Spatial scales and domains of each model, with specific focus on the interface between the models, to avoid any double-counting of area and/or fluxes.
- Detailed definition of the state variables and their correspondence between the models, or the need for appropriate conversions, to ensure that the correct quantities are passed.

ACKNOWLEDGEMENTS

The sponsoring groups for each of the model linkage examples described above were as follows:

- **Housatonic PCB Study**
  - US EPA, Region I, Boston MA
  - Contact: Ms Susan Svirsky
  - (Performed under contract to Weston Solutions, Inc.)

- **MN Nutrient Study**
  - US EPA, OW/OST, Washington, DC
  - Contact: Dr. James N. Carleton

- **King County Watershed Modeling**
  - King County, Dept of Natural Resources, Water and Land Resources, Seattle, WA
  - Contact: Mr. Jeff J. Burkey

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REFERENCES


