Part 5. HSPF and MODFLOW—Capabilities, Limitations, and Integration

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Hydrologic Models—HSPF and MODFLOW

The precipitation-runoff model HSPF and the groundwater-flow model MODFLOW were used to evaluate the effects of water-management strategies in the Pawtucket River Basin as described in the previous chapters. HSPF and MODFLOW are designed differently and serve different purposes. Each model simulates hydrologic processes through the calculation of a water budget, but the components of the simulated water budget and how the budgets are calculated differ greatly.

In HSPF, water budgets are simulated on the basis of hydrologic response units (HRUs) that characterize the water fluxes and storage in pervious and impervious areas from direct inputs of meteorological time-series data. HRUs provide a distributed calculation of surface runoff, interflow, and groundwater flow to streams by processes that determine the fate of water through various losses and storage components. Flows from HRUs are typically directed to streams and routed by the kinematic-wave method to simulate streamflow. User-specified variable values control HRU processes and streamflow routing. HSPF capabilities make it an appropriate tool for the continuous simulation of total streamflow.

In MODFLOW, water budgets are simulated on the basis of specified boundary conditions, stresses, and hydrogeologic properties of the aquifer by numerical finite-difference methods to determine groundwater heads and fluxes (baseflow). Boundary conditions, stresses, or both can remain constant (steady state) or vary in time (transient) through user-specified values at the beginning of each time increment (referred to as a stress period). MODFLOW capabilities make it an appropriate tool for simulation of groundwater elevation and baseflow discharge to streams.

The appropriate model for simulating hydrologic conditions and posing questions about how those conditions vary in response to change depends largely on the nature of the problem and the water-management decisions to be made. The purpose of this section is to compare HSPF and MODFLOW simulation results for specific scenarios to provide a better understanding of capabilities and limitations of both models. This in part relies on understanding some of the functional differences between the models and how these differences can affect simulations.

Functional Differences between HSPF and MODFLOW

HSPF and MODFLOW represent hydrologic processes in different ways that are described in detail in the respective model documentation. Two pragmatic differences between the models are the temporal and spatial representations of hydrologic conditions or features, often referred to as the model discretization, which can have a large effect on the simulation of hydrologic processes. Temporal discretization affects the representation of time-varying hydrologic conditions, whereas spatial discretization affects the representation of the hydrologic characteristics of the basin or aquifer. Spatial discretization is determined largely by the extent of the model domain, and by the underlying hydrologic processes represented in each model.

HSPF simulations are typically made with an hourly time step (as in the Pawcatuck River Basin model) driven by time-series data with the same time step. MODFLOW simulates steady-state or transient conditions that reflect long-term average or time-varying conditions, respectively. Typically, transient simulations use a monthly stress period to reflect seasonal fluctuations (like most stress periods specified in this study); however, shorter stress periods can be specified (such as the weekly stress period specified for the 2002 summer period). For each stress period, a unique set of stressors, boundary conditions, or both are specified; typically, this entails changes in recharge (boundary condition), groundwater withdrawals (stressor), or both, but changes are not limited to these properties. The averaging of stressors such as withdrawals over time can affect simulation results.

Spatially, HSPF is considered by some to be a lumped-parameter model because the HRUs that define the model are amorphic—that is, they are not explicitly represented spatially. Rather, they are represented by the total area of each HRU that contributes to a reach. Others consider HSPF to be a spatially distributed model because each HRU uniquely represents hydrologic processes that are appropriately distributed throughout the basin. The combined areas of all HRUs to a reach determine the overall hydrologic response at a specified point (node) in the model. Hydrologic fluxes to any point in the model can be computed by the summation of HRU water budgets that compose the contributing area to that point.

It should be noted that there is little basis for evaluating the accuracy of computed flows from a specific HRU because the model-calibration points (streamflow-gaging stations) generally receive water from the aggregate of many different HRUs.

In MODFLOW, spatial discretization is governed by the size of the model grid and the necessity to keep the total number of cells in the grid within manageable limits in terms of computational speed and output size. The model-grid spacing determines the level of detail in the spatial representation of hydrologic properties of the aquifer. The hydrologic properties of each cell are typically regionalized and calibrated to point information distributed over the model domain, such as well logs, observation well heads, and streamflow at gaging stations. The calibration processes for MODFLOW and HSPF are similar in that individual components of the models are not explicitly calibrated; rather, the models are calibrated on the basis of the composite response of multiple components to point information such as streamflows at gaging stations or water levels at observation wells.

In addition to the temporal and spatial limitations imposed by a specific model, a key factor to consider in the evaluation of simulation results is the hydrologic processes that are simulated. Alley and others (2002) articulated this consideration for groundwater models; however, the statement applies equally to other deterministic models:

> "Accuracy of model predictions is constrained by the correctness of the model (i.e., proper representation of relevant processes) and uncertainty in model parameters. The latter uncertainty is due to the limited accuracy with which parameter values can be measured and, more important, to the substantial heterogeneity inherent in aquifer characteristics. The inability to describe and represent this heterogeneity adequately is a fundamental problem in groundwater hydrology and will continue, even with improved models, to place limits on the reliability of model predictions. The links between spatial heterogeneity and model uncertainty also depend on the type of questions being asked. For example, reasonable estimation of head distributions in an aquifer may require only limited understanding of spatial heterogeneity. On the other hand, confidence in predictions of chemical concentrations at a specific location can be very sensitive to minor uncertainty in the spatial distribution of hydraulic properties, even for relatively homogeneous porous media."

Although there are uncertainties associated with a given hydrologic process simulated by any model, fundamental differences in the process being considered can make the choice of the most appropriate model simple. For example, when the issue pertains to groundwater levels, MODFLOW would be the appropriate choice. When the issue pertains to streamflow, the choice of model can be more difficult because of inherent differences in the flow components simulated and the relation of the flow stressors to surface-water and groundwater interactions. These interactions are difficult to observe and measure, and are further complicated by many natural processes and human activities that commonly have been ignored in water-management considerations and policies (Winter and others, 1998).

Comparison of Three Example HSPF and MODFLOW Results

In the Pawcatuck River Basin, HSPF and MODFLOW often produced different results for the same type of scenario, underscoring some of the fundamental differences between these models. Three examples were chosen to illustrate how (1) temporal discretization, herein referred to as time-step averaging, (2) spatial discretization, and (3) streamflow-depletion calculations can affect model results.

Example 1. Effects of a Pumped Well on Streamflow in Meadow Brook

The effects on streamflow of a hypothetical well (RIW–481A) pumped at a constant rate of 1.55 ft^3/s (1 Mgal/d) were simulated in lower Meadow Brook (MEAD2; fig. 5–1 and table A4–2). In MODFLOW, the pumped well was simulated at a distance of 200 ft from Meadow Brook under steady-state and transient conditions. Steady-state simulations represent average conditions from January 1, 2000, to September 30, 2004; transient simulations represent monthly conditions over the same period, except for May through September 2002, during which average weekly conditions are represented. Baseflow at the upstream boundary of MODFLOW in Meadow Brook was specified as the baseflow component of discharge calculated by HSPF at MEAD1 (fig. 5–1). Recharge values specified in MODFLOW for steady-state and transient simulations were derived from the flow into active-groundwater storage in HSPF as described in the recharge section in Appendix Part 3.

MODFLOW simulated steady-state flow at the outlet of MEAD2 without RIW–481A pumping was about 6.8 ft^3/s; with pumping, flow in the reach decreased by 1.36 ft^3/s, or about 0.19 ft^3/s less than the pumping rate of the well. The difference between streamflow loss and the withdrawal rate indicates that under steady-state conditions, simulated water to the well is captured from outside the surface-water subbasin divide; the captured water would otherwise likely discharge to the Pawcatuck River given the proximity of the well to the PAWC4 subbasin (fig. 5–1).

HSPF simulated flow at the outlet of MEAD2 over the same period averaged about 14.1 ft^3/s without RIW–481A pumping and about 12.5 ft^3/s with the well pumping. The difference in average streamflow with and without pumping is equal to the withdrawal rate because, in the HSPF simulation, all water to the well is satisfied from flow that would otherwise discharge to Meadow Brook. Although the contribution of water to a pumped well from other reaches could be assigned in the HSPF model (in this example, 12 percent of

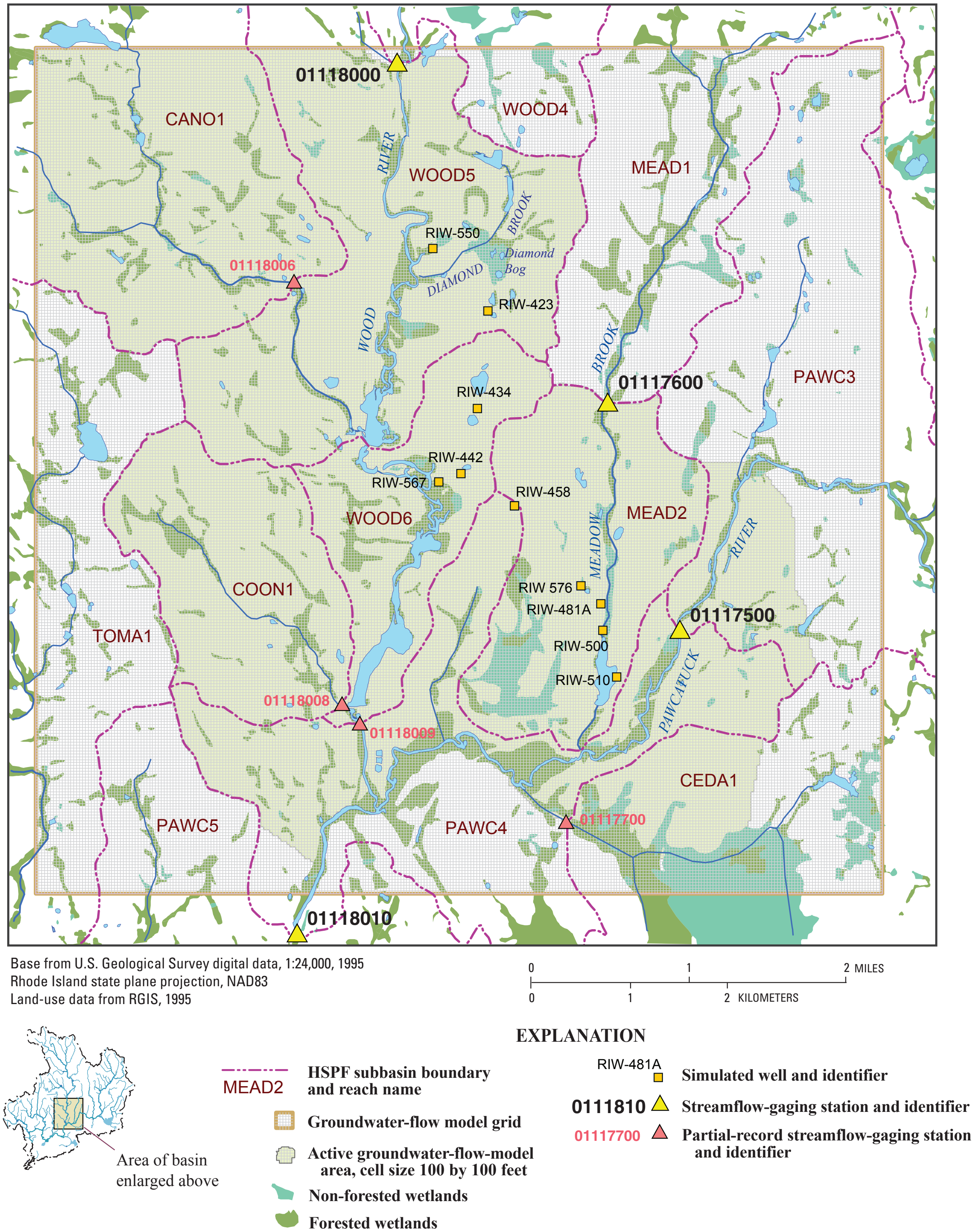

Figure 5–1. Hydrologic Simulation Program-FORTRAN (HSPF) and the modular groundwater-flow model (MODFLOW) representation of Meadow Brook and lower Wood River area, Pawcatuck River Basin, southwestern Rhode Island. (Surface-water sites described in table A2–4.)

the water to RIW–481A is likely obtained from PAWC4 under steady-state conditions), the amount of withdrawal that should be assigned to other reaches is not known without the information gained through MODFLOW simulations.

MODFLOW simulations demonstrate that the contributing area to the pumped well is not bound by the surface-water divide. Under average 2000–04 conditions, HSPF simulated flow in Meadow Brook was about twice that of MODFLOW steady-state simulated flows, but because average streamflow was greater than the withdrawal rate of RIW–481A, the relative differences between models for simulated flows with and without pumping were minor. MODFLOW transient simulations indicate that the relative difference in flows simulated with and without pumping differs considerably between models at low flows. Transient MODFLOW simulations from January 1, 2000 through September 30, 2004 indicate that flow in MEAD2 ranged between zero and about 32 ft^3/s (fig. 5–2). During the normally wet spring months when the simulated streamflow was greater than the withdrawal rate, streamflow decreased in proportion to withdrawals from RIW–481A (1.55 ft^3/s). During low-flow periods, particularly the summers of 2000, 2001, and 2002, MODFLOW simulated streamflow stopped flowing at MEAD2 even without RIW–481A pumping. As a result, MODFLOW simulations indicate that withdrawals from RIW–481A had little or no effect on streamflow because Meadow Brook had little or no simulated flow prior to pumping. Thus, MODFLOW-simulated changes in streamflow from pumping were limited to the periods when the brook had flow prior to the additional withdrawal; generally this resulted in extended periods of no flow because the simulated low flows prior to RIW–481A pumping were near or below the withdrawal rate during low-flow periods. This is particularly evident in simulated 2001 summer flows, when withdrawals composed an appreciable fraction of the simulated flows (fig. 5–2).

Daily HSPF simulations for the same period indicate that flow at MEAD2 ranged between about 2.0 and 100 ft^3/s without RIW–481A pumping and between 0.3 and 100 ft^3/s with RIW–481A pumping (fig. 5–2). HSPF-simulated streamflow at the upstream streamflow-gaging station at MEAD 1 (fig. 5–1) is generally in good agreement with observed and estimated flows (Appendix Part 2; fig. A2–15) indicating that simulated flows in MEAD2 are better represented by HSPF than MODFLOW. The resulting interaction of pumping RIW–481A on streamflow, therefore, cannot be clearly defined by MODFLOW simulations, and the resulting decline in the water table around RIW–481A is likely oversimulated.

Another consideration that could affect the interpretation of HSPF model results is changes in groundwater storage that are not directly simulated. Observed and HSPF-simulated flows at MEAD1 often fell below the 1.55 ft^3/s pumping rate specified for RIW–481A. If flows in the reach near the

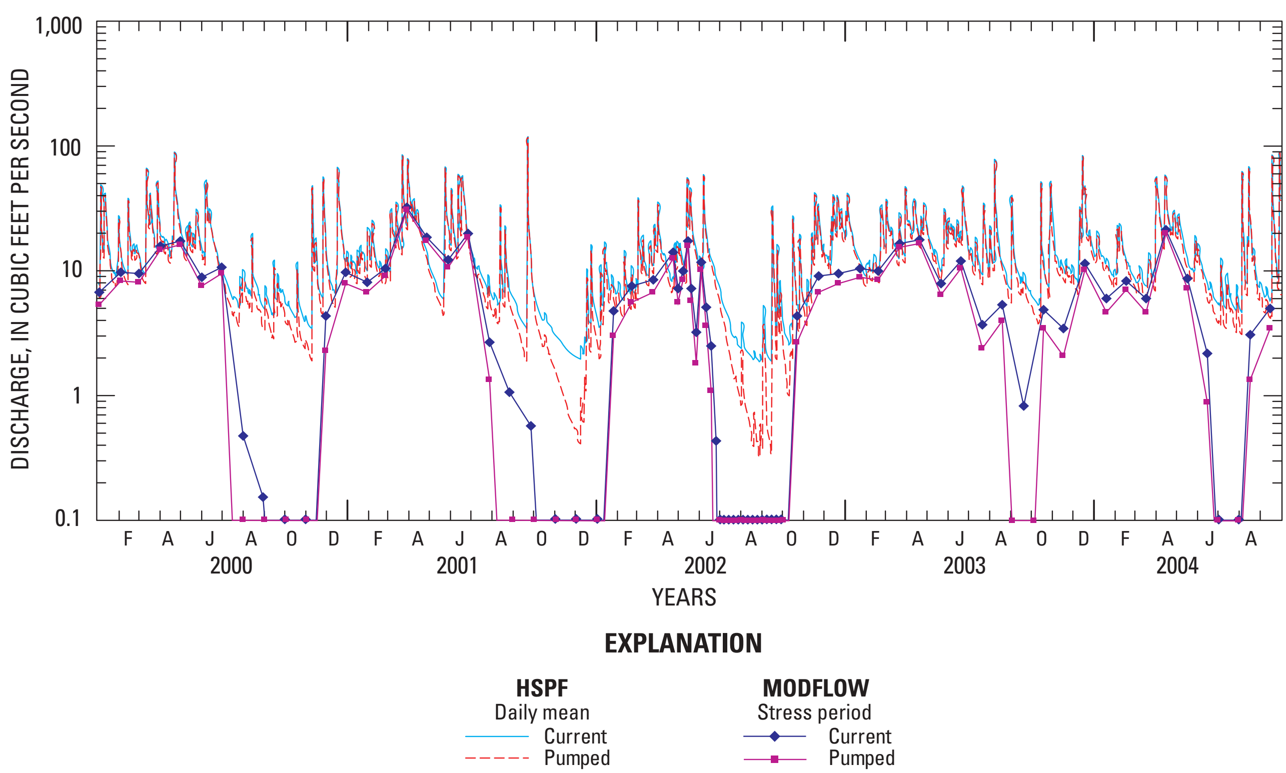

Figure 5–2. Streamflow from January 1, 2000, through September 30, 2004, under 2000–04 (current) conditions and under current conditions with a well pumped at constant rate of 1 million gallons per day (pumped) simulated by the precipitation-runoff model Hydrologic Simulation Program-FORTRAN (HSPF) and the modular groundwater-flow model (MODFLOW) in lower Meadow Brook (MEAD2, RCHRES 48), Pawcatuck River Basin, southwestern Rhode Island. (Site location shown in figure 5–1 and described in table A2–4.) Months on x-axis are February, April, June, August, October, and December for years shown.

pumped well were less than the withdrawal rate, withdrawals in excess of the streamflow would be neglected without further modifications to the HSPF model to compensate for the loss in groundwater storage. These modifications can be made through the Special Action feature in HSPF that accounts for withdrawals in excess of streamflow to mimic depleted groundwater storage, which is then replenished when streamflow exceeds withdrawals (Zarriello and Ries, 2000). In this example, flows at MEAD2 did not fall below the withdrawal because of the additional contributing area between MEAD1 and MEAD2. Had streamflow near the pumped well been less than the withdrawal rate, the effect of lost storage on subsequent streamflows would not be realized in HSPF simulations without adding a Special Action similar to the one developed by Zarriello and Ries (2000).

In MODFLOW streamflow is tracked cell by cell; therefore, interaction between the stream and aquifer is closely tied to the model cells closest to the pumped well. Conceivably, this spatial accountability provides a better estimate of flow in the vicinity of the pumped well where the interaction between surface water and groundwater is most dependent on flow, but its success is contingent on the accuracy of MODFLOW-simulated streamflow. In this example, the MODFLOW simulated flows are not as representative of actual flows as are the HSPF simulated flows, which can lead to other problems in the interpretation of model results as described. Consideration should also be given the fact that MODFLOW simulates only the baseflow component of streamflow; thus, actual flows are underrepresented at times that could result in a different aquifer response to a withdrawal. It should also be noted that a reasonably good connection between the stream and the aquifer is assumed; if the stream and the aquifer are not well connected, a different set of conclusions could be reached.

Example 2. Effects of Withdrawals near Diamond Bog

The simulation of surface-water and groundwater interactions can be affected by the spatial discretization of the model. Simulation of a hypothetical well, RIW–550, in the Wood River subbasin at WOOD5 (fig. 5–1) near Diamond Bog, an important ecological resource, illustrates the effects of the model spatial discretization on simulation results. RIW–550 was simulated in MODFLOW about 500 ft from the Wood River and about an equal distance to Diamond Brook with a constant pumping rate of 1.55 ft^3/s (1 Mgal/d). In MODFLOW, Diamond Brook is explicitly represented, whereas in HSPF, Diamond Brook was lumped into the representation of the WOOD5 subbasin. In both HSPF and MODFLOW simulations, the effect on the Wood River of pumping RIW–550 at 1.55 ft^3/s was essentially the same, other than the fractional differences in flow associated with the flow components simulated by each model. However, the effects of the pumped well on Diamond Bog could be greatly influenced by the spatial discretization of MODFLOW.

In MODFLOW simulations, streamflow in Diamond Brook was critical in the calculation of the response of the aquifer to pumping as described in Part 3. In summary, the water-level change in Diamond Bog in response to pumping was highly dependent on the simulated flow in Diamond Brook. Withdrawals from RIW–550 were often comparable to or greater than the flow in the brook. As the simulated flow in the brook becomes less than the withdrawal rate, the drawdown from the pumping well increases and expands laterally, a response similar to that described for the transient simulations of a pumped well near Meadow Brook. Therefore, the accuracy of the water-level response in Diamond Bog to pumping is highly dependent on the accuracy of the simulated flow in Diamond Brook, which is unknown. Other factors can also affect the interaction between surface water and groundwater, such as the hydraulic connection between the brook and the aquifer and the specified elevation of the streambed; however, the accuracy of these model variable values is not well known for this area, a problem common in most groundwater models because of the difficulty in obtaining representative values over a wide area.

In general, variable values are empirically estimated during the model calibration. The accuracy of these variables can be further compromised in MODFLOW as the variable values represent larger cell areas. If the cell sizes increase to where less than one cell separates Diamond Brook and Diamond Bog from Wood River, the resulting model would have insufficient detail (spatial discretization) to differentiate the effects of pumping on these features. Had a single groundwater-flow model been developed for the entire Pawcatuck River Basin, the spatial detail would likely have been inadequate to represent the influence of Diamond Brook on pumping near the bog. This is an example of why two separate groundwater-flow models were developed to allow for better spatial resolution of hydrologic properties in key areas of the basin. Simulations of surface-water and groundwater interactions are further complicated by temporal conditions that may provide additional sources of water to the pumped well, such as ponded water in the bog or adjacent wetlands, or localized time-varying recharge, and other factors not accounted for in the model.

The HSPF model of the Pawcatuck River Basin was not discretized at a scale fine enough to directly evaluate the effects of pumping on Diamond Brook (the drainage area to Diamond Brook at its mouth is about 0.9 mi^2 in a model constructed to simulate the entire 303-mi^2 Pawcatuck River Basin), nor was the model capable of simulating groundwater levels. If the model had been developed at a scale sufficient to represent flow in Diamond Brook, then additional information would be required to determine the portion of the withdrawal that is captured groundwater discharge to, or induced infiltration from, the brook. Captured groundwater flow to or induced infiltration from Diamond Brook is complex, varies with time, and is best represented by a transient groundwater model. As previously noted, these simulations are highly dependent on the accuracy of simulated flow in Diamond Brook and on how accurately the hydraulic connection between the brook and the aquifer in simulated.

Example 3. Effects of Converting from Surface-Water to Groundwater Withdrawals

Converting withdrawals from surface-water to groundwater sources can be beneficial to aquatic habitat because of the time lag and damping of peak demand on streamflow induced by withdrawing water from the aquifer instead of the stream. Simulating the change in streamflow caused by converting withdrawals from surface-water to groundwater sources can be greatly influenced by averaging irregular withdrawals over time and by the assumptions inherent in STRMDEPL, which is used in HSPF to compute the lag effects of a pumped well on streamflow depletion. This is illustrated by examining the effects of moving withdrawals from surface-water to groundwater sources in the lower Beaver River (BEAV3).

In 2000–04, irrigation withdrawals were made directly from streams at seven locations in BEAV3 (fig. 5–3). MODFLOW and HSPF simulations examined the effects of moving five of these withdrawals to a series of groundwater wells located about 2,000 to 3,000 ft from the river to an area about midway between BEAV3 and QUEN7 (the lower Usquepaug-Queen River). Simulations included moving a surface-water withdrawal (AQU10A) from QUEN7 to the same area as the withdrawals moved from BEAV3. MODFLOW simulations also investigated the effects of several withdrawal scenarios that consolidated groundwater withdrawals, but results described in Part 3 indicate no appreciable differences in streamflow depletion of BEAV3. Consequently, effects of consolidating individual pumped wells are not addressed in this section.

HSPF simulations also included converting two downstream withdrawals (AB3B and AB5A) to groundwater withdrawals in BEAV3 (fig. 5–3). Wells AB3B and AB5A supply water to about 18 percent of the total irrigated area in the lower Beaver River subbasin. The general effects of time-step averaging and limitations of STRMDEPL, however, are not appreciably affected by differences in the withdrawals simulated with and without wells AB3B and AB5A in HSPF and MODFLOW, respectively.

The simulated effects of an irregularly pumped well on streamflow depend on the temporal discretization of the model. The temporal discretization dictates the extent to which the withdrawal variations are averaged or smoothed in the simulation time step (HSPF) or stress period (MODFLOW). Irrigation withdrawals are particularly affected by time-step averaging because they are typically made only during part of the day.

In HSPF, time-step averaging is mostly an issue with postprocessing of model results because simulations are made with an hourly time step; however, averaging withdrawals input to the model could affect the simulated streamflow response. For example, when irrigation withdrawals that turn on and off during the day are averaged, the resulting data would damp peak withdrawals and cause withdrawals during periods of no pumping. This effect becomes more pronounced as the time period over which withdrawals are averaged increases or withdrawal variability increases, and is most pronounced as they increase simultaneously. The effect of time-step averaging in the postprocessing of HSPF-simulated streamflow is illustrated in BEAV3 in figures 5–4A and B. The simulated hourly hydrograph (fig. 5–4A) during July through early September 2002 show an intradaily oscillation that reflects the surface-water withdrawal pattern; the daily mean hydrograph (fig. 5–4B) for the same time interval does not show this oscillation because of the smoothing effect of averaging hourly values over the day.

The effects of time-step averaging of variable withdrawals, such as irrigation withdrawals, become less relevant the farther the withdrawal is moved from the stream because of the inherent damping of streamflow depletion by the aquifer. It should also be noted that the extent to which time-step averaging affects model results is directly related to the rate of withdrawal in relation to the rate of streamflow. In general, the importance of time-step averaging decreases as the withdrawals compose a smaller fraction of total streamflow and increases as the withdrawals compose a larger fraction of streamflow. This effect can be seen in the HSPF-simulated hourly streamflow under direct surface withdrawals (LT–Cdmd) during June 2002 when withdrawals composed only a small fraction of total streamflow relative to the later summer months when withdrawals composed a larger fraction of total streamflow (fig. 5–4A).

In MODFLOW simulations, irrigation withdrawals were averaged over weekly or monthly stress periods. The smoothing effect of averaging irregular withdrawals over this period of time can diminish or mask the potential benefits of moving the withdrawal from a stream to a groundwater source, particularly when the withdrawal is large with respect to streamflow. During the 2002 irrigation season (June through September), estimated average monthly withdrawals in BEAV3 ranged from 0.46 to 2.01 ft^3/s. During the same period, weekly, daily, and hourly withdrawals ranged from zero to a high of 2.05, 2.35, and 5.68 ft^3/s, respectively (fig. 5–5). Averaging the hourly withdrawals over a day or over a month cut the peak hourly withdrawal rate by as much as 60 to 90 percent, respectively. In this particular example, the most pronounced effect of time-step averaging is when withdrawals occurred once during the week (June 11–18), yielding an average weekly rate about 94 and 86 percent less than the peak hourly and daily withdrawal rates, respectively. Note that these values include withdrawals from wells AB3B and AB5A, which were included in the HSPF simulations, but not in the MODFLOW simulations; exclusion of these withdrawals in the HSPF simulations would decrease the withdrawals from BEAV3 by about 20 percent from that shown. In MODFLOW, the simulated effect of direct withdrawals from the river was obtained by subtracting the average withdrawal from the simulated baseflow for a stress period. As a result, much of the short-term variation in the

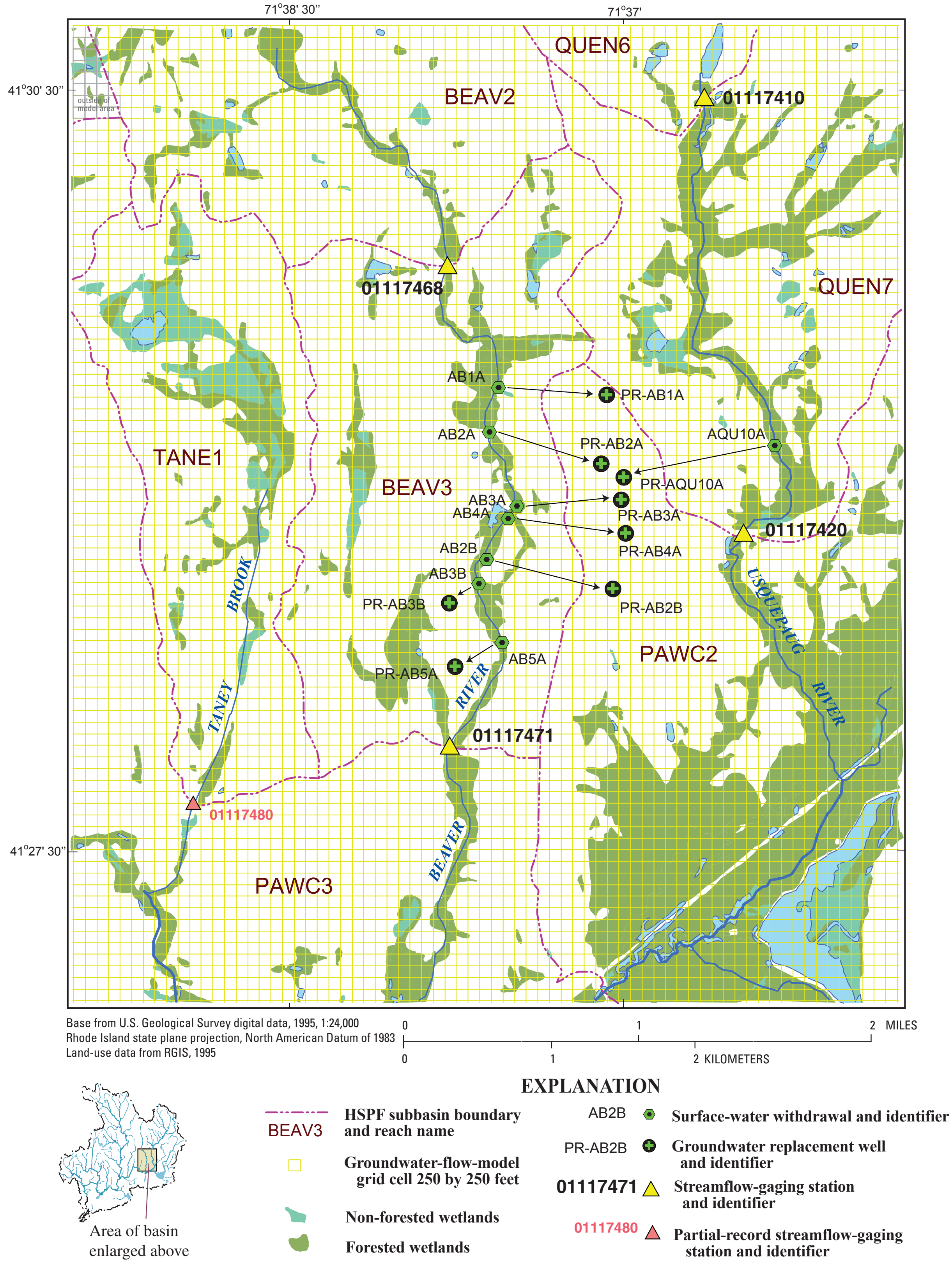

Figure 5–3. Hydrologic Simulation Program-FORTRAN (HSPF) and modular groundwater-flow model (MODFLOW) representation of the lower Beaver River area, Pawcatuck River Basin, southwestern Rhode Island. (Surface-water sites described in table A2–4 and groundwater sites described in table 4–1.)

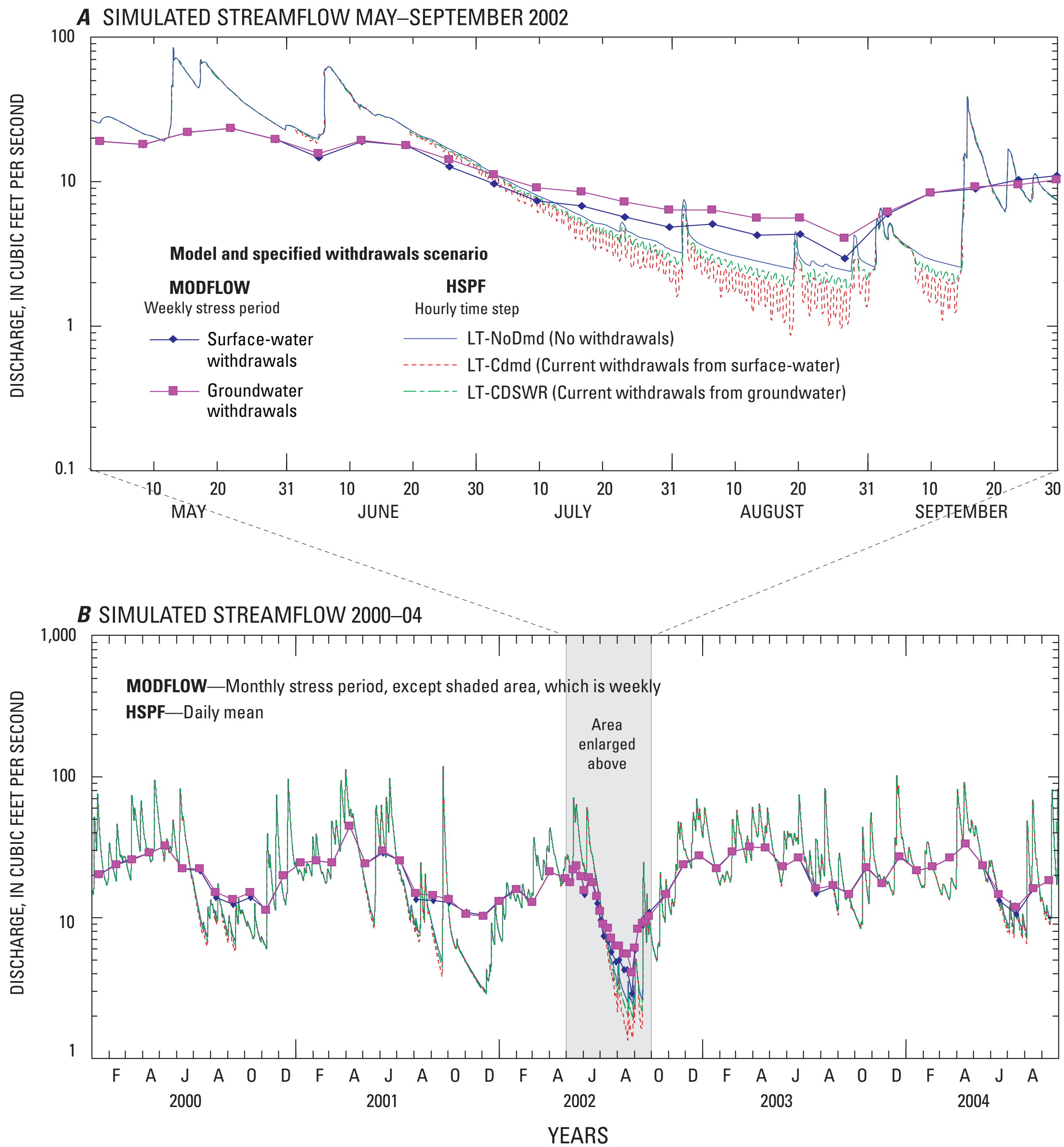

Figure 5–4. Simulated streamflow from *(A)* May through September 2002 and *(B)* January 1, 2000, through September 30, 2004, under current conditions with selected irrigation withdrawals converted from surface-water to groundwater sources with the precipitation-runoff model Hydrologic Simulation Program-FORTRAN (HSPF) and the modular groundwater-flow model (MODFLOW) in lower Beaver River (BEAV3, RCHRES 43, 01117471), Pawcatuck River Basin, southwestern Rhode Island. (Location shown in figure 5–3). Months on x-axis are February, April, June, August, October, and December for years shown. (Site location shown in figure 5–3 and described in table A2–4.)

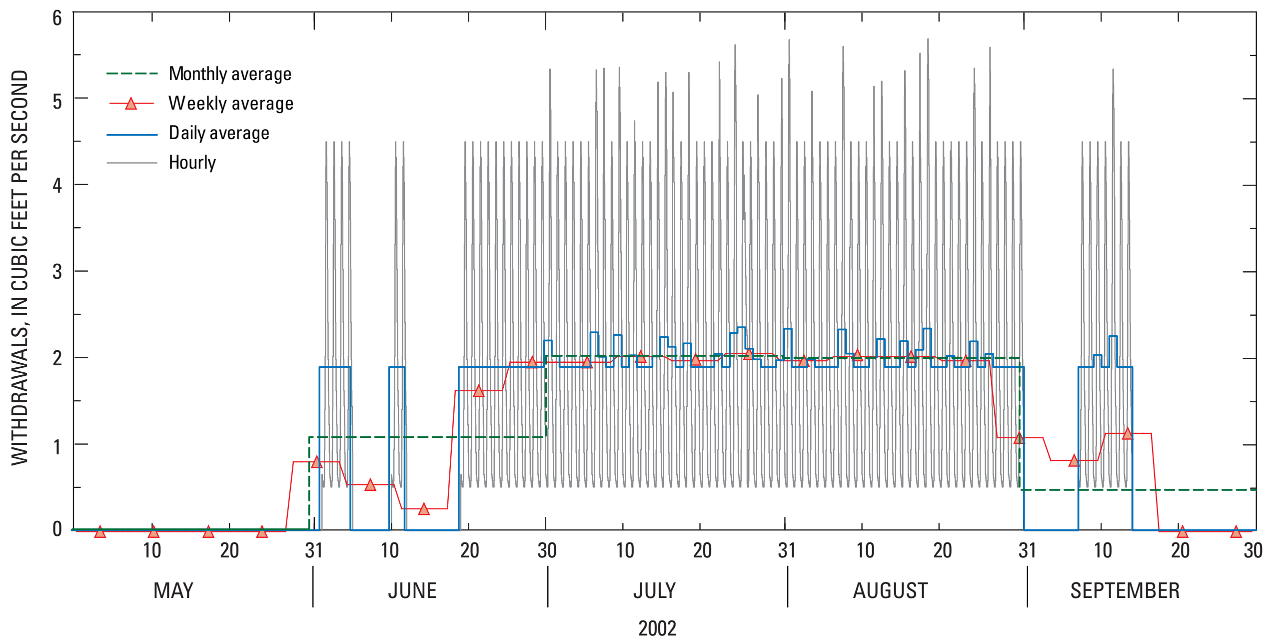

Figure 5–5. Effects of time-step averaging of estimated irrigation withdrawals, May through September 2002, in the lower Beaver River (BEAV3, RCHRES 43, 01117471), Pawcatuck River Basin, southwestern Rhode Island. (Site location shown in figure 5–3 and described in table A2–4.)

streamflow response to direct withdrawals is lost due to time-step averaging.

For example, in June 2002 withdrawals from BEAV3 included distinct periods of pumping and no pumping (fig. 5–5). The monthly average withdrawal in June 2002 specified in MODFLOW was 1.07 ft^3/s, which results in undersimulation of streamflow by about 1 ft^3/s during days of no pumping and oversimulation by about 0.9 ft^3/s on days with pumping. These values represent between 5 and 10 percent of the MODFLOW-simulated streamflow at the time. The amount by which streamflows are oversimulated or undersimulated depends on the length of the stress period and the withdrawals during that period. Additionally, withdrawals from groundwater are not as prone to the effects of time-step averaging as direct stream withdrawals because of the lag time and damping effects of withdrawals on streamflow depletion by the aquifer. It should be noted that although time-step averaging can cause inaccuracies in simulated flows, the models themselves are still valid because the mass balance of water within the relevant time interval is unaffected by time-step averaging (that is, there is no net gain or loss of water).

Converting withdrawals from surface- to groundwater sources in the BEAV3 subbasin also illustrates the limitations of STRMDEPL used in HSPF to simulate the effects of a pumped well on streamflow. In the HSPF simulation LT–CDSWR, five of the seven surface-water withdrawals were moved from BEAV3 to groundwater wells in the contributing area of the PAWC2 subbasin (fig. 5–3). As such, the effects of withdrawals from these wells on streamflow was removed entirely from BEAV3 and shifted to PAWC2. MODFLOW simulations, on the other hand, indicate that on average, only about 2 percent of the water came from outside the BEAV3 subbasin when surface-water withdrawals were converted to groundwater withdrawals in PAWC2; average streamflow from January 2000 through September 2004 in BEAV3 increased from 18.3 to 18.6 ft^3/s. It should be noted that boundary conditions specified in MODFLOW did not force water to the pumped wells to come from a particular surface-water subbasin; rather, the source of water to the pumped well is determined on the basis of calculated groundwater-flow direction, which is affected by the specified hydraulic conductance and the computed hydraulic gradient between the aquifer and the stream. The effects of converting from surface-water to groundwater withdrawals on streamflow in BEAV3 may be diminished by withdrawals from AQU10A (moved from QUEN7), which was also moved to the same general area in PAWC2 as the five withdrawals moved from BEAV3. Furthermore, MODFLOW simulations during dry periods indicate that the source water to the six pumped wells comes from storage or areas outside the basin, or both; near the end of August 2002, streamflow in BEAV3 increased from about 2.9 to 4.1 ft^3/s when withdrawals were converted from surface-water to groundwater sources, respectively. Thus, MODFLOW simulations indicate that HSPF oversimulated streamflow in BEAV3 when direct stream withdrawals were converted to groundwater withdrawals outside the drainage divide.

Without prior knowledge of the source of water to a pumped well, allocation of stream depletion among different reaches in HSPF cannot be made. This is problematic when a pumped well alters the groundwater flow path in ways that are not easily determined, such as in areas near the water-table divide or in areas where the water-table gradient is low or poorly defined. These conditions are further complicated by temporal changes in boundary conditions and largely unknown parameter values that control the interaction between groundwater and surface water.

Simple allocations of streamflow depletions on the basis of subbasin divides can be inaccurate and lead to incorrect conclusions. Allocations made on the basis of distance from neighboring streams alone can also be misleading; in this example, wells are about equal distance from BEAV3 and QUEN7, but the MODFLOW simulations indicate the majority of the water withdrawn is water that would otherwise discharge to BEAV3. Although numerical groundwater-flow-model simulations are best suited for this type of analysis, constructing an accurate model requires detailed field investigations, particularly at the local scale, to ensure that simulated streambed conductance, elevation, and aquifer heterogeneity adequately represent actual geohydrologic conditions.

Integrating HSPF and MODFLOW Models

Coupled groundwater and surface-water models help address some of the complexities of groundwater and surface-water interactions and the problems associated with time discretization and simulation of flow components described above. The Integrated Hydrologic Model (IHM) formally couples HSPF and MODFLOW models (Ross and others, 2003; Aly and others, 2003) and allows each model to work independently at its own time step or stress period. The results of each model are fed back and forth to each other at their specified time step or stress period to provide a more complete representation of hydrologic processes than cannot be achieved by the individual models alone. Although this can greatly improve the simulation of hydrologic processes and, thus, the potential model uses, the formally coupled model is still subject to the same spatial-discretization limitations as the individual models. The spatial limitations, as noted previously, can influence results and interpretation.

Compounding the model limitations are uncertainties associated with the input variable values required by each model. Issues of model uncertainty lead to questions of equifinality—that is, alternative model structures and variable values can only be rejected (Beven and Binley, 1992; Beven, 1993). Alternative model structures and variable values can be accepted that could potentially lead to conflicting results. The question remains as to whether fully integrated surface-water and groundwater models limit or broaden the range of possible acceptable model alternatives. Integrated models may limit the range of acceptable variable values because of the improved representation of hydrologic processes; however, the added complexity of an integrated model, coupled with an increased number of input variables, could also increase variable uncertainty and the range of model alternatives.

IHM links HSPF Hydrologic Response Units (HRUs) with MODFLOW cells to pass information between their operational units. HSPF passes recharge from the active groundwater component (AGWO) of the HRUs to the appropriate MODFOW cell. MODFLOW, in turn, passes hydraulic head information to HSPF for the simulation of lower-zone storage processes and discharge of groundwater to stream reaches. In addition, IHM better accounts for head-dependent evapotranspiration losses in the unsaturated (vadose) zone. For these reasons IHM was tested early in the present study to determine its potential use.

Testing of HSPF and MODFLOW Integration in the Usquepaug-Queen River

The IHM model was tested in the 36-mi^2 Usquepaug-Queen River subbasin (RCHRES 1-20) (fig. A2–4) by using modified versions of the previously developed HSPF (Zarriello and Bent, 2004) and MODFLOW (Dickerman and others, 1977) models. The MODFLOW model was rebuilt using a 200- by 200-ft cell spacing that extended to the basin boundaries. Aquifer properties were similar to those used by Dickerman and others (1977), except upland tills are simulated in the modified groundwater-flow model. The HSPF model was modified to better represent head-dependent processes between MODFLOW and HRUs. This entailed duplicating the original 15 pervious-area HRUs (PERLNDs) in the model across the 20 model subbasins, resulting in 300 unique HRUs that were mapped to MODFLOW cells. Mapping HRUs to MODFLOW cells was done through GIS and the creation of an ACCESS database table that identifies the proportional area of each HRU and other hydrologic characteristics, such as field capacity, associated with each MODFLOW cell. For the IHM test basin, the database that maps HRUs to MODFLOW cells was about 70,000 records. In addition to these records, ACCESS tables are required to map MODFLOW cells to HSPF reaches and to pass MODFLOW-simulated baseflow back to HSPF for flow routing with non-baseflow components of flow simulated by HSPF.

Once the IHM interface files were complete, the integrated model ran HSPF with an hourly time step and MODFLOW ran with a daily stress period. Although the IHM model initially ran, the model would inexplicably stop during the early part of the simulation period. This may have been caused by the instability of the MODFLOW simulation of upland tills, which is characterized by constant wetting and drying from variable recharge, a thin unconfined upper layer, and high relief. The problem was not investigated further because a fully coupled HSPF-MODFLOW model for the entire Pawcatuck Basin, which is about 10 times the size of the Usquepaug-Queen test subbasin, was determined to be impracticable for several reasons. These reasons include limitations of a workable MODFLOW cell size, the number of additional HRUs needed to represent head-dependent conditions throughout the basin, and the size of the database needed to link the models. It was also determined that the project objectives could be met by informally linking HSPF and MODFLOW, whereby HSPF would generate recharge for MODFLOW as described in the development of the MODFLOW models in Appendix Part 3.