Summary and Conclusions

The Pawcatuck River Basin includes 303 mi^2 in southwestern Rhode Island and southeastern Connecticut. The streams, ponds, and groundwater aquifers in the basin are valuable high-quality water resources that provide water for domestic and public supplies, irrigation, and a rich aquatic ecosystem. Streamflow records for several rivers for the summer irrigation season indicate that water withdrawals may be affecting aquatic habitat and diversity, water quality, and the value of the rivers as a scenic and recreational resource. Concerns over the effects of water withdrawals on streamflow, pond levels, groundwater levels, and aquatic habitat prompted the development of a surface-water model, groundwater models, and conjunctive-management models for the basin by the U.S. Geological Survey (USGS) in cooperation with the U.S. Department of Agriculture–Natural Resources Conservation Service (NRCS) and the Rhode Island Water Resources Board (RIWRB). The results of this study can be used to assist Federal, State, and local officials, environmental organizations, and private citizens in evaluating the water resources, water management, water-management alternatives, and land-use changes in the basin.

Climate, streamflow, groundwater-level, pond-level, and water-use data were collected throughout the Pawcatuck River Basin during 2000–04, the study period, to support development of the three models. Additionally, hydrogeologic data were compiled for the modeling efforts from previous studies throughout the basin. The surface-water (precipitation-runoff) model for the entire basin was developed by using the Hydrologic Simulation Program-FORTRAN (HSPF) model. The groundwater-flow models for the lower Wood River and eastern Pawcatuck River areas in the basin were developed by using MODFLOW. Conjunctive-management models were also developed for smaller areas within the groundwater-model areas of the basin. These hydrologic models were used to evaluate current (2000–04) conditions, long-term conditions, effects of water withdrawals on streamflow and levels, water-management alternatives, and land-use changes in the basin. Additionally, the streamflow-depletion results from MODFLOW were compared to the results of a streamflow-depletion algorithm in the HSPF model for the two groundwater-model areas.

Part 1. Water Resources in the Pawcatuck River Basin

Climatic data were collected at two stations installed for the study and compiled from four National Oceanic and Atmospheric Administration (NOAA) stations in and near the Pawcatuck River Basin. Precipitation during the study period was similar to the long-term normal, although from August 2001 through 2002 precipitation was about 17.3 in. below normal. Streamflow data were collected at nine long-term streamflow-gaging stations and at nine additional stations installed for the study. During the entire study period streamflows were close to the long-term average for the basin, but the period of below-normal precipitation from August 2001 through 2002 resulted in below-normal streamflows from September 2001 through October 2002, except for May and June 2002. Additional streamflow data in the basin were collected through monthly streamflow measurements at 36 partial-record stations during 2002–04. To help calibrate the models, daily streamflows were estimated by applying the mathematical procedure Maintenance of Variance Extension (MOVE.1) to the 36 partial-record stations for the entire study period. Climatic and streamflow data (measured and estimated) were used to calibrate the HSPF and MODFLOW models.

Groundwater-level data were collected from 19 wells that are part of the USGS long-term groundwater-monitoring network. Continuous records were collected at 4 of the 19 wells during the entire study period and at another 4 wells during 2002–04. Data from the two model areas (lower Wood River and eastern Pawcatuck River) were used in calibrating the MODFLOW groundwater-flow models. Monthly pond-level data were collected at 23 sites during 2003–04.

Water-withdrawal data for 16 wells were compiled from five major municipal suppliers in the basin. During the study period, the average withdrawal rate for these 16 wells was 7.18 Mgal/d. Four of the five water suppliers increased withdrawals noticeably each year during May through September and especially during July and August. The one exception was water withdrawals by a school; these withdrawals decreased during the summer months when most of the students were not at the school.

Water-withdrawal data were collected at 11 turf-farm sites for the period of 2002–04 or 2000–04. During the entire study period (2000–04), these turf farms averaged 3,399 gal/d/acre during days of irrigation. The number of days of irrigation per year during the irrigation season (May 1 through October 31) averaged about 31, but ranged from 0 days (one farm in 2003) to 75 days (one farm in 2001). Water-withdrawal data were collected for three golf courses (one with a surface-water supply and two with groundwater supplies) in the basin for 2002–04 or 2000–04. During the study period, these golf courses averaged 1,752 gals/d/acre during days of irrigation. The average number of days of irrigation during the irrigation season (April 16 through November 15) ranged from 75 days at the golf course with surface-water withdrawals to 131 days at the two golf courses with groundwater withdrawals. The number of days of irrigation per year ranged from 62 days at the golf course with surface-water withdrawals to 208 days at one of the two golf courses with groundwater withdrawals.

The water-withdrawal data collected at the turf farms and golf courses were then used to develop logistic-regression equations to estimate the probability of irrigation on specific days during the respective irrigation seasons for turf farms and golf courses. The equations were based on total precipitation and potential evapotranspiration during the previous 2 to 20 days, depending on the equation, proceeding each day of estimation. One equation was developed for turf farms and two equations were developed for golf courses, one for surface-water withdrawals and one for groundwater withdrawals. Once the days of irrigation for 2000–04 were estimated by the appropriate equations, the average hourly irrigation patterns determined for the turf farms or golf courses were then applied to the acreage of the unmetered sites. For the pre-study period of 1960–99, irrigation withdrawals had to be estimated for all turf farms and golf courses by using the appropriate logistic-regression equations, climate data during 1960–99, the acreage from 2000–04, and the hourly irrigation pattern from 2000–04.

Part 2. Simulation of Water-Use and Land-Use Changes on Streamflow with a Precipitation-Runoff Model (HSPF)

Simulations of the effects of withdrawal practices and land-use changes on streamflow were developed in conjunction with the Pawcatuck Watershed Partnership (WUSG) and were made with the calibrated HSPF model for the period 1960–2004. Simulations included the following scenarios: no withdrawals, current withdrawal, conversion of selected surface-water irrigation withdrawals to groundwater withdrawals, future water-supply demands, and land-use change. The first four scenarios focused on withdrawal alternatives in 12 subbasins in 3 regions of the Pawcatuck River Basin—the Usquepaug-Queen River and Beaver River area, the eastern Pawcatuck River area, and the lower Wood River area. For each subbasin, the effects of withdrawal alternatives were evaluated by examining changes in the daily mean flow-duration curves simulated for the 1960–2004 period and the hourly flow hydrographs for August 2002, the month of lowest flow during the calibration period. The analysis was limited to 13 selected sites that were of most interest to the WUSG, but any of the 84 model reaches defined could be used in the analysis.

In general, the largest differences between current withdrawals and no withdrawals in the simulations were in four subbasins in the eastern Pawcatuck River area—the Chipuxet River (two locations), the Chickasheen River, and the headwaters of the Pawcatuck River. Currently municipal water-supply and agricultural withdrawals are substantial in this part of the basin, including the largest municipal water-supply withdrawal, which is in the Mink Brook area (part of the headwaters of the Pawcatuck River subbasin). Simulated flow-duration curves indicate that current withdrawals decreased the lowest flows in comparison to simulations with no withdrawals by about 40 percent in the upper Chickasheen Brook and by about an order of magnitude (up to 80 percent) in the lower Chipuxet River and the headwaters of the Pawcatuck River. A marked departure between simulated flow-duration curves with and without withdrawals begins at about the 50-percent duration in each of the eastern Pawcatuck River reaches examined, indicating withdrawals appreciably alter median to low streamflow in these reaches. The only other subbasin that showed a substantial difference between low flows with and without withdrawals was the Beaver River subbasin; at the 99.8-percent flow duration, streamflow under no withdrawals was about two times greater than under current demands.

The effects of moving withdrawals from surface water to groundwater at selected sites were most pronounced in the daily mean flow-duration curves for the Beaver and Chipuxet River subbasins, where irrigation withdrew the largest percentage of streamflow during low-flow periods. Hourly flow fluctuations in the August 2002 hydrograph were greatly reduced or eliminated entirely by moving irrigation withdrawals from surface water to groundwater in subbasins with irrigation demands, even if the switch to groundwater did not result in appreciable differences in the daily flow-duration curves.

Potential future water withdrawals were simulated at well sites selected by the RIWRB. Simulations included moving selected irrigation withdrawals from surface water to groundwater. Results indicate that hypothetical water withdrawals of 1 Mgal/d in the eastern Pawcatuck River subbasins could result in zero flow in the upper Chipuxet River and decrease the lowest flows by as much as an order of magnitude. A hypothetical 1 Mgal/d withdrawal from the Meadow Brook subbasin decreased the lowest flows by about half. Flows in other reaches affected by simulated future withdrawals generally did not show much change because the cumulative future withdrawals from those reaches were small relative to the streamflow.

Simulations of land-use change (build-out analysis) evaluated the effects of land-use change only, change in water withdrawals only, and the combined effects of land- and water-use change. Land-use change was mostly determined on the basis of a statewide future land-use map compiled under the provisions of the Rhode Island Comprehensive Planning and Regulation Act of 1988. Developable lands were further restricted on the basis of steep bedrock, extremely rocky areas, and protected areas and buffers around water bodies and wetlands. Overall, about 10 percent of the basin was classified as developed in 1995, but about 50 percent of the basin could be developed under the restrictions described above. The largest change, which affected about a third of the basin, was from forest to low-to-medium-density residential development. The change in developed land use in the subbasins ranged from zero to about 75 percent of subbasin area, with a median change of about 40 percent.

The effects of water-use change associated with land-use change (build-out analysis) were simulated on the basis of housing density, an occupancy rate of 2.5 people per unit, and a water-use factor of 70 gal/d/person. Water use ranged from 44 to 1,400 gal/d/acre for low- to high-density residential development, respectively. In most areas of the basin it was assumed that 20 percent of the water use was consumptive (lost from the basin), and that the remaining 80 percent was returned through onsite septic systems. The exception to this was in the eastern (South Kingstown) and southwestern (Westerly and Stonington) parts of the basin where the entire water demand is considered lost from the basin because these areas are served by municipal water suppliers and sewers that return wastewater outside the basin. The domestic water use in the basin at buildout was estimated as 21.8 Mgal/d or about 4 times the current domestic water use.

Water use for new commercial and industrial development was estimated per unit area by using reported values for 1995–99 (1.22 Mgal/d) and distributing this demand over the total area at buildout (8,414 acres). Results indicate that at buildout, commercial and industrial water use would be about 7.47 Mgal/d for the basin or about a 5-fold increase over the reported 1995–99 commercial and industrial water use. In the buildout analysis irrigated land, other than land used by golf courses, was assumed to be replaced by developable land unless otherwise protected.

Buildout was simulated for the upper Chipuxet River, lower Beaver River, lower Wood River, and lower Pawcatuck River subbasins. The buildout plans for these areas reflect changes in water demand, land use, or both. Withdrawals in the upper Chipuxet River subbasin currently are minor, but about 54 percent of the subbasin is developable. The simulations for the lower Beaver River subbasin reflect large changes in land use, but changes in water withdrawals are expected to be less pronounced because they are expected to be partially offset by a decrease in agricultural withdrawals. The simulations for the lower Wood River subbasin reflect change in a large pristine basin. Anticipated changes for the lower Pawcatuck River subbasin reflect the overall change in the entire basin.

In general, simulations for buildout indicated that high flows would increase slightly and low flows would decrease slightly as a result of land-use change relative to simulations for land-use conditions in 1995, but the changes were generally not large. In some instances, decreased infiltration from urbanization was offset, or more than offset, by decreased evapotranspiration from deep-rooted vegetation. For example, simulation results for the lower Wood River subbasin showed slightly higher low flows under buildout than under 1995 land-use conditions. In subbasins where water is currently extracted for agricultural irrigation, the irrigation withdrawals can exceed the urban buildout withdrawals that replace them, which results in higher simulated low flows under buildout conditions than under current conditions. The extent to which streamflow changes in response to development depends on exactly how the land is developed; development is expected to differ widely and to produce effects different from those simulated, particularly in local areas.

The Pawcatuck Basin HSPF model was conceptualized and calibrated to evaluate the effects of withdrawals on streamflow. Many water-resource-management issues can be evaluated through model simulations, but the model may not be appropriate for some analyses. Thus, care should be taken to consider the model uncertainties and limitations to ensure that inappropriate interpretation of simulation results does not lead to inaccurate conclusions.

Part 3. Simulated Effects of Withdrawals on Groundwater Flow (MODFLOW Models)

Groundwater-flow models were developed for two areas in the Pawcatuck River Basin—the lower Wood River and eastern Pawcatuck River areas—to assess the potential effects of groundwater pumping on streamflows and water levels at proposed irrigation and municipal water-supply sites in the study area, to compare results simulated by MODFLOW and the streamflow-depletion algorithm in the HSPF model, and to evaluate alternatives for the conjunctive management of the ground- and surface-water resources of the basin.

The simulations included analyses of the effects of constant and varying pumping and constant and varying recharge rates, the effects of constant pumping and varying recharge rates, and the effects of different well distances from streams under constant and varying pumping rates. Simulations were made to compare and contrast the effects of these changes on smaller and larger streams with lower and higher flows, respectively, to determine whether the responses of the streams and the surrounding aquifer to the changes in simulated stresses differed with stream size.

For constant pumping and constant recharge representing average conditions, the simulated decrease in streamflow in both a large and a small stream (with higher and lower flow, respectively) was about equal to the total pumping rate, with the remainder of the withdrawal derived from aquifer storage. As the recharge rate varied with time, however, the streamflow varied in response to the change in recharge, and the amount of base-flow reduction from pumping also varied. The simulated pumping rates from proposed wells near both of the streams were the same; however, the effects of pumping on the two streams differed substantially.

During wet periods when simulated streamflow was at or above average, the reduction in streamflow was similar to that calculated in the simulation in which pumping and recharge were constant. During the summer and early fall when simulated streamflow without pumping was at or near zero, however, the calculated reduction in streamflow from pumping decreased as streamflow decreased, because as a stream goes dry, it can no longer be a source of water to the pumped well. When a pumped well can no longer meet the demand for water by depleting streamflow, the demand must be met from another source, usually aquifer storage. Once the stream is dry, the water required to meet the simulated pumping rate is obtained solely from aquifer storage, a process resulting in drawdowns in the aquifer much greater than would have been produced near a flowing stream.

An analysis of the effects of varying the distances between pumping wells and streams was done to determine if the effects of instream withdrawals for turf irrigation during low-flow periods could be reduced if the withdrawals were shifted away from the streams. This analysis showed that streamflow increased during the normally dry summer months as the distance between the pumping wells and the rivers was increased because of the time lag in the response of the streams to the pumping stress. As a result, simulated irrigation pumping during the summer did not affect streamflow until later in the fall when streamflows are typically higher.

These simulations indicate that moving the irrigation withdrawals from the rivers to wells away from the rivers resulted in increased streamflows relative to current conditions during the summer low-flow periods and lower flows relative to current conditions in the early fall. The benefit of shifting streamflow depletion from the summer to the fall is that, by the fall, streamflow is increasing from increased recharge. In general, the effect of pumping on streamflow is greater when the base-flow depletion represents a smaller percentage of the total streamflow.

Part 4. Conjunctive-Management Models as Tools for Water-Resources Planning

The results of conjunctive-management modeling may be used to help balance groundwater and surface-water withdrawals needed for water-supply and aquatic-habitat protection. Conjunctive-management models were developed for two areas in the Pawcatuck River Basin to evaluate the potential for improvements in water-withdrawal strategies. These two areas are referred to herein as the eastern Pawcatuck River conjunctive-management-model (EPRCMM) area and lower Wood River conjunctive-management-model (LWRCMM) area.

Conjunctive-management models were developed for each area by combining the results of statistical analysis of water-use data, simulations with the transient MODFLOW groundwater models, and simulations of streamflow from the basinwide HSPF surface-water model. In both areas, models with maximum withdrawal capacities of 1.0, 1.4, and 2.0 Mgal/d were tested to illustrate the dynamic interplay among stream-depletion criteria, well-network design (the number, type, and location of withdrawal sites), and production capacity of the water-withdrawal network. The streamflow-response coefficients developed as part of the optimization process were useful for evaluating the timing and magnitude of streamflow depletions from withdrawals near different streams. A streamflow-management paradigm based on potentially allowable depletions that humans can control, rather than a minimum-streamflow paradigm, was developed for use by water-resource managers. Simulation results indicate that well-site selection, water-use patterns, and the timing of the annual minimum of the daily mean streamflows affected total annual water yields in the lower Wood River model area. Results from conjunctive-management models for the eastern Pawcatuck River model area indicate that well capacity was the limiting factor for maximizing withdrawals. Postoptimization analysis demonstrated the use of management-model results to estimate the risks of extreme low flows under different withdrawal plans. The examples demonstrated how conjunctive-management models may be used to balance water use with ecological protection.

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

Water-resource managers rely on tools such as HSPF and MODFLOW to address water issues by simulating hydrologic responses of watersheds under alternative conditions or management strategies. The choice of model, or even the need for a model, however, largely depends on the questions posed. The fundamental differences between HSPF and MODFLOW were illustrated by comparing simulation results for the same type of simulation scenario. Simulation results for three examples from the study were used to describe the effects of stream-aquifer interactions and temporal and spatial discretization on flow components.

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

In the lower Meadow Brook subbasin, a hypothetical well pumping at 1 Mgal/d was simulated 200 ft from the stream. Streamflow simulated with MODFLOW, with and without withdrawals, included several periods of no flow during the summer months, whereas streamflow simulated with showed flow during all periods. The HSPF-simulated flows were generally in good agreement with the Meadow Brook streamflow-gaging station records, but MODFLOW undersimulated streamflows. As a result, induced infiltration from Meadow Brook may be undersimulated by MODFLOW, with more water to the well captured from the neighboring subbasin (PAWC4), depletion of groundwater storage (with a lower water table), or both. This result and its implications underscore the importance of streamflow in representing hydrologic processes that influence how a system responds to a stressor. One reason HSPF-simulated flows are closer to measured flow is that HSPF simulates all flow components, whereas MODFLOW simulates only the baseflow component of streamflow. On the other hand, MODFLOW better represents the interaction between Meadow Brook and the aquifer near the pumped well by simulating changes in groundwater head and induced infiltration from the stream, provided the simulated streamflow does not incorrectly fall below the withdrawal rate.

Example 2. Effects of Withdrawals near Diamond Bog

A hypothetical well pumping at 1 Mgal/d was also simulated in the lower Wood River (WOOD5) near Diamond Bog, which is considered an important ecological resource. The well was simulated about 500 ft from the Wood River and about an equal distance from Diamond Brook. Streamflow simulated in Diamond Brook was critical in determining the response of the aquifer to pumping in Diamond Bog for the same reasons described for the pumped well near Meadow

Brook. Water-level changes simulated by MODFLOW in Diamond Bog in response to pumping are highly dependent on the simulated streamflow in Diamond Brook, which was frequently comparable to or less than the withdrawal rate. As the simulated flow in the brook decreased to less than the withdrawal rate, the drawdown in the aquifer around the pumped well increased and expanded laterally enough to influence the interaction between the bog and the pumped well. Simulations by HSPF, which is designed to simulate flows in the entire Pawcatuck River Basin, did not show the effects of pumping on streamflow in Diamond Brook, nor would HSPF be capable of simulating the interaction between the bog and the aquifer.

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

Changes in streamflow caused by converting withdrawals from surface water to groundwater are affected by the averaging of irregular withdrawals and by the assumptions inherent in the program (STRMDEPL) used to compute the lag effects of a pumped well on streamflow depletion in HSPF. In the lower Beaver River the hourly simulated hydrograph shows a daily oscillation from July through early September 2002 that reflects the intradaily withdrawal pattern; this oscillation does not appear in the daily mean hydrograph because the hourly oscillations are smoothed by the daily average. In MODFLOW simulations, which averaged irrigation withdrawals over weekly or monthly stress periods, the peak withdrawal rates decreased by as much as 94 percent, diminishing or masking their effects on streamflow. This simulation illustrated the potential benefits of converting in-stream withdrawals to groundwater, particularly if the withdrawal is large with respect to streamflow.

In HSPF simulations of the lower Beaver River subbasin, the effects of converting in-stream withdrawals to groundwater are influenced by where streamflow depletion is applied. MODFLOW simulations do not force water to a pumped well from a particular source; rather, the groundwater flow path to the well is determined on the basis of the specified hydraulic conductance and the computed hydraulic gradient between the aquifer and the stream. In HSPF simulations, the streamflow depletion from withdrawals of the pumped wells near the lower Beaver River subbasin surface-water divide were only simulated in the subbasin where the wells are located. MODFLOW simulations, however, indicate that these wells near the lower Beaver River surface-water divide drew groundwater that would otherwise discharge to the lower Beaver River as baseflow. This result indicates that HSPF may oversimulate the benefits of converting in-stream withdrawals to groundwater.

Thus, streamflow depletions allocated on the basis of subbasin surface-water divides can be inaccurate and lead to incorrect conclusions. 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 problem applies to areas where a pumped well alters the groundwater flow path in ways that are not easily determined, such as near the groundwater (water-table) subbasin divide or where the water-table gradient is small or poorly defined. Although MODFLOW simulations are best suited for this type of analysis, constructing an accurate model commonly requires detailed field investigations, particularly at the local scale, to ensure that the controlling hydrologic factors are well defined.

One model used by itself can not adequately address all the hydrologic complexities of the real world, but understanding the capabilities and limitations of HSPF and of MODFLOW provides insight into the many factors that affect simulations and the management decisions made from those simulations. An integrated model can minimize some of the weaknesses of one model by coupling it with the strengths of the other model. The complexities of an integrated model are large, and further testing of integrated models would be needed to determine their potential use. An integrated model was tested for this study but it was determined to be impracticable due to limitations of a workable MODFLOW cell size, the number of additional hydrologic response units (HRUs) needed to represent head-dependent conditions throughout the basin, and the size of the database needed to link the models. Instead, HSPF and MODFLOW were informally linked in this study.

Water-resource managers rely on tools such as HSPF and MODFLOW to address water-resources issues by simulating alternative management strategies. The choice of model, or even the need for a model, however, largely depends on the questions posed. Each model has strengths and weaknesses related to the differing hydrologic processes the models are intended to simulate and the spatial and temporal scales of the models. Comparison of selected results simulated by these two models demonstrates these limitations and the judgment required to determine the suitability of a particular model for making management decisions.

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