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

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The Hydrological Simulation Program-FORTRAN (Bicknell and others, 2000), hereafter referred to as HSPF, was developed and calibrated for the 303-mi^2 Pawcatuck River Basin to evaluate the effects of withdrawals and land-use change on streamflow. A summary of model development and calibration follows, but details of this work are presented in appendix 2.

The basin is represented by hydrologic response units (HRUs) composed of 17 pervious areas (PERLNDs) and 2 impervious areas (IMPLNDs) developed from a combination of land-use, surficial-geology, and soil types that are linked to 84 stream reaches (RCHRESs) (sites shown in fig. 2–1 and described in table A2–4). The area of various HRUs contributing to a reach and the linkage of reaches to one another form subbasins in the model. Forested HRUs are the dominant land-use type composing about 62 percent of the basin area; most forested areas overlie till (about 35 percent of the basin area). Wetlands are also an important HRU, composing about 14 percent of the basin area.

The model was calibrated from January 1, 2000, to September 30, 2004, with measured and estimated flows at 17 continuous-record streamflow-gaging stations and 34 partial-record stations. The parameter estimation program (PEST) was used to refine the empirical model calibration and to evaluate parameter sensitivities and uncertainties. Simulated and observed hydrographs, flow-duration curves, and scatterplots indicate that the model is generally well calibrated. Statistics computed to assess the model fit, including the coefficient of determination (R^2) and the model-fit efficiency (MFE), also indicate that the simulated flows are in good agreement with the observed flows. Simulated daily mean flows at the 17 continuous streamflow-gaging stations had a median R^2 of 0.81 and ranged between 0.66 and 0.87; the median MFE was 0.79 and ranged between 0.59 and 0.86. Although the model is generally well calibrated to observed streamflows, users should be aware of the model limitations and uncertainties discussed in appendix 2. Scenarios are, therefore, best viewed as relative change rather than absolute change; this perspective minimizes the effects of model limitations and uncertainties in the interpretation of model results.

Simulated annual water budgets for the 2000–04 calibration period indicate that the baseflow component of streamflow from areas overlying sand and gravel, till, steep-rocky areas, and wetlands account for about 98, 71, 22, and 22 percent of the total average flow, respectively. The remaining flow was generated mostly from interflow (fast-responding subsurface flow) except in steep-rocky areas and wetlands where flow was about equally split between interflow and surface runoff. About 59 percent of the average moisture supply to the basin was discharged to the streams, 38 percent was lost to evapotranspiration, and the remaining 3 percent went into storage. Moisture supply discharged to streams, on average, comprises 91 percent subsurface discharge (interflow and baseflow) and about 9 percent surface runoff. During March 2001, a wet period, streamflow comprised about 20 percent surface runoff, 35 percent interflow, and 47 percent groundwater. During August 2002, a dry period, evapotranspiration loss was about twice as great as the moisture supply to the basin; thus, streamflow was mostly discharge from groundwater storage.

The Pawcatuck River Basin HSPF model was developed as a tool to evaluate the effects of withdrawal practices and land-use change on streamflow. Results are intended to provide information for making water-resources-management decisions. In December 2002, the Pawcatuck Watershed Partnership Water-Use Stakeholders Group (WUSG), in conjunction with the USGS, agreed to the following model scenarios:

- No withdrawals—provides information that approximates unaltered streamflow conditions;
- Current withdrawal practices—provides information on long-term streamflow under current (2000–04) withdrawals, which in conjunction with simulations of no withdrawals, provides the baseline information for evaluating other water-management practices;
- Conversion of selected irrigation withdrawals from surface-water to groundwater sources—provides information on the potential benefits of the lag effect of groundwater withdrawals on streamflow;
- Future water-supply withdrawals—provides information on the potential effects of new groundwater withdrawals identified by the RIWRB on streamflow; and
- Buildout—provides information on the effects of changes in land use and water demand on streamflow; scenarios identify the effects of land-use change only, water-demand change only, and the combined effects of both types of changes.

Each of these scenarios required a new model-run file (uci) that altered model input data or structure, or both. Each new uci file is uniquely identified by its prefix name; simulation output is uniquely identified with the IDSCEN attribute and a unique Data Set Number (DSN) in the Watershed Data-Management (WDM) system. Model-run file names and DSNs for the output results associated with the scenario simulations are summarized in table 2–1. Model scenarios were simulated with an hourly time step for the 1960–2004 period using the PROVID station (fig. 1–1) climate data adjusted to the concurrent climate data measured in the basin at the FBWR station during the 2000–04 period (appendix 2).

Effects of Withdrawals on Streamflow

Simulation results can be output at any of the 84 model-reach nodes; however, reporting results from all reaches is impractical. The WUSG requested that water-use scenarios focus on 13 reaches in the central and eastern part of the basin (fig. 2–1). These reaches were selected because of known flow alteration, their ecological importance, or both. Model results from the upper Meadow Brook subbasin (RCHRES 47, MEAD1) are not included in the discussion that follows because there was little change between scenarios.

Simulations with average 2000–04 withdrawals and without withdrawals indicate the different effects of these two sets of conditions on long-term streamflow. These simulations also provide a baseline for other simulations. Simulations without withdrawals better reflect natural-flow conditions, but also reflect current land-use conditions and factors such as distributed domestic withdrawals that are incorporated into the model-parameter calibration.

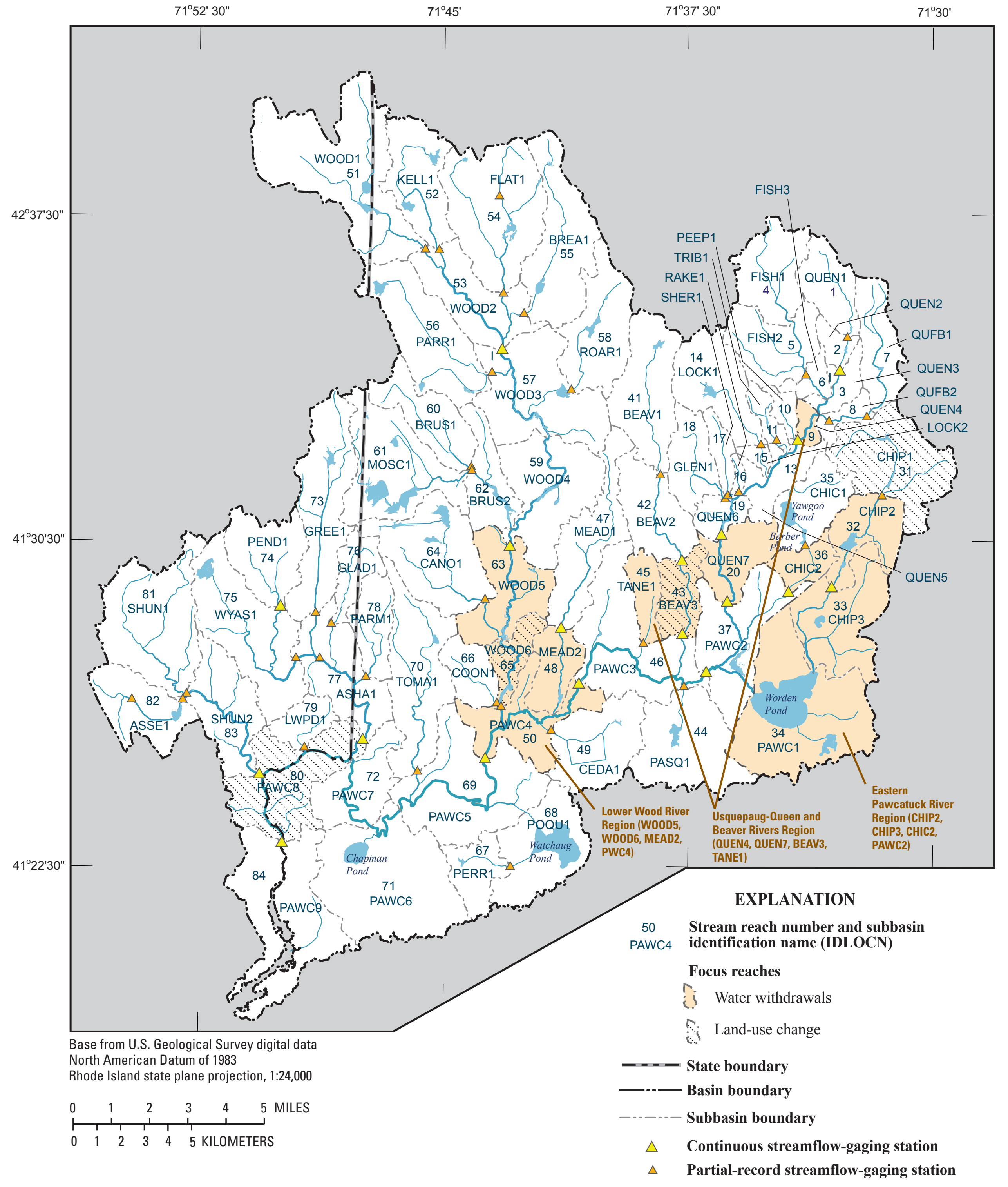
Long-term (1960–2004) simulation of current withdrawals (LT–CDmd) entailed developing long-term withdrawal data that represents average 2000–04 withdrawal practices. Estimates of long-term irrigation withdrawals were determined by logistic-regression equations that relate irrigation needs to antecedent conditions and measured use rates as described in Part 1. Measured withdrawals, mostly for the 2000–04 period, were used where available. Simulations of no withdrawals (LT–NoDmd) entailed zeroing out withdrawals specified in the External Source block of the uci file by use of the multiplier field (MULT). Simulation results for no withdrawals were output to DSN 6001 to 6080 and to DSN 6101 to 6180 for average 2000–04 withdrawals.

Simulation of selected irrigation withdrawals from surface-water to groundwater sources (LT–CDSWR) entailed constructing new times-series data of total withdrawals for each reach affected by this change. Irrigation withdrawals are mostly in the eastern Pawcatuck River or lower Wood River subbasins. The new withdrawal time series represent the combined calculated streamflow depletion of individual withdrawals converted from surface-water to groundwater sources, plus any continued direct surface-water withdrawals or streamflow depletion from existing pumped wells in the reach. In some cases, conversion of an irrigation withdrawal from a surface-water to a groundwater source entailed moving the withdrawal to a new reach. Overall, 10 of the 37 individual irrigation withdrawals were converted from surface-water to groundwater sources. Of these, 8 withdrawals were moved to a different subbasin mostly from the lower Beaver River subbasin to an adjacent subbasin on the Pawcatuck River. Results of this simulation were output to DSN 6201 to 6280 in the WDM file.

Table 2–1. Summary of model simulations and target data-set numbers for Hydrologic Simulation Program-FORTRAN (HSPF) of the Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut.

[uci, model user control input file; DSN and IDSCEN, Data-set number and scenario-identification attribute in the watershed-data-management (WDM) file, respectively; Mgal/d, millions of gallons per day]

uci and IDSCEN name	Range of output DSNs	Description
		Withdrawal simulations
LT–NoDmd	6001–6080	No withdrawals (no demands).
LT–CDmd	6101–6180	Average 2000–04 withdrawals (current demands).
LT–CDSWR	6201–6280	Same as LT–CDmd with selected irrigation withdrawals converted from surface-water to groundwater sources.
LT–CDWRB	6301–6380	Same as LT–CDSWR with potential water-supply wells pumped at 1 Mgal/d.
		Buildout simulations
LT–BldCD	6401–6480	Potential land-use change and 2000–04 water use (current demand).
LT–95LFD	6601–6680	1995 Land use and potential water use change (future demand).
LT–BldFD	6701–6780	Potential land-use and water-use change.



Base from U.S. Geological Survey digital data
North American Datum of 1983
Rhode Island state plane projection, 1:24,000

Figure 2–1. Focus reaches where the effects of water-withdrawal and land-use changes were examined with the Hydrologic Simulation Program-FORTRAN (HSPF) model of the Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut.

Potential new groundwater withdrawals (LT–CDWRB) were simulated for 14 sites identified by the RIWRB. Withdrawals from these sites were made through an additional specified outflow (exit gate) added to the appropriate reach. This modification allows for greater flexibility in future applications of the model; withdrawal rates at these sites can be modified easily, or turned on or off as desired without affecting other withdrawals in the model. For the purpose of this scenario, each of the 14 potential withdrawals was pumped at a constant rate of 1 Mgal/d (1.55 ft^3/s) that results in a constant rate of streamflow depletion. The LT–CDSWR uci file was the base simulation for this scenario and, thus, the simulation results also reflected the conversion of select irrigation withdrawals from surface-water to groundwater sources. Water withdrawn from new withdrawals was assumed to be lost from the basin (water was not returned to the basin through wastewater discharge or other means). Results of this simulation were output to DSN 6301 to 6380 in the WDM file.

Results of the simulations are shown for the 12 focus reaches as daily mean flow-duration curves for the 1960–2004 period and as hydrographs of hourly flow for August 2002, the month of lowest flow during the calibration period. The August 2002 period was chosen over other historically drier periods because actual withdrawal information was used to the extent that it was available. The results were divided into three general regions of the basin—(1) Usquepaug-Queen and Beaver Rivers, (2) eastern Pawcatuck River, and (3) lower Wood River (fig. 2–1). Within each region, results are presented for four reaches. Reaches are associated with HSPF subbasins; however, the reaches and the model output examined include the cumulative effects of the upstream drainage area.

Usquepaug-Queen and Beaver Rivers Region

The Usquepaug-Queen and Beaver Rivers region includes the Queen River at Liberty (QUEN4, combined flow of RCHRES 9 and 10), the Usquepaug River near its mouth to the Pawcatuck River (QUEN7, RCHRES 20), the lower Beaver River (BEAV3, RCHRES 43), and Taney Brook (TANE1, RCHRES 45), which enters the Pawcatuck River just below the confluence with the Beaver River (fig. 2–1). QUEN4, QUEN7, and BEAV3 have cumulative drainage areas of 20.1, 36.4, and 11.8 mi^2, respectively, all of which include irrigation withdrawals. TANE1 is a small headwater subbasin with a drainage area of 1.61 mi^2 and does not include municipal or irrigation withdrawals.

Daily mean flow-duration curves for QUEN4 indicate only a slight difference at the lowest flows between no withdrawals and average 2000–04 withdrawals or the other conditions simulated (figs. 2–2A and 2–3A). Irrigation withdrawals above this reach were simulated from eight individual sources for golf courses, turf farms, and other agricultural operations. During the summer months (June through August) irrigation withdrawals in and upstream of this reach averaged 0.80 ft^3/s. One possible reason why the simulations with and without withdrawals show little difference in flow at QUEN4 is because most of the withdrawals were from upper Queens Fort Brook (QUFB1, RCHRES 7). Most of the active groundwater and 80 percent of the interflow from QUFB1 is routed out of the subbasin to account for apparent differences between the surface and subsurface subbasin divides (see appendix 2 discussion about the calibration of this reach and Zarriello and Bent (2004) for details about the complexity of the flow paths in this part of the basin). Because flows are limited by diversion of subsurface flow, withdrawals from this subbasin have only a minor effect on downstream flows. As a result, the effects of withdrawals at QUEN4 are mostly limited to those in the upper Queen River and the lower Queens Fort Brook subbasins, which collectively accounted for about 12 percent of the total withdrawals (about 0.14 ft^3/s) above QUEN4 during the 2000–04 period. It should also be noted that all irrigation withdrawals above QUEN4 were estimated. No RIWRB potential withdrawal sites were located above this reach; therefore, the streamflow response for this simulation (LT–CDWRB) is the same as for the average 2000–04 withdrawal simulation (LT–CDmd). Effects of other potential withdrawals on streamflow in the former Ladd School development area were previously simulated with an earlier HSPF model and described by Zarriello and Bent (2004).

Daily mean flow-duration curves for QUEN7 indicate that flows above the 90-percent duration are moderately affected by average 2000–04 withdrawals (fig. 2–2B). At the 99.8-percent flow duration, daily mean flows under no withdrawals were about 30 percent greater than under average 2000–04 withdrawals. Simulations indicate that converting selected irrigation withdrawals (including one that accounts for about a fifth of the total irrigation demand from the reach) from surface-water to groundwater sources (LT–CDSWR) can increase low flows (fig. 2–2B) and appreciably dampen the intradaily flow fluctuations compared to average 2000–04 withdrawals (fig. 2–3B). During August 2002, this conversion resulted in streamflow that was slightly above the maximum daily flow under average 2000–04 withdrawals, which generally reflects the period of the day when direct stream withdrawals ceased and streamflow was affected only by withdrawals from pumped wells.

Streamflow in BEAV3 responded similarly in the same withdrawal scenarios simulated in QUEN7, but in a somewhat more pronounced manner. At the 99.8-percent flow duration, streamflow under no withdrawals was about two times greater than under average 2000–04 withdrawals (fig. 2–2C). Converting irrigation withdrawals from surface-water to groundwater sources increased low flows in the Beaver River to nearly the same level as under no demand. This pronounced change in low flows was, at least in part, a result of moving about 70 percent of the total irrigation withdrawals from BEAV3 to pumped wells in the PAWC2 (RCHRES 37) subbasin (fig. 2–1). The effect of converting from surface-water to groundwater sources may be less than indicated because, although the pumped wells are in a different model subbasin, the contributing area to these wells could continue to affect the groundwater discharge to the lower Beaver River and could

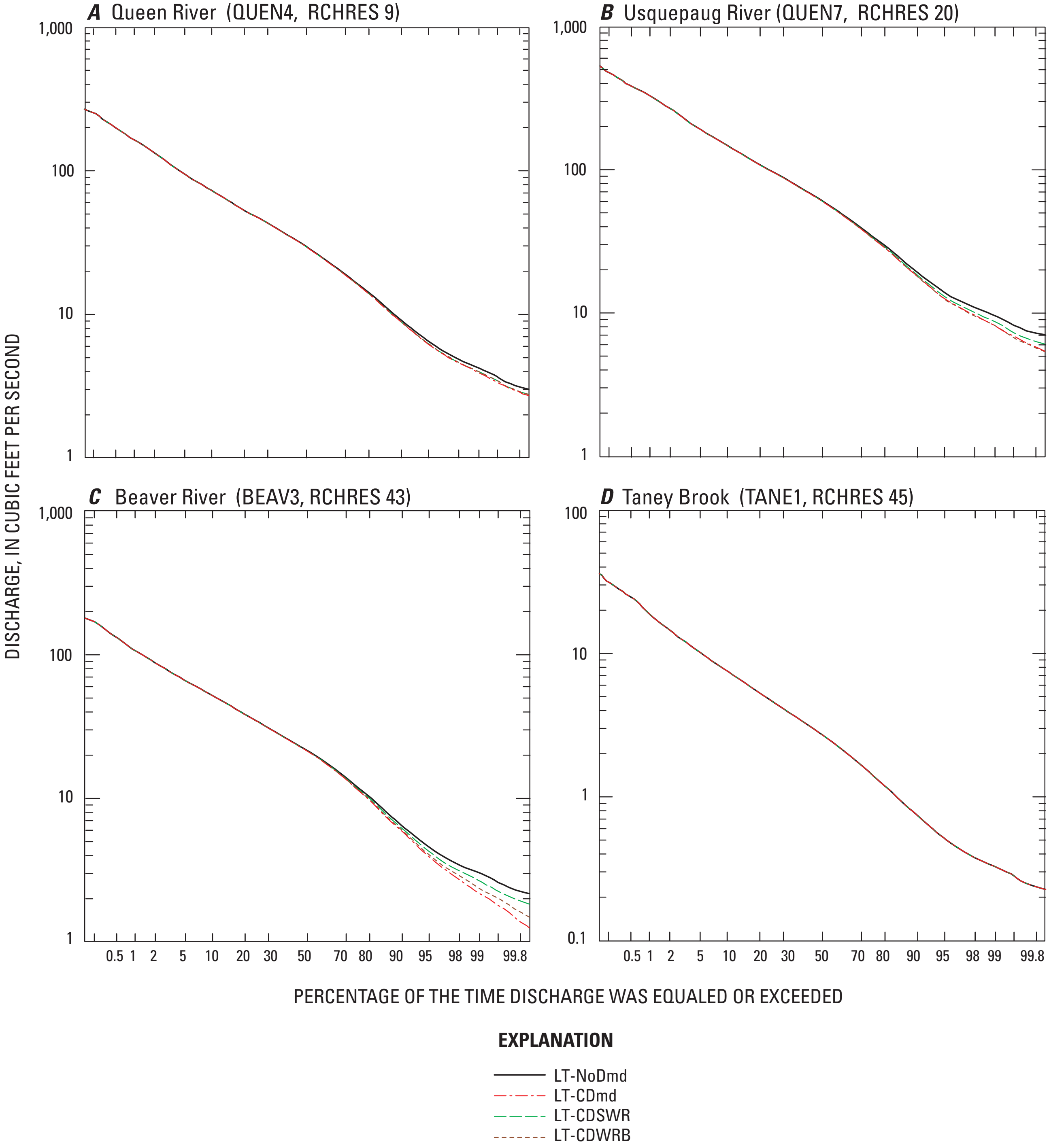


Figure 2–2. Flow-duration curves of simulated daily mean streamflow (1960–2004) under no withdrawals (LT–NoDmd), current (2000–04) withdrawals (LT–CDmd), current withdrawals with selected irrigation withdrawals converted from surface-water to groundwater sources (LT–CDSWR), and current withdrawals with potential new withdrawals (LT–CDWRB) at *(A)* Queen River (QUEN4, RCHRES 9); *(B)* Usquepaug River (QUEN7, RCHRES 20); *(C)* Beaver River (BEAV3, RCHRES 43); and *(D)* Taney Brook (TANE1, RCHRES 45), Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

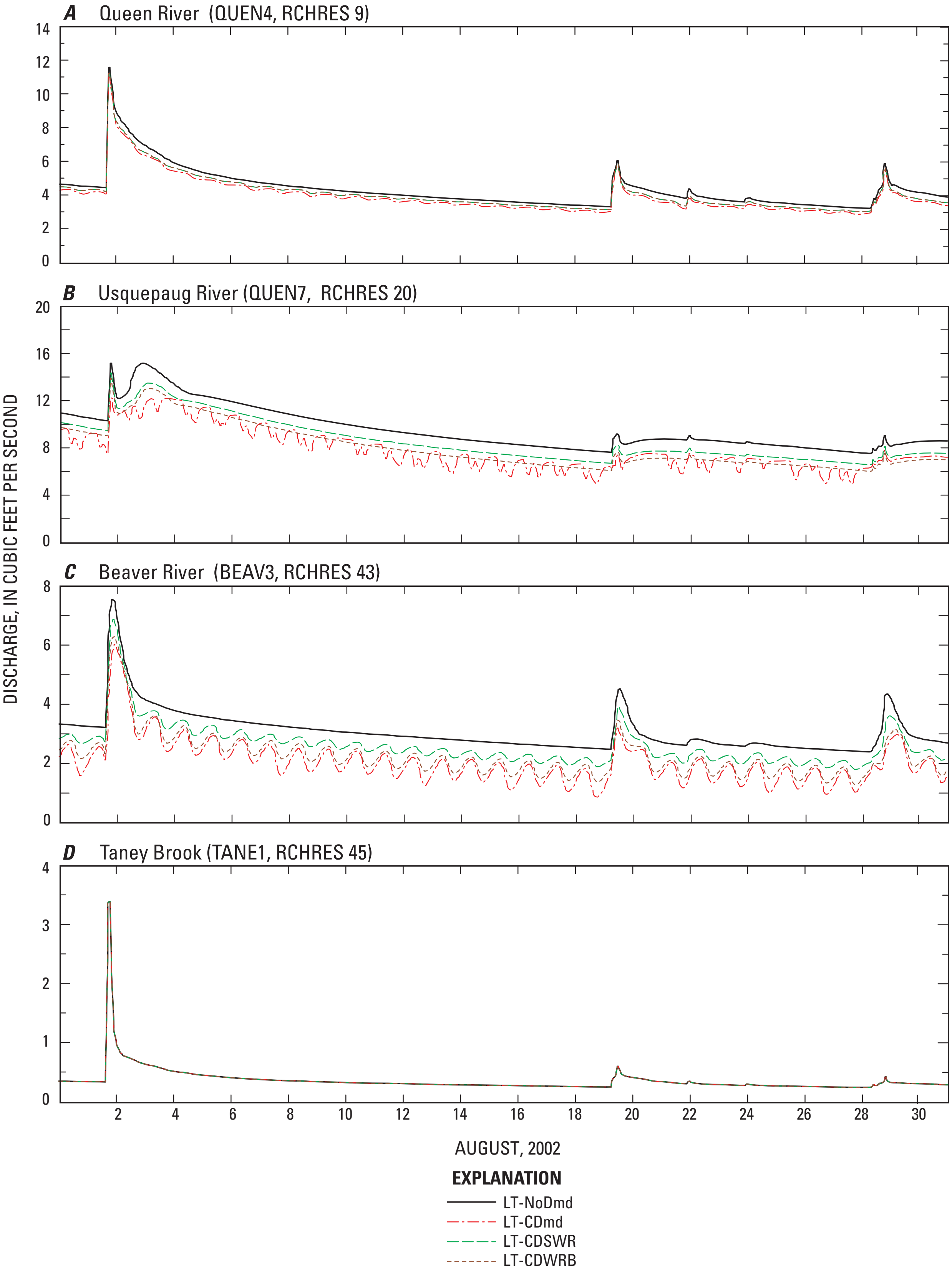


Figure 2–3. Simulated hourly streamflow in August 2002 under no withdrawals (LT–NoDmd), current (2000–04) withdrawals (LT–CDmd), current withdrawals with selected irrigation withdrawals converted from surface-water to groundwater sources (LT–CDSWR), and current withdrawals with potential new withdrawals (LT–CDWRB) at *(A)* Queen River (QUEN4, RCHRES 9); *(B)* Usquepaug River (QUEN7, RCHRES 20); *(C)* Beaver River (BEAV3, RCHRES 43); and *(D)* Taney Brook (TANE1, RCHRES 45), Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

also affect groundwater discharge to the lower Usquepaug River (QUEN7). The simulation of withdrawals from four potential supply wells in the Beaver River subbasin (LT–CDWRB) indicate that any gains in low flows from converting irrigation withdrawals from surface-water to groundwater sources are offset by the additional water-supply withdrawals. The potential supply wells are also near the subbasin surface-water divide, which could affect simulated streamflows because part of the water to the well may come from areas outside of the subbasin as described above. Under average 2000–04 withdrawals, the intradaily flow fluctuations from irrigation withdrawals varied by about 1 ft^3/s, which is about 50 percent of the daily peak flow for most days during August 2002 (fig. 2–3C). Intradaily streamflow fluctuations were damped considerably by converting from surface-water to groundwater sources, but this damping effect also reflects moving most of irrigation withdrawals to the PAWC2 subbasin.

In about 40 percent (29 of 70) of the subbasins used to develop the Pawcatuck River Basin HSPF model, water withdrawals are not specified. In some subbasins, such as Taney Brook (TANE1), no withdrawals are specified resulting in no change in streamflow (figs. 2–2D and 2–3D) among the scenarios simulated. Simulation results are shown for Taney Brook because they were requested by the WUSG, but results from this subbasin also represent about half of the HSPF Pawcatuck River subbasins in that little, if any, change in streamflow results from the water management scenarios simulated. Results from this subbasin also demonstrate that the model can be used to evaluate streamflow at ungaged locations under a range of climatic conditions or to evaluate other water-management scenarios that may affect a particular subbasin.

Eastern Pawcatuck River Region

The eastern Pawcatuck River region (fig. 2–1) includes the lower Chipuxet River (CHIP2, RCHRES 32 and CHIP3, RCHRES 33), the upper Pawcatuck River (PAWC1, RCHRES 34), and the lower Chickasheen Brook (CHIC2, RCHRES 36). CHIP2 and CHIP 3 are near the headwaters of the eastern Pawcatuck River Basin and comprise cumulative drainage areas of 9.69 and 15.4 mi^2, respectively with substantial municipal and agricultural withdrawals. PAWC1 has a cumulative drainage area of 25.8 mi^2 that includes the Mink Brook drainage area, which is the source area for the largest supply withdrawals in the entire Pawcatuck River Basin. CHIC2 is a small tributary subbasin to the upper Pawcatuck River with a cumulative drainage area of 4.82 mi^2 that includes several withdrawals for irrigation.

Simulations indicate that streamflows in the eastern Pawcatuck River region (RCHRES 31 through 36) were the most affected of the reaches examined (figs. 2–4 and 2–5). Flow-duration curves indicate that average 2000–04 withdrawals decrease the lowest flows relative no withdrawals by about 40 percent in Chickasheen Brook (CHIC2), and by about an order of magnitude in the lower Chipuxet River (CHIP2) and Pawcatuck River (PAWC1). The daily mean flow-duration curves for average 2000–04 withdrawals and no withdrawals noticeably deviate from one another at about the 50-percent duration for each of the eastern Pawcatuck River reaches examined; this indicates that withdrawals appreciably alter median to low streamflow in these reaches.

Withdrawals from the eastern Pawcatuck River region serve a combination of water needs; withdrawals are predominantly for municipal supply in PAWC1 (nearly 100 percent of total withdrawals) and predominantly for irrigation in CHIP2 and CHIC2 (about 98 and 100 percent of total withdrawals, respectively). Because of these differences in water use, the simulated streamflow responses to the alternative water-management scenarios vary. In CHIP2, about 70 percent of the cumulative irrigation withdrawals were converted from surface-water to groundwater sources in scenario LT–CDSWR. This conversion increased low flows slightly above the 90-percent daily mean flow duration (fig. 2–4A) relative to current demands, but the effect on intradaily flow fluctuations is more pronounced (fig. 2–5A). The moderating effect of converting source water prevents the intermittent cessation of flow in CHIP2 during low-flow periods, such as mid-August 2002 (fig. 2–5A) and generally maintains flow about equal to the daily maximum flow under average 2000–04 withdrawals. The sporadic cessation of flow during the day is not reflected in the flow-duration curves (fig. 2–4A) because the curves represent daily mean flows. Simulations indicate that the addition of a well pumped at 1 Mgal/d (LT–CDWRB) in CHIP2 results in a daily mean flow of less than 0.1 ft^3/s about 1 percent of the time (fig. 2–4A); flows were generally equal to the daily minimum flow under average 2000–04 withdrawals (fig. 2–5A).

Farther downstream in the Chipuxet River (CHIP3), the ratio of total cumulative withdrawals to streamflow decreases, and although differences in streamflow with and without withdrawals are appreciable (fig. 2–4B), they are less pronounced than in CHIP2. Intradaily streamflow fluctuations also diminish (fig. 2–5B) in CHIP3 relative to CHIP2 because an increasing percentage of the total withdrawals are for municipal-supply purposes (about 2 and 14 percent in CHIP2 and CHIP3, respectively), and about 40 percent of the cumulative irrigation withdrawals are obtained from groundwater sources in the CHIP3 subbasin. Differences between streamflow simulated under average 2000–04 demand (LT–CDmd) and converted irrigation (LT–CDSWR) are small for the reasons above and because only about 17 percent of the existing irrigation withdrawals were affected by this change. The simulation of potential supply wells includes two wells in the CHIP3 subbasin that, together with the potential upstream supply well, cumulatively withdraw 3 Mgal/d (LT–CDWRB). This simulation indicates that the daily mean flow in CHIP3 drops below 1 ft^3/s about 1 percent of the time and is about an order of magnitude lower than under no withdrawals at the 99-percent flow duration (fig. 2–4B). The decrease in flow caused by the additional withdrawals relative to the other simulations is also apparent in the August 2002 hydrograph (fig. 2–5B).

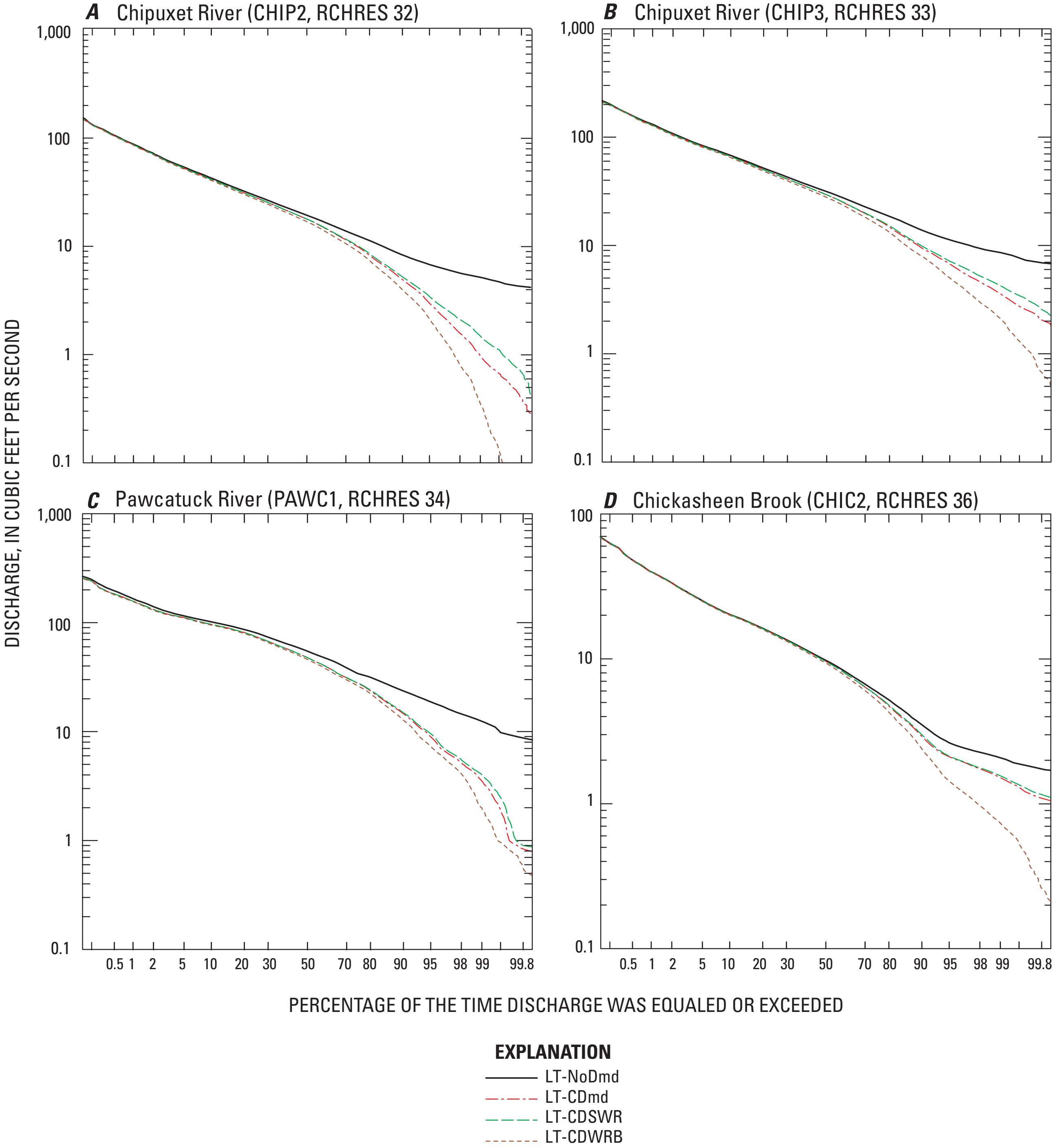


Figure 2–4. Flow-duration curves of simulated daily mean streamflow (1960–2004) under no withdrawals (LT–NoDmd), current (2000–04) withdrawals (LT–CDmd), current withdrawals with selected irrigation withdrawals converted from surface-water to groundwater sources (LT–CDSWR), and current withdrawals with potential new withdrawals (LT–CDWRB) at *(A)* Chipuxet River (CHIP2, RCHRES 32); *(B)* Chipuxet River (CHIP3, RCHRES 33); *(C)* Pawcatuck River (PAWC1, RCHRES 34); and *(D)* Chickasheen Brook (CHIC2, RCHRES 36), Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

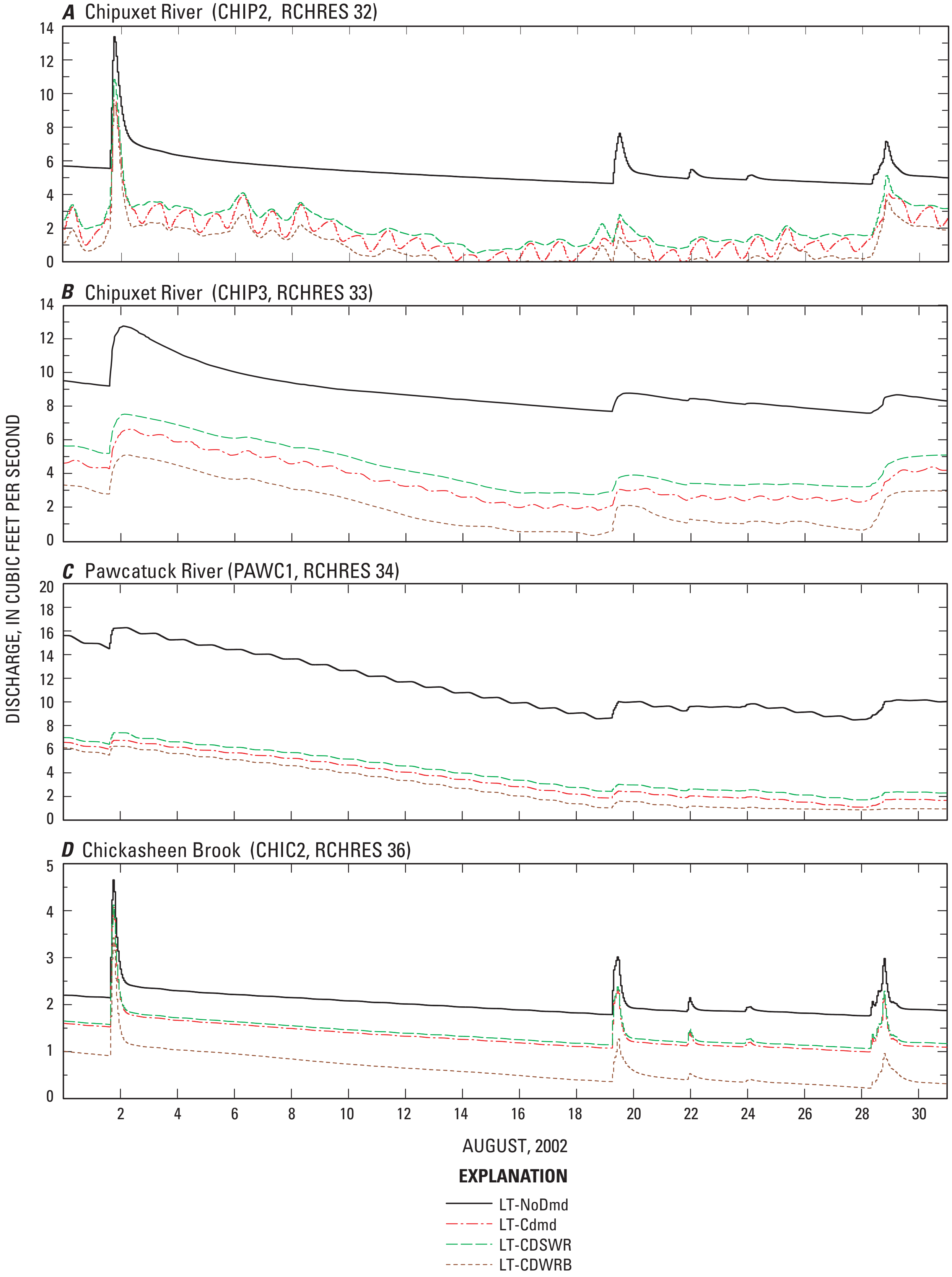


Figure 2–5. August 2002 simulated hourly streamflow under no withdrawals (LT–NoDmd), current (2000–04) withdrawals (LT–CDmd), current withdrawals with selected irrigation withdrawals converted from surface-water to groundwater sources (LT–CDSWR), and current withdrawals with potential new withdrawals (LT–CDWRB) at *(A)* Chipuxet River (CHIP2, RCHRES 32); *(B)* Chipuxet River (CHIP3, RCHRES 33); *(C)* Pawcatuck River (PAWC1, RCHRES 34); and *(D)* Chickasheen Brook (CHIC2, RCHRES 36), Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

Simulations at PAWC1 reflect the cumulative affects in the Chipuxet River subbasins (CHIP1 through CHIP3; RCHRES 31 through 33) and in its own subbasin area, which includes the Mink Brook source area for major supply withdrawals. Cumulatively, total withdrawals in and above this reach are about 64 percent for municipal supply and 36 percent for irrigation. The ratio of current cumulative withdrawals to streamflow at the outflow of the PAWC1 is the largest of the 12 reaches examined; hence, differences between streamflow simulated under average 2000–04 withdrawals and no withdrawals are among the most pronounced. At extreme low flows (greater than the 99-percent flow duration), the daily mean streamflow simulated under average 2000–04 withdrawals was about an order of magnitude lower than under no withdrawals (fig. 2–4C). Converting select irrigation withdrawals from surface-water to groundwater sources resulted in streamflow that differed little from that under average 2000–04 withdrawals (figs. 2–4C and 2–5C) for reasons similar to those described for CHIP3. Simulations with potential supply wells (LT–CDWRB) did not differ appreciably from other simulations with withdrawals in PAWC1 as none were simulated in the PAWC1 subbasin and any change resulted from potential supply wells in upstream subbasins. Simulated hourly hydrographs indicate a small diurnal fluctuation in all simulations including those with no withdrawals (fig. 2–5C). Unlike intradaily streamflow fluctuations caused by direct surface-water irrigation withdrawals in other reaches examined, these fluctuations reflect diurnal evaporative losses from Worden Pond, the largest open water body in the Pawcatuck River Basin, and from expansive wetlands surrounding the pond. These diurnal fluctuations were larger in an alternative model (described in appendix 2) that simulated the wetlands in this part of the basin as a virtual RCHRES.

Extreme low flows in the lower Chickasheen Brook (CHIC2) under average 2000–04 withdrawals were about 41 percent lower than under no withdrawals (fig. 2–4D). These differences were less in CHIC2 than in other reaches in the eastern Pawcatuck River region examined because the ratio of water withdrawal to streamflow was less. Converting irrigation withdrawals from surface-water to groundwater sources resulted in only minor differences in streamflow relative to current withdrawals (figs. 2–4D, 2–5D). Although the affected withdrawal accounted for nearly half the total peak withdrawal in and above CHIC2, the conversion affected only one withdrawal in the CHIC1 subbasin, whose affect on streamflow is damped by the storage in Yawgoo and Barber Ponds. Simulation of potential water-supply withdrawals included one well in CHIC2, which resulted in a sharp decrease in streamflow (about an order of magnitude at extreme low flows); this response reflects a large increase in the ratio of water withdrawals to streamflow at low flows.

Lower Wood River Region

The lower Wood River region (fig. 2–1) includes the lower Meadow Brook (MEAD2, RCHRES 48), Pawcatuck River (PAWC4, RCHRES 50), and Wood River (WOOD5 and WOOD6, RCHRES 63 and 65, respectively). MEAD2 is a small tributary with a cumulative drainage area of 7.37 mi^2 that drains into the Pawcatuck River just above the mouth of the Wood River and is considered an important ecological resource by the environmental community. PAWC4 is centrally located in the Pawcatuck River Basin and represents a cumulative drainage area of 205 mi^2 below the confluence of the Pawcatuck and Wood Rivers. WOOD5 and WOOD6 are the two most downstream reaches in the Wood River and have cumulative drainage areas of 85.1 and 89.0 mi^2, respectively.

Changes in streamflow that result from average 2000–04 withdrawals relative to no withdrawals were not appreciably different except in PAWC4 (figs. 2–6 and 2–7). In PAWC4, the differences between simulations with average 2000–04 withdrawals and no withdrawals are attributed to water withdrawals in the eastern Pawcatuck River Basin that continue to affect streamflow in this reach, even with the moderating effect of the Wood River flow contribution. The Wood River subbasin composes nearly half the contributing area to PAWC4 and is minimally affected by withdrawals. Simulations indicate that outflow from PAWC4 under average 2000–04 withdrawals were about 30 percent less than without withdrawals above the 99-percent flow duration. The effects of withdrawals in MEAD2, WOOD5, and WOOD6 were negligible because the ratios of cumulative withdrawals to streamflow are small in these reaches.

Simulations indicate that converting selected irrigation withdrawals from surface-water to groundwater sources had a negligible effect on streamflow in the reaches examined in this region. In reaches that already show negligible differences in streamflow with and without withdrawals, such as in MEAD2, WOOD5, and WOOD6, converting from surface-water to groundwater sources will have little effect on streamflow. In addition, most withdrawals in this region are from groundwater sources and the ratio of total withdrawal to streamflow in these reaches is generally small relative to the other reaches examined. Although converting the largest irrigation withdrawal affecting flow in WOOD6 (about 70 percent of the total withdrawal volume) from a surface-water to a groundwater source had no appreciable effect on the daily mean flow (fig. 2–6D) the intradaily streamflow fluctuations, although small, were removed (fig. 2–7D). Similarly, the cumulative effect of converting select withdrawals from surface-water to groundwater sources had no appreciable effect on the daily mean flow at PAWC4 (fig. 2–6B), but damped the small intradaily streamflow fluctuations (fig. 2–7B). These simulations underscore that the effects on streamflow of converting withdrawals from surface-water to groundwater sources depend

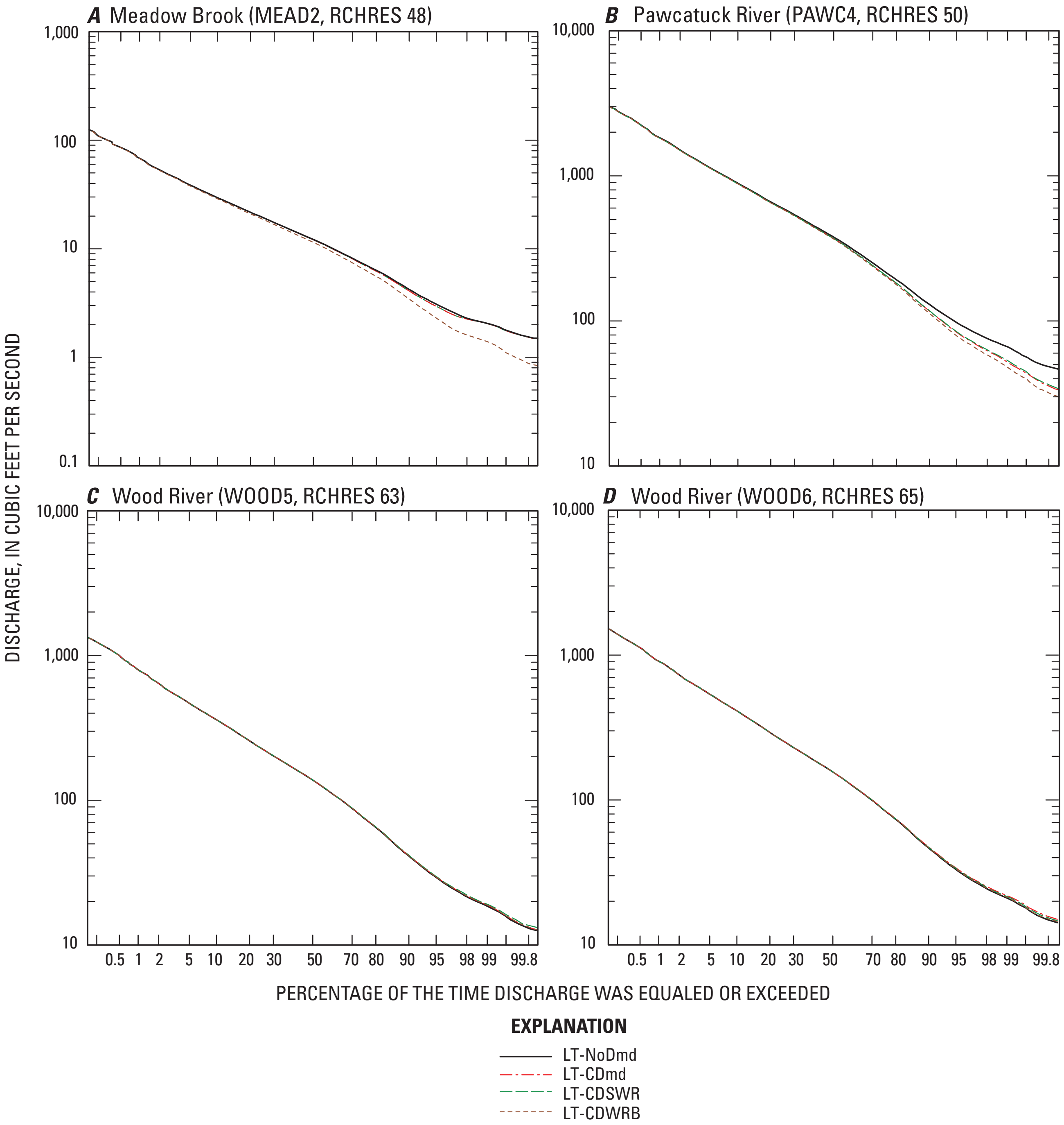


Figure 2–6. Flow-duration curves of simulated daily mean streamflow (1960–2004) under no withdrawals (LT–NoDmd), current (2000–04) withdrawals (LT–CDmd), current withdrawals with selected irrigation withdrawals converted from surface-water to groundwater sources (LT–CDSWR), and current withdrawals with potential new withdrawals (LT–CDWRB) at *(A)* Meadow Brook (MEAD2, RCHRES 48); *(B)* Pawcatuck River (PAWC4, RCHRES 50); *(C)* Wood River (WOOD5, RCHRES 63); and *(D)* Wood River (WOOD6, RCHRES 65), Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

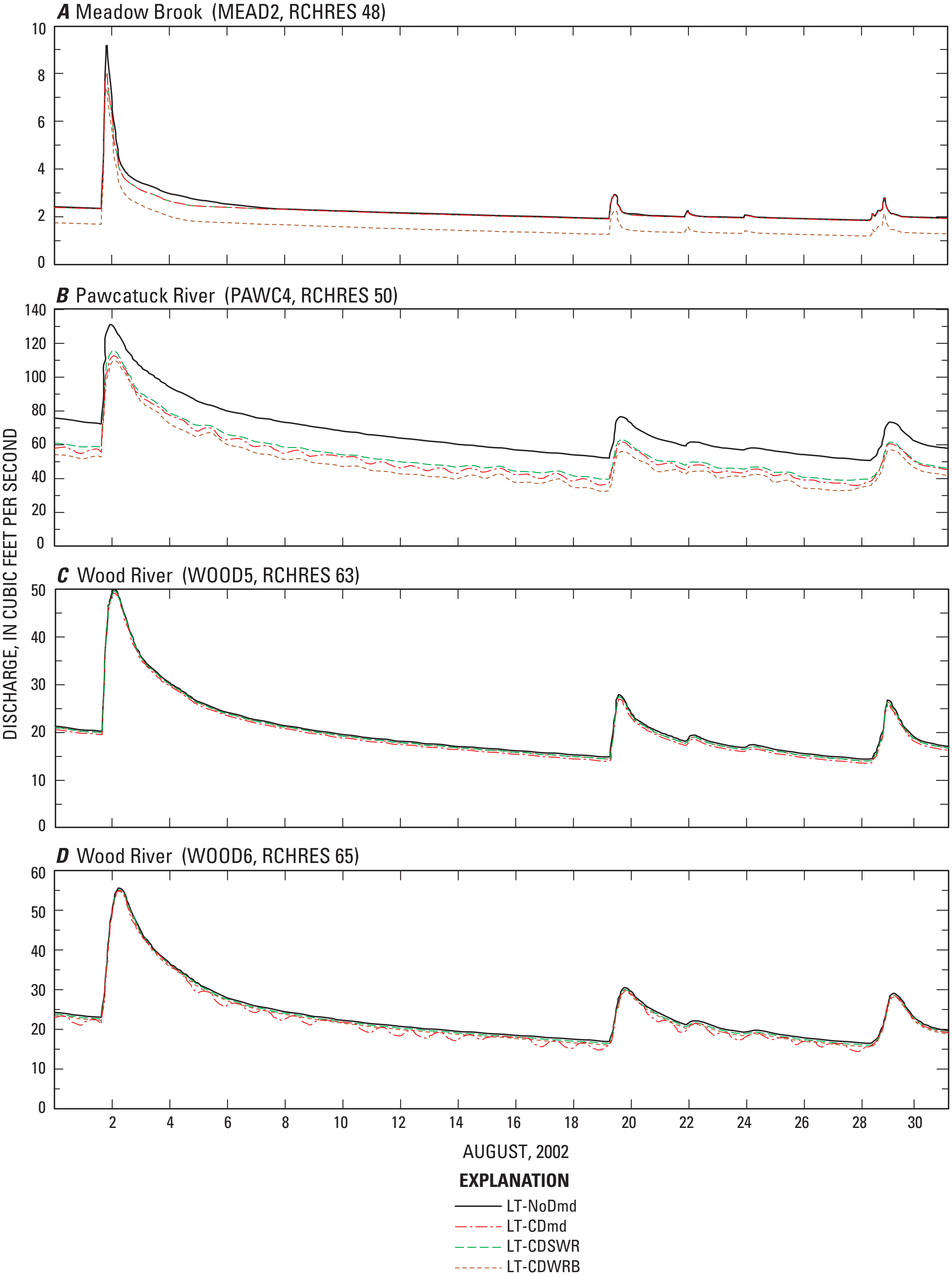


Figure 2–7. August 2002 simulated hourly streamflow under no withdrawals (LT–NoDmd), current (2000–04) withdrawals (LT–CDmd), current withdrawals with selected irrigation withdrawals converted from surface-water to groundwater sources (LT–CDSWR), and current withdrawals with potential new withdrawals (LT–CDWRB) at selected model reaches at *(A)* Meadow Brook (MEAD2, RCHRES 48); *(B)* Pawcatuck River (PAWC4, RCHRES 50); *(C)* Wood River (WOOD5, RCHRES 63); and *(D)* Wood River (WOOD6, RCHRES 65), Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

on the cumulative ratio of total withdrawals to streamflow, the percentage of the total withdrawals that are converted, and the extent of the lag effect on streamflow depletion from an irregularly pumped well.

The effects of simulated potential water-supply withdrawals differed among the subbasins examined. In MEAD2, two potential water-supply wells, pumped at a combined rate of 2 Mgal/d, resulted in about a 40 percent decrease in low flows compared to streamflow simulated with and without withdrawals (figs. 2–6A and 2–7A). Potential supply withdrawals in or upstream of WOOD5 and WOOD6, have combined withdrawal rates of 2 and 3 Mgal/d, respectively, but result in no appreciable change in flow relative to average 2000–04 withdrawals (figs. 2–6C–D, 2–7C–D) because the ratios of withdrawal to streamflow in these reaches is small. Similarly, although the cumulative withdrawal from potential supply wells at PAWC4 is 15 Mgal/d, these withdrawals only have a small effect on streamflow even at the lowest flows because the ratio of the withdrawals to streamflow is still relatively small.

Magnitude of Flow Alteration Relative to Streamflow

The effects of flow alteration can be evaluated in a variety of ways including their deviation from target-flow statistics (Tennant, 1976; U.S. Fish and Wildlife Service, 1981; Richter and others, 1996; Poff and others, 1998) or flow requirements determined from a hydraulic criterion at critical points in a reach (Nelsen, 1984; Espegren, 1996; Bovee and others, 1998). Although these methods provide useful information for assessing water-quantity needs, they are not continuous measures of flow alteration. One method of evaluating flow alteration over the range and frequency of expected flows is to represent the magnitude of withdrawal relative to the magnitude of flow at specific flow durations.

The ratios of average summer withdrawals during 2002–04 to daily mean flow at various flow durations simulated without withdrawals for the 1960–2004 period were determined at the 12 focus reaches examined. The summer withdrawals were used because in many parts of the Pawcatuck River Basin withdrawals are seasonal and summer withdrawals reflect an upper end member. In addition, the 2002–04 withdrawals were used because this period reflects the best available withdrawal information. Total withdrawals include direct surface-water withdrawals combined with the computed streamflow depletion from groundwater withdrawals. The 1960–2004 simulated streamflow without withdrawals is considered an approximation of long-term natural streamflow conditions. Streamflow at various flow durations were determined from the mean daily flow-duration curves at each station (figs. 2–2, 2–4, 2–6). The percent of time the withdrawal-to-flow ratio was equaled or exceeded (fig. 2–8) is inversely related to the percent of time streamflow was equal or exceeded. For example, when the withdrawal-to-flow ratio was equaled or exceeded 10 percent of the time, the flow was equal or exceeded 90 percent of the time. The graph indicates the relative flow alteration in the reaches examined and the percentage of time a given withdrawal-to-streamflow ratio is exceeded.

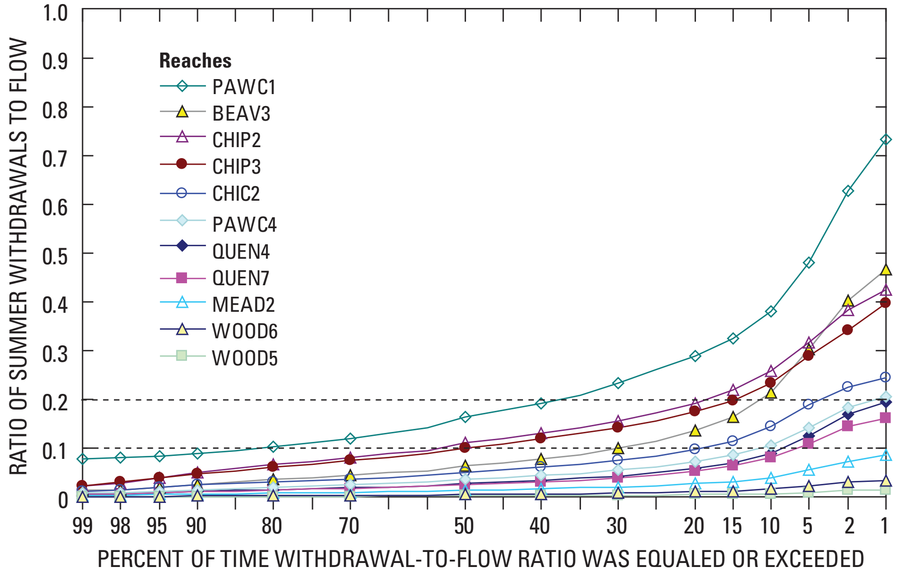


Figure 2–8. Percentage of time the ratio of average summer withdrawals (2002–04) to simulated mean daily streamflow without withdrawals (1960–2004) is equaled or exceeded at selected reaches in the Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 2–1 and described in table A2–4.)

Of the 12 subbasins examined, PAWC1 stands out as the most flow-altered reach. At PAWC1, the cumulative withdrawal extracts 20 percent or more of the daily mean streamflow about 40 percent of the time; withdrawals can exceed daily mean streamflow by 50 percent or more about 5 percent of the time. The ratios of withdrawals to daily mean streamflow at BEAV3, CHIP2, and CHIP3 generally cluster and represent the next most flow-altered reaches. Withdrawals in and above these reaches extract from 10 to 20 percent of the daily mean streamflow about 20 to 50 percent of the time; at very low flows, withdrawals extract about 40 percent of the daily mean streamflow. For CHIC2, PAWC4, QUEN4, and QUEN7 the withdrawal-to-streamflow ratios also tend to cluster; withdrawals extract from 10 to 25 percent of the daily mean streamflow about 10 percent of the time or less. The ratio of withdrawals to streamflow in MEAD2, WOOD5, and WOOD6 never exceed 10 percent of the daily mean streamflow and are generally considered to be minimally flow altered. Streamflow is unaltered by withdrawals in TANE1.

The effects of withdrawals on streamflow become evident as the ratio of withdrawals to streamflow increases. This can be seen by comparing the plots of streamflow with and without withdrawals (figs. 2–2, 2–4, 2–6) to the plot of the withdrawal-to-streamflow ratio (fig. 2–8) for a specific reach. In general, as the ratio exceeds 0.1, the daily mean flow-duration curves with and without withdrawals begin to noticeably separate. Once the ratio exceeds 0.2, the flow-duration curves with and without withdrawals markedly separate. Examination of the withdrawals-to-streamflow ratios over a wide range of flows and the corresponding exceedence probabilities can be a useful tool for optimizing water resources for habitat protection and water-supply needs.

Effects of Potential Future Land Use and Water Use on Streamflow

Scenarios that reflect potential future buildout conditions were designed to evaluate the effects of (1) land-use change only, (2) water-use change only, and (3) combined effects of land-use and water-use change. Simulation of land-use change entailed modifying the areas of HRUs representing different types of land cover in the schematic block of the uci file. Any increase in HRU area representing development was offset by a corresponding decrease in HRU area representing open space, forest, or both. Simulation of water-use change at buildout entailed changing the associated External Source block of the uci file accordingly.

Method for Estimating Land-Use Change

The effect of potential land-use change (herein referred to as buildout) on streamflow was simulated by changing types of HRU areas to reflect changes possible under current zoning and land-use plans while maintaining the same total area of each subbasin. Buildout was first determined on the basis of a statewide buildout land-use map for Rhode Island compiled under the provisions of the Rhode Island Comprehensive Planning and Regulation Act of 1988 that identified current and potential lands for residence, business, industry, municipal facilities, public recreation, institutional facilities, mixed use, and open space (Paul Jordan, Rhode Island Department of Environmental Management, written commun., September 2006). This map was supplemented in the Connecticut part of the basin by town-zoning ordinances from North Stonington (Marc Tate, North Stonington IT, written commun., October 17, 2006) and Stonington (Jason Vincent, Stonington Planning Department, written commun., October 17, 2006). The remaining townships in the Connecticut part of the basin—Voluntown and Sterling—compose small percentages of the basin area (1.9 and 2.6 percent, respectively) and are mostly classified as State forest that is protected from development. The small amount of developable area in these townships was assumed to be available for low- to moderate-density residential development.

The statewide buildout map did not identify all areas designated in other sources as protected or as having limited development potential. For this reason, lands with development restrictions were compiled from several sources from RIGIS and MAGIC that included: (1) land owned by the Audubon Society, (2) land owned or managed by The Nature Conservancy or Municipal Land Trust, (3) land owned by State and local governments assigned protection status, and (4) wildlife-management areas. Combined, these restrictions limit development in about a third of the basin. Further development restrictions were added on the basis of proximity to water, wetlands, or bedrock outcrops, which are typically steep and identified in the state soil surveys (SSURGO) as unsuitable for development. A 50-ft buffer was added to streams, lakes, ponds, and wetlands. Within this buffer, and in areas with soils mapped as bedrock outcrop, steep (greater then 15 percent) slopes, or extremely rocky, land use was maintained as classified in the 1995 land cover. Water features and buffers surrounding these features restricted development in about 18 percent of the basin. Bedrock outcrops and associated steep slopes restricted development in about 4 percent of the basin. Areas classified as golf courses on the 1995 land-use map (fig. 2–9) were assumed to remain unchanged.

Areas classified as developed on the 1995 land-use map were assumed to be available for redevelopment in the future, but were not subject to a change in land-use type. Thus, areas suitable for future development were limited to open space, forest, turf farms, and other agricultural lands if not otherwise restricted from development. The same land-use categories developed for the model HRUs (fig. 2–9) that combined many different land classifications were used to develop the potential buildout map (fig. 2–10). The largest change was from forest to low- and medium-density residential development, which affected about a third of the basin. Other changes in land use by HRU are summarized in table 2–2. Overall, about 10 percent of the basin was classified as developed in 1995, but based on model results about 50 percent of the basin could

Table 2–2. Area of Hydrologic Response Units (HRUs) represented for 1995 land use and potential buildout land use in the Hydrologic Simulation Program-FORTRAN of the Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut.

[mi^2, square mile; S&G, Sand and gravel. Values may be affected by rounding]

HRU	Description	1995 land use		Buildout land use		Land-use change 1995 to buildout		
		Area (mi^2)	Percentage of basin	Area (mi^2)	Percentage of basin	Difference (mi^2)	Percent difference	Percent change over entire basin
1	Commercial, industrial, and transportation over S&G	0.61	0.20	1.10	0.37	0.50	82	0.17
2	Medium-high- to high-density residential over S&G	3.08	1.0	3.85	1.3	0.77	25	0.26
3	Low- to medium-low-density residential over S&G	8.09	2.7	41.1	14	33.0	408	11
4	Open space over S&G	15.7	5.2	5.41	1.8	-10.3	-65	-3.4
5	Forest over S&G	49.4	16	21.6	7.2	-27.7	-56	-9.2
6	Golf courses	1.81	0.61	1.81	0.61	0	0	0
7	Turf	4.40	1.5	1.51	0.50	-2.89	-66	-0.97
8	Other irrigated	1.04	0.35	0.13	0.04	-0.92	-88	-0.31
11	Commercial, industrial, and transportation over till	0.39	0.13	0.88	0.29	0.49	127	0.16
12	Medium-high- to high-density residential over till	2.51	0.84	4.10	1.4	1.59	63	0.53
13	Low- to medium-low-density residential over till	9.81	3.3	65.4	22	55.6	567	19
14	Open space over till	13.5	4.5	3.16	1.0	-10.3	-77	-3.4
15	Forest over till	107	36	56.3	19	-50.5	-47	-17
16	Steep slope or rocky soils	28.7	9.6	28.7	9.6	0	0	0
17	Water	5.18	1.7	5.18	1.7	0	0	0
18	Nonforested wetland	10.1	3.4	10.1	3.4	0	0	0
19	Forested wetland	33.7	11	33.7	11	0	0	0
20	Impervious residential	1.85	0.62	7.78	2.6	5.93	320	2.0
21	Impervious commercial	3.00	1.0	7.72	2.6	4.71	157	1.6

be developed within the restrictions described above. Most of the development, both current and potential that was simulated in the model, is in low- to medium-density residential housing.

The change in land use differed widely among subbasins. Potential buildout was estimated to affect about 44 percent of the basin, or about a 34-percent increase in developed land use. The median developed area by subbasin increased from about 8 percent under 1995 land-use conditions to about 49 percent under potential buildout conditions. Individual subbasin development ranged from about 0.2 to 50 percent under 1995 land-use conditions and about 2 to 86 percent under potential buildout conditions. Estimated effective impervious area increased from about 1.6 percent of the basin area under 1995 land-use conditions to about 5 percent under potential buildout conditions. The change in developed land use by subbasin ranged from zero to about 75 percent of the subbasin area, with a median change of about 40 percent.

Method for Estimating Future Water Use

Land-use change often affects the demand for water. To evaluate the effects of future water demands on streamflow in the basin under potential buildout conditions, water-use changes associated with land-use change were estimated. Water-use change varied by water-use category and the type of supply system.

Water-use rates were assigned to the original development land-use categories on the 1995 land-use map and to the projected buildout land use by subbasin. The original data layers were used in this analysis rather than the generalized land use represented in the model to preserve the detailed land-use information. For example, the original land-use data layer has five classes of residential development differentiated on the basis of density, whereas the model simplified these into two density classes. From the detailed

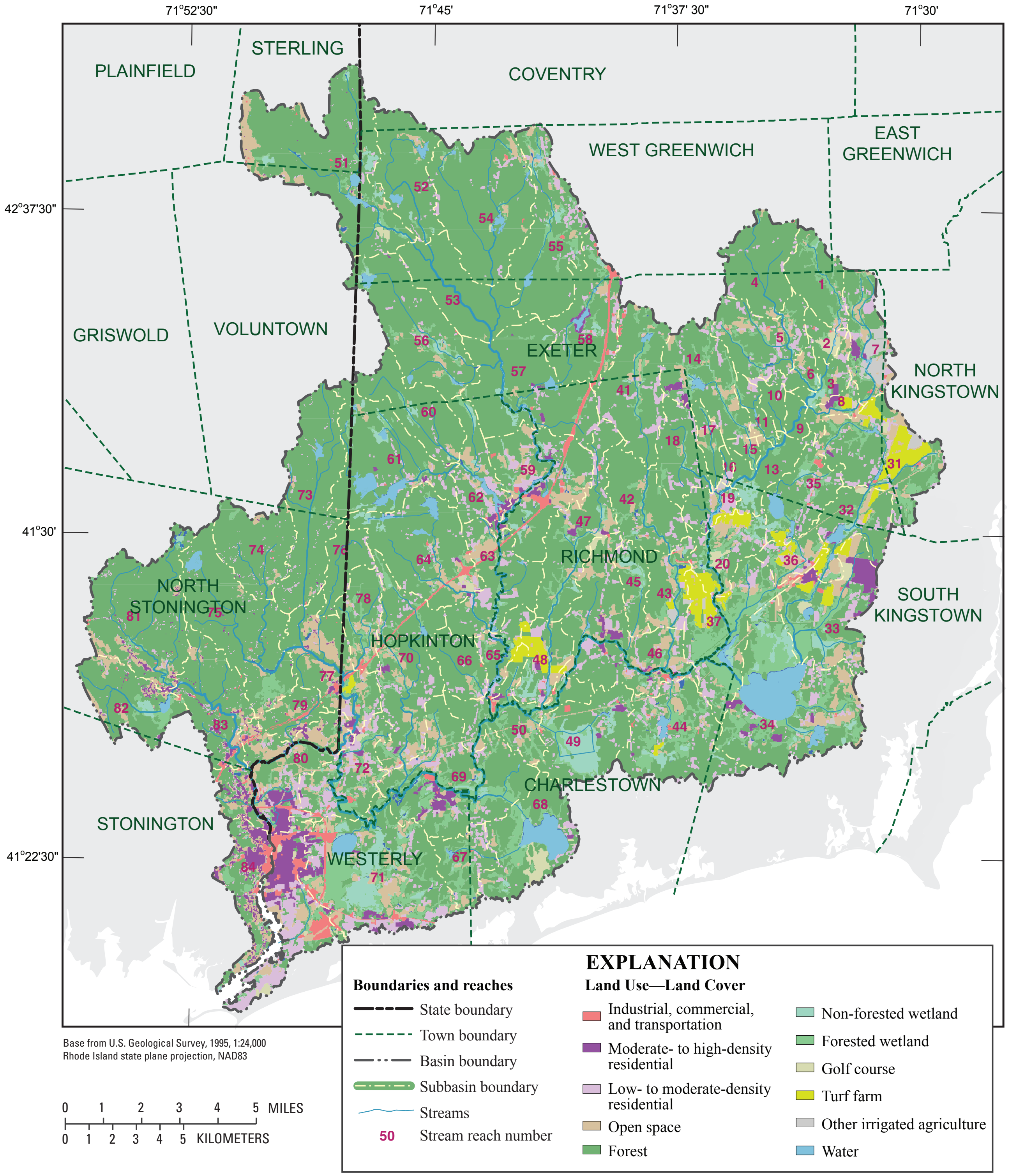
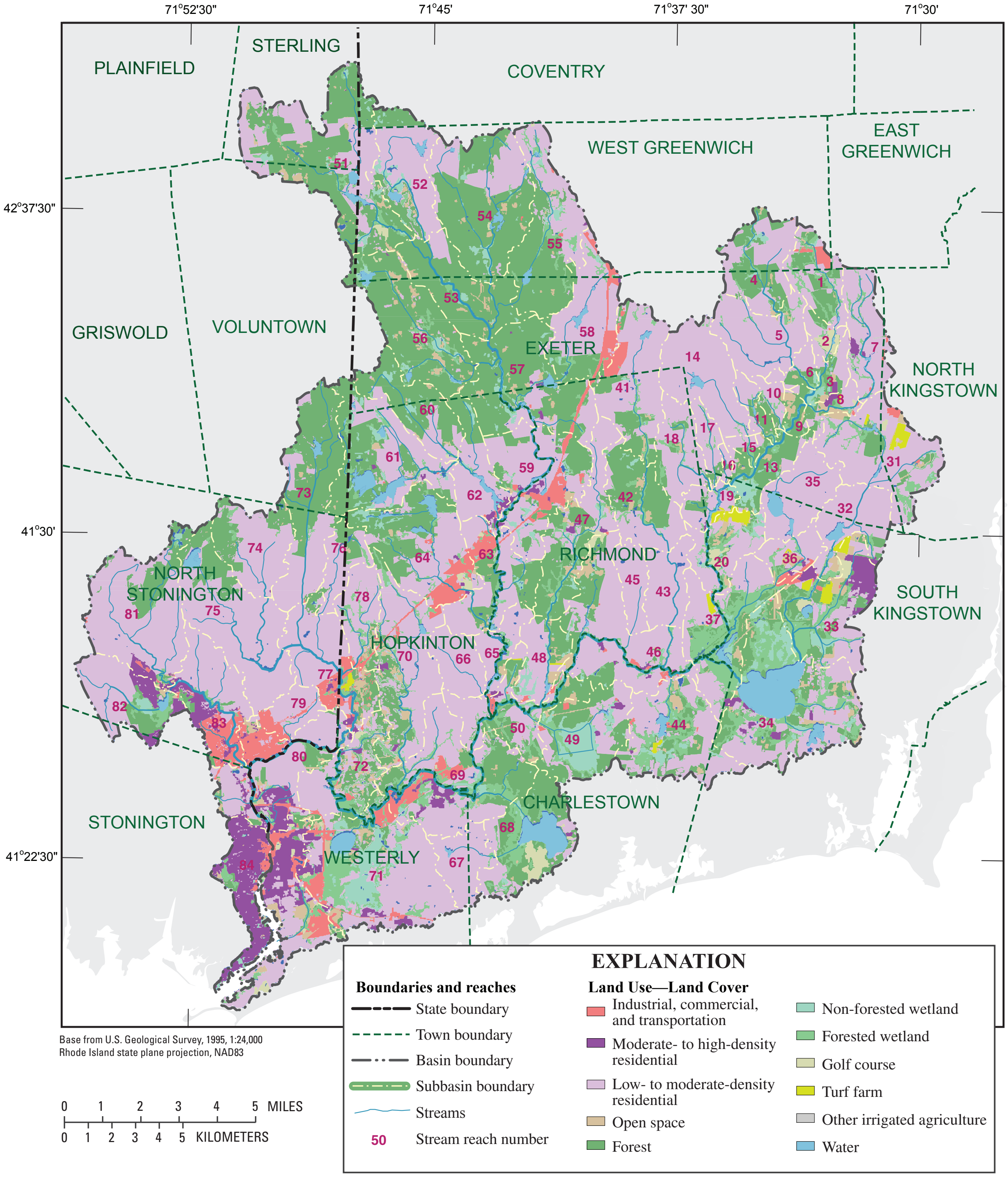


Figure 2–9. Representation of 1995 land use simulated in the Hydrologic Simulation Program-FORTRAN (HSPF) of the Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut. (Sites described in table A2–4.)



Note: development limited in buffers surrounding water and wetlands, and areas of bedrock, steep slope, or extremely rocky are not shown for clarity

Figure 2–10. Representation of buildout land use simulated in the Hydrologic Simulation Program-FORTRAN (HSPF) of the Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut. (Sites described in table A2–4.)

Table 2–3. Domestic water-use rates for residential land-use categories used to estimate potential water use under buildout conditions in the Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut.

[gal/acre, gallons per acre; >, greater than; <, less than]

Residential housing-density classification	Units per acre		Domestic water use (gal/acre)
	Range	Applied to estimate water use	
High	>8	8	1,400
Medium to high	4 to 7.9	4	700
Medium	1 to 3.9	1	175
Medium to low	0.5 to 1	0.5	87.5
Low	<0.5	0.25	43.8

residential land-use classes, domestic water use was estimated by subbasin by multiplying the number of housing units in each category (table 2–3) by the median occupancy and a usage factor. A household occupancy of 2.5 people is about the median reported by the U.S. Census Bureau (2000) for the each of the major towns in the basin; the reported occupancy ranged from 2.4 to 2.8 people per unit. An average household-usage factor of 70 gal/d/person reported for the 1995–99 period by Wild and Nimiroski (2004) was used for domestic water use in the basin; reported use rates ranged from 67 to 71 gal/d/person for public and self-supply, respectively. Most of the domestic water use in the basin is self-supplied.

The increase in the self-supply water use at buildout was represented in the model as a withdrawal from each reach through the External Source block. For buildout areas that are self-supplied and have on-site septic, which reflects buildout in most subbasins, withdrawals were calculated as 20 percent of the difference between the current water use (estimated from the 1995 land-use map) and water use at buildout. Twenty percent of the total net difference was assumed to represent consumptive water use or water that is lost from the basin, through practices such as lawn watering, and the remaining 80 percent was assumed to be returned within the basin through onsite septic systems. The net difference in self-supply water in the calibrated model and buildout was used because the calibrated model incorporates the consumptive self-supply in the model-parameter values.

In areas with municipal water-supply—lower Chipuxet River, Mink Brook, a small area around Richmond in the Wood River, and lower Pawtucket River around Westerly—the change in water use was calculated in one of two ways. For systems that service areas completely inside the Pawcatuck River Basin (Richmond and Westerly), the change in water use was estimated by using the buildout analysis described above. For the Richmond area, 20 percent of the net change between current and buildout water use (0.261 Mgal/d) was taken out of RCHRES 59 because this area is not served by public sewer so most of the buildout withdrawals were assumed to be returned through onsite septic disposal. If a public-sewer system was built, the treated wastewater effluent could be returned at a specified rate and RCHRES. For the Westerly area, the entire net change between current and buildout water use (1.61 Mgal/d) was assumed to be withdrawn from the existing production wells (from RCHRES 69 and 71) at a rate proportional to the current rate of withdrawals. Increased withdrawal from reach 80 was not considered because withdrawals from this reach were assumed to be at or near capacity. The entire net change in demand was assumed to discharge near the mouth of the Pawcatuck River Basin through the current public-sewer system.

The second method was applied to estimate increased water use at buildout in the lower Chipuxet River and Mink Brook. Change in water-use from current and buildout land-use conditions was estimated by methods previously described; however, most of the withdrawals from these subbasins are for water demands outside of the basin. Future water-use projections for these external demands were obtained from estimated 2020 water-supply needs reported by the water suppliers; these projected demands were added to the change in withdrawals from within the subbasins. The reported 2020 water-supply needs may not reflect the full potential buildout demands, however. All additional withdrawals in these areas were assumed to leave the basin through public sewers that discharge wastewater out of the basin.

The total domestic water use calculated from 1995 land use was estimated to be 5.19 Mgal/d; this is about 10 percent more than the total domestic water use (4.72 Mgal/d) reported by Wild and Nimiroski (2004), but the good agreement indicates that estimating potential water use on the basis of land use is a reasonable method. The domestic water use in the basin under buildout was estimated at 21.8 Mgal/d for the entire basin or about four times the domestic water use estimated from 1995 land use and 2000 census information (U.S. Census Bureau, 2000).

Water use for commercial and industrial users was estimated on a per unit area basis by applying the 1.22 Mgal/d rate reported for 1995–99 by Wild and Nimiroski (2004) for this type of use over the 1,368 acres classified as commercial and industrial on the 1995 land-use map; this yielded a rate of about 8.9×10^{-4} Mgal/d/acre. Multiplying this rate per unit area by the area of commercial and industrial development at buildout (8,414 acres) yielded a rate of 7.50 Mgal/d over the entire basin. This result represents about a six-fold increase over the reported 1995–99 commercial and industrial water use. Withdrawals for commercial and industrial use were made from the appropriate reaches where this type of development could occur.

In the analyses of the potential withdrawals at buildout, water withdrawals for agricultural purposes were eliminated from the model because these areas were assumed to be developable. Irrigation demands for golf courses were maintained at the current level (2000–04 use) because these areas were assumed to remain unchanged in the future.

Effects on Streamflow

Buildout simulations were evaluated at four reaches—upper Chipuxet River (CHIP1; RCHRES 31), lower Beaver River (BEAV3; RCHRES 43), lower Wood River (WOOD6; RCHRES 65) and lower Pawcatuck River (PAWC8; RCHRES 80) (fig. 2–1). The upper Chipuxet River subbasin in the calibrated model includes minor withdrawals, but about 54 percent of the subbasin is buildable (near the upper quartile of buildable area for all subbasins). Thus, potential changes in this subbasin reflect large changes in both land use and water use. The lower Beaver River reflects potentially large land-use changes in BEAV1, BEAV2, and BEAV3 (RCHRES 41, 42, and 43), but the potential change in water use is less pronounced relative to CHIP1. Streamflow in the lower Wood River (RCHRES 51 through 66) reflects the overall effects of change in a large tributary that flows through one of the most pristine watersheds in southeast coastal New England. Simulation results for the lower Pawcatuck River reflect the overall change in streamflow over the entire basin (only the downstream-most subbasin, PAWC9, is not included at this model RCHRES).

In general, simulations under buildout indicate that high flows and low flows increase slightly as a result of land-use change relative to simulations under 1995 land-use conditions (fig. 2–11). Increased high flows are normally expected as a basin becomes more urbanized, but increased low flows are not. Increased low flows, although slight, result from decreased evapotranspiration (ET) losses that are reflected in the model parameter values for developed and undeveloped HRU types (see discussion of the model water budget in appendix 2 for more information). Changes in ET may, or may not, occur because most buildout change in the basin was from forested to low-density residential development, but the loss of deep-rooted vegetation that drives ET loss may not be appreciable enough as a result of this change to cause changes in low flows. In localized areas of intense urban development, changes in flow can be greater than those simulated at the subbasin scale. Increased effective impervious area can decrease low flows because of decreased infiltration and increased surface runoff. The simulated changes in flow could also differ if low-impact development (LID) strategies are employed. Thus, the extent to which streamflow changes in response to development depends on exactly how the land is developed; this can vary widely and produce effects different from those shown in figure 2–11, particularly in localized areas. In addition, there is no direct calibration of the model to specific land-use types and the exact nature of the development is unknown; combined, these factors underscore the uncertainty of hydrologic changes that result from land-use change.

In subbasins where agricultural lands become urbanized, the water used for agricultural irrigation can exceed the potential water use at buildout, resulting in higher low flows after development. The extent of this type of change depends on the extent of current irrigation water use and the potential and type of future development. In the Beaver River, annual irrigation use, largely concentrated in the lower part of the subbasin, averaged about 0.30 Mgal/d during 2000–04; however, irrigation is concentrated during the summer months when flows are typically low and the actual use can exceed the annual average by an order of magnitude or more. The change in water use associated with land-use change, largely to low-density residential, in the Beaver River subbasin averaged about 0.17 Mgal/d. As a result, low flows (above the 90-percent flow duration) increased about 50 percent under the simulated buildout conditions (fig. 2–11B).

Near the basin outlet of the Pawtucket River at Westerly (RCHRES 80), the hydrological effects of land-use change increased high flows at the 0.1-percent flow duration by about 11 percent. Simulations of potential land-use change with 2000–04 withdrawals (LT–BldCD) indicate that low flows (above the 90-percent flow duration) are similar to flows with no demands (fig. 2–11D). A possible explanation for this similarity is the decrease in evapotranspiration loss from forests to predominantly low-density residential development is about proportional to the water lost to withdrawals. Simulations of water-use change associated with buildout and keeping land use constant (LT–95LFD) are similar to flows under 2000–04 withdrawals, which reflects that most of the additional water use is returned to the basin and that overall change in water use is small relative to flow near the mouth of the Pawcatuck River.

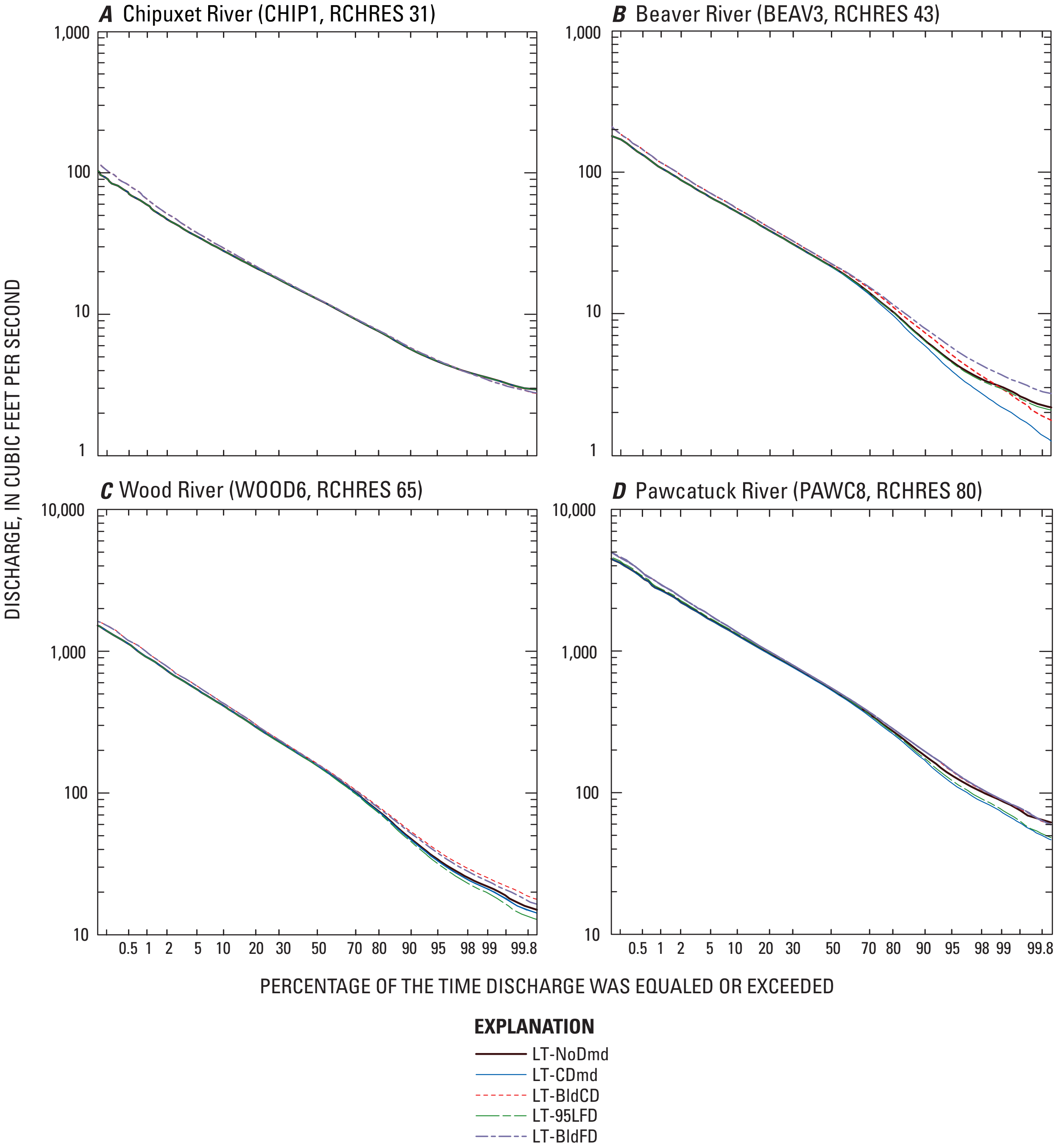


Figure 2–11. Flow-duration curves of simulated daily mean streamflow (1960–2004) under no withdrawals (LT–NoDmd), current withdrawals (LT–CDmd), and potential buildout conditions representing effects of change in land-use only (LT–BldCD), change in water-use only (LT–95LFD), and the combined effects of land-use and water-use change (LT–BldFD) at *(A)* Chipuxet River (CHIP1, RCHRES 31); *(B)* Beaver River (BEAV3, RCHRES 43); *(C)* Wood River (WOOD6, RCHRES 65); and *(D)* Pawcatuck River (PAWC8, RCHRES 80), Pawcatuck River Basin, southwestern Rhode Island and southeastern Connecticut. (Site locations shown in figure 2–1 and described in table A2–4.)