A Simulation-Optimization Model for Evaluation of Ground-Water Development Options Constrained by Minimum Streamflow Requirements and Water-Supply Demands

Paul M. Barlow[1], David P. Ahlfeld[2], Gregory E. Granato[1]
[1]*U.S. Geological Survey, pbarlow@usgs.gov, ggranato@usgs.gov, Northborough, MA, USA*
[2]*University of Massachusetts, ahlfeld@ecs.umass.edu, Amherst, MA, USA*

ABSTRACT

Simulation-optimization models that couple transient, numerical simulation with optimization techniques have been developed to evaluate hydrologic, hydrogeologic, and water-management controls on ground-water development options for alluvial-valley stream-aquifer systems representative of those in the northeastern United States. Simulation-optimization models are particularly useful in this process because they provide an effective tool to evaluate tradeoffs between alternative definitions of minimum streamflow requirements that are protective of aquatic and riparian ecosystems (which can be difficult to determine) and total ground-water withdrawals. Results of one of these simulation-optimization models for the Big River Basin of Rhode Island indicate that small changes in specified minimum streamflow requirements and the annual pattern of water-supply demands can lead to large changes in the amount of ground water that is available for withdrawal on a sustainable basis.

INTRODUCTION

A continuing challenge to many communities in the United States, including those in the northeastern United States, is that of developing sustainable ground-water supplies that meet increased water-supply demands but are simultaneously protective of aquatic and riparian ecosystems. Ground-water withdrawals from shallow, high-yielding, alluvial-valley aquifers in the Northeast typically cause streamflow reductions (depletions) in hydraulically connected streams and rivers. Streamflow depletions caused by pumping can be an environmental problem when such depletions reduce the amount of streamflow that is available to aquatic communities below minimum levels required to sustain healthy ecosystems. Coupled simulation-optimization models can be a useful approach to determine optimal ground-water development strategies because they provide an effective tool to evaluate the relations among minimum streamflow criteria, water-supply demands, and sustainable ground-water withdrawal rates. Such models have been developed for the Hunt and Big River Basins of Rhode Island (Barlow and Dickerman, 2001; Barlow and others, 2003; Granato and Barlow, 2005). This paper describes the development and selected applications of a simulation-optimization model for the Big River Basin (Granato and Barlow, 2005; fig. 1), a largely untapped and potential future source of water for the State.

STUDY AREA AND SIMULATION MODEL

The Big River Basin is a 36-square-mile area that is underlain by glacial stratified deposits, till, and bedrock. The stratified deposits, which are composed of gravel, sand, silt, and clay, comprise the major aquifer in the basin, and are currently the source of water to two large-capacity public-supply wells (wells 4 and 5, fig. 1). Eleven additional well sites in the basin have been identified as potential future locations for ground-water development. The basin contains three primary rivers, the Carr, Mishnock, and Big Rivers. Average annual streamflows are about 13.1 ft^3/s (cubic feet per second) for the Carr River above its confluence with the Big River (site C, fig. 1) and 7.5 ft^3/s and 62.4 ft^3/s for the Mishnock and Big Rivers, respectively, at their outflow locations from the basin (sites B and D, fig. 1).

Granato and others (2003) developed a 5-layer, transient ground-water flow model to simulate an average annual cycle of monthly hydrologic stresses in the basin. The active area of the model—that is, the area of the model in which ground-water heads are simulated—is about 11 square miles (fig. 1). The model is based on the MODFLOW code (Harbaugh and McDonald, 1996), including the stream-routing package (Prudic, 1989) to simulate ground-water/surface-water interactions. The model was calibrated to

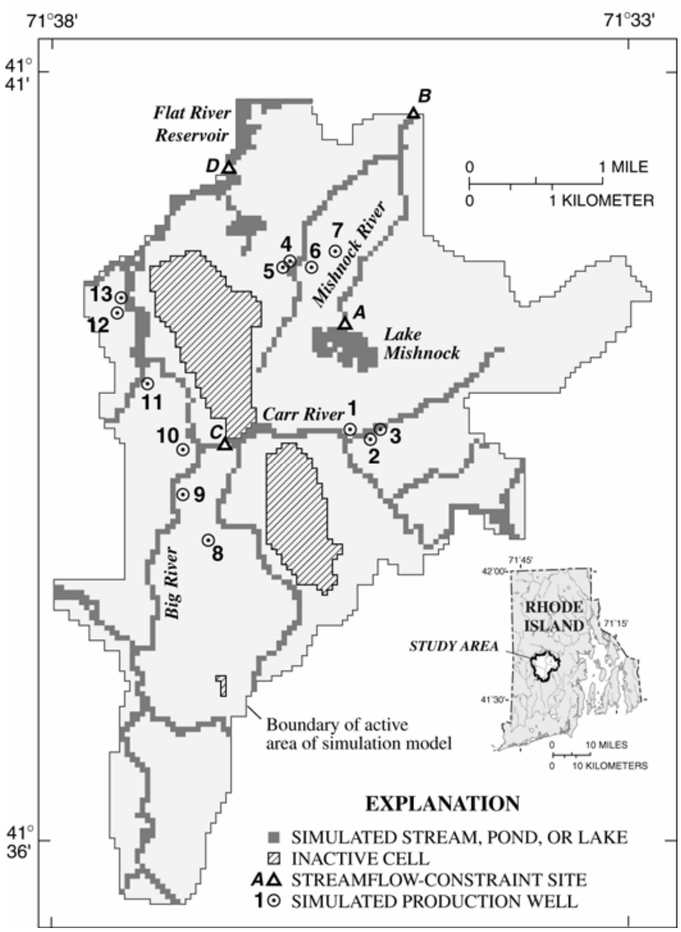

Figure 1. Location of Big River Basin, Rhode Island. (Figure modified from Granato and Barlow, 2005)

ground-water levels and streamflows representative of monthly hydrologic conditions during the 35-year period 1964-98. The model uses a dynamic equilibrium approach, in which there is no net change in storage in the simulated flow system over the average annual hydrologic cycle. Model-calculated ground-water levels and streamflow can vary over the annual cycle in response to simulated stresses, but at the end of each cycle, the system returns to the condition that occurred at the beginning of the cycle (Barlow and Dickerman, 2001; Barlow and others, 2003).

FORMULATION AND SOLUTION OF THE OPTIMIZATION MODEL

Formulation of the optimization model consists of defining a set of decision variables, an objective function, and a set of constraints. The decision variables of the model are the monthly withdrawal rates at each of the 13 candidate production wells, $Qw_{i,t}$, where *i* identifies the well site (*i* = 1, 2, … 13) and *t* the month (*t* = 1, 2, …12). The objective of the model was to maximize the total annual ground-water withdrawals from the aquifer:

$$\max imize \sum_{i=1}^{13} \sum_{t=1}^{12} ND_t Qw_{i,t} \quad (1)$$

where ND_t is the number of days in month t.

The optimal value of the objective function was limited by a set of constraints that was varied from one model application to the next. The first types of constraints were maximum rates of streamflow depletion specified at four streamflow-constraint sites shown on figure 1:

$$Qsd_{j,t} \leq (Qsd_{j,t})_{max} \quad (2)$$

where $Qsd_{j,t}$ is streamflow depletion at streamflow-constraint site *j* in month *t* and $(Qsd_{j,t})_{max}$ is the maximum rate of streamflow depletion allowed at site *j* in month *t*. The four constraint locations include the outlet of each river basin (the Carr, Mishnock, and Big Rivers) and the outfall location of Lake Mishnock; each of these four locations has been of interest to water-resource management agencies. Streamflow-depletion constraints were specified for all months of the year.

The second types of constraints were minimum and maximum withdrawal rates at each well:

$$(Qw_{i,t})_{min} \leq Qw_{i,t} \leq (Qw_{i,t})_{max} \quad (3)$$

where $(Qw_{i,t})_{min}$ and $(Qw_{i,t})_{max}$ are the minimum and maximum withdrawal rates, respectively, at well *i* in month *t*. Minimum and maximum withdrawal rates of 0 and 1.40 Mgal/d (million gallons per day), respectively, were specified for each well.

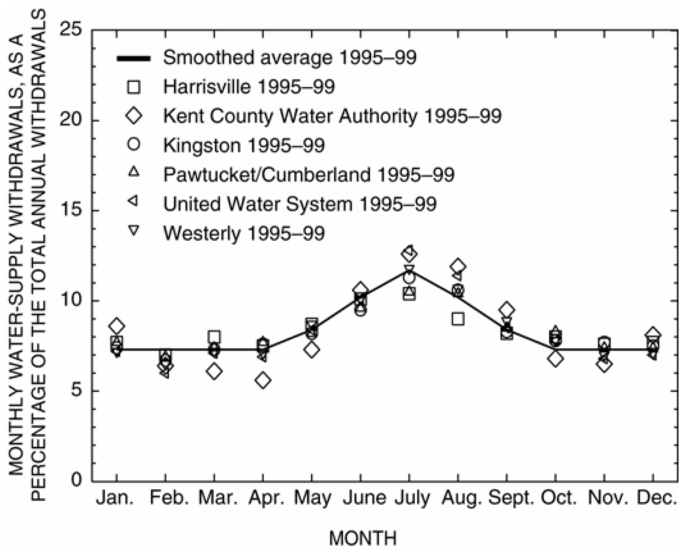

Figure 2. Typical ground-water demand patterns for six water-supply systems in Rhode Island. (Figure modified from Granato and Barlow, 2005)

For some model applications, a third requirement was made that the annual pattern of total monthly withdrawals in the basin must be consistent with typical patterns of monthly water demand in Rhode Island (fig. 2). This requirement was specified as a set of 11 constraints that control the relation among total withdrawals from one month to the next:

$$\sum_{i=1}^{13} Qw_{i,t_1} = \alpha_{t_{1,2}} \sum_{i=1}^{13} Qw_{i,t_2} \qquad (4)$$

where Qw_{i,t_1} and Qw_{i,t_2} are the withdrawal rates at well *i* in months t_1 and t_2, respectively; and $\alpha_{t_{1,2}}$ is the ratio of the percentage of total demand in month t_1 to total demand in month t_2 (adjusted for the ratio of the number of days in each month). The distribution of specified demands ranged from a minimum of 7.3 percent of total annual demand during the months of October through April to a maximum of 11.6 percent during July (black line on figure 2).

A response-matrix technique was used to solve each formulation of the optimization model. The technique has been widely applied in ground-water management problems and is described in detail by Gorelick and others (1993) and Ahlfeld and Mulligan (2000). As applied here, the assumption was made that the rate of streamflow depletion at each streamflow-constraint site, $Qsd_{j,t}$, is a linear function of the rate of ground-water withdrawal at each well *i* during each month *t*. By assuming linearity, it is possible to determine total streamflow depletion at a constraint site by summation of the individual streamflow depletions caused by pumping at each well in each month. This summation is written for each site *j* in each month *t* as

$$Qsd_{j,t} = \sum_{i=1}^{13} \sum_{k=1}^{t} r_{j,i,k} Qw_{i,k} \qquad (5)$$

where $r_{j,i,k}$ is a dimensionless unit response coefficient equal to the amount of streamflow depletion at site *j* in month *t* in response to a unit withdrawal at well *i* in month *k*. The right-hand side of equation 5 is substituted for $Qsd_{j,t}$ in equation 2. Response coefficients for each well/streamflow-constraint site pair were calculated by use of the transient-simulation model of the basin. After calculation of the complete response matrix, each formulation of the optimization model was solved using linear-programming software.

APPLICATIONS OF THE SIMULATION-OPTIMIZATION MODEL

The simulation-optimization model initially was run for several alternative definitions of maximum rates of streamflow depletion allowed at each streamflow-constraint site (Granato and Barlow, 2005). In these runs, optimal withdrawal rates were limited only by streamflow-depletion constraints (equation 2) and minimum and maximum withdrawal rates at each well (equation 3). The streamflow-depletion alternatives correspond to several minimum streamflow criteria being considered for regulation by the State of Rhode Island. Each streamflow criterion is defined as the minimum amount of streamflow per square mile of drainage area required at each streamflow-constraint site throughout the year. For example, point A on figure 3 is the modified U.S. Fish and Wildlife Service (USFWS) aquatic base-flow criterion of 0.5 $ft^3/s/mi^2$ (cubic feet per second per square mile of drainage area). Although the minimum streamflow requirements at each site are constant throughout the year, the allowable rates of streamflow depletion vary by month.

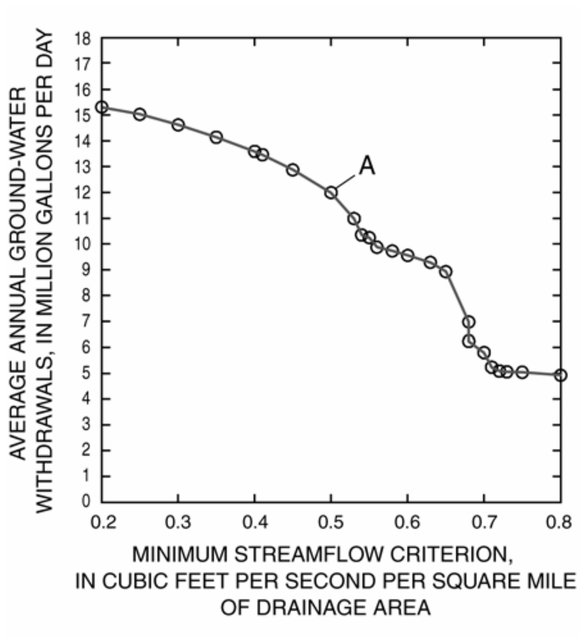

Figure 3. Relation between minimum streamflow criteria and total ground-water withdrawals calculated by the simulation-optimization model of the Big River Basin. Each open circle on the figure represents a model run. (Figure modified from Granato and Barlow, 2005)

This is because depletions are calculated by subtracting the minimum annual criterion from the estimated average streamflow for each month at each constraint site.

The graph on figure 3 summarizes the tradeoffs that are possible between ground-water withdrawals from the basin and specified minimum streamflow criteria. For the several criteria evaluated, model-calculated average annual withdrawal rates range from a minimum of 5 Mgal/d for the most restrictive criteria to a maximum of about 15 Mgal/d for the least restrictive. The graph indicates that relatively small changes in the streamflow criteria can result in large changes in model-calculated withdrawal rates. For example, a decrease in the average withdrawal rate of almost 4 Mgal/d was calculated for an increase in the streamflow requirement from 0.65 $ft^3/s/mi^2$ to 0.72 $ft^3/s/mi^2$. The nonlinear shape of the graph results from the unique hydrologic and hydrogeologic characteristics of the basin and the distribution of pumping wells and streamflow-constraint sites used in the simulation-optimization model. One of the informative results of the study was that optimal withdrawal rates for the three wells located in the Carr River Basin (wells 1-3, fig. 1) were generally low, even though the hydraulic properties of the aquifer near the well sites would be favorable for large-capacity supply wells. The low model-calculated withdrawal rates result from the fact that the Carr River naturally loses water to the underlying aquifer, thereby causing the maximum rates of allowable streamflow depletion in the river to be relatively small.

The timing of water-supply demands is a critical factor in water-resource planning. As in many locations, typical demand patterns in Rhode Island (fig. 2) are such that the highest demands generally occur during the summer, when streamflows are relatively low. These demand patterns can have a substantial impact on the total amount of ground water that can be withdrawn in a basin over a typical year. For example, an average annual withdrawal rate of 12 Mgal/d was determined for the basin using the USFWS Streamflow

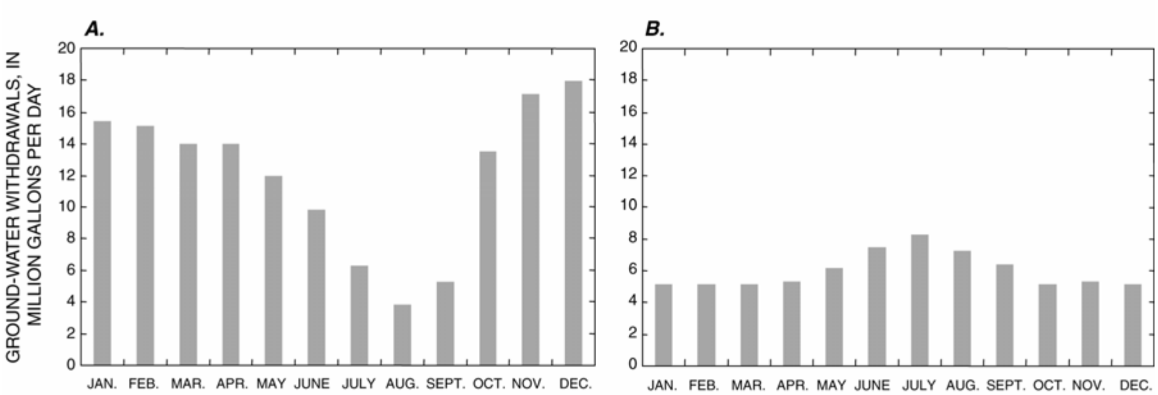

Figure 4. Optimal monthly withdrawal patterns calculated for (A) the case with no constraints on water-supply demands and (B) the case in which water-supply demands are greatest during the summer months.

criterion of 0.5 $ft^3/s/mi^2$ and no consideration of the variability in the annual pattern of water-supply demands; withdrawal rates determined for this condition are highest (above 12 Mgal/d) from October through April and lowest in July, August, and September (fig. 4A). If the same streamflow criterion is used, however, and the monthly withdrawal pattern in the basin is constrained to mimic that of the typical demand pattern shown by the data on figure 2 (using constraint equation 4), then the average annual withdrawal rate for the basin decreases to about 6 Mgal/d, with highest withdrawal rates occurring during the summer months (fig. 4B).

CONCLUSIONS AND FUTURE DIRECTIONS

Simulation-optimization modeling is an effective means to evaluate tradeoffs between various hydrologic constraints and the sustainable use of ground-water resources. Simulation-optimization models developed for coupled ground-water/surface-water systems of Rhode Island are providing insight into the dependence of ground-water development options on minimum streamflow standards and patterns of water-supply demands. An important, yet poorly understood variable is that of hydrologic variability—specifically, the effects of periodic droughts and resulting low-streamflow conditions on ground-water development options. Future investigations should be directed toward this important topic.

The simulation-optimization models developed in this work were solved in a two-step process, in which the response coefficients were first calculated in a series of MODFLOW simulations and then each optimization-model formulation was solved separately using linear-programming software. It is anticipated that future applications of the formulations outlined here will be solved using the recently published GWM (Ground-Water Management) Process of MODFLOW-2000 (Ahlfeld and others, 2005). GWM provides the capability to determine ground-water withdrawal (or injection) schedules that meet a variety of constraints, including specified streamflow (or streamflow-depletion) requirements, maximum drawdowns, and water-supply demands. GWM uses a response-matrix approach and internally coded solution algorithms to solve several types of linear, nonlinear, and mixed-binary linear ground-water management formulations.

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