AVAILABILITY OF GROUND-WATER RESOURCES AT THE CROTON-ON-HUDSON WELL FIELD CROTON-ON-HUDSON, NEW YORK

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EXECUTIVE SUMMARY

The Village of Croton-on-Hudson retained Geraghty & Miller, Inc. to evaluate the possibility of developing additional ground-water resources at its well field adjacent to the Croton River. Earlier studies had indicated that substantially greater volumes of ground water were available from the well field above and beyond the 1.0 million gallons per day (mgd) to 1.25 mgd currently pumped from five wells.

The evaluation was conducted by means of installing observation wells, conducting an aquifer test, and analyzing the results of the test. Four observation wells were installed to obtain site-specific geologic data and to provide water-level monitoring points for the subsequent aquifer test. A preliminary step-test was performed to test the performance of Well 3. The aquifer test was performed during April 11 to April 15, 1988, with Well 3 being pumped at over 1,300 gallons per minute (gpm).

Data collected during the aquifer test and other site information were evaluated through the use of a computer numerical flow model to determine aquifer hydraulic characteristics and to predict the safe yield of the aquifer under normal and drought conditions. Recommendations were developed for management of the well field

The results of the modeling effort are as follows:

1. The Croton River is the predominant source of water that is pumped from the well field.

2. Under normal (nondrought) conditions, five high-capacity wells located at the existing well locations can provide 5.5 mgd on a continuing basis.

3. Under normal conditions, five high-capacity wells that are distributed more evenly than the existing well locations can provide 6 mgd on a continuing basis.

4. Under normal conditions, three wells (one new high-capacity well in the upper part of the well field, Deep Well 1, and Well 3) can provide 5 mgd on a continuing basis.

5. Under severe drought conditions, assuming no flow in Croton River and no other sources of recharge of the aquifer, the well field has 41 days of water at a pumping rate of 1.3 mgd and 16 days of water at 2.6 mgd.

Four recommendations result from the Geraghty & Miller, Inc. study.

1. The two upper wells should be taken out of service and replaced with one deep, large-diameter production well in the upper part of the well field, near Well OW-5. This recommendation results from the inefficiency of the upper wells, the prolific geology near Well OW-5, and the results of the modeling analysis, which show that a better distribution of pumping centers will increase the yield of the well field. In addition, new piping directly to the main distribution system should accompany this new well in order to cut back on losses from the current piping system.

2. When the replacement well is drilled, the borehole should penetrate the bedrock. The small increment of extra drilling is a cost-effective way to explore the potential for usable ground-water resources in the bedrock.

3. Install a higher capacity pump in Well 3. This well can yield substantially more water than the capacity of the existing pump. With the high-capacity pump in place in existing Well 3, Deep Well 1, and in the recommended well in the upper part of the well field,

system needs will be satisfied by two wells, thereby providing an opportunity for maintenance on a rotating basis at the third well.

4. A water-level monitoring program should be initiated to monitor the well field under actual conditions, including periods of drought and low river stage. Water levels in the monitoring wells should be recorded to determine optimum operating rates.

INTRODUCTION

The Village of Croton-on-Hudson retained Geraghty & Miller, Inc. in January 1988 to provide assistance in evaluating the possibility of developing additional water resources to satisfy the demand of an expanding population. The sole source of the village's public water supply is the valley-fill aquifer underlying and adjacent to the Croton River between New Croton Dam and Quaker Bridge. The current daily pumpage from the well field ranges from 1.0 to 1.25 million gallons. Previous hydrogeologic studies by Geraghty & Miller (Geraghty & Miller, Inc. 1970; 1978) concluded that there was a likelihood that a significantly greater volume of water could be extracted from the aquifer.

This report describes the most recent hydrogeologic work that Geraghty & Miller has performed at the Croton well field. Four observation wells were installed in the well field, and a long-term aquifer test was run on Well 3. Data were collected from this test to evaluate the true potential of Well 3 and also to determine important hydraulic properties of the aquifer. Following this test, a numerical flow model of the aquifer was developed by Geraghty & Miller's modeling group to quantify the importance of each contributing water source to the aquifer system and to assess the water-level drawdown impacts under several pumping scenarios. The model performed predictive simulations of the sustained yield of the well field under nondrought conditions and also of the maximum possible pumping time of the well field under drought conditions. In both types of simulations, the effects of distributed pumpage were analyzed.

DESCRIPTION OF WELL FIELD

Hydrogeology

The Village of Croton's well field extracts ground water from an accumulation of unconsolidated deposits of sand and gravel in the narrow V-shaped bedrock valley of the Croton River. Records of test borings show that silts and clays are mixed with the coarser sediments and stratified in discontinuous layers. The steep walls of the valley are composed of fractured and faulted crystalline bedrock. The maximum depth from the valley floor to bedrock is approximately 100 ft and the width of the valley floor varies from 100 to 700 ft. The well field is located within the broadest section of the valley approximately 4,000 ft downstream from the New Croton Dam and spillway.

Potentially, the valley-fill aquifer receives replenishment from five sources of water: (1) precipitation recharge, (2) infiltration of overland runoff, (3) stream bed leakage, (4) underflow beneath New Croton Dam, and (5) direct leakage from the bedrock units. All these sources were quantified with the exception of leakage from the bedrock units. Metamorphic crystalline bedrock generally constitutes a poor aquifer and the possible contribution of limestone bedrock below the floor of the valley is not known. For these reasons, the bedrock units were simulated as non-contributing or no-flow boundaries in the modeling analysis described later in this report.

Pumping Network

The current pumping system for the village public water supply consists of five wells, designated Deep Well 1, Well 3, Shallow Well 2, Upper Well 1, and Upper Well 2. The well locations are shown on Figure 1. The total designed pumping capacity of these wells is approximately 2.6 million gallons per day (mgd), based on the following yields: Deep Well 1 providing 700 gallons per minute (gpm); a total combined pumpage from Upper Wells 1 and 2 and Shallow Well 2 providing 700 gpm, and Well 3 providing 400 gpm. The wells are pumped on a rotating schedule and presently yield approximately 1.0 to 1.1 mgd. The pumping rates, operating schedule, and average production rates of the wells during the March 1988 investigation are shown in Table 1.

Upper Wells 1 and 2 are pumped into Shallow Well 2; the combined water is then pumped into the distribution system. Examination of the two upper wells indicated that the pumps are old, in poor condition, and working very inefficiently. The pumping rates of the wells cannot be determined because they are not equipped with flow meters; however, they appear to be pumping low volumes of water on an intermittent basis.

Using Well 3, Geraghty & Miller performed a 4-day aquifer test, which involved pumping the well at a constant steady rate that would stress the aquifer while water-level drawdowns were measured at established monitoring points (observation wells). This test was designed to verify Geraghty & Miller's hypothesis from previous studies that Well 3 was capable of yielding substantially greater volumes of water and to measure the hydraulic properties of aquifer transmissivity (the aquifer's capacity to transmit water) and aquifer storativity (the water-storage property of the aquifer)

AQUIFER TEST METHODOLOGY

Installation of Observation Wells

During March 1988, four observation wells were drilled and installed within the well field under the direction of a Geraghty & Miller hydrogeologist. The geologic logs are presented in Appendix A. The locations of these wells, designated OW-4 through OW-7, are shown on Figure 1. The purpose of the observation wells was to obtain site-specific geologic data and to provide water-level monitoring points for the aquifer test

The locations of the wells were selected to monitor the effects of the hydrogeologic boundaries of the aquifer system under test pumping conditions. The bedrock walls were presumed to form impermeable barrier boundaries while the Croton River was expected to act as a continuous recharge boundary. Wells OW-4 and OW-7 are on a line perpendicular to the valley bedrock walls and the Croton River, and Wells OW-4, OW-5, and OW-6 line up parallel to these physiographic features. The impervious nature of the bedrock was expected to appear during the pumping test as a steepening of the water-level drawdown curve through time when the cone of depression created by the pumping reached the valley walls. A flattening of the drawdown curve would indicate arrival of recharge from induced river infiltration. Well OW-4 was situated adjacent to Well 3 to provide a better understanding of the relationship between the screen setting of Well 3 and the aquifer characteristics at that location.

The observation wells were drilled by the D.L. Maher Company of North Reading, Massachusetts, using the wash boring method. Well construction logs are included in Appendix A. Wells OW-4, OW-6, and OW-7 are constructed of PVC and screened over the entire thickness of the aquifer to eliminate any effects of partial penetration. As Well OW-5 was located outside of the effective area of partial penetration, it was unnecessary to screen the entire saturated thickness of the aquifer. The drill cuttings from

Well OW-5 indicated excellent aquifer material, and this site is a likely area for developing additional water resources. In view of this information, Well OW-5 was constructed with an 80-slot steel screen so that it could be pumped. The large volume of water (60 gpm) obtained from this 2.5-inch diameter well during development indicates that the aquifer material in this area is potentially capable of producing more water.

Water-Level Monitoring Network

Following installation of the new observation wells, Geraghty & Miller surveyed the elevations of the new wells and all other water-level measuring points to be monitored during the aquifer test. The monitoring network consisted of the pumping well (Well 3), the four new observation wells (OW-4 through OW-7), two existing abandoned wells (a shallow well, designated 1A, and a deep well, designated "6-inch steel", a shallow supply well (Shallow Well 2), and two surface-water gages, one along the Croton River (CRE) and the other along a branch of the Croton River (CRW). The elevation data and the well construction details are presented in Table 2.

Ideally, no other pumping activities occur in the area during an aquifer test. However, since the village needed to continue pumping to meet the public demand for water, the pumping schedule was adjusted to minimize the effects on the test data. A week prior to the start of the test, all wells were turned off except for Deep Well 1, which was pumped at a steady rate of 580 gpm until the end of the test. This procedure allowed the ground-water system to stabilize before the start of the test, and the concurrent pumping of Deep Well 1 did not adversely affect the test data. Two sets of synoptic water-level measurements are presented in Table 3. The March 30, 1988 measurements were collected while the system was under its normal operating schedule, and the April 11, 1988 measurements were taken after the system had stabilized and the only well pumping was Deep Well 1.

To monitor the water levels throughout the testing period, automatic water-level recorders were installed on selected wells. A Stevens continuous water-level recorder was installed on Well 1A and on the river at location CRW. The Stevens recorder operates by utilizing a horizontal drum and chart which is turned through float action. This float action is proportional to changes in water levels, and a stylus moves across the chart at a constant speed. The combined movement of the drum and stylus provides a graphic record of water level versus time. Test Well 3 and Observation Wells OW-4, OW-6, and OW-7 were equipped with pressure transducers and connected to a computerized data logger to monitor water levels during the test

The United States Geological Survey (USGS) maintains a stream gaging station along the Croton River below New Croton Dam, approximately 2,500 ft upstream from the well field. Gaging data were obtained to determine stream flow conditions during the aquifer testing period, as well as to evaluate the historical stream flow record. During the aquifer test, the river discharge ranged between 187 and 241 ft^3/second. These values are high compared to average conditions, as discussed later in this report (Sustained Yield Analysis section).

Installation of Pump and Discharge Lines

As the existing pump did not have sufficient capacity for the required test pumping rate, the D.L. Maher Company temporarily replaced the vertical turbine pump in Well 3 with one of greater capacity. Discharge lines were installed to transport the pumped water to the branch of the Croton River at a location approximately 200 ft downstream from Well 3, far enough to prevent infiltration of the pumped water back into the aquifer. The water was discharged through a manifold and two discharge lines, each equipped with an in-line gate valve. At the end of each discharge line, an orifice and manometer were installed to determine the flow rate through each line. Published orifice and manometer tables were used to measure the discharge rate

Installation of Rain Gauge

To monitor precipitation that might cause the water table to rise significantly, a rain gage was installed in the well field. However, no measurable precipitation occurred during the test.

Preliminary Aquifer Test

On April 8, 1988, a preliminary aquifer test was run on Well 3 to check the performance of the pump and the well, to establish the pumping rate to be used for the final test, and to preset the flow valves for the main test. The well was pumped for 1 to 2 hours at each of four increasingly higher pumping rates while water-level drawdown in Well 3 was measured. The four rates utilized were 740 gpm, 1000 gpm, 1250 gpm, and 1350 gpm. Based on these data, a pumping rate of 1328 gpm was selected for the test as it appeared that this rate could be sustained for a 4-day period without dewatering the well yet adequately stressing the aquifer

Aquifer Test

A 4-day aquifer test was conducted on Well 3 from 1:30 p.m. on April 11, 1988 to 1:30 p.m. on April 15, 1988 Throughout this period, Well 3 was pumped at a steady continuous rate of 1328 gpm and observations were made of the aquifer response to this pumping stress. Comprehensive quantitative analyses were completed using the water-level changes observed during the test to estimate aquifer storage and transmissivity values.

Prior to the start of the test, static water-level conditions were measured at all monitoring points with a chalked steel tape and a M-scope. Throughout the aquifer test, and also for the first 4 hours of recovery at the end of the test, water-level measurements were collected from Well 3 and all water-level monitoring points. Following termination of the test, recovery data were collected to confirm the results of the drawdown test. The timing of drawdown (and recovery) measurements is important because drawdown varies with the logarithm of time. As a result, a progressively longer period of time is allowed between measurements as the test proceeds. The schedule shown in Table 4 was followed for measuring the water levels, thus allowing a uniform plot of water-level data on a logarithmic scale.

AQUIFER TEST ANALYSIS

To establish a conceptual understanding of the valley-fill aquifer flow system, the available hydrogeologic data were reviewed in detail. As part of this review, a comprehensive analysis to determine aquifer parameters was completed using aquifer response during the pumping test.

A computer program named AQTESOLV was used to analyze the drawdown data. AQTESOLV is an interactive, menu-driven program that allows the user complete control of the analysis of the aquifer test data. The program automatically estimates aquifer parameters using the Marquardt nonlinear least-squares technique and gives the analyst the option of interactively matching type curves to data directly on the computer screen.

AQTESOLV's automatic parameter estimation feature provides greater power in analyzing aquifer test data than ordinary graphic methods of analysis. Sensitivity of solutions to individual aquifer parameters are rapidly evaluated and statistical measures of the uncertainty are automatically obtained. The time drawdown response of seven observation wells and the pumping well were subjected to analysis and solved for three types of aquifer test conditions:

CONFINED AQUIFER TESTS using the nonequilibrium methods of Theis (1935) and Cooper-Jacob (1946).

SEMICONFINED (LEAKY) AQUIFER TESTS using the nonequilibrium methods of Hantush (1955) with or without storage in aquitards

UNCONFINED AQUIFER TESTS using the nonequilibrium methods of Theis (1935) and Cooper-Jacob (1946) with Jacob's correction for reduction in saturated thickness.

A range of transmissivity and storage coefficient values was determined for each well by the three analytical methods described above; these values are shown in Table 5. Each method produced consistent and similar results for each well. Graphic displays of the time-drawdown data and type curves are presented in Appendix B. The observed range of transmissivity is less than an order of magnitude for all values. Wells 1a, 2, 6, and 7 exhibit time-drawdown responses that fit the analytical solutions reasonably well. The transmissivity values observed for these wells range over a factor of only two (22 to 47 ft^2/min).

The coefficient of storage values obtained from the analysis of the aquifer test ranged between 2.8×10^{-3} and 0.2. An average value of 0.1 is reasonable for a storage coefficient for an unconfined aquifer

NUMERICAL FLOW MODEL

Introduction

Properly calibrated and constructed ground-water models are quickly becoming fundamental tools to estimate system response to various alternative resource management strategies. The foundation of each particular model application requires hydrogeologic data from a properly conceived and implemented field program. The complexity of the selected model must be based upon both the objectives of the investigation and the quality of the available data. The most effective applications are those which properly match the objectives, the quality of data, and the mathematical technique into an integrated application.

As shown in Figure 2, the process of constructing and calibrating a ground-water flow model consists of several distinct, but interrelated steps including (1) data review, (2) conceptual model development, (3) model calibration, (4) diagnostic checking, and (5) sensitivity analysis. These steps must be successfully completed prior to using the flow model as a predictive tool. For this study, the aim of the analysis is to develop a ground-water flow model suitable for predicting water levels over a wide range of future or historical conditions and scenarios. Predictive simulations related to the Croton valley-fill aquifer were performed only after model calibration. In the predictive mode, the calibrated flow model was then used to make analyses relating to the sustained yield of the aquifer.

Objectives of the Modeling Analysis

The objectives of this modeling study were as follows:

1. Develop a numerical flow model based upon existing hydrogeologic data and the aquifer testing program.

2. Perform a steady-state calibration and sensitivity analysis in order to estimate values for hydraulic parameters and characterize the importance of several water sources on the model calculations (i.e., underflow, precipitation recharge, stream infiltration) and the sustained well field yield.

3. Perform a series of transient simulations using the calibrated flow model to assess the potential sustained yield of the Croton well field under natural (nondrought) conditions.

4. Perform a series of simulations using worst-case (drought) conditions to assess the performance of the Croton well field at selected pumping rates.

For this study, well field performance was measured in terms of maintaining water elevations above the top of the well screen, the maximum allowable drawdown for efficient and trouble-free operations. Worse-case scenarios were designed to represent drought conditions. For these simulations, aquifer yield is derived solely from aquifer storage.

Method of Investigation

The hydrogeologic information available for the Croton River valley-fill system is sufficient to warrant only a two-dimensional analysis. Thus, a two-dimensional, finite-element flow model was constructed using the SEFTRAN-PC code, and steady-state calibration was performed. This model required the specification of certain boundary and initial conditions in order to approximately simulate the physical flow conditions observed within the valley-fill aquifer system. Some of the required conditions for the model were based upon field testing and observation; others were assumed based upon our hydrogeologic judgment and experience. Two important hydraulic properties of the system were selected as the calibration parameters: riverbed leakage and hydraulic conductivity. These calibration parameters were systematically varied and simulations were made. Water elevations calculated by the model were compared to elevations recorded in the observation wells prior to the aquifer test when the well field was pumping.

Subsequent adjustment(s) were made to these two parameters until an adequate match between model-calculated and observed water elevations was obtained. When the river leakage parameter was calibrated, an assumed precipitation recharge value was applied to the model; this was based on existing available data for the aquifer. The mathematical solution (calibration) arrived at for this application is, therefore, not considered unique; but, the parameters determined by the calibration process are representative and are in the range of those expected for a valley-fill aquifer. Because certain parameters in this model calibration have been assumed, model results and interpretations should be used judiciously when predictions or interpretations about flow system response to various pumping stresses are made. Although the predictive calculations of this two-dimensional model are not absolute, the system response can be expected to be approximately correct.

Code Selection

The SEFTRAN-PC code was selected to simulate the flow system in the Croton River valley. SEFTRAN is a two-dimensional finite-element code which can be used to simulate ground-water flow and solute transport processes in fully saturated porous media. The formulation of the governing equations and the numerical approximation are based on a simplification of the Galerkin finite-element method. The simplification, called the influence coefficient technique, uses rectangular and triangular elements to reduce the computational requirements of numerical integration. SEFTRAN is thus more efficient than most finite-element codes and it also maintains flexibility in defining complex flow regions

The code has undergone extensive verification, validation, and benchmarking.

Discretization

The reliability of both the calculations and interpretations drawn from a mathematical computer model is, in part, a function of how well the model approximates the physical system. The principal means of describing the physical phenomena in mathematical terms is discretization of the model domain with boundary conditions. Discretization permits the transfer of spatial information about a continuous physical system to the computer algorithm so that the mathematical calculations can be performed.

The finite-element mesh used for this application covers an area of 5624 ft by 1082 ft, extending from the New Croton Dam to a location approximately 700 ft north of the Quaker Bridge (Figure 3). The grid consists of 504 square and rectangular elements that vary in size from 20 ft to 385 ft in the x direction running approximately north-south, and from 31 ft to 155 ft in the y direction (approximately east-west). Larger elements were used near the boundaries of the model where less detailed calculations are required. In the vicinity of the Croton well field, the size of the elements is much smaller for greater accuracy. An attempt was made to place a node for each well location in the well field.

The existing database indicate that the valley-fill sediments have a relatively homogeneous nature; since more detailed information was not available, no attempt was made to discretize the model domain vertically into multiple layers. Based on an analysis of well logs obtained from the study area, a uniform base of aquifer elevation equal to -30 ft mean sea level (msl was set for each element in the grid. The saturation of each element in the mesh is computed from the calculated hydraulic head in the element and the base elevation.

Boundary Conditions

To represent the physical boundaries of the model domain, mixed boundary conditions, including constant head and constant flux, were prescribed in the numerical model. No-flow conditions were fixed along (1) the eastern and western limits of the aquifer at the bedrock walls of the Croton River valley, and (2) the bedrock base of the valley-fill aquifer. The assignment of no-flow conditions in these locations is based on the assumption that due to the large permeability contrast between the bedrock and the river alluvium, a negligible amount of ground water leaks from the valley walls into the adjacent valley-fill sediments. Insufficient data are available to quantify the contribution of bedrock leakage to flow in the valley-fill aquifer;

however, the simplifying assumption of no leakage leads to a conservative estimate of the maximum sustained yield for the Croton well field.

Under normal conditions, the Croton River is an important source of ground-water recharge for the valley-fill sediments which supply water to the Croton well field. The SEFTRAN-PC code allows one-dimensional "line elements" to be superimposed on the finite-element grid to represent head-dependent flux boundary conditions such as rivers and streams. In the computer flow model, 18 line elements were used to represent the Croton River. The line elements supply leakage to the aquifer, given the river stage and the river-leakage factor specified for each line element

The hydraulic head assigned to each line element was estimated using a calculated river gradient for the Croton River. Points along the river which had known elevations were used in the computation of this gradient. River elevations were obtained from the USGS 7.5-minute topographic quadrangle (Ossining, New York), river stage data measured at the USGS upper gaging station on the Croton River near New Croton Dam, and the CRE staff gage installed by Geraghty and Miller. Of the data which were used to calculate the gradient of the river, the river elevation measured at station CRE was considered the most reliable. The river elevation obtained at CRE used to calculate the gradient of the

Croton River was measured on March 30, 1988 prior to the start of the pumping test. This field measurement of river stage helped constrain the estimates of river stage in the model

The river leakage factor for the line elements is defined as follows:

river leakage factor = K'B / b'

where

K' = vertical hydraulic conductivity of the river bed

b' = thickness of the riverbed

B = effective width of the river.

The effective width of the Croton River was determined from maps of the area; however, field data describing the hydraulic conductivity and thickness of the streambed of the Croton River were not available. As a result, the river leakage factor had to be estimated during model calibration.

Constant head conditions were specified at the New Croton Dam (upper) and Quaker Bridge (lower) boundaries of the model to approximate aquifer conditions during March 1988. Measured water-level data were not available at the upper and lower boundary locations. Therefore, aquifer hydraulic heads at these boundaries were assumed to be in equilibrium with the Croton River.

Under normal operating conditions, five wells pump water from the Croton well field. These wells cycle on and off each day with no single well operating constantly. The water-level measurements which were used as calibration targets were obtained on March 30, 1988 while the well field was operating under normal pumping conditions. Average production rates were calculated for each well using the pumping rate of each well and the fraction of time during which the well operates. Actual and average production rates for each well are shown in Table 1. In the flow model, the average rates were assigned as points of constant flux or steady-state (see Figure 4). Due to the cyclic nature of the pumping, it is likely that a true steady-state is never reached near the wells. By assigning an average production rate to each well and modeling the well field as a steady-state system, some error is introduced into the model. This error cannot be assessed due to the lack of continuous water-level data, which are needed to determine the change in the hydraulic head distribution as wells are turned off and others are turned on.

Model Calibration

The purpose of steady-state model calibration is to adjust hydrogeologic parameters in the numerical model until the model accurately predicts hydraulic conditions found in the field. During the calibration precedure, model parameters are adjusted until water levels calculated by the model match water levels observed in the field. When more than one parameter is adjusted in the calibration precedure, the solution that is obtained may not be unique. To increase the probability of reaching a solution which accurately represents the physical system, knowledge of the system is essential. Field measurements of hydrogeologic properties at the study site help constrain model parameters adjusted during model calibration and increase the reliability of the model predictions.

In the Croton-on-Hudson well field model, hydraulic conductivity of the valley-fill sediments and the river leakage factor were parameters that were adjusted during the calibration precedure. In addition, due to the lack of water-level data at the upper and lower boundaries and near the Croton River, hydraulic head at the boundaries and at the line elements were also adjusted to achieve the best match between calculated and observed water levels

Calibration targets are water levels measured in the field which are used to check the accuracy of a numerical model's calculations. Water levels measured in five wells were used as calibration targets in the Croton well field model. Four of these wells (OW-4, OW-5, OW-6, and OW-7) were installed by Geraghty & Miller as observation wells for the April 1988 aquifer test. The fifth well used in the calibration was Well 1A. On March 30, 1988, prior to the start of the aquifer test, water-level measurements were taken in each well. These measured water levels, shown in Table 3, were used as calibration targets in the model, and they are assumed to represent the dynamic system under the normal pumping rates discussed earlier.

The hydraulic head distribution predicted by the final calibrated flow model for the Croton well field is shown in Figure 4. The annotations on the axes of the figure give the location of this map within the model domain shown in Figure 3. The flow model sensitivity analysis, described in the next section of this report, presents the agreement between observed and calculated water levels at the calibration targets. The following subsections describe the adjustment of the hydraulic parameters during the calibration of the Croton well field model.

Hydraulic Conductivity

The coefficient of transmissivity for the valley-fill sediments was estimated from drawdown measurements obtained at eight wells monitored during the April 1988 aquifer test (Table 5). Hydraulic conductivities were obtained from these transmissivities by dividing the transmissivities by the saturated thickness of the aquifer. The values of hydraulic conductivity ranged from 0.265 ft/min to 1.02 ft/min with an average value of 0.57 ft/min. As hydraulic conductivity data were not available outside of the Croton well field, for the scope and purpose of the present model, it was assumed that hydraulic conductivity was distributed uniformly throughout the entire model domain.

During the calibration of the model, hydraulic conductivity was varied from 0.265 ft/min to 1.02 ft/min. A hydraulic conductivity value of 0.45 ft/min provided the best match between observed and calculated hydraulic head. This value agrees well with the average field measurement of 0.57 ft/min.

River Leakage Factor

The river leakage factor was also adjusted during the calibration procedure. This parameter was varied from 0.0036 ft/min to 0.36 ft/min, with a value of 0.036 ft/min providing the best match between calculated and observed hydraulic heads. Water levels were very responsive to changes in the river leakage factor, which lent confidence to the estimated value of the river leakage factor. Field data relating to the hydraulic properties of the riverbed, such as hydraulic conductivity and thickness of the riverbed, could further constrain the river leakage factor

Hydraulic Head at Upper and Lower Boundaries

The specified heads at the upper and lower boundaries of the model were adjusted as part of the model calibration. Varying the hydraulic head assigned along the upper and lower boundaries had little effect on the hydraulic heads calculated at the calibration targets; however, the flow balance was affected by these changes.

To assess the impact of the constant head specification on the model calibration, a constant flux was applied to the upper and lower model boundaries. The constant flux value used for both boundaries was 220,000 gpd. This value was determined by Leggette and Jacob (1938) to be the amount of underflow in the Croton River valley while the river is flowing. When a constant flux of 220,000 gpd was assigned at the upper and lower boundaries, very little change was observed in the residuals calculated at the calibration targets. In addition, the hydraulic head at the boundaries varied less than 2 feet from the hydraulic head which was estimated from the gradient of the river. Thus, these calculations add credibility to the heads prescribed at the upper and lower boundaries of the model. To be fully confident of the values assigned at the boundaries, water-level information is needed at both boundaries and a water budget study should be implemented throughout the valley. In the final calibration, constant heads of 47 and 34 ft were assigned to the upper and lower boundaries, respectively

Sensitivity Analysis

The implementation of a sensitivity analysis is an important phase in any ground-water modeling study. The purpose of a sensitivity analysis is to determine the relative control of different hydrogeologic parameters on the hydraulic head distribution in the model domain. A discrete sensitivity analysis is accomplished by varying individual hydraulic parameters in a numerical model and observing the response of the system to these changes. If the system is insensitive to changes in a specific parameter, difficulty may arise in estimating a value for that parameter during model calibration. Thus, it becomes critical to obtain detailed field data to constrain the insensitive parameter. On the other hand, a sensitive parameter will produce large changes in hydraulic heads for relatively small changes in the parameter. Thus, sensitive parameters can be estimated during model calibration with a higher degree of confidence

In the present study, five parameters were analyzed in the sensitivity analysis phase of the modeling effort:

1. Hydraulic conductivity
2. River leakage factor
3. Hydraulic head at the upper and lower boundaries
4. Hydraulic head in the river elements

5. Precipitation recharge

Each of these five parameters were varied individually and the system's response to these changes was measured. The change in residual heads at the five calibration targets which accompanied the change in each parameter was used to assess the sensitivity of the hydrogeologic system to each parameter. The residual head is defined as follows:

residual head = calculated head - observed head

The results of this analysis are shown in Table 6.

A discussion of the model sensitivity to each of the five parameters is given below.

Hydraulic Conductivity

Hydraulic conductivity was varied within the range of values obtained from field tests in several model runs (see simulations 1, 8, and 9; Table 6). Values ranged from 0.20 ft/day to 1.02 ft/day. Calculated residuals that resulted from these runs varied markedly with each hydraulic conductivity change. As a result of the system's sensitivity to hydraulic conductivity and due to the quantity of the hydraulic conductivity field measurements, confidence is placed in the value of the hydraulic conductivity estimated from the model calibration.

River Leakage Factor

The river leakage factor was a very sensitive parameter in the Croton well field model. Order of magnitude changes in the river leakage factor produced significant changes in hydraulic heads at the calibration targets. The changes in head ranged from 0.1 ft to more than 2.5 ft (see simulations 48, 76, and 77; Table 6).

Hydraulic Head at Upper and Lower Boundaries

The constant head values assigned at the upper and lower boundaries were varied to assess their effect on the overall hydrogeologic system (see simulations 17-21; Table 6). In the final calibration, the hydraulic heads prescribed at the New Croton Dam (upper) and Quaker Bridge (lower) boundaries were 47 ft and 34 ft, respectively. During the sensitivity analysis, the hydraulic head assigned along the upper boundary was systematically varied from 44 ft to 54 ft, while the hydraulic head assigned along the lower boundary was varied from 24 ft to 39 ft. The hydraulic heads obtained for the final calibration run for the New Croton Dam and Quaker Bridge boundaries, respectively, are 47 ft and 34 ft (see simulation 48; Table 6)

Varying values at the constant heads fixed at these boundaries had little effect on the residual heads at the calibration targets. For example, when the constant head value assigned at the upper boundary was changed from 49 ft to 54 ft, the residuals changed by an average of only 0.06 ft. Although the constant head specification did not greatly affect the residual heads measured at the calibration targets, the rate of ground-water flow into the system at the upper boundary changed markedly. The rate of ground-water recharge entering the system from the upper boundary changed from 60 ft^3/min to 246 ft^3/min. This increase in ground-water inflow at the upper boundary was accompanied by an overall decrease in the amount of water that entered the aquifer from river leakage.

Two important conclusions can be drawn from these results. First, hydraulic heads at the Croton well field do not vary much with changes in the constant head boundaries, but the rate of water entering or leaving the model area from the upper and lower boundaries does vary substantially. Second, the Croton River acts as a reservoir for the Croton valley-fill aquifer. It provides ground-water recharge to the aquifer when other sources of water are unable to counterbalance the amount of water leaving the system due to pumping or flowing out of the system at the lower boundary.

Hydraulic Head in the River Elements

The hydraulic head assigned at each line element representing the Croton River was varied in three aquifer simulation runs (simulations 1, 6, and 7; Table 6). In each model run, the gradient along the river was kept constant but the hydraulic head (river stage) in individual river elements was varied. As shown in Table 6, large changes in residuals resulted from changes in the river level. This shows that hydraulic heads in the aquifer are very sensitive to changes in the stage of the Croton River. Consequently, the sustained yield of the Croton well field is largely controlled by the water level in the Croton River. Furthermore, because the stage of the Croton River is highly variable, the maximum yield of the Croton wells is also highly variable.

Precipitation Recharge

Two aquifer simulations were run to determine the sensitivity of hydraulic heads in the valley-fill aquifer to variations in the rate of precipitation recharge. In the first model run, no precipitation recharge was prescribed. In the second run, 15 inches per year (in/yr) of precipitation recharge was assigned to the model. The average change in the residuals at the five calibration targets was very small (less than 0.1 ft), which indicates that precipitation recharge is a relatively unimportant source of water in valley-fill aquifer

PREDICTIVE SIMULATIONS

Introduction

Predictive simulations were performed using calibrated ground-water flow model for the Croton River valley. Steady-state and transient simulations were made to examine (1 the maximum safe yield of the well field, (2) the impact of drought conditions on the yield of well field. In both types of simulations, the effect of distributed pumpage was analyzed

Sustained Yield Analysis

Model simulations were performed to predict the sustained yield of the Croton-on-Hudson well field under normal (nondrought) conditions. The hydraulic parameters from the calibrated steady-state flow model were used in the sustained yield analysis with two modifications. First, the river stage in the Croton River was adjusted to reflect average streamflow conditions. The stage of the river is a very sensitive parameter in the flow model. Streamflow records for the Croton River show that discharge in the river is highly variable with short periods of high flow that are related to releases from the New Croton

Streamflow data obtained from the USGS gaging station below New Croton Dam were examined to determine estimates of the average discharge in the Croton River for the period of October 1984 through September 1987. From these data, two estimates of the average streamflow were derived, the median and the mode. The mode or most commonly occurring discharge was 11 ft^3/sec, and the median or 50th percentile was 26 ft^3/sec.

The second modification to the configuration of the model used in the predictive simulations was the assignment of constant fluxes at the upper and lower boundaries of the model. Maintaining constant heads at these locations produced an unrealistic flow of water across these boundaries; therefore, the estimate of underflow by Leggette and Jacob (1938) equal to 220,000 gpd was prescribed at these locations. As noted in the sensitivity analysis, the assignment of constant head or constant flux conditions at these boundaries has little effect on computed water levels at the Croton well field.

To apply these streamflow estimates in the model, the median and mode discharges were converted to an equivalent river stage. A stream rating curve was obtained from the USGS to relate discharge in the Croton River to river stage, and an estimate of river stage was approximated for each line element in the flow model (the river stage approximation procedure is reported in Appendix C). Pumping to determine the sustained yield in the aquifer was simulated under these average streamflow conditions.

The simulations of sustained yield pumping used the river stages corresponding to the estimated median streamflow of 26 ft^3/sec. Hydraulic heads in the pumping wells were set at levels 1 to 2 feet above the top of the well screens. As in the previous simulations of drought conditions, the top of each well screen was conservatively set at 10 ft msl. Thus, the saturated aquifer thickness at the pumping wells is approximately 40 ft.

An extremely important limiting assumption in this analysis is the estimated streamflow rate in the Croton River. The estimated sustained yields in this analysis are approximately equal to or greater than the most common Croton River discharge rate (11 ft^3/sec) estimated from recent data. Therefore, because most of the ground water pumped by the wells is drawn from the Croton River, it is very important that actual stream discharges exceed this value.

Predictive simulations of the sustained yield of the aquifer were performed for three pumping scenarios. The first two scenarios looked at five ideal wells and assumed each well was capable of pumping the theoretical rate. In the first case, the theoretical wells are at the same locations as the existing wells (Deep Well 1, Well 3, Shallow Well 2, Upper Well 1, and Upper Well 2). In the second configuration, the five ideal wells are at the present locations of Deep Wells 1, Well 3, and Upper Well 1, plus two new locations in the central part of the well field, as shown in Figure 5. The third predictive simulation of sustained yield was performed with a total of three wells in the well field: an ideal well located in the upper part of the aquifer near Well OW-5, and existing Deep Well 1 and Well 3, with pumping rates specified that reflect the actual pumping capacities of the latter two wells.

Given the current configuration of well locations and assuming ideal wells and pumping capacities of 100-percent efficiency, the sustained yield predicted by the simulation was approximately 11 mgd. This sustained yield would be cut in half, however, if the efficiency of each pumping well were 50 percent. Although the well efficiency has only been estimated for Well 3 (presented in Appendix C), it is likely that the total sustained yield of the well field with five new wells would be at least 5.5 mgd.

Another simulation was performed using the hypothetical well locations that would more evenly distribute pumpage throughout the aquifer. With five wells simulated, the sustained yield of 100-percent efficient wells was about 12 mgd. Again, assuming some loss of well efficiency, the yield should be 6 mgd or more

The third simulation looked at the sustained yield of the well field with a minimum amount of rehabilitation to the existing system. A pumping rate of 700 gpm was specified for Deep Well 1 and a pumping rate of 1300 gpm was specified for Well 3. A new well, which would pump more efficiently than the current network, was hypothetically located in the upper part of the aquifer. Accounting for a loss of well efficiency at the new well, the sustained yield is approximated at 5 mgd

Drought Conditions

To represent the Croton River valley aquifer under drought conditions, transient (time-dependent) simulations were performed using the SEFTRAN-PC code. The goal of these simulations was to determine how long water could be pumped from the Croton well field under worst-case conditions.

In order to simulate drought conditions, all sources of water entering the model domain were cut off. No-flow boundaries were prescribed at all boundaries of the model so that ground water was unable to leak into or out of the system from the valley walls or the upper and lower ends of the river valley. Realistically, some ground water would enter the model domain under drought conditions at the New Croton Dam and Quaker Bridge boundaries of the model; ever, by assigning no-flow boundaries at all edges of the model domain, a conservative estimate of ground water available for consumption is achieved. Ground-water recharge derived from the Croton River was also removed from drought simulations. This was accomplished by removing the line elements which represented the river during the steady-state simulations. Since the Croton River has gone dry in the past, the assumption that the river does not provide ground-water recharge during drought conditions is reasonable.

Two sets of transient worst-case scenarios were modeled using three different pumping rates with two different well configurations. Total well field pumping rates used in the model were 1.3 mgd, 1.9 mgd, and 2.6 mgd. The rate of 1.3 mgd represents the pumping rate needed to meet the demands expected in the near future; 1.9 mgd represents the pumping rate during the April 1988 aquifer test; and 2.6 mgd represents the estimated capacity of the Croton-on-Hudson well field. In the first configuration of wells, the net volume being pumped from the well field was distributed over the five existing wells (Deep Well 1, Well 3, Shallow Well 2, and Upper Wells 1 and 2) and the pumpage was not distributed equally over the five wells, but was distributed using the relative pumping rate that presently exists at each well.

The second set of worst-case scenario analyses used the same well configuration as in the third sustained yield analysis (Deep Well 1, Well 3, and a new upper well with pumpage equally distributed among the three wells.

A uniform storativity of 0.10 was assigned in all transient simulations. This value is the average storativity value derived from the April 11 aquifer test. A storativity of 0.10 is indicative of an unconfined aquifer. The simulations representing drought conditions were run until simulated water levels fell below the tops of the well screens. The tops of the screen elevations are only known for wells 1 and 3 (1.3 and 8.0 ft msl, respectively). For the purposes of these simulations, a conservative estimate of the top of the screen elevation equal to 10 ft msl was used for all pumping wells. The amount of time required for this to occur varied considerably with changes in pumping rate.

The pumping rates that were simulated for the analysis of the current well field configuration under severe drought conditions are reported in Table 7. Since Wells 1 and 3 are located close together, it is reasonable to assume that the drawdown effects for a particular combined pumping rate of Wells 1 and 3 would be similar, regardless of the individual rates at the two wells. This assumption is useful because the designed pumping capacity of Deep Well 1 is approximately 700 gpm, and the capacity of Well 3 would be approximately 1,300 gpm with the installation of a larger capacity pump. Due to the shallow depth and intermittent yield of Shallow Well 2, a constant rate of 20 gpm was fixed at this well. This rate approximates the estimated amount of water that presently is contributed by Shallow Well 2. The relatively low pumping rates assigned to the two upper wells reflect estimates of the capability of the present system.

The amount of time that the existing well field was able to pump at each of the three designated rates is shown in Table 7. Under severe drought conditions, the model calculated that the well field could pump 1.3 mgd for up to 41 days and at twice that rate for 16 days. Doubling the pumping rate more than halves the maximum pumping time under drought conditions. Simulated water levels in the five pumping wells at the three pumping rates are shown in Figures 6 through 8.

The maximum simulated pumping time for the well field under drought conditions was analyzed with the following three wells: a new well in the upper part of the well field, Deep Well 1, and Well 3. In these analyses, pumpage rates were equally distributed among the three wells to maximize the efficiency of the system. These pumpage rates are listed in Table 7. The model calculates that the three wells could pump a total of 1.3 mgd for up to 45 days, and twice the pumpage rate, 2.6 mgd, could be maintained for 17 days. The maximum pumping times for these three wells are presented in Table 7. It is evident from these simulations that evenly distributing pumpage allows longer pumping times during drought conditions. The simulated water levels in these three wells at total pumping rates of 1.3 mgd, 1.9 mgd, and 2.6 mgd are shown in Figures 9 through 11.

SUMMARY AND CONCLUSIONS OF MODELING ANALYSIS

A steady-state flow model was constructed and calibrated against field data to evaluate the current and future yield of the Croton well field. This flow model calibration was based on a limited data base consisting of water levels measured in wells and the Croton River prior to and during a 4-day pumping aquifer test, stream measurements obtained from the USGS gaging station below New Croton Dam, selected well logs available for the well field, and interpretations of the geologic framework in the Croton River valley.

Given the assumptions that were required for the model, the calibration should not be viewed as unique. Nevertheless, the model serves as a valuable tool for (1) studying the interrelationships between various components of the Croton River valley-fill aquifer flow system, (2) understanding the response of the aquifer to various pumping stresses, streamflow conditions, and drought periods, and

(3) providing insight for future data collection and predictive modeling investigations.

As part of the quantitative analyses for this modeling study, the hydraulic properties of the Croton River valley-fill aquifer were estimated in two ways. First, data from a 4-day aquifer test of pumping Well 3 in the Croton well field were evaluated by analytical solutions to determine the coefficients of transmissivity and storage for the aquifer. From these analyses, the transmissivity of the aquifer was found to range between 22 ft^2/min and 47 ft^2/min. The storage coefficient (specific yield) of the aquifer was estimated between 0.003 and 0.2, which are typical values for an unconfined aquifer. During the calibration of the flow model, an average aquifer transmissivity value equal to 32 ft^2/min was obtained, which demonstrates close agreement with the estimates obtained from the analytical solution techniques.

The flow model analysis showed that the Croton River is the most important source of water for the Croton well field; however, field data describing the streamflow, river stage, and riverbed hydraulic property characteristics of the Croton River are incomplete. Values for these river properties were defined through careful adjustment during the model calibration and sensitivity analysis phases of the study. Therefore, as a result of these required assumptions in the model, any model predictions must be used with appropriate caution. In the future, it is recommended that additional field activities concentrate on the collection of data for characterizing the relationship between the Croton River and the valley-fill aquifer

Predictive simulations were performed to analyze the sustained yield of the aquifer under nondrought conditions. The maximum sustained yield of the valley-fill aquifer with five hypothetical, equally distributed wells was estimated by the model simulation at greater than 6 mgd. With five hypothetical wells somewhat less evenly arranged within the well field, the sustained yield would drop to 5.5 mgd. A configuration with three wells was simulated, and the yield was calculated at 5 mgd. The latter well configuration would require only moderate rehabilitation of the existing pumping system. All of these analyses include very important assumptions about flow in the Croton River.

A series of simulations were performed to analyze the system under severe drought conditions. A set of worst-case conditions was selected, including no precipitation recharge and no streamflow in the Croton River. The results indicated that with the current well field pumping at a rate of 1.3 mgd, water levels in the wells can be maintained above the tops of the screens for more than 1month. Doubling this pumping rate reduces this safety period to approximately 16 days. Additional simulations performed with two existing wells and one new well demonstrated that distributing the pumpage more evenly will provide a slightly longer safe pumping period.

RECOMMENDATIONS

The following recommendations have been developed to provide for increasing the yield of the Croton well field.

1. The two upper wells should be taken out of service and replaced with one deep, large-diameter well located in the vicinity of Well OW-5. Water pumped from this well should be piped directly to the main distribution system instead of through the existing lines into Shallow Well 2. This recommendation is based on the following information: (1) the upper wells are highly inefficient; (2) under the current distribution system for the upper wells, pumped water is recharged back to the aquifer; (3) the geologic material encountered during the drilling of Well OW-5 appears to have excellent water-yielding properties; and (4) the modeling analysis concluded that distributing pumpage within the well field would significantly increase the volume of water that could be obtained from the aquifer over the long term.

2. When this replacement well is drilled in the vicinity of the upper wells, the boring should be extended into the bedrock. This would be a cost-effective approach to exploring the potential ground-water resources of the bedrock aquifer.

3. Consideration should be given to installing a higher capacity pump in Well 3. This well can yield significantly more water than it does with the present pump. Under high water-table conditions, such as those which existed during the test, the aquifer sustained simultaneous pumping of Well 3 and Deep Well 1 at rates of 1,328 gpm and 580 gpm,respectively. Having a total of three high-capacity production wells would permit one pump to be out of service (in case of breakdown or maintenance requirements) and still provide for sufficient yield.

4. A water-level measuring program that would monitor aquifer response to actual hydrogeologic conditions should be initiated. This program should include monitoring during dry spells to observe the effects of a low river stage on the aquifer. The water levels in production wells should be monitored to establish optimum pumping rates and operating schedules for wells

that would not draw water levels down below the tops of the well screens.

Respectfully submitted,

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