Simulation of a Valley-Fill Aquifer System to Delineate Flow Paths, Contributing Areas, and Traveltime to Wellfields in Southwestern Broome County, New York

By Stephen W. Wolcott and William F. Coon

ABSTRACT

A valley-fill aquifer system that extends along a 14-mile reach of the Susquehanna River valley in southwestern Broome County, N.Y., is a major source of water supply to local municipalities and industries, but is highly susceptible to contamination from human activities. Protection of ground-water supplies requires accurate delineation of the areas that are the sources of water pumped by wells. A previously developed two-layer steady-state ground-water flow model of the aquifer system was upgraded with an improved method of simulating stream-aquifer interactions, then recalibrated and coupled to a particle-tracking program. Three-dimensional, ground-water flow modeling coupled with particle tracking is the most reliable method of simulating ground-water flow paths in multiaquifer systems such as this; it also allows delineation of contributing areas to wellfields. A primary advantage of three-dimensional particle-tracking analysis is that it shows the complexities of the flow paths in each aquifer.

Model and particle tracking analyses indicate that groundwater frequently follows convoluted three-dimensional flow paths. The contributing areas of individual supply wells in this aquifer system each has a unique flow pattern and shape. Results of the model simulation indicate that recharge from precipitation, rivers, and tributaries contribute 35 percent, 29 percent, and 25 percent, respectively to the aquifer system and that pumpage from supply wells accounts for 67 percent of the discharge from the aquifer system. Particle-tracking results indicate that the simulated contributing areas to the 24 supply wells includes most of the valley floor.

INTRODUCTION

Ground-water contamination can adversely affect the health and economy of communities that depend on ground water for municipal and industrial use. Therefore, ground-water protection is becoming an integral part of local, state, and federal strategies for protection of public-water supplies. Congress established the Wellhead Protection Program through amendments to the Safe Drinking Water Act of 1974. Within these amendments is the requirement that each State identify the land area that contributes water to public-supply wells and enact programs to prevent contamination of ground water underlying these areas.

In this report, the term “contributing area” is used to designate the land area that contributes water to a supply well, the synonymous term “capture zone” are also commonly used. These terms should not be confused with the term “recharge area” which is generally defined as land-surface area from which an aquifer receives recharges (Barlow, 1997).

Analysis of complex multi-aquifer systems has improved greatly with the development of algorithms that track the movement of simulated ground water particles within numerical flow models. Particle tracking is a modeling technique that allows delineation of contributing areas of a well by computing the movement of water particles from the point at which they enter the flow system at land surface to a discharging well. The starting locations of particles that reach the well define the area that contributes water to that well. Numerical modeling coupled with particle tracking is an improvement over simpler analytical methods and two-dimensional flow-net analyses because it enables delineation of recharge areas in complex multi-aquifer flow systems. Although two-dimensional flow-net analysis is useful for systems with simple, two-dimensional flow, construction of a two-dimensional flow net to represent three-dimensional flow is difficult and can yield inaccurate results because it disregards vertical flow. Particle tracking provides a relatively simple, yet quantitatively powerful, alternative to flow-net analysis for delineation of contributing areas to public-supply wells and is superior to these methods for complex multiaquifer systems (Barlow, 1997).

The valley-fill aquifer system in the study area, a 14-mi reach of the Susquehanna River valley in southwestern Broome County, N.Y. (fig. 1), is the sole source of water supply to more than half the population of Broome County (Yager, 1986) but is highly susceptible to contamination from human activities (Waller and Finch, 1982). During 1981, 26.1 Mgal/d was pumped from 24 municipal and industrial wells screened in the valley-fill aquifer. The valley-fill material in the Susquehanna River and Chenango River valleys, which converge at Binghamton, is 1 to 2 miles wide and is commonly 100 to 200 ft thick but can be as much as 300 ft thick in some places (Randall, 1972). The unconsolidated materials that form the valley fill range from sand and gravel in the most productive parts of the aquifer to silt and clay in the many discontinuous confining units. The Susquehanna and Chenango Rivers and tributary streams that cross the valley fill are in direct hydraulic connection with the aquifer system in many places and, thus, can provide significant recharge to wells.

In 1989, the U.S. Geological Survey (USGS) in cooperation with the New York State Department of Environmental Conservation and the U.S. Environmental Protection Agency, began a study to delineate, by numerical particle-tracking methods, the contributing areas to the 24 municipal and industrial supply wells in the valley system for use in water-resources planning.

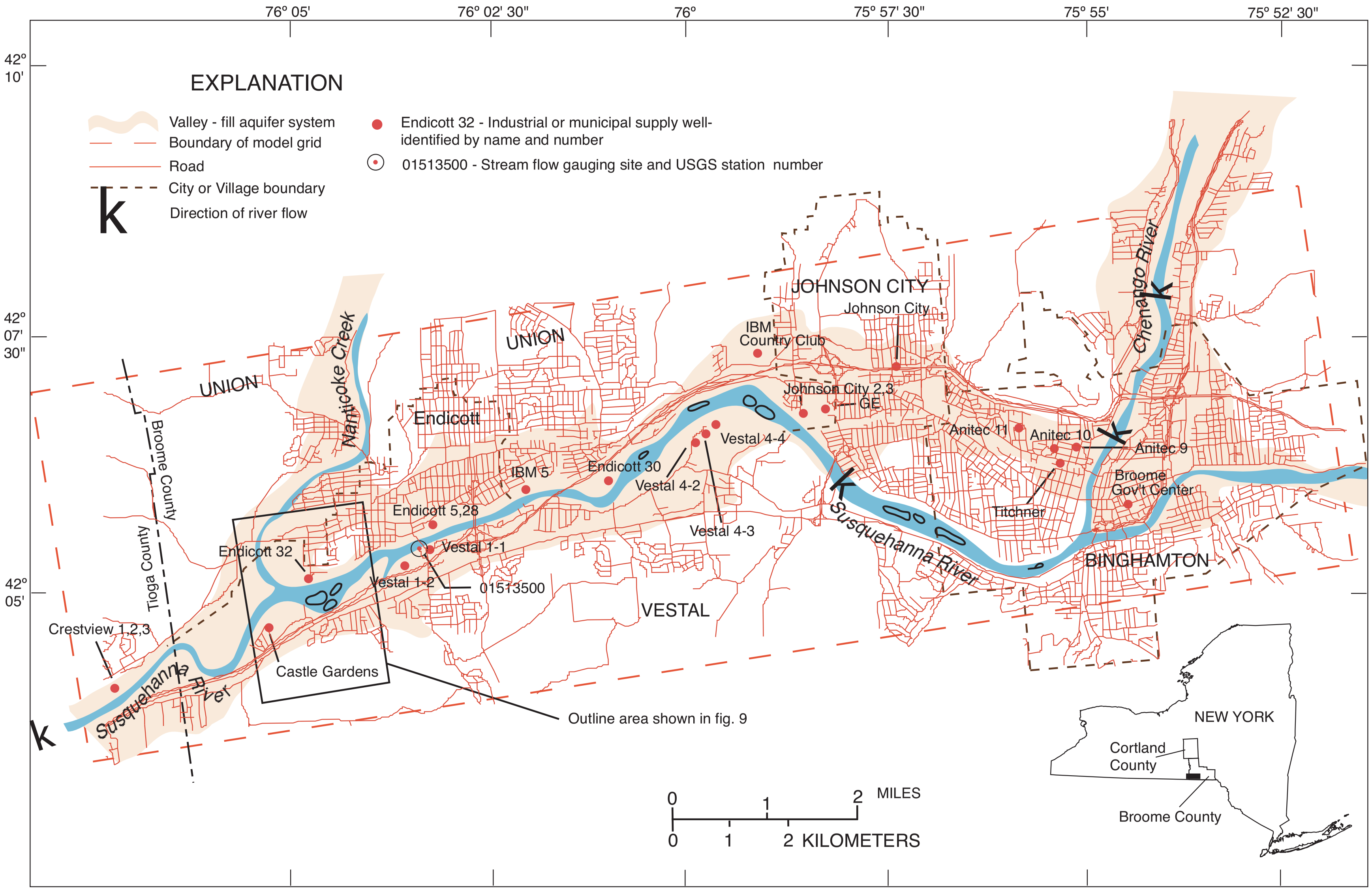
Purpose and Scope

This report describes a particle-tracking analysis of the ground-water flow system of the Susquehanna River valley. It includes (1) a brief description of the valley-fill aquifer system, (2) a discussion of the modifications to a previously documented ground-water flow model of the aquifer system; (3) an explanation of particle tracking analyses, and (4) maps delineating the simulated contributing areas and ground-water flow paths to water-supply wells as indicated by flow modeling and particle tracking.

Previous Studies

Most of the data for this study were obtained in previous investigations. Hollyday (1969) made a preliminary evaluation of the hydrogeology of the Susquehanna River basin in New York State that included an economic feasibility study for developing ground water for public supply. Holecek and others (1982) mapped in detail the surficial geology, water-infiltration potential, aquifer thickness, and potentiometric surface of the valley-fill aquifer system throughout the Endicott, Johnson City, and Binghamton area. Randall (1972) assembled records of wells and test borings and provided a detailed analysis of the aquifer system from western Binghamton to central Johnson City. Waller and Finch (1982) summarized the work of Holecek and others (1982), in the Endicott, Johnson City, and Binghamton valley-fill aquifer system and cited all pertinent references to date. MacNish and Randall (1982) developed a method for estimating the yield of stratified-drift aquifers in the Susquehanna River basin by accounting for and combining principal factors that control aquifer recharge, such as precipitation, seepage, and infiltration.

These initial studies provided much of the information needed to define the aquifer geometry and the hydrogeologic properties and processes used in two numerical ground-water flow models of the area. The first, constructed by Randall (1986) used the computer program of Trescott and Larson (1976) and represented the study area described in this report (fig. 1). The second, constructed by Yager (1986) and used the computer program of McDonald and Harbaugh (1988) and simulated ground-water flow within a 0.8 mi^2 area about 2 mi east of Randall's (1986) modeled area. Yager (1991) used this model with nonlinear regression to estimate the hydraulic conductivity of riverbed and aquifer material.



Base from US Geological Survey, 1974, 1:500,000

Figure 1. Map of study area showing locations of aquifer and ground-water flow model boundaries, major geographic features, and municipal and industrial supply wells in the Susquehanna River valley in southwestern Broome County, N.Y.

Approach

The delineation of contributing areas of municipal and industrial wells in this study consisted of two steps: (1) upgrading and recalibrating the numerical ground-water flow model developed by Randall (1986); and (2) application of particle-tracking to the simulated results.

The aquifer geometry, hydrogeologic characteristics, and development of the ground-water flow numerical model on which this study was based, are summarized in Randall (1986). In this study the model was upgraded as follows: (1) the input data to the Trescott and Larson (1976) ground-water flow model were converted into an input data set compatible with the McDonald and Harbaugh (1988) ground-water-flow model (MODFLOW) (A.L. Kontis, U.S. Geological Survey, written commun. 1989), (2) recharge wells that were used to simulate tributary stream inflow to the ground-water system were eliminated and replaced with the Stream Package of Prudic (1989), (3) constant-head nodes that were used to simulate interaction of the aquifer with the Susquehanna and Chenango Rivers were replaced through the application of the Stream Package, and (4) the original model, which displayed a systematic bias between simulated and observed heads, was recalibrated such that differences between observed and simulated heads were minimized and randomly distributed.

Contributing-area boundaries, ground-water flow paths, and traveltimes along flow paths were delineated by the numerical particle-tracking computer program MODPATH (Pollock, 1999). MODPATH is a post-processing procedure that uses the flow between model cells obtained from a MODFLOW steady-state simulation to compute and display flow paths (Pollock, 1999).

Acknowledgments

Ground-water withdrawal data, site maps, and data on pumping operations were provided by the Broome County Department of Health, International Business Machines Corp., Anitec Image Corp., and General Electric. The authors thank Allan Randall of the U.S. Geological Survey (retired) for hydrogeologic descriptions of the study area.

SIMULATED HYDROGEOLOGIC SYSTEM

The valley-fill aquifer system that was simulated in this study encompasses about 30 mi^2 along a 14-mi reach of the Susquehanna River valley (fig. 1). The primary sources of recharge to the system are direct infiltration of precipitation, induced infiltration from the Chenango and Susquehanna Rivers, and natural infiltration from tributary streams where they cross the valley floor. The primary discharges from the aquifer are the withdrawals of ground water for municipal and industrial supply and seepage to the Susquehanna and Chenango Rivers. The ground-water flow system has been documented in detail by Randall (1980) and is described briefly below.

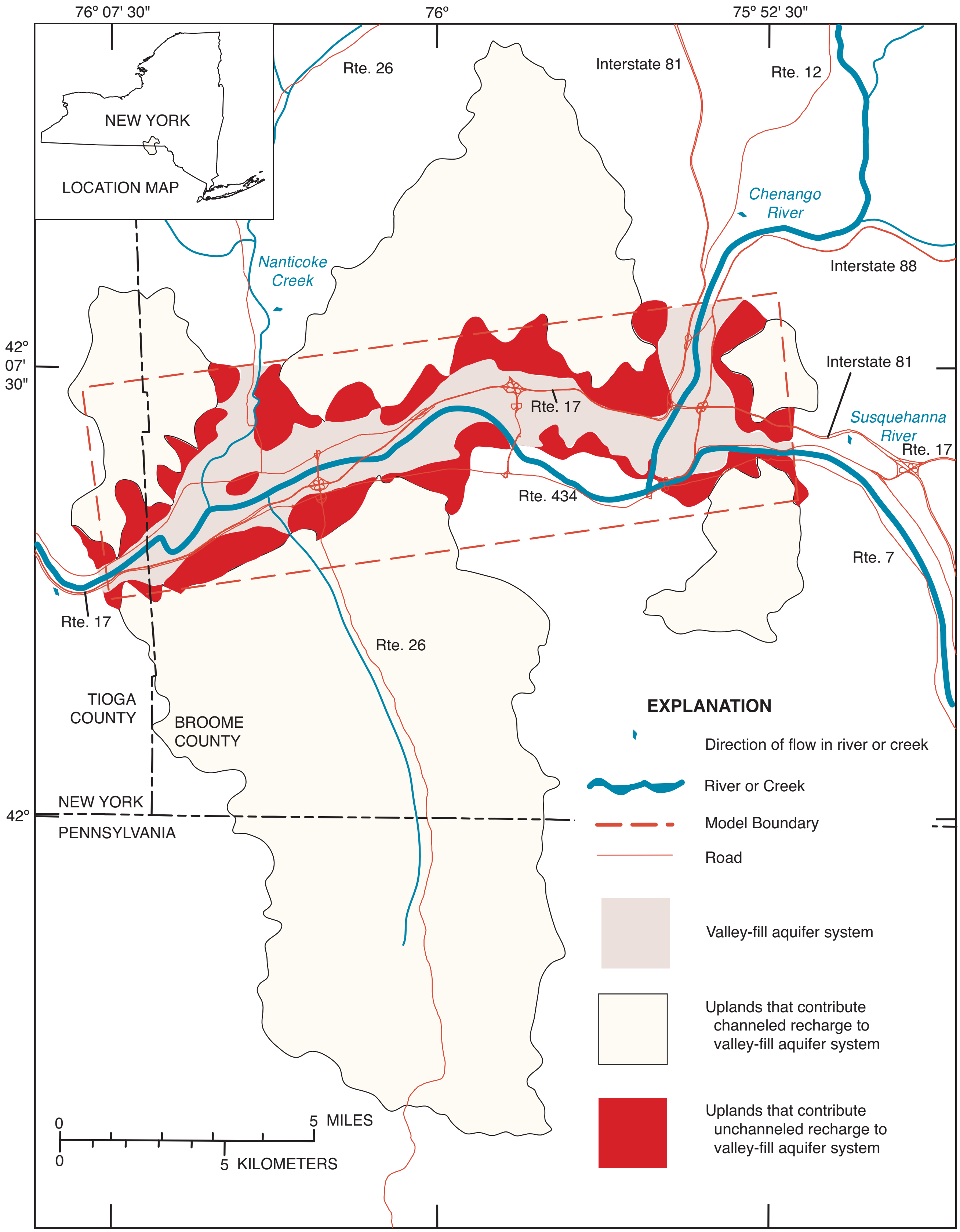
Description

The valley-fill aquifer system lies within the bedrock valleys of the Susquehanna and Chenango Rivers. The bedrock surface along the center of the valley is about 100 to 200 ft below land surface but can reach depths of 300 ft locally. The aquifer consists mostly of sand and gravel with discontinuous confining units of silt and clay, and has a wide range in horizontal and vertical hydraulic conductivity. Recharge from precipitation enters the system at the water table. Water also enters or leaves the aquifer along the course of rivers and their tributary streams. Recharge from precipitation and infiltration from streams and rivers generally moves through the aquifer toward supply wells or discharges to the Susquehanna River.

Recharge

Sources of aquifer recharge to the valley-fill aquifer system are (1) precipitation that infiltrates to the aquifer, (2) precipitation that falls on hillsides bordering the aquifer and infiltrates into the aquifer along the valley edges (unchanneled upland recharge), (3) natural infiltration from tributary streams (channeled upland recharge) and from the two rivers that cross the valley floor, and (4) induced infiltration from streams and rivers in areas near supply wells. Locations of channeled and unchanneled areas that contribute recharge to the valley-fill aquifer system are shown in figure 2.

Recharge rates applied to the valley floor as calculated by Randall (1986) are 15.5 in/yr. Unchanneled flow from hillsides is applied as recharge



Base from US Geological Survey, 1974, 1:500,000

Figure 2. Map of model area and vicinity showing channeled and unchanneled upland areas that contribute recharge to the valley-fill aquifer.

to the valley floor on upper aquifer and range from 15.5 to 155 in/yr depending on the local setting. A full description of the methods used to calculate these rates are given in Randall (1986). Infiltration rates from streams and rivers varies locally and is described further on in the section "Stream-aquifer relations".

The largest source of recharge is precipitation that directly infiltrates the valley-fill aquifer system. Precipitation in the Susquehanna River valley averages 36 in/yr, of which 21 to 24 in/yr reaches the water table (Randall, 1986). The distribution of recharge from precipitation is assumed for modeling purposes to be uniform throughout the valley. Natural infiltration from tributary streams and rivers that cross the valley floor, and induced infiltration from streams and rivers near production wells, each provide nearly as much recharge as precipitation, but the amount of natural and induced infiltration from streams and rivers varies locally and occurs only where the head in the underlying aquifer is lower than the stage in the stream or river. Induced infiltration is greatest near supply wells that are close to, and hydraulically connected to rivers (Randall, 1986).

Discharge

Ground water discharges from the aquifer to (1) municipal and industrial supply wells, (2) the Chenango and Susquehanna Rivers, (3) tributary streams that cross the valley floor, and (4) the atmosphere through ground-water evapotranspiration. Pumping constitutes by far the largest discharge from the aquifer system. Under nonpumping conditions, the largest discharge would be seepage from the aquifer to the Chenango and Susquehanna Rivers. Pumping alters the ground-water flow patterns and decreases the discharge of ground water to rivers and streams. Tributary streams that cross the valley floor generally recharge the aquifer system along their courses. Exceptions occur where they enter the Susquehanna and Chenango Rivers, where the head in the aquifer is higher than the stream stage and results in the discharge of ground water from the aquifer to the stream. Ground-water evapotranspiration is seasonally variable and may be substantial in areas with a shallow water table, but it was not simulated in this study.

Randall (1986) used average pumping rates for April 1981 for his steady-state simulation. During this period, withdrawals from the valley-fill aquifer system averaged 26.1 Mgal/d, of which 21.1 Mgal/d was withdrawn from 18 municipal wells and 5.0 Mgal/d from 7 industrial supply wells. More recent (1990) average annual withdrawal rates indicate that pumpage for municipal supply decreased to 15.1 Mgal/d, and industrial pumpage increased to 6.8 Mgal/d. The increases in industrial pumping occurred at industrial wellfields in the City of Binghamton and at eight industrial recovery and interceptor wells in the Village of Endicott. Municipal and industrial ground-water withdrawals during these periods are listed in table 1.

Hydrologic Boundaries

The upper boundary of the valley-fill aquifer system is the water table (a flux boundary) where recharge from precipitation enters the system. The Chenango and Susquehanna Rivers, as well as the tributary streams crossing the valley floor, are considered part of the upper boundary in the model because considerable exchange of water occurs between the rivers and streams and the aquifer.

The lateral boundaries of the valley-fill aquifer system are the bedrock valley walls. The largest total flux along this boundary is the inflow of unchanneled runoff from the bordering till and bedrock uplands. Minor fluxes of ground water occur as underflow where the Chenango and Susquehanna Rivers enter the model area and where the Susquehanna River exits the model area. The lateral boundaries are simulated as constant-flux boundaries.

The bottom of the simulated flow system the bedrock, which and is represented as a no-flow boundary. Bedrock crops out at or near the valley sides and ranges from 100 to 200 ft below land surface at the center of the valley, although is not necessarily deepest below the Chenango or Susquehanna Rivers; it also crops out near the confluence of Nanticoke Creek and the Susquehanna River in the center of the valley.

Hydraulic Characteristics

The valley-fill aquifer system can be considered to consist of an upper and a lower aquifer. Both consist of sand and gravel with interbedded stringers of silt and clay in some areas. The upper and lower aquifers are separated in most places by a silt and clay confining unit, but where this unit is absent the two aquifers are in direct hydraulic contact with each other. The horizontal hydraulic conductivity of the upper aquifer ranges from 10 ft/d to 225 ft/d and averages about 130 ft/d. The vertical water-transmitting capacity of the

Table 1. Municipal and industrial ground-water withdrawals during April 1981 and 1990 in the Susquehanna River valley, Broome County, N.Y.

[Well locations shown on figs. 3A and 3B. Withdrawal rates are in ft^3/s (cubic feet per second. Mgal/d, million gallons per day.]

	USGS local well no.	Location		Model layer[2]	Model cell		Withdrawal rate	
Well owner and name [1]		Latitude	Longitude		Row	Column	April 1981[3]	1990[4]
Owego; Crest View 1	TI 590	42°04' 04"	076°07' 08"	lower	55	6	0.13	0.12
Owego; Crest View 2	TI 592	42°04' 07"	076°07' 12"	lower	57	7	.04	.06
Owego; Crest View 3	TI 591	42°04' 05"	076°07' 09"	lower	56	7	.03	.06
Vestal; 1-1	BM 73	42°05' 25"	076°03' 22"	lower	38	40	1.70	----
Vestal; 1-2	BM 61	42°05' 18"	076°03' 37"	lower	40	37	.83	----
Vestal; 1-3	BM 62	42°05' 19"	076°03' 40"	lower	39	36	----	1.73
Vestal; 4-21	BM 60	42°06' 28"	075°59' 54"	lower	19	82	1.70	1.64
Vestal; 4-31	BM 86	42°06' 37"	075°59' 50"	lower	16	84	.60	.49
Vestal; 4-4	BM 196	42°06' 42"	075°59' 44"	lower	14	86	2.34	1.15
Vestal; 5-1, Castle Gardens	BM 42	42°04' 42"	076°05' 20"	lower	48	20	.05	.13
Endicott; 5	BM 89	42°05' 39"	076°03' 10"	lower	32	43	5.50	1.67
Endicott; 28, Park Well	BM 90	42°05' 40"	076°03' 07"	lower	31	44	3.40	1.58
Endicott; 30, Endwell	BM 139	42°06' 06"	076°01' 01"	upper	26	68	1.50	----
Endicott; 32, Ranney Well	BM 50	42°05' 04"	076°04' 50"	lower	43	26	8.35	8.24
Endicott; 36, Endwell	BM 136	42°06' 05"	076°01' 02"	upper	26	68	----	.23
Endicott; 37, Endwell	BM 713	42°06' 06"	076°01' 01"	upper	26	68	----	.51
Endicott; Purge Well	BM 714	42°05' 07"	076°05' 01"	upper	41	24	----	1.11
IBM; Supply Well 5	BM 133	42°06' 02"	076°02' 06"	lower	25	56	.62[5]	.75
IBM; EN 38, Recvry Well	BM 715	42°06' 26"	076°02' 47"	upper	14	49	----	.01
IBM; EN 107, Recvry Well	BM 716	42°06' 25"	076°02' 53"	upper	14	48	----	.01
IBM; EN 120, Intrcptr Well	BM 717	42°06' 12"	076°02' 49"	upper	19	48	----	.03
IBM; EN 133, Intrcptr Well	BM 718	42°06' 13"	076°03' 02"	upper	18	46	----	.22
IBM; EN 154, Intrcptr Well	BM 719	42°06' 16"	076°03' 18"	upper	16	43	----	.09
IBM; EN 160, Intrcptr Well	BM 720	42°06' 11"	076°02' 50"	upper	19	48	----	.03
IBM; EN 175, Intrcptr Well	BM 721	42°06' 11"	076°02' 34"	upper	20	50	----	.01
IBM; EN 185, Intrcptr Well	BM 722	42°06' 10"	076°02' 36"	upper	20	50	----	.03
IBM; Country Club	BM 234	42°07' 16"	075°59' 13"	upper	5	92	.44	.48
Johnson City; 2	BM 208	42°06' 46"	075°58' 42"	lower	15	97	2.40	2.52
Johnson City; 3	BM 210	42°06' 47"	075°58' 42"	lower	15	97	3.00	2.56
Johnson City; 6	BM 224	42°07' 03"	075°57' 46"	lower	11	106	----	.91
Johnson City; 7, Ballpark	BM 231	42°07' 11"	075°57' 24"	lower	9	110	2.80	1.39
General Electric	BM 533	42°06' 49"	075°58' 26"	lower	15	100	.30	.28
Anitec; 3	BM 183	42°06' 36"	075°55' 42"	lower	27	123	----	.13
Anitec; 5	BM 188	42°06' 38"	075°55' 46"	lower	26	122	----	1.89
Anitec; 7	BM 161	42°06' 29"	075°54' 51"	lower	33	135	----	1.09
Anitec; 9	BM 174	42°06' 31"	075°55' 05"	lower	31	131	1.72	----
Anitec; 10	BM 166	42°06' 30"	075°55' 18"	lower	31	128	1.22	.13
Anitec; 11	BM 192	42°06' 40"	075°55' 58"	lower	24	120	.64	1.58
Titchener	BM 147	42°06' 16"	075°55' 19"	lower	37	127	.06[5]	.04[5]
Broome Gov't Ctr; Well 23	BM 723	42°05' 50"	075°54' 44"	upper	48	136	----	.50
Broome Gov't Ctr; Well 24	BM 724	42°05' 49"	075°54' 43"	upper	48	136	----	.50
Broome Gov't Ctr; Exchange and Hawley St	BM 725	42°05' 50"	075°54' 40"	upper	48	138	1.00[5]	----

[1] Recvry, Recovery; Intrcptr, interceptor; Gov't, government; Ctr, center.

[2] System is designated as upper and lower aquifers, simulated by upper and lower model layers.

[3] April 1981 withdrawal rates were used for model simulation and total 40.37 ft^3/s (26.09 Mgal/d).

[4] 1990 withdrawal rates are provided to show current conditions and total 33.90 ft^3/s (21.91 Mgal/d).

[5] Withdrawal rate is estimated from owner's incomplete records.

confining unit (represented as leakance between layers and defined as the vertical hydraulic conductivity divided by the thickness of the confining unit) is about 0.6 (ft/d)/ft in areas where the upper and lower aquifers are in direct contact with each other, and about 2.0 x 10^{-5} (ft/d)/ft in areas where the confining layer clearly separates the upper from the lower aquifer. Transmissivity of the lower aquifer ranges from 1,000 ft^2/d at the valley sides to 40,000 ft^2/d within isolated pockets found mostly along the center of the valley, and averages about 10,000 ft^2/d. These estimates of horizontal hydraulic conductivity of the upper layer, vertical water-transmitting capacity of the confining unit, and transmissivity of the lower layer are based on the results of model simulations and aquifer tests conducted by Randall (1986).

Ground-Water Flow Patterns

Under average climatic conditions, ground water flows downgradient from recharge areas such as the valley floor, or as unchanneled runoff near the valley walls or as channeled runoff from tributary streams, moves through the aquifer discharging to production wells or to the Chenango or Susquehanna Rivers. Most of the recharge that enters the upper aquifer discharges to these two rivers in the valley; the rest moves unimpeded into the lower aquifer in areas where the confining unit is absent. Most wells that tap this aquifer system are screened in the lower aquifer; the largest discharge from this unit is from these wells. The rate at which water moves through the lower aquifer toward these wells increases with increased pumping and decreases with distance from the well.

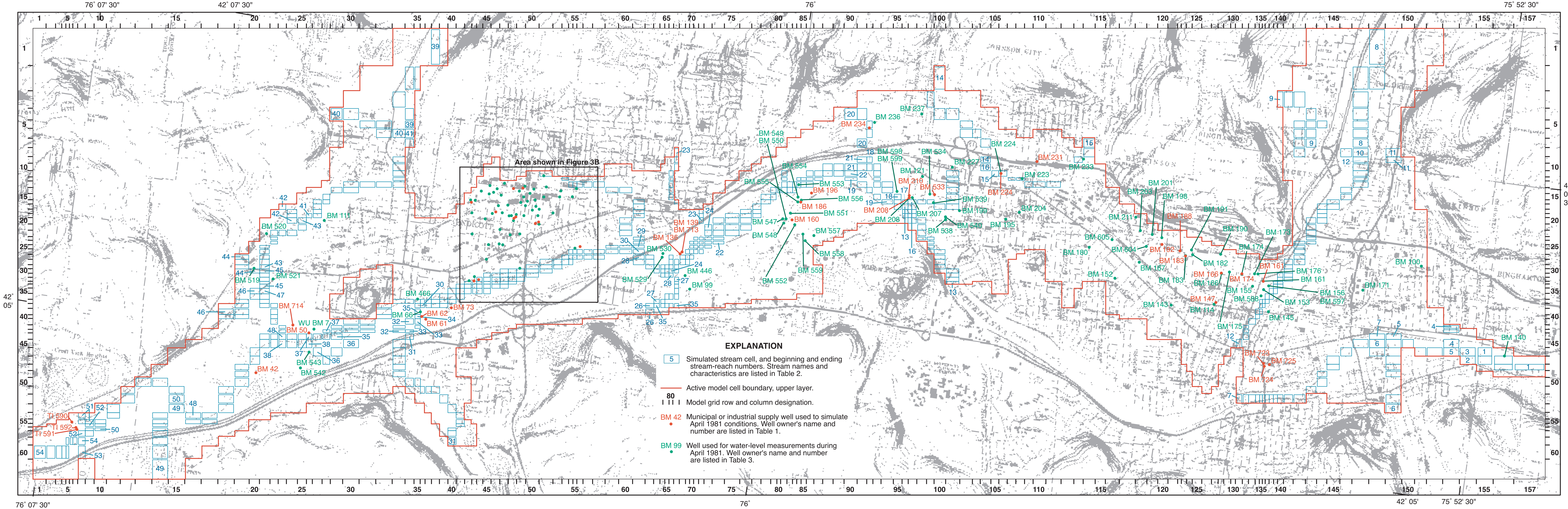
Simulation Enhancements

Enhancements to the data sets of Randall (1980) were adapted for MODFLOW by A.J. Kontis (U.S. Geological Survey, written commun., 1989) and include (1) the addition of a modular computer package (Stream Package) to improve simulation of stream-aquifer interactions (Prudic, 1989), and (2) recalibration of the model to provide random areal distribution of differences between simulated and observed heads. These enhancements are discussed below. The domain of the model grid and locations of stream nodes and supply wells are shown on figure 3A. Figure 3B is a detail of the Endicott wellfield area). A hypothetical valley-fill cross section (fig. 4) adapted from Randall (1986, fig. 6) indicates a typical geological configuration and the water-bearing units and their representation in the two-layered model.

Stream-Aquifer Relations

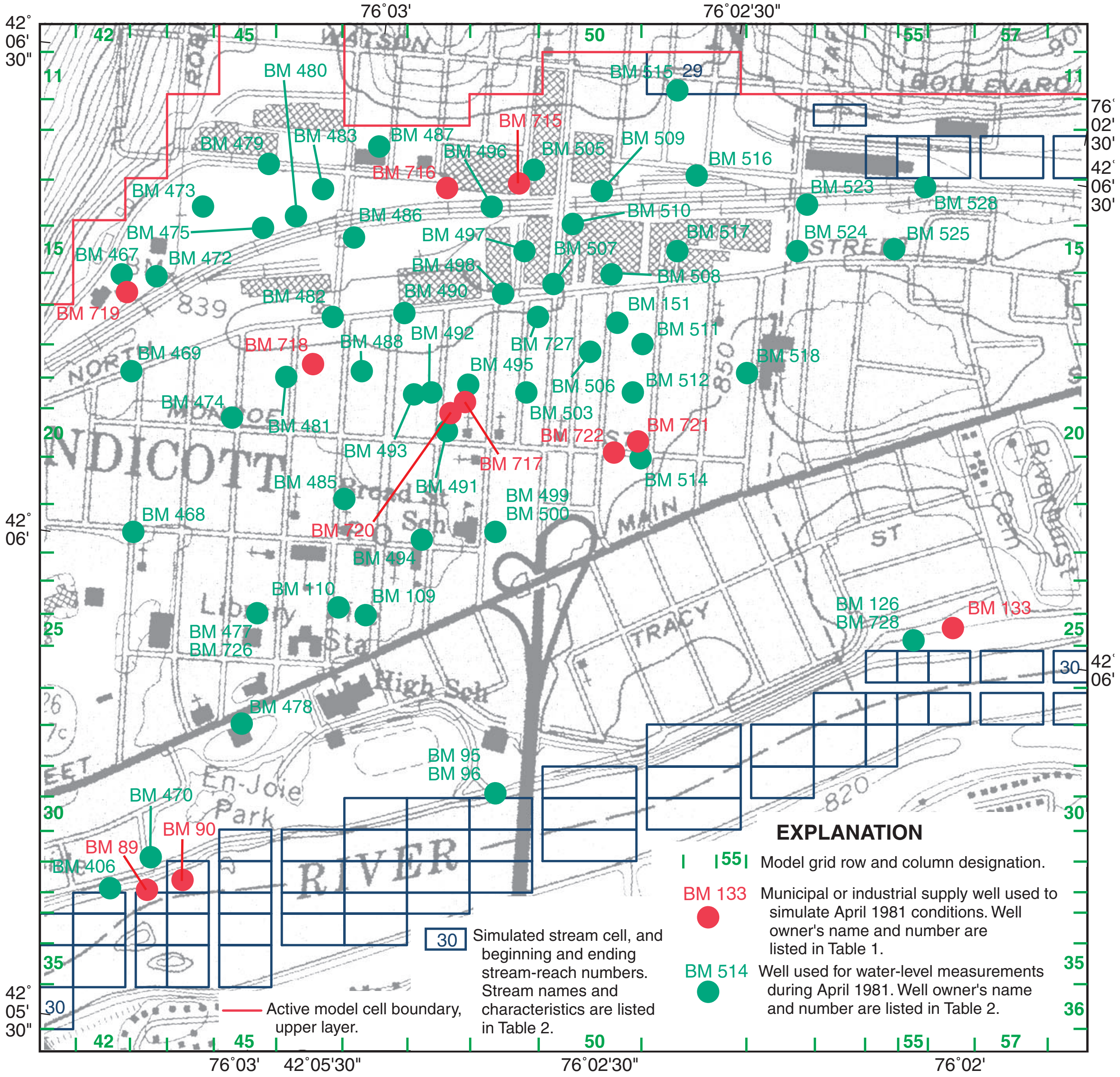
In Randall's (1986) ground-water flow model, rivers and major streams were represented by constant-head nodes and tributary streams crossing the valley floor that contribute recharge to the aquifer by infiltration where simulated as recharge wells. In the present study, simulation of stream-aquifer relations was improved by use of the Stream Package of Prudic (1989) which simulates flux between the stream and the aquifer. This flux is dependent on (1) the difference between head in the aquifer and stage in the stream or river, and (2) the hydraulic properties of the streambed. Stream discharge is specified in the upstream nodes of each stream and increases in gaining reaches and decreases in losing reaches. The maximum rate of seepage from a stream to the aquifer is equal to the discharge of the stream, and the minimum rate of seepage is zero, which occurs if the stream has gone dry. Stream nodes were placed at the locations of all streams and rivers that appear on 7.5-minute USGS quadrangle maps (fig. 3A and 3B). Stream discharge was not simulated at model cells that correspond to concrete culverts or channels that cover the streambed and thereby prevent infiltration.

Two methods were used to calculate the initial stream discharge at the upstream node where a stream or river enters the active area of the model. The initial stream discharge values for the Susquehanna and Chenango Rivers and Nanticoke Creek were calculated as the drainage area at upstream nodes, multiplied by the streamflow (per unit area) determined from the average stream discharge at the Susquehanna River at Vestal, N.Y. (station 01513500, fig. 1). The magnitude of the initial values for these rivers is not critical because the flux between the river and the aquifer is insignificant in relation to the discharge in the river. The initial discharge values for the remaining streams were calculated through a method developed by MacNish and Randall (1982), as the product of (1) the drainage area at the point where the stream enters the active part of the model grid, and (2) the average annual recharge from precipitation to surficial stratified-drift aquifers in the Susquehanna River basin as indicated in MacNish and Randall (1982, fig. 14), multiplied by (3) the average flow duration for streams draining till-covered upland areas



Base from U.S. Geological Survey, 7.5-minute topographic quadrangles, 1:24,000
Apalachin, 1969; Binghamton East, 1968; Binghamton West, 1968; Castle Creek, 1968; Chenango Forks, 1968; Endicott, 1969; Maine, 1969

Figure 3. Map showing model grid and locations of stream cells, observation wells, and supply wells in valley-fill aquifer system of the Susquehanna River valley in southwestern Broome County, N.Y.



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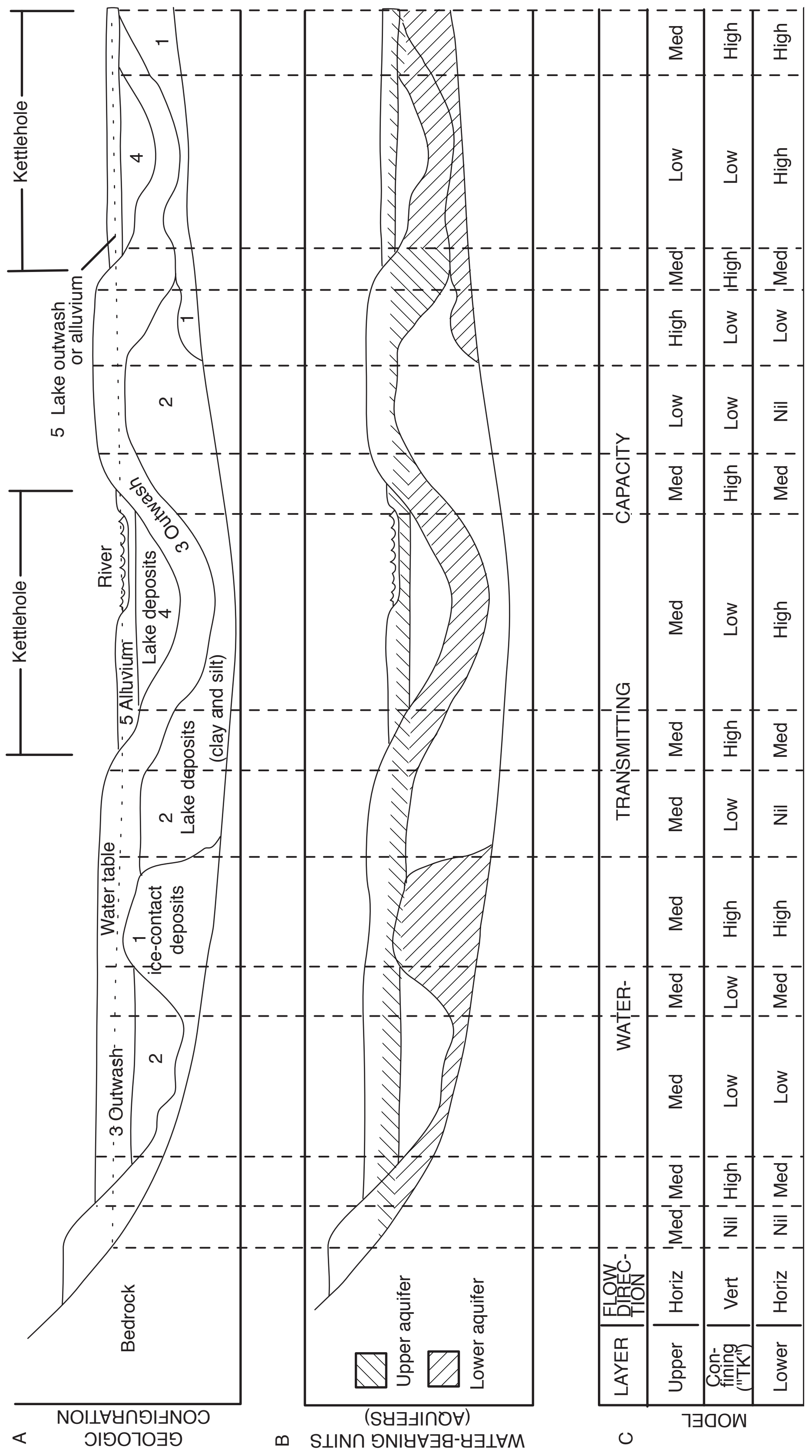


Fig. 4. A hypothetical valley-fill cross-section from Randall (1986, fig. 6) showing geologic configuration, water bearing units, and subsequent model representation

in the Susquehanna River basin, as indicated in MacNish and Randall (1982, fig. 15). The average flow duration for streams draining till-covered upland areas in the Susquehanna River basin is based on a duration of about 38 percent computed for April 1981 at the Susquehanna River at Vestal (station 01513500, figure 1). Accurate discharge values for these small tributary streams is critical because natural and induced infiltration can cause them to dry up.

A streambed is hydraulic characteristics at a particular node in the model is incorporated into a streambed-conductance term defined as the product of streambed leakance (ratio of streambed vertical hydraulic conductivity to streambed thickness) and the area of the streambed. Selection of streambed-thickness and streambed vertical hydraulic conductivity values was based on values given by Reynolds (1987) for the surficial outwash aquifer in Cortland County to the north (fig. 1 inset), and Yager (1986, 1991) in the valley-fill aquifer system of the Susquehanna River 2 mi upstream from the study area. A streambed thickness of 2.0 ft was chosen for the Susquehanna and Chenango Rivers, 1.0 ft for Nanticoke and Choconut Creek and 0.5 ft for the remaining tributary streams (fig. 3A and 3B). Streambed thickness probably is highly variable, but the available data are insufficient to quantify the variability. A streambed vertical hydraulic conductivity of 0.30 ft/d was chosen for the Susquehanna and Chenango Rivers; values for the remaining tributaries ranged from 0.50 to 2.50 ft/d. Values close to 0.50 ft/d were chosen for tributary streams in areas near the Susquehanna or Chenango Rivers to reflect the values used for these two major rivers. Most other tributaries were assigned values of 1.50 ft/d, on the basis of results from the model calibrated by Randall (1986). Estimates of river and tributary stream depth (stage) range from 10 ft for the Susquehanna and Chenango Rivers to 0.5 ft for small tributary streams. These values were based on field observations and used for calculation of head in the stream. The estimated hydrologic characteristics of simulated streams are listed in table 2; locations of stream cells and stream reaches are shown on figures 3A and 3B.

Model Recalibration

The model was calibrated to surface-water and ground-water data collected in April 1981, a period assumed to represent average steady-state conditions. Flow duration at the Susquehanna River at Vestal (station 01513500, figure 1) was 38 percent during that month. The locations and the amounts of ground water withdrawn by each well are listed in table 1. Observed water levels were compared with simulated values to assess the ability of the model to accurately represent the valley-fill aquifer system.

Randall’s (1986) data sets as converted for use with the MODFLOW ground-water model, required minor adjustments to the boundary conditions and hydraulic properties, and the addition of the Stream Package (Prudic, 1989). The bottom boundary of the upper model layer was lowered slightly and smoothed in the Endicott area, where the aquifer thins near the valley side. Other minor adjustments were made to the bottom boundaries of the upper model layer where justified by well-log data. Hydraulic conductivity in the Endicott area also was adjusted. These adjustments helped eliminate numerical instabilities in that area. Transmissivity of the lower model layer was adjusted in areas containing several production wells in accordance with data from previous aquifer tests. Most water levels that resulted from these adjustments closely matched observed water levels. Tributary stream discharges were simulated with the stream package (Purdic, 1989) described in the “Stream-aquifer relations” section.

The numerical stability of the model was found to be sensitive to the initial water levels that were used to calculate a steady-state solution. When all model parameters were adjusted numerical instabilities in the form of widely oscillating water levels were generated for various configurations of starting water levels. The widest ranges of values, which were mostly in the upper model layer, were eliminated when MODFLOW was modified such that the saturated thickness in cells of the upper layer was set to a small finite thickness (0.1 ft) whenever it decreased to zero. The resulting heads in the upper layer were then examined, and if a particular head was below the bottom of the layer, it was raised to an elevation of 1 ft above the bottom of the upper layer. Use of this set of smoothed heads as the initial heads in the conventional version of MODFLOW eliminated the numerical instability.

Improvements in steady-state solutions during model calibration were identified through a comparison of the differences between observed and simulated heads (table 3) while (1) the distribution of the differences was kept random, and (2) the overall water budget was kept consistent with Randall's

Table 2. -Estimated hydrologic characteristics used in model simulation of the Susquehanna River and its tributaries in southwestern Broome County, N.Y.

[Stream cells and model stream-reach locations are shown in figs. 3A and 3B. Trib, tributary; mi^2, square miles; ft, feet; ft^3/s cubic feet per second; ft/d, feet per day.]

Stream name	Simulated stream reach	Drainage area at first active model cell (mi^2)	Simulated discharge at first active model[1] (ft^3/s)	Depth of water in stream (ft)	Streambed thickness (ft)	Vertical hydraulic conductivity of streambed (ft/d)
Susquehanna River	1, 3, 5, 7, 13, 17, 18, 19, 21, 22, 24, 28, 30, 35, 36, 37, 38, 48, 50, 52, 54	2270	2940[2]	10.0	2.0	0.30
Unnamed trib. to Susquehanna River	2	.53	.37	.5	.5	1.50
Chamberlain Creek	4	1.17	.83	.5	.5	1.50
Pierce Creek	6	5.92	4.10	.5	.5	1.50
Chenango River	8, 10, 12	1590	[2]2060	10.0	2.0	.30
Unnamed trib. to Chenango River	9	.38	.26	.5	.5	1.50
Brandywine Creek	11	1.04	.74	.5	.5	1.50
Finch Hollow	14	3.95	2.69	.5	.5	.75
Little Choconut Creek	15, 16	12.9	8.79	.5	.5	.75
Unnamed trib. to Susquehanna River	20	.88	.60	.5	.5	1.50
Patterson Creek	23	7.09	4.74	.5	.5	1.50
Willow Run	25, 27	1.26	.86	.5	.5	1.50
Unnamed trib. to Willow Run	26	.51	.35	.5	.5	1.50
Brixius Creek	29	1.79	1.02	.5	.5	1.50
Choconut Creek	31, 32, 33, 34	56.3	38.4	2.0	1.0	1.00
Nanticoke Creek	39, 41, 43, 45, 47	101	[2]130	2.0	1.0	[3]1.00
Day Hollow Creek	40	5.99	3.89	.5	.5	1.50
Unnamed trib. to Nanticoke Creek	42	.35	.23	.5	.5	1.50
Unnamed trib. to Nanticoke Creek	44	.38	.25	.5	.5	1.50
Dead Creek	46	1.08	.70	.5	.5	.50
Tracy Creek	49	8.51	5.53	.5	.5	2.50
Unnamed trib. to Susquehanna River	51	1.05	.68	.5	.5	1.50
Unnamed trib. to Susquehanna River	53	.62	.40	.5	.5	1.50

[1] Simulated streamflow at first active model cell calculated by method described in MacNish and Randall (1982) unless otherwise stated.

[2] Simulated model streamflow at first active model cell is product of (1) drainage area and (2) streamflow per square mile as calculated from average streamflow at Susquehanna River at Vestal (station 01513500) during April 1981.

[3] Vertical streambed conductivity is 0.25 ft/d at stream cells near Susquehanna River.

(1986) ground-water flow model. The root-mean-square difference (RMS) between the simulated and observed heads was used to quantify model improvements as adjustments were made. The RMS of the calibrated model was about 3 ft in both layers. The simulated water budget for the valley-fill aquifer system of the Susquehanna River (table 4) indicates that direct infiltration of precipitation is the greatest single source of recharge and contributes 35 percent of the total recharge. Infiltration from the Susquehanna and Chenango Rivers and tributary streams crossing the valley floor contribute 29 and 25 percent, respectively. Withdrawals by supply wells have induced more infiltration than would occur under natural conditions. Unchanneled upland recharge, which occurs at the model's lateral boundaries, contributed 11 percent of the total recharge to the aquifer system.

Table 3. Observed and simulated steady-state water levels for April 7-10, 1981, in Susquehanna River valley aquifer system in southwestern Broome County, N.Y.

[Well and model-cell locations are shown in figures 3A and 3B. Water-level data from Randall (1986)

Well owner and number or name	USGS local number	Location		Model layer	Model cell		Water-level altitude		Difference (feet)
		Latitude	Longitude		Row	Column	Observed	Simulated	
Village of Endicott									
Endicott Kelly well	WUBM7	42° ˚05’06”	076˚04’47”	lower	42	26	786.78	787.89	1.11
USGS Mercerau Park	BM 466	42˚05’27”	076˚03’44”	lower	36	35	803.64	800.55	-3.09
IBM En 96	BM 467	42˚06’17”	076˚03’19”	upper	15-6	42-3	819.23	825.06	5.83
IBM En 59	BM 468	42˚06’01”	076˚03’15”	upper	22	42-3	819.48	815.15	-4.33
IBM En 95	BM 469	42˚06’11”	076˚03’17”	upper	18	43	820.71	822.01	1.30
Endicott 23	BM 470	42˚05’41”	076˚03’10”	upper	31	43	794.25	799.46	5.21
Endicott 6	BM 406	42˚05’39”	076˚03’13”	lower	32	43	758.30	757.55	-0.75
IBM En 66	BM 472	42˚06’17”	076˚03’16”	upper	15	43-4	822.12	827.77	5.65
IBM En 69	BM 473	42˚06’22”	076˚03’13”	upper	13-4	44-5	827.75	831.10	3.35
IBM En 60	BM 474	42˚06’09”	076˚03’08”	upper	19-20	45	822.29	823.78	1.49
IBM En 70	BM 475	42˚06’21”	076˚03’08”	upper	14-5	45	827.25	830.02	2.77
IBM En 61	BM 477	42˚05’57”	076˚03’04”	upper	24	45	820.89	816.07	-4.82
IBM End-1	BM 726	42˚05’57”	076˚03’04”	lower	24	45	805.69	803.89	-1.80
IBM End-3	BM 478	42˚05’50”	076˚03’04”	lower	27	45	802.12	797.32	-4.80
IBM En 71	BM 479	42˚06’25”	076˚03’08”	upper	13	45-6	828.57	831.88	3.31
IBM En 26	BM 480	42˚06’22”	076˚03’05”	upper	14	46	828.69	831.12	2.43
IBM En 94	BM 481	42˚06’12”	076˚03’04”	upper	18	46	822.30	825.29	2.99
IBM En 76	BM 482	42˚06’16”	076˚03’01”	upper	16-7	46-7	826.68	827.28	0.60
IBM En 72	BM 483	42˚06’24”	076˚03’03”	upper	13	46-7	829.09	831.78	2.69
IBM En 63	BM 110	42˚05’58”	076˚02’57”	upper	24-5	46-7	819.79	818.60	-1.19
IBM En 62	BM 485	42˚06’05”	076˚02’58”	upper	21	46-7	822.65	824.46	1.81
IBM En 74	BM 486	42˚06’21”	076˚03’00”	upper	14-5	47	829.63	830.63	1.00
IBM En 98	BM 487	42˚06’27”	076˚02’59”	upper	13	47	835.70	831.69	-4.01
IBM En 91	BM 488	42˚06’13”	076˚02’58”	upper	18	47	823.91	825.99	2.08
Endicott Motor Inn	BM 109	42˚05’58”	076˚02’55”	lower	24	47	803.95	800.39	-3.56
IBM En 24	BM 490	42˚06’17”	076˚02’55”	upper	16	47-8	827.07	828.44	1.37
IBM En 93	BM 491	42˚06’10”	076˚02’50”	upper	19-20	48	822.68	825.90	3.21
IBM En 92	BM 492	42˚06’12”	076˚02’52”	upper	18-9	48	822.98	826.32	3.34
Endicott Trust	BM 493	42˚06’12”	076˚02’53”	lower	19	48	816.31	819.42	3.11
IBM En 64	BM 494	42˚06’03”	076˚02’51”	upper	22	48	823.09	824.09	1.00
IBM En 29	BM 495	42˚06’13”	076˚02’49”	upper	18-9	48-9	823.07	826.56	3.49
IBM En 27	BM 496	42˚06’23”	076˚02’29”	upper	14	49	832.11	831.60	-0.51
IBM En 21	BM 497	42˚06’22”	076˚02’46”	upper	15	49	831.60	830.64	-0.96
IBM En 19	BM 498	42˚06’19”	076˚02’47”	upper	16	49	829.95	829.47	-0.48
IBM En 22	BM 499	42˚06’04”	076˚02’45”	upper	22	49	822.89	823.97	1.08
IBM End-2	BM 500	42˚06’04”	076˚02’45”	lower	22	49	803.87	801.81	-2.06
Endicott stable	BM 95	42˚05’48”	076˚02’42”	upper	29	49	804.50	804.44	-0.06
Endicott stable 8" TW	BM 96	42˚05’48”	076˚02’42”	lower	29	49	802.54	800.60	-1.94
IBM En 6	BM 503	42˚06’13”	076˚02’44”	upper	18-9	49-50	822.09	827.02	4.93
IBM En 77	BM 727	42˚06’18”	076˚02’44”	upper	16-7	49-50	827.68	829.07	1.39
IBM En 34	BM 505	42˚06’27”	076˚02’46”	upper	13	49-50	830.98	832.45	1.47
IBM En 78	BM 506	42˚06’16”	076˚02’39”	upper	17-8	50	827.50	828.32	0.82
IBM En 35	BM 507	42˚06’20”	076˚02’43”	upper	15-6	50	829.40	830.31	0.91
IBM En 81	BM 508	42˚06’21”	076˚02’38”	upper	15-6	50	830.01	830.31	0.30
IBM En 58	BM 509	42˚06’26”	076˚02’40”	upper	13-4	50	831.34	832.40	1.06
IBM En 32	BM 510	42˚06’24”	076˚02’42”	upper	14	50	831.64	831.99	0.35

Table 3. (continued) Observed and simulated steady-state water levels for April 7-10, 1981, in Susquehanna River valley aquifer system

Well owner and number or name	USGS local number	Location		Model layer	Model cell		Water-level altitude		Difference (feet)
		Latitude	Longitude		Row	Column	Observed	Simulated	
IBM Cafeteria	BM 511	42°06’17”	076°02’35”	lower	17	50	823.32	822.22	-1.10
IBM En 80	BM 512	42°06’14”	076°02’35”	upper	18-9	50-1	827.34	827.22	-0.12
IBM En 23	BM 151	42°06’18”	076°02’37”	upper	16-7	50-1	827.89	829.10	1.21
IBM En 79	BM 514	42°06’10”	076°02’34”	upper	20	50-1	822.97	825.87	2.90
IBM En 84	BM 515	42°06’33”	076°02’35”	upper	11	51	839.82	837.83	-1.99
IBM En 83	BM 516	42°06’28”	076°02’32”	upper	13	51	833.29	833.88	0.59
IBM En 82	BM 517	72°06’23”	076°02’33”	upper	15	51	828.63	830.45	1.82
IBM En 65	BM 518	42°06’16”	076°02’26”	upper	18	52	828.79	827.15	-1.64
Town of Union									
IBM Glendale GR 2	BM 519	42°05’31”	076°05’30”	lower	28	20	815.62	815.56	-0.06
IBM Glendale GR 4	BM 520	42°05’48”	076°05’25”	lower	21	21-2	824.78	820.58	-4.20
Rose/Batch Plant	BM 521	42°05’27”	076°05’17”	lower	31	22	805.25	806.52	1.27
Oliver Main	BM 111	42°05’58”	076°04’50”	lower	19	28	809.50	814.38	4.88
IBM En 86	BM 523	42°06’27”	076°02’23”	upper	14	52-3	833.62	831.36	-2.26
IBM En 87	BM 524	42°06’24”	076°02’23”	upper	15	52-3	829.96	828.71	-1.25
IBM En 30	BM 525	42°06’25”	076°02’15”	lower	15	54-5	829.52	826.09	-3.43
IBM Well Field 2	BM 126	42°06’01”	076°02’09”	lower	25	55	796.81	801.01	4.20
IBM Well Field 3	BM 728	42°06’01”	076°02’09”	lower	25	55	796.88	801.01	4.13
IBM En 89	BM 528	42°06’29”	076°02’13”	upper	13-4	55-6	835.26	835.31	0.05
Endicott B7	BM 529	42°06’02”	076°01’13”	lower	27	64	809.31	807.33	-1.98
Endicott B2	BM 530	42°06’04”	076°01’13”	upper	26	64-5	805.25	807.04	1.79
USGS Hill Park 6"	BM 598	42°06’48”	075°58’50”	lower	14	95	807.43	804.88	-2.55
Johnson City 1	BM 207	42°06’46”	075°58’40”	lower	15	97	799.00	794.40	-4.60
Johnson City 2	BM 208	42°06’46”	075°58’42”	lower	15	97	794.00	794.40	0.40
General Electric 2	BM 534	42°06’49”	075°58’29”	lower	15	99	808.32	805.46	-2.86
IBM Country Club 2	BM 236	42°07’19”	075°59’10”	upper	5	93	814.96	812.88	-2.08
USGS Hill Park 1"	BM 599	42°06’48”	075°58’50”	upper	14	95	812.81	810.70	-2.11
USGS	BM 121	42°06’57”	075°58’35”	upper	11	98	809.09	808.41	-0.68
Goudey Station 1	BM 538	42°06’38”	075°58’17”	upper	19-20	99	815.68	812.30	-3.38
Goudey Station 3	BM 539	42°06’45”	075°58’26”	upper	16-7	99-100	811.33	808.24	-3.09
Goudey Station 2	BM 540	42°06’39”	075°58’17”	upper	19-20	100-1	818.27	813.22	-5.05
USGS Bm 119	BM 199	42°06’43”	075°58’09”	upper	17-8	101-2	818.98	814.38	-4.60
Town of Vestal									
Castle Gardens	BM 542	42°04’47”	076°04’52”	lower	48	25	802.07	802.36	0.29
James Dittrich	BM 543	42°04’55”	076°04’48”	upper	46	26	802.10	800.89	-1.21
Vestal 1-3 (1-14)	BM 66	42°05’21”	076°03’41”	lower	39	36	803.90	800.64	-3.26
H.J. Russell	BM 446	42°05’55”	076°00’57”	lower	31	69	807.10	808.91	1.81
Vestal 4-1	BM 99	42°05’49”	076°00’53”	lower	35	70	814.96	811.36	-3.60
Monarch A	BM 547	42°06’28”	076°00’00”	upper	20	81	799.72	803.09	3.37
Monarch B	BM 548	42°06’26”	075°59’59”	upper	20-1	81	800.23	803.73	3.51
DEC TH-1	BM 549	42°06’28”	075°59’58”	lower	20	81	801.68	803.01	1.33
DEC TH-2	BM 550	42°07’27”	075°59’58”	lower	20	81	799.12	803.01	3.89
Barney Dickenson	BM 551	42°06’31”	075°59’56”	lower	18	82	799.19	799.70	0.51
USGS Prentice Rd. Is. 6"	BM 552	42°06’26”	075°59’52”	lower	20-1	83-4	799.88	802.22	2.34
USGS Prentice Rd. Is. 2.5"	BM 553	42°06’45”	075°59’53”	upper	13	84	808.40	807.66	-0.74
Vestal B-6	BM 554	42°06’39”	075°59’52”	lower	15	84	803.64	801.74	-1.90
Vestal B-3	BM 555	42°06’37”	075°59’52”	lower	16	84	794.44	797.36	2.92
Vestal B-2	BM 556	42°06’38”	075°59’50”	lower	15-6	85	796.03	799.42	3.39

Table 3. (continued) Observed and simulated steady-state water levels for April 7-10, 1981, in Susquehanna River valley aquifer system

Well owner and number or name	USGS local number	Location		Model layer	Model cell		Water-level altitude		Difference (feet)
		Latitude	Longitude		Row	Column	Observed	Simulated	
NYG&E 3	BM 557	42°06’22”	075°59’46”	upper	22	85	802.78	808.65	5.87
NYG&E 1	BM 558	42°06’19”	075°59’44”	upper	23-4	85-6	820.32	824.65	4.33
NYG&E 2	BM 559	42°06’22”	075°59’39”	upper	22-3	87	839.56	832.04	-7.52
Village of Johnson City									
USGS Bm 120	BM 237	42°07’26”	075°58’41”	upper	4	98	820.41	813.84	-6.57
Johnson City 5TH ST.	BM 227	42°07’03”	075°58’17”	lower	10	101	806.79	811.55	4.76
Johnson City 6	BM 224	42°07’03”	075°57’46”	lower	11	106	811.42	811.95	0.53
USGS Bm 118	BM 195	42°06’42”	075°57’39”	lower	20	106	823.91	820.10	-3.81
Wilson Hospital	BM 204	42°06’46”	075°57’31”	lower	18-9	107-8	822.33	819.97	-2.36
Johnson City 4	BM 223	42°07’02”	075°57’32”	lower	12	108	811.60	811.59	-0.01
City of Binghamton									
USGS Harry L. Drive	BM 233	42°07’15”	075°56’55”	upper	8-9	113-4	839.79	837.89	-1.90
USGS Bm 116	BM 180	42°06’34”	075°56’44”	upper	25-6	114	824.02	826.88	2.86
ANITEC 27T	BM 605	42°06’39”	075°56’30”	lower	24	116	822.00	823.21	1.21
USGS Bm 101	BM 152	42°06’21”	075°56’25”	upper	32	116	844.97	845.03	0.06
USGS Bm 111	BM 211	42°06’51”	075°56’17”	upper	19-20	117-8	818.54	823.82	5.28
ANITEC 24T	BM 203	42°06’45”	075°56’13”	lower	22	118	814.10	819.08	4.98
ANITEC 25T	BM 604	42°06’38”	075°56’08”	lower	25	118	812.20	819.15	6.95
Fairbanks Co.	BM 167	42°06’30”	075°56’11”	lower	28	118	816.12	820.08	3.96
ANITEC 23T	BM 201	42°06’44”	075°56’05”	lower	22	119	813.30	816.51	3.21
ANITEC 21T	BM 198	42°06’43”	075°55’59”	lower	23	120	813.40	813.69	0.29
USGS Bm 117	BM 143	42°06’12”	075°55’47”	upper	38	121	850.80	842.58	-8.22
ANITEC 3	BM 183	42°06’36”	075°55’42”	lower	27	123	812.20	814.31	2.11
ANITEC 4	BM 191	42°06’39”	075°55’39”	lower	26	124	812.00	814.15	2.15
ANITEC 2A	BM 182	42°06’37”	075°55’38”	lower	27	124	813.10	814.08	0.98
USGS Bm 114	BM 114	42°06’15”	075°55’20”	lower	37	127	813.95	815.12	1.17
USGS Bm 113	BM 190	42°06’39”	075°55’20”	upper	27	128	811.09	809.92	-1.17
ANITEC 10	BM 166	42°06’30”	075°55’18”	lower	31	128	797.30	798.53	1.23
ANITEC 6	BM 175	42°06’31”	075°55’13”	lower	31	129	810.32	805.68	-4.64
ANITEC 9	BM 174	42°06’31”	075°55’05”	lower	31	131	804.11	802.29	-1.82
ANITEC 8	BM 173	42°06’32”	075°54’57”	lower	31	133	812.42	815.84	3.42
USGS Well K	BM 155	42°06’26”	075°54’57”	lower	34	133	822.03	821.20	-0.83
USGS Bm 115	BM 176	42°06’32”	075°54’55”	lower	31	134	813.80	819.43	5.63
ANITEC 33T	BM 588	42°06’22”	075°54’51”	lower	36	134	824.07	823.77	-0.30
ANITEC 7	BM 161	42°06’29”	075°54’51”	lower	33	135	822.93	823.37	0.44
USGS Well I	BM 153	42°06’25”	075°54’50”	lower	34	135	823.28	824.13	0.85
USGS Bm 112	BM 145	42°06’15”	075°54’45”	upper	39	137	826.35	826.68	0.33
USGS Well J 6"	BM 156	42°06’27”	075°54’47”	lower	34	137	826.10	826.15	0.05
USGS Well J2 1/2”	BM 597	42°06’27”	075°54’47”	upper	34	137	825.89	826.88	0.99
USGS Bm 107	BM 171	42°06’31”	075°53’47”	lower	35	147	830.77	832.48	1.71
USGS Bm 100	BM 100	42°06’46”	075°53’12”	upper	29	151	839.45	841.11	1.66
USGS Bm 106	BM 140	42°06’09”	075°52’12”	lower	46-7	156	840.00	834.29	-5.71

[1] USGS, U.S. Geological Survey; IBM, International Business Machines; DEC, New York State Department of Environmental Conservation; NYG&E, New York Electric and Gas.

[2] Root-mean-square difference between observed and simulated water levels for nodes containing observation wells open to the upper layer is 3.09 ft, and that for nodes in the lower layer is 2.99 ft.

Pumpage is by far the largest item in the simulated water budget and represents 67 percent of the total discharge. Discharge from the aquifer to the Susquehanna and Chenango Rivers almost equals infiltration from these rivers to the aquifer and constitutes 22 percent of the total discharge. Under natural conditions (non-pumping), discharge from the aquifer to the rivers would be greater since the rivers typically act as discharge areas. Discharge from the aquifer to tributary streams crossing the valley floor represents only 10 percent of the total discharge and generally occurs near the major rivers.

Table 4. Simulated steady-state ground-water budget under average conditions of April 1981 for valley-fill aquifer system of the Susquehanna River, southwestern Broome County, N.Y.

[Mgal/d, million gallons per day; ft^3/s, cubic feet per second]

Source	Rate		Percent of total
	Mgal/d	ft^3/s	
Recharge to aquifer from:			
Direct infiltration of precipitation	13.68	21.17	35.3
Unchanneled uplands	4.32	6.68	11.1
Susquehanna and Chenango Rivers	11.05	17.09	28.5
Tributary streams	9.72	15.04	25.1
TOTAL	38.77	59.98	100.0
Discharge from aquifer to:			
Supply wells	26.09	40.37	67.3
Susquehanna and Chenango Rivers	8.62	13.34	22.3
Tributary streams	4.04	6.26	10.4
TOTAL	38.76	59.97	100.0

PARTICLE TRACKING

Delineation of the contributing areas of a supply well requires identification of the surface and subsurface areas from which water flows to that well. The common methods of delineating wellhead-protection-areas, such as use of arbitrarily fixed radii or calculated fixed radii, simplified shapes, on analytical methods (U.S.E.P.A., 1987; Risser and Maddon, 1994) cannot adequately reflect the complexities of the Susquehanna River valley aquifer system. Analytical methods do not accurately account for partial penetration of the aquifer by the stream and rivers, nor of flow through confined aquifers. Therefore, the numerical ground-water flow model modified from Randall (1986), updated with the Stream Package (Prudic, 1989) and coupled with the particle-tracking computer program MODPATH (Pollock, 1994), was used to delineate contributing areas for supply wells in the study area. In addition, the graphics capability of MODPATH was used to delineate flow paths and traveltime along the flow paths. This visual information helped to define the three-dimensional movement of ground water in this aquifer system.

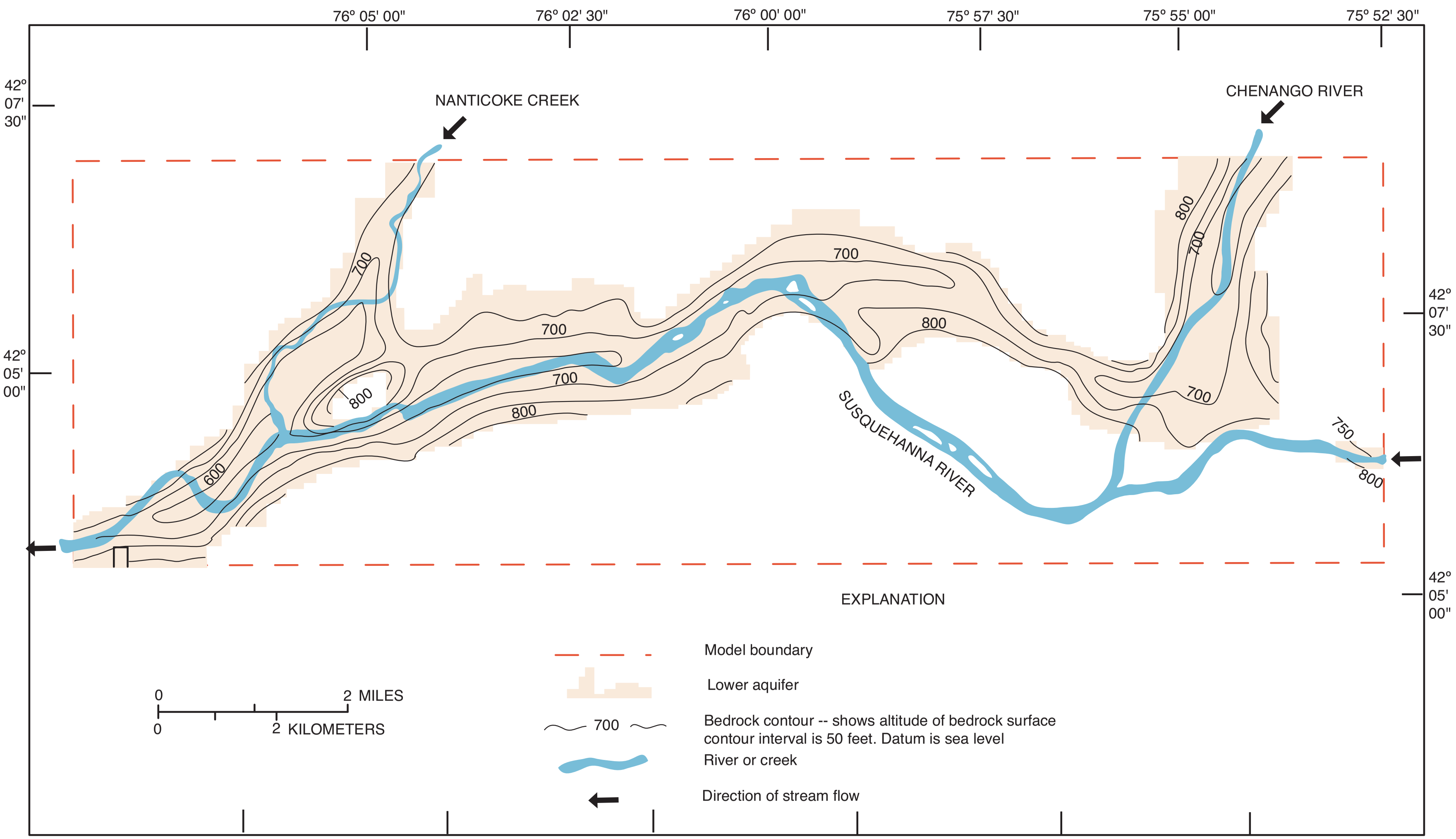
Methods

Flow paths generated by MODPATH are determined by velocity components computed from the head and intercell flow rates of the calibrated steady-state flow model. Each directional velocity component is assumed to vary linearly within each model cell. The position of a particle along a flow path can be estimated from this velocity, and its traveltime within each cell can be calculated. Starting locations of the particles can be specified, and the particles can be tracked either forward to discharge areas or backward to recharge areas.

Applying particle-tracking analysis to the steady-state ground-water model requires values for the altitude of the top and bottom of (1) the confining unit in cells in which it is present and (2) the lower model layer. These altitudes were not required for computation of ground-water levels or flows by MODFLOW because altitudes for the confining unit and lower model layer were not explicitly specified. The exchange of water from the upper to the lower model layer is controlled by the vertical hydraulic conductivity of a quasi-three-dimensional confining unit. In the lower model layer, transmissivity is specified; therefore, the altitudes of the top and bottom of the aquifer are not required. The altitude of the bottom of the lower model layer is equivalent to the bedrock surface altitude (fig. 5A) as estimated from well logs throughout the valley. The altitude of the top of the lower layer was based on well logs and the vertical hydraulic conductivity values. The confining unit was assumed to be absent in areas of high vertical hydraulic, and the altitude of the top of lower layer was equal to the bottom of the upper layer. The confining unit increases in thickness as the vertical hydraulic conductivity decreases. The thickness of the lower aquifer in the model is shown in figure 5B.

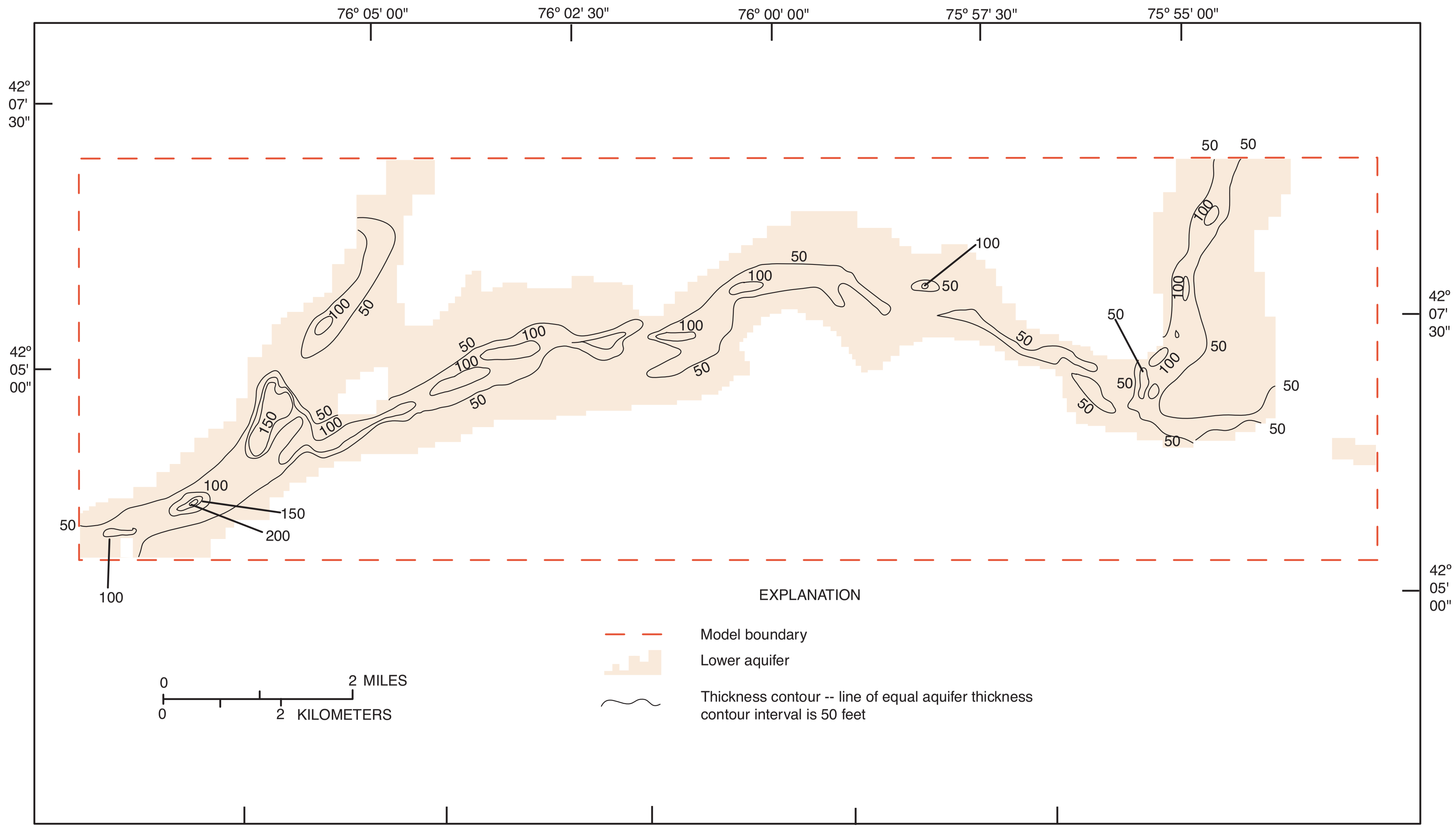
Analysis

Particle-tracking analysis of ground-water flow to each municipal and industrial supply well entailed (1) delineation of the ground-water-contributing area of



Base from US Geological Survey, 1974, 1:500,000

Figure 5A. Map of model area showing lower model layer of Bedrock-surface altitude



Base from US Geological Survey, 1974, 1:500,000

Figure 5B. Map of model area showing lower model layer of thickness of aquifer each well, (2) plotting the flow paths from areas of recharge to the supply wells, and (3) calculation of distances that particles would travel along flow paths in 3 years.

Contributing Areas

Delineation of ground-water contributing areas for the wells entailed placing an equal number of fluid particles on the upper face of each cell in the upper model layer and tracking the particles forward movement in response to the gradient toward discharge areas or wells. The contributing area of a given well is defined as the area that encompasses the starting locations of particles that travel to that well. Contributing areas for the 24 industrial and municipal supply wells within the valley-fill aquifer system of the Susquehanna River, as indicated by simulation of April 1981 steady-state conditions, are shown in figure 6.

Delineation of contributing areas required interpretation because some model cells were converted into no-flow cell by the iterative solution process and were thereby excluded from the analysis. In a MODFLOW simulation, if the head in a given cell falls below the bottom of a cell in which transmissivity is a function of saturated thickness, then flow within that cell ceases, and the cell is considered dry. Flow paths within “dry” cells cannot be computed in a MODPATH analysis. In reality, areal recharge can pass through the area represented by the cell along a vertical path to the lower model layer. In this analysis, flow in that cell became “dry” was considered to be part of the contributing area of the adjacent active cell identified in the MODPATH analysis.

The contributing areas delineated from the MODPATH analyses are affected by “weak internal sinks”, which are specified-flux or head-dependent discharge cells that do not capture all flow that passes into them because the model discretization is too coarse. Weak internal sinks in the model include some cells with supply wells and gaining streams. For example, a simulated well that pumps only a part of the water that flows into that cell would be a weak internal sink. Strong internal sinks, by contrast, capture all flow that passes into the model cell. The MODPATH analysis cannot determine whether a fluid particle that enters a cell that is specified as a weak sink will pass through the cell or will stop within the cell (Pollock, 1999).

The majority of weak sinks in the model area, were associated with river or stream cells in which the flow into a cell exceeded the flow discharged to the stream. In this situation, particles that enter the cell do not terminate at the weak stream sink, but rather pass through the cell to a nearby production well. Thus, a MODPATH analysis that uses only strong sinks will result in a minimum contributing area, whereas one that uses only weak sinks will yield a maximum contributing area. In some areas of the model, the designation of a cell as either a weak or strong sink does not greatly affect the dimensions of the contributing area (Pollock, 1999). In this study, both the maximum and minimum contributing areas (corresponding to weak and strong sinks, respectively) were delineated. The maximum contributing areas for weak sinks and minimum contributing areas for strong sinks are shown on figures 6A and 6B. The shapes of the contributing areas are irregular and are strongly affected by local hydrogeologic features and pumping rates of nearby supply wells. With either type of sink most of the valley floor to contributes flow to the 24 supply wells. In general the strong-sink option causes the Susquehanna River to alter the shape of most of the contributing areas whereas the weak sink option produces a larger total contributing area. Many of the wells with high pumping rates have extensive contributing areas that reach to the valley walls, where unchanneled upland flow recharges the system. With either option the contributing area commonly extends beyond the model boundaries into the upland area.

Flow Paths

Whereas forward particle-tracking a useful method for delineation of contributing areas, backward particle tracking can be used to delineate specific flow paths of particles that reach supply wells. Backward particle-tracking flow path analyses also help depict the system’s three-dimensional character which cannot be discerned from simulated water levels alone. Delineating the flow paths to production wells entails placing fluid particles at the faces or center of a model cell containing a production well and tracking the particles backward toward their point of origin.

The flow paths for particles placed at the industrial and municipal supply wells and tracked backward to their point of recharge are shown in figure 7 (upper model layer) and figure 8 (lower model layer). In MODPATH simulations, the movement of particles through the confining unit is assumed to be vertical. In this study, internal sinks were specified as strong sinks. The plotted flow paths in figure 7 show particles during their travel in the upper model layer. These particles have been tracked backward from a specified production well in the upper model layer or from lower model layer below to their place of origin such as the valley floor, contributing upland areas, rivers, or tributary streams. Likewise, plotted flow path in figure 8 show particles while traveling through the lower model layer. In most cases these particles have been tracked backward from a specified supply well screened in the lower model layer and appear to "end" where they enter the upper model layer, either directly or through the confining layer above. The flow paths in both model layers (figures 7 and 8) indicate that particles travel long, convoluted paths from their source of recharge to supply wells. The longest paths generally originate at valley sides where the aquifer systems receives recharge from unchanneled upland areas. Long flow paths also tend to be associated with large withdrawal rates. Particles rapidly enter the lower model layer in places where the confining layer is highly permeable or absent and travel directly to a supply well. In certain localities where the hydraulic connection between the upper and lower layers is decoupled particles in the lower model layer are able to flow in a direction opposite that of the stream or river in the upper model layer. The shortest flow paths are those where recharge originates at land surface near a well, or where the well induces infiltration from a nearby stream or river. Note that the spacing of flow paths around supply wells in figures 7 and 8 is arbitrary, and the rate of ground-water flow between any two adjacent flow paths varies. Clusters of many flow paths, therefore, does not necessarily indicate a high rate of ground-water flow.

Traveltime

MODPATH also can be used to estimate the velocity at which fluid particles travel along a defined flow path and thereby indicate the distance traveled in a given time period. Traveltimes are useful for evaluating the advective component of transport of conservative (non-reactive) constituents and, thus, can be used in the design of monitoring-well networks for aquifer protection and remediation.

The simulated flow paths of particles from wells to the in point of recharge were analyzed to obtain he distances traveled in a 3-year period. Particles were placed at the center of model cells containing supply wells and were tracked backwards for 3 years toward their source of recharge. The 3-year period was chosen because it to clearly displays the speed at which water particle travel to supply wells in this valley-fill aquifer system.

The velocity of ground-water flow is a function of flow and the porosity of the aquifer material, as given by the following equation:

$$v = \frac{Q}{An} ,$$

where v = the velocity of the particle, Q = flow and n = the porosity, and A is the area through which the flow passes (Pollock, 1989). Flow rates were calculated from the results of the recalibrated ground-water flow simulation and values of porosity were obtained from Heath (1983) and Driscoll (1986).

Distance traveled along a flow path in a given time span is inversely proportional to the porosity; therefore, particles would travel twice as far along flowpaths if the porosity of aquifer material were reduced by one-half. The sensitivity of flowpath length to differing values of effective porosity is illustrated in figures 9A and 9B which depicts the flow paths in the upper and lower model layers, respectively, for a municipal supply well, (Endicott 32, Ranney well, Bm 50, figures 1 and 3A). Set of low, medium, and high porosity values were used in each MODPATH simulation. These are listed in table 5. Differences in length of the 3-year flow paths are more pronounced in the lower layer than in the upper layer, presumably because most flow paths in the upper layer reach the major source of recharge, the Susquehanna River, within 3 years. The 3-year travel distances along flow paths to municipal and industrial supply wells as calculated from the medium porosity values (table 5), are shown in figure 7 for the upper model layer and figure 8 for the lower model layer. The shortest flow paths originate at the Susquehanna River, which provides recharge by induced infiltration and the longest originate in recharge areas at land surface or at the valley walls where unchanneled runoff from the uplands enters the aquifer system. Most flow paths are not longer than 4,000 ft. The differences among flow-path length resulting from porosity differences in the

Figure 6   is a 3-page foldout

Figure 7. is a 3-page foldout

Figure 8. is a 3-page foldout

lower layer are large enough that the 3-year travel distances shown in figures 7 and 8 should be interpreted with caution. Actual measured values of effective porosity would decrease uncertainty in the estimated travel distances.

Table 5. Ranges in porosity used in model-sensitivity analysis for unconsolidated material in valley-fill aquifer system in Susquehanna River valley, southwestern Broome County, N.Y.

[Data from Heath (1983) and Driscoll (1986). Values are in percent. Units are depicted in fig. 4.]

Model layer	Type of material	Porosity		
		Low	Medium	High
Upper	sand and gravel	20	30	40
Confining unit	silt and clay	35	45	55
Lower	sand and gravel	20	30	40

Limitations

Particle tracking is only as accurate as the ground-water flow model to which it is coupled. The model used in this study is an approximation of a complex aquifer system. The weak- or strong-internal sink question that results from the model discretization introduces ambiguity into the particle-tracking analysis. Furthermore, contributing-area analyses indicate that much of the recharge that enters at the valley sides originates from the uplands, but the flow paths within the uplands are unknown because they are beyond the model boundaries. The supply-well-pumpage values used for delineation of contributing areas for this study area are based on April 1981 rates which do not represent current (1999) pumping rates. Therefore, caution should be used when applying the results of this study to current conditions. Despite these limitations, particle tracking is an effective means of delineating contributing areas and flow paths to wells, and of estimating the travel times along flow paths.

SUMMARY

A previously developed numerical steady-state ground-water flow model of a 14-mi reach of the Susquehanna River valley that contains 24 supply wells in southwestern Broome County, N.Y., was converted into a MODFLOW data set and was upgraded with the Stream Package of Prudic (1989) and recalibrated. The resulting model output was then coupled to the MODPATH particle-tracking routine to delineate (1) ground-water contributing areas, (2) particle flow paths, and (3) distances traveled along those flow paths in 3 years. Delineation of the contributing areas entailed placing particles on the upper face of all upper model layer cells and tracking them forward, and plotting the points of origin of those particles that discharge to municipal and industrial supply wells. Flow paths were delineation entailed placing particles at the center of model cells containing a pumping well and tracking the particles backward to their source. The 3-year travel distance of particles along flow paths ending at production wells, based on medium porosity values obtained from the literature, did not exceed 4,000 ft.

Results of this investigation indicate that simulated flow paths to the 24 supply wells within the valley-fill aquifer system are three dimensional, and that the contributing areas to these wells together include most of the valley floor. The techniques used in this study enabled delineation of ground water flow paths that could not be predicted by conventional analytical methods.

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