Simulation of Ground-Water Flow and Areas Contributing Recharge to Extraction Wells at the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Clinton County, Pennsylvania

By Curtis L. Schreffler

In cooperation with the U.S. Environmental Protection Agency

Scientific Investigations Report 2006-5167

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

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Suggested citation:

Schreffler, C.L., 2006, Simulation of ground-water flow and areas contributing recharge to extraction wells at the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Clinton County, Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2006-5167, 45 p.

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Conversion Factors and Datum

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Mass		
ton, short (2,000 lb)	0.9072	megagram (Mg)
Flow rate		
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Vertical coordinate information is referenced to the National Geodectic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Abstract

Extensive remediation of the Drake Chemical Superfund Site has been ongoing since 1983. Contaminated soils were excavated and incinerated on site between 1996 and 1999. After 1999, remedial efforts focused on contaminated ground water. A ground-water remediation system was started in November 2000. The source area of the contaminated ground water was assumed to be the zone 1 area on the Drake Chemical site. The remedial system was designed to capture ground water migrating from zone 1. Also, the remediation system was designed to pump and treat the water in an anoxic environment and re-infiltrate the treated water underground through an infiltration gallery that is hydrologically downgradient of the extraction wells. A numerical ground-water flow model of the surrounding region was constructed to simulate the areas contributing recharge to remedial extraction wells installed on the Drake Chemical site. The three-dimensional numerical flow model was calibrated using the parameter-estimation process in MODFLOW-2000. The model included three layers that represented three poorly sorted alluvial sediment units that were characterized from geologic well and boring logs.

Steady-state ground-water flow was simulated to estimate the areas contributing recharge to three extraction wells for three different pumping scenarios—all wells pumping at 2 gallons per minute, at approximately 5 gallons per minute, and at 8 gallons per minute. Simulation results showed the contributing areas to the three extraction wells encompassed 92 percent of zone 1 at a pumping rate of approximately 5 gallons per minute. The contributing areas did not include a very small area in the southwestern part of zone 1 when the three extraction wells were pumped at approximately 5 gallons per minute. Pumping from a fourth extraction well in that area was discontinued early in the operation of the remediation system because the ground water in that area met performance standards. The areas contributing recharge to the three extraction wells did encompass zone 1 at a pumping rate of 8 gallons per minute. At pumping rates of 2 gallons per minute, the contributing areas for the three extraction wells did not encompass zone 1.

Introduction

The Drake Chemical Superfund Site includes approximately 8 acres in the City of Lock Haven and Castanea Township, Clinton County, Pa. (fig. 1). The Drake Chemical plant, where ingredients for dye intermediates, pesticides, and other compounds were manufactured, operated on site from 1962 to 1981. As a result of activities at the plant, surficial soils and underlying unconsolidated material as well as ground water were contaminated. The U.S. Environmental Protection Agency (USEPA) began emergency removal work at the site in 1982. The site was listed on the National Priorities List (NPL) on September 8, 1983. From the spring of 1996 to the spring of 1999, more than 295,000 tons of contaminated soil were excavated and processed through an on-site incinerator. Following the completion of the soil treatment, a ground-water remediation system was constructed and began operating in November 2000. The remediation system pumped and treated the contaminated ground water in an anoxic environment. The treated water was re-infiltrated underground through an infiltration gallery that was hydrologically downgradient of the Drake Chemical site extraction wells. The USEPA requested the assistance of the U.S. Geological Survey (USGS) to determine the areas contributing recharge, herein referred to as contributing areas, to the remedial extraction wells that were designed to capture ground water migrating from zone 1 on the Drake Chemical site (fig. 2). Zone 1 was assumed to be the source area of the ground-water contamination. The extraction wells were in zone 2 and the infiltration gallery was in zone 3 (fig. 2).

The American Color and Chemical (ACC) property (fig. 2), a Resource Conservation Recovery Act (RCRA) site, is adjacent to the Drake Chemical site. Remediation of contaminated ground water at the ACC property began approximately at the same time as the Drake Chemical remediation project. The RCRA and Superfund Programs of the USEPA are working together on the ground-water remediation systems on both sites. Therefore, ACC remedial activities are included in this investigation.

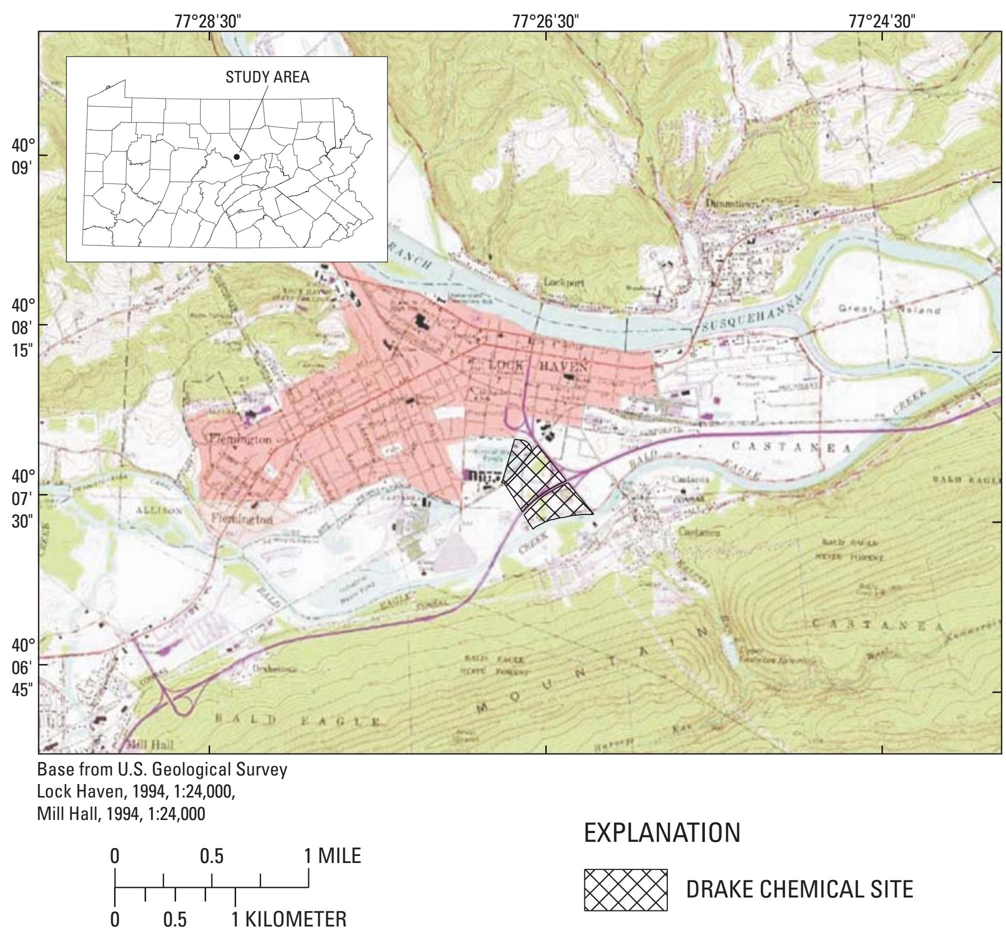

Figure 1. Location of Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

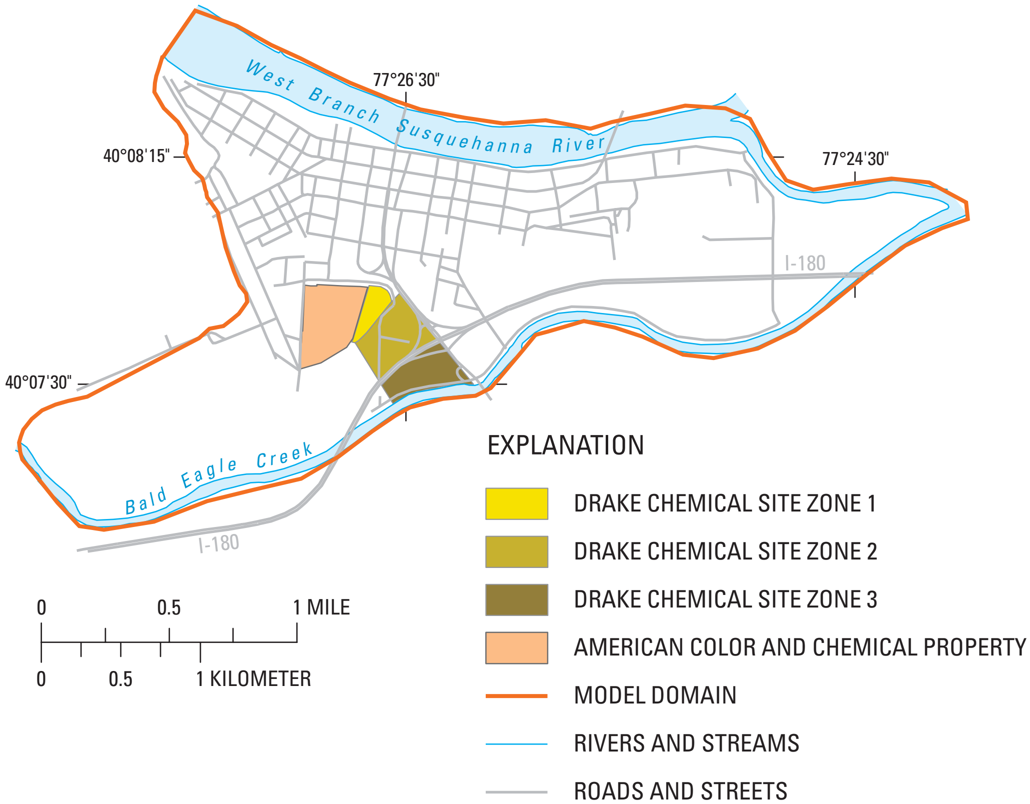

Figure 2. Location of zones 1, 2, and 3 at the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

Purpose and Scope

This report describes the construction of a numerical ground-water flow model that was used to simulate regional ground-water flow in the unconsolidated alluvial materials in the vicinity of Lock Haven, Pa. The focus of the modeling efforts was on an area including the Drake Chemical site and the ACC property (fig. 2). Steady-state model simulations were run with constant input parameters except for varying pumping rates for three extraction wells on the Drake Chemical site. The report presents plan-view contributing areas to three extraction wells under three different pumping rate scenarios and an evaluation is presented to determine if the resulting contributing areas are capturing ground water migrating from zone 1 on the Drake Chemical site.

Modeled Area

The modeled area covers approximately 3.2 mi^2 in the vicinity of Lock Haven in southern Clinton County, Pa. The modeled area extends westward to the borough of Flemington and eastward to the confluence of the West Branch Susquehanna River and Bald Eagle Creek. The northern extent of the modeled area is the West Branch Susquehanna River and the southern extent is the Bald Eagle Creek.

Previous Investigations

Lohman (1938) described the geology and ground-water resources in south-central Pennsylvania. Peltier (1949) mapped the pleistocene terraces of the Susquehanna River in Pennsylvania. Taylor and others (1983) characterized the ground-water resources of the West Branch Susquehanna River Basin. Taylor (1977) characterized the geology and mineral resources of the Lock Haven Quadrangle, Clinton and Lycoming Counties, Pa. Numerous site investigations and characterizations have been done at the Drake Chemical site and at the adjacent ACC property by consulting firms.

Geology

Unconsolidated Quaternary-age alluvial sediments underlie the study area. These sediments consist of silts, clays, sands, gravels, and cobbles. The sediments range from poorly to well-sorted strata. The alluvial sediments near the extraction wells drilled on the Drake Chemical site were poorly sorted. The unconsolidated sediments are underlain by Lower Devonian- and Upper Silurian-age shaly limestones, sandstones, and shales. The bedrock units were assumed to not substantially contribute to the ground-water system and were not represented in the model.

Simulation of Ground-Water Flow

A three-dimensional finite difference numerical model of the Drake Chemical site was constructed to simulate areas contributing recharge to three on-site extraction wells. The MODFLOW-2000 code (Harbaugh and others, 2000) was used to simulate regional steady-state ground-water flow. Post-processing of ground-water flow results was done to estimate the contributing areas. Results of the steady-state model simulations represent conditions that do not change through time and represent a steady-state ground-water system that has reached equilibrium, the inputs and outputs of ground water in the system are equal. Steady-state conditions could be used to effectively simulate ground-water flow because the interquartile ranges in water levels in three monitor wells in which continuous measurements were collected were less than 2 ft. The 25-percentile, mean, and 75-percentile daily depth below land surface water level in monitor well Cn-398 were 9.17, 9.97, and 11.01 ft, respectively, for the period of record December 13, 2001, to September 30, 2005 (appendix 1). The 25-percentile, mean, and 75-percentile daily depth below land surface water levels in monitor well Cn-399 were 9.38, 10.16, and 11.09 ft, respectively, for the period of record December 13, 2001, to September 30, 2005 (appendix 1). The 25-percentile, mean, and 75-percentile daily depth below land surface water levels in monitor well Cn-419 were 9.32, 10.07, and 11.07 ft, respectively, for the period of record December 13, 2001, to September 30, 2005 (appendix 1). The simulations showed average conditions over a long period of time. Thus, the resulting contributing areas are representative of the climatic and hydrologic conditions, particularly areal recharge, river and creek stages, and pumping rates, used for the simulations. Contributing areas would have different shapes and sizes under different climatic or hydrologic conditions, for example during wet or drought periods or during periods when river and creek stages are higher or lower than the stages used in the simulations.

The model was constructed on the basis of relevant geologic information in order to represent the geologic conditions that control the rate and direction of ground-water flow. Boundary conditions, such as rivers and streams, were selected to best represent local hydrologic influences on the ground-water system. The model was calibrated using the nonlinear parameter-estimation program, which is a part of MODFLOW-2000 (Hill and others, 2000). MODPATH (Pollock, 1994), a particle-tracking module linked to MODFLOW, was used to calculate and display contributing areas to the extraction wells.

Model Design, Layers, and Boundary Conditions

A MODFLOW-2000 model was constructed using a grid of 144 rows and 182 columns. The grid was aligned at an angle that minimized the number of inactive model cells for the irregularly shaped study domain (fig. 3). In the vicinity of the Drake Chemical site, the spatial discretization per grid cell was 30 ft. The spatial discretization was increased outward from the Drake Chemical site to 45, 67.5, and 100 ft to a maximum cell size of 200 ft per grid cell.

The model was vertically discretized into three layers. The layers are a three-dimensional representation of the hydrogeologic units of the study area. The ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity of all layers was 1. The system was modeled as an isotropic system with respect to hydraulic conductivity of the different layers. Layer 1 was modeled as an unconfined layer; layers 2 and 3 were modeled as confined. The area is near the confluence of two major surface-water systems, the West Branch Susquehanna River and the Bald Eagle Creek. These streams were used as model boundaries. The altitude and configuration of the hydraulic heads at the site prior to the implementation of the remedial extraction system was the initial starting hydraulic-head condition.

Model Layers

Geologic logs from monitor wells and borings from environmental-consultant reports and USGS references were compiled and evaluated to determine the vertical discretization for the model. Twenty geologic well and boring logs from the Drake Chemical site, 36 geologic well and boring logs from the surrounding area, and 2 borings from nearby highway-bridge sites were used in the evaluation (fig. 4). The geologic and boring logs were entered into a spatially related stratigraphic contouring software package and unit thickness or isopach maps were generated for the three model layers. The density of the data points in the vicinity of the Drake Chemical site, which was the most important area in the model to characterize, was sufficient to define the complexity of the alluvial system. Conversely, the extrapolation of lithologic data from the Drake Chemical site to the remaining area of the model had greater uncertainty in the characterization of lithology but had lessor importance to the modeling objective. However, it is recognized that the lack of lithologic data outside the Drake Chemical site area is a weakness of this model.

Geologic and boring logs were interpreted on the basis of the descriptions provided by the well or boring logger. The uppermost layer (layer 1) was considered to consist of silts, clays, and fill materials. The middle layer (layer 2) was considered to consist of sands and silts. The bottom layer (layer 3) was considered to consist of sands, gravels, and cobbles. The generated isopach maps were used as input to the model.

Altitudes for the top and bottom of the three layers generated from the isopach maps were obtained using the pre-pro-

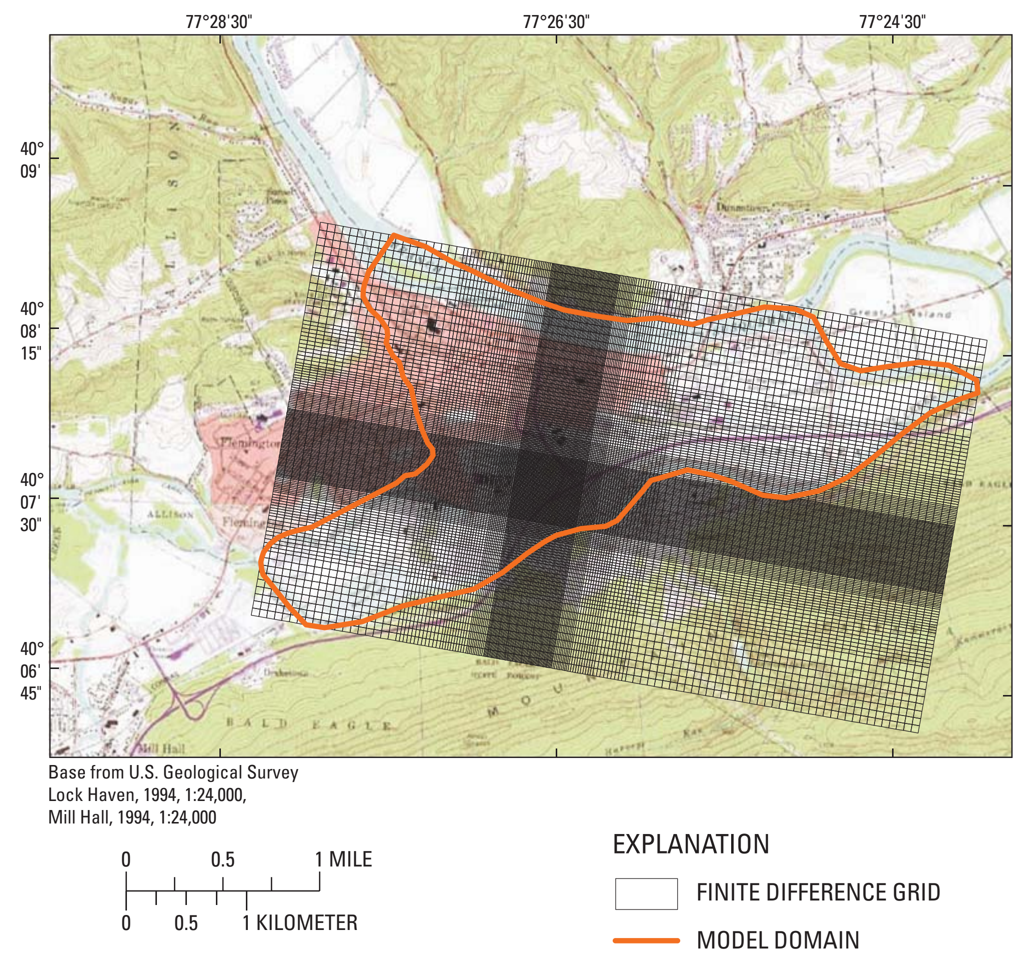

Figure 3. Finite difference grid and model domain of the ground-water flow model for the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

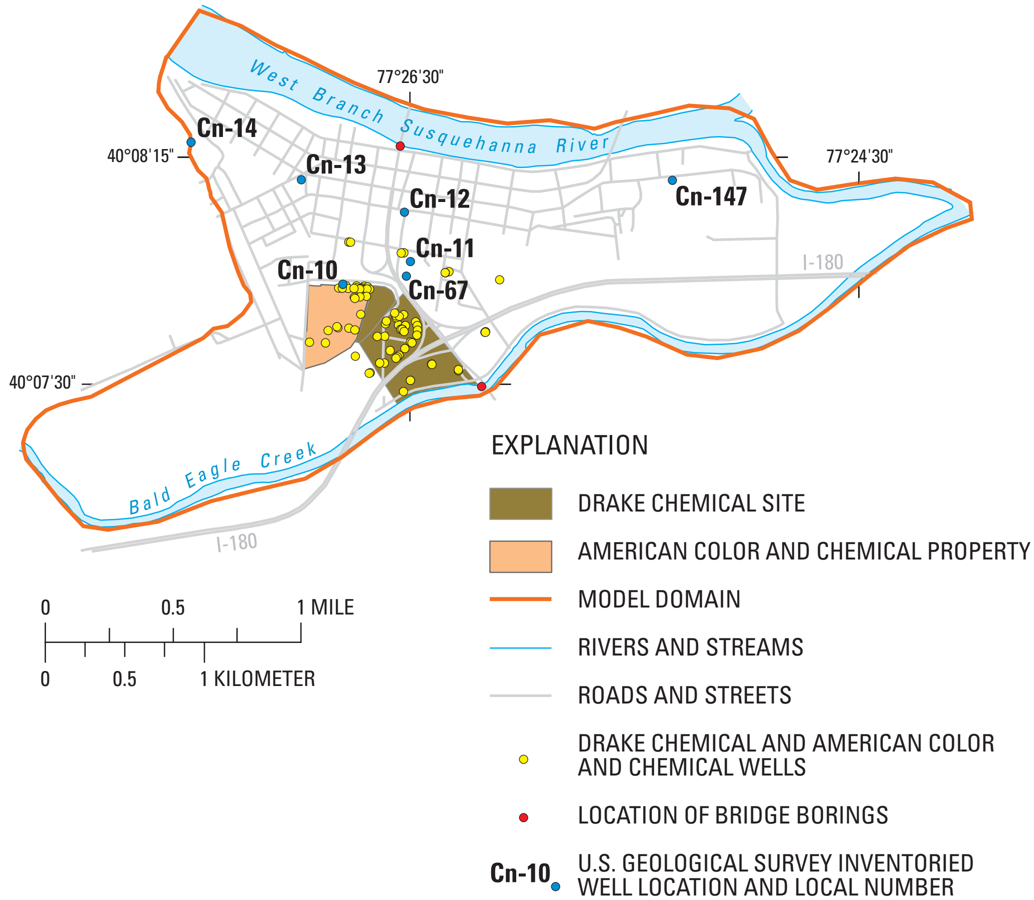

Figure 4. Locations of geologic well and boring logs used to construct thickness maps in the vicinity of the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

cessing software package Argus ONE (Argus Interware, Inc., 1997). The top of the model or land surface was compiled from environmental consultant planimetric surveys of the Drake Chemical site, the ACC property, and the surrounding area. Topographic contours from USGS Lock Haven and Mill Hall 1:24,000 quadrangle maps were joined to the site-specific data to complete the land-surface elevations for the entire modeled area.

Subtracting unit thickness, determined from the isopach map, from land surface yielded estimated structure contours of the bottom of layer 1. For example, the altitude of the top of layer 1 was the land surface and the altitude of the bottom of layer 1 was the thickness of layer 1 subtracted from the land-surface altitude. The altitude of the bottom of layer 1 also was assigned to be the altitude of the top of layer 2. Subtracting the thickness of layer 2, generated from the isopach maps, from the altitude of the top of layer 2 yielded the altitude of the bottom of layer 2. The altitude of the top of layer 3 was the altitude of the bottom of layer 2, and subtracting the thickness of layer 3 yielded the altitude of the bottom of layer 3.

Layer 1, the silt unit, consisted of silt, clay, fill materials, and re-worked soil. The thickness of this unit in the vicinity of the Drake Chemical site ranged from 4 to 12 ft with a local lense of 18 ft thick just west of the site (fig. 5). Layer 2, the sand unit, consisted of sand, silt, and some gravel. The thickness of this unit in the vicinity of the Drake Chemical site ranged from 8 to 16 ft thick; the thickest part of the unit was south of the Drake Chemical site (fig. 6).

Layer 3, the gravel unit, consisted of cobbles, gravels, sands, and silts. The thickness of this unit in the vicinity of the Drake Chemical site ranged from 4 to 24 ft thick (fig. 7). In the western part of the modeled area, the gravel unit lies directly on top of bedrock, but in the northern part of the Drake Chemical site and farther north toward the Susquehanna River in the model domain, the unconsolidated alluvial material thickened to approximately 100 ft below the land surface in a buried valley. Geologic data concerning the composition of the alluvial deposits north of the Drake Chemical site were sparse, and because of the lack of descriptive data, the make up and extent of the buried valley was not well defined. Because the extraction wells were drilled to bedrock on the Drake Chemical site (approximately 40 ft below land surface), any deeper unconsolidated aquifers in the buried valley to the north towards the Susquehanna River were not included in the model construction. Also, ground-water contributions from bedrock aquifers below layer 3 were assumed to be insignificant and were not modeled.

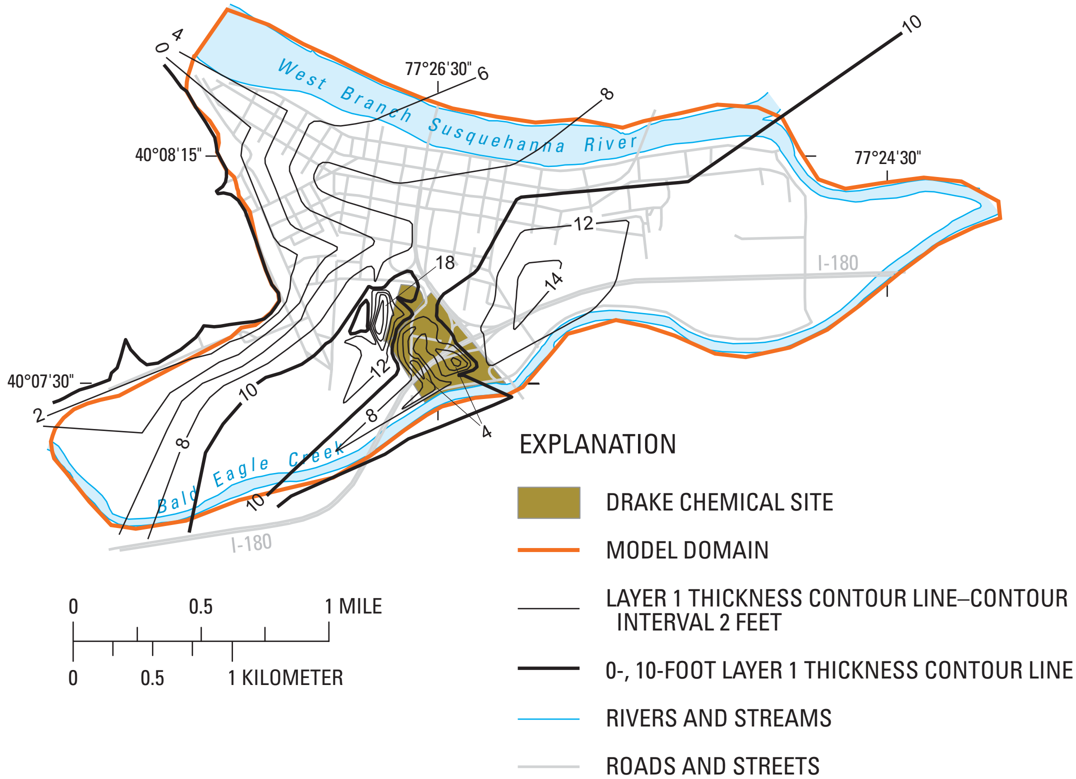

Figure 5. Thickness contours of the silt layer (layer 1) used in the ground-water flow model for the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

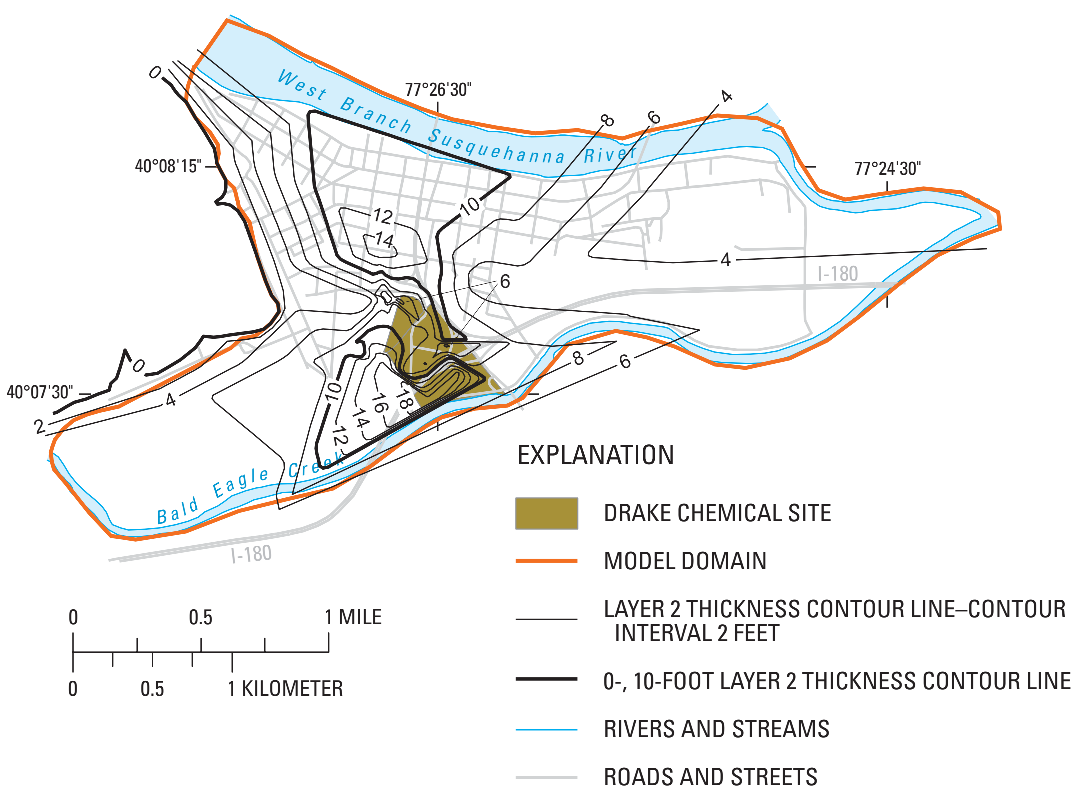

Figure 6. Thickness contours of the sand layer (layer 2) used in the ground-water flow model for the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

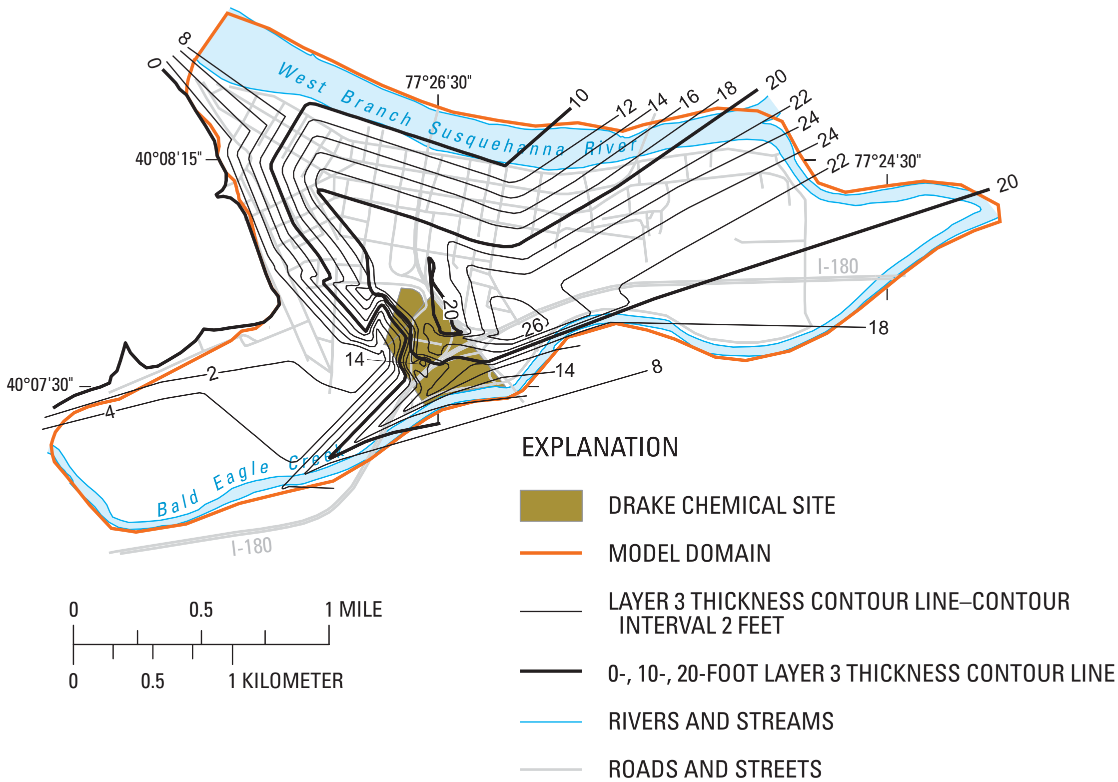

Figure 7. Thickness contours of the gravel layer (layer 3) used in the ground-water flow model for the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

Locations of north-south and west-east trending cross sections from the model are shown on figure 8.

Model Boundaries

The northern boundary of the model is the West Branch Susquehanna River. The southern boundary of the model is the Bald Eagle Creek. The eastern boundary of the model is the confluence of the Bald Eagle Creek and the West Branch Susquehanna River. These boundaries were simulated in MODFLOW using the river package (fig. 9). The bottom elevations of these two rivers were sloped on a gradient from west to east in the direction of flow. The bottom elevation of the West Branch Susquehanna River in the western part of the model was 537 ft above NGVD 29. The bottom of the river was sloped to the southeast to the confluence of Bald Eagle Creek where the bottom elevation of the riverbed was 532 ft above NGVD 29. The bottom elevation of the Bald Eagle Creek in the western part of the model was 540 ft above NGVD 29. The bottom of the Bald Eagle Creek was sloped to the east to the confluence with the West Branch where the bottom elevation of the riverbed was 532 ft above NGVD 29. The stage of the Susquehanna River was estimated using the stage measured at the USGS streamflow-gaging station (01545800) West Branch Susquehanna River at Lock Haven, Pa., and the stage of the Bald Eagle Creek was estimated using the stage of USGS streamflow-gaging station (01548005) Bald Eagle Creek near Beech Creek Station, Pa. The streamflow-gaging station on the West Branch of the Susquehanna River is in the model domain and the streamflow-gaging station on Bald Eagle Creek is approximately 5 mi to the west of the model domain. The riverbed conductance of the West Branch Susquehanna River was set to 1.0×10^{-4} and the riverbed conductance of the Bald Eagle Creek was set to 7.5×10^{-5}. The riverbed-conductance values were arbitrarily set and were not measured.

The western boundary was set to the extent of the alluvial sediment deposits as mapped by Taylor (1977). A general-head boundary, with a constant head of 580.5 ft and a conductance of 2.87×10^{-5}, was used in the western part of the model domain (fig. 9). The general-head boundary was assigned to layer 3. The western boundary for layers 1 and 2 was a no-flow boundary. The general-head boundary conductance was an arbitrary value that was not measured. The underlying bedrock was assumed to not substantially contribute to the alluvial ground-water system and was not simulated. Therefore, the bottom of layer 3 was a no-flow boundary.

A horizontal-flow barrier was included in the model in the location of zone 1 on the Drake Chemical site (fig. 9). The horizontal-flow barrier represented a sheet pile driven to the top of bedrock in this vicinity (R. Schrock, U.S. Environmental Protection Agency, oral commun., 2001). Minimal data on the hydraulic effect the sheet pile had on water movement were available, but the sheet pile was not installed as a hydraulic bar-

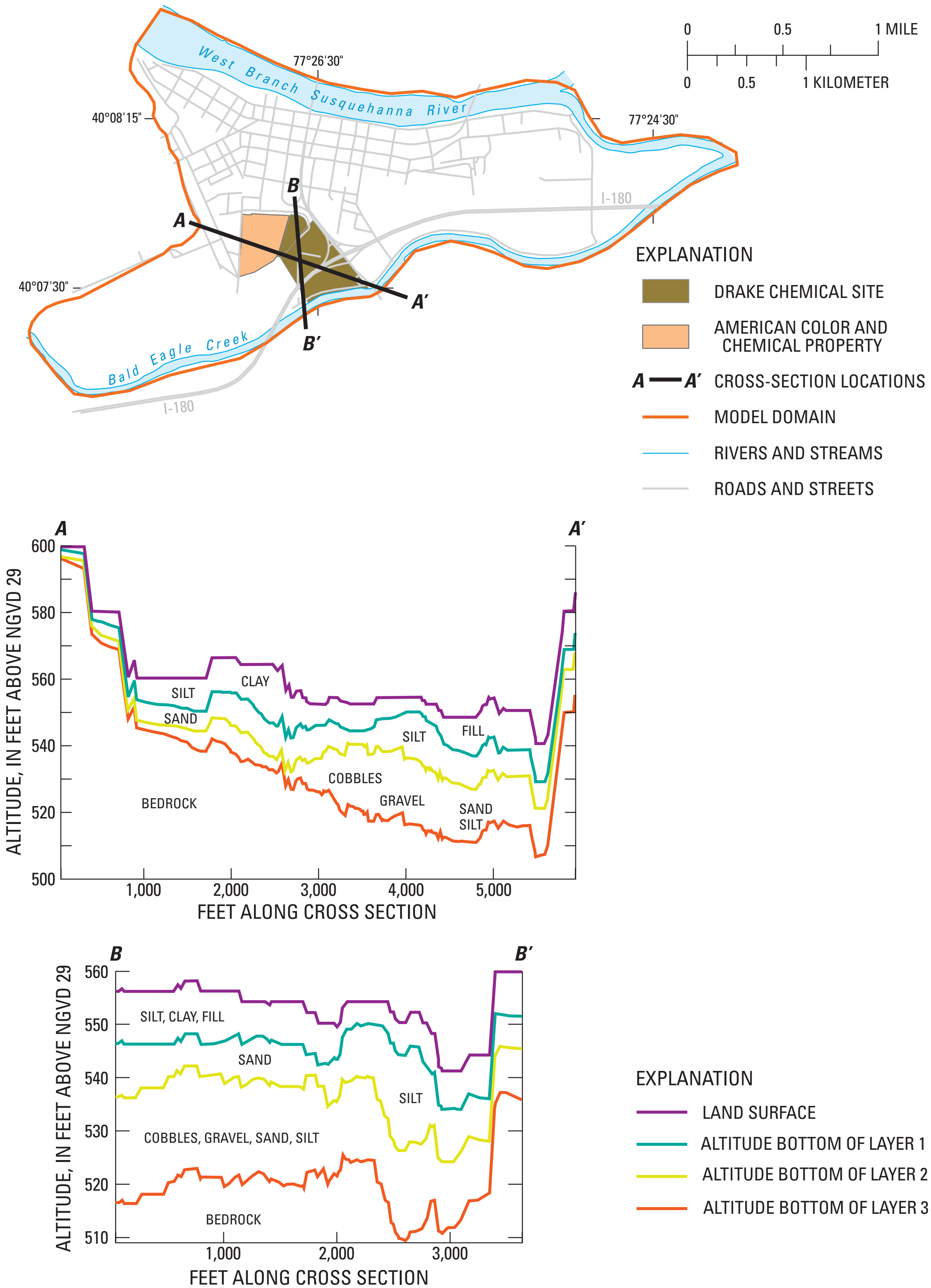

Figure 8. Locations of cross sections, west-east (A-A′) trending and north-south (B-B′) trending, for the ground-water flow model at the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

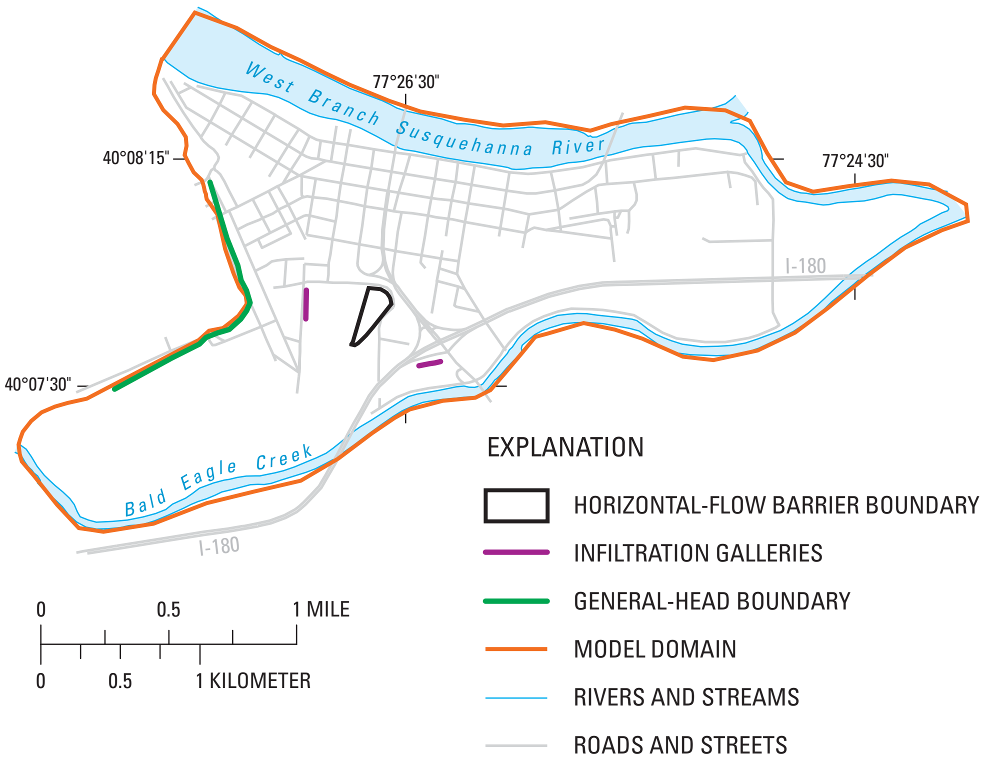

Figure 9. Locations of boundary conditions for the ground-water flow model, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

rier. The sheet pile was installed to stabilize unconsolidated material during excavation of soil that was to be incinerated. The horizontal-flow barrier was included in all three layers and simulated in layers 1 and 2 as 4 ft thick with a conductance of 0.001 ft/min. For layer 3, the thickness was simulated as 1 ft thick with a barrier hydraulic conductivity of 0.001 ft/min (table 1).

Inputs to the model for the ground-water budget for simulations were recharge, some infiltration of water from the rivers, the general-head boundary in layer 3, and the re-infiltration of treated water back into the system at the infiltration gallery locations. Recharge was assumed to be distributed uniformly to the top of layer 1 over the entire modeled area. However, during simulations, many areas of layer 1 would dry up and not re-wet and the cell would become inactive, allowing no further recharge into the model. Therefore, instead of applying recharge to the top of layer 1, recharge was applied to the uppermost active layer in the model, so in some cases, recharge was added directly to layer 2. The reason layer 1 dried up was twofold: 1) the layer is relatively thin, in most areas less than 10 ft thick, and 2) the hydraulic conductivity of layers 2 and 3 are an order of magnitude greater, thus water drains into these layers and moves laterally and does not stay in layer 1. On the western part of the ACC property, a bedrock high exists and the unconsolidated sediments are thin. Layer 1 did not dry up in this area because of the thinning of layers 2 and 3. The re-infiltrated water was distributed along a line, which represented the infiltration galleries, at the cumulative rate of all the extraction wells (fig. 9). The infiltration gallery for the Drake Chemical site was in zone 3, downgradient of zone 1, and the infiltration gallery for ACC was on the western ACC property boundary. Outputs from the model for the ground-water budget for the simulations were withdrawals from extraction wells and discharge to the West Branch Susquehanna River and Bald Eagle Creek.

Table 1. Properties of the horizontal-flow barrier, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

Model layer	Thickness (feet)	Hydraulic conductivity (feet per minute)
Layer 1	4.0	0.001
Layer 2	4.0	.001
Layer 3	1.0	.001

Calibration of Numerical Model and Errors

The model was calibrated using the Parameter-Estimation Process of MODFLOW-2000 (Hill and others, 2000). The program estimates the optimal values of parameters, such as recharge and hydraulic conductivities, in order to minimize model errors that are based on comparisons of simulated hydraulic heads to field-collected water-level measurements adjusted to altitudes, which are termed residuals. Model errors are defined as the sum of squared weighted residuals. For this model, the calibration was done using only hydraulic-head observations. Model-calibration criteria was to match simulated to observed water-level elevations to within +/- 1.60 ft, which was 15 percent of the overall range of water-level fluctuations in monitor wells Cn-398 and Cn-399. The period of record for both monitor wells was December 13, 2001, through September 30, 2005 (appendix 1).

The model was calibrated to steady-state conditions for a time period after pumping began. Water levels were measured in 59 wells on and near the vicinity of the Drake Chemical site on January 13, 2003 (fig. 10). On January 13, 2003, three extraction wells were being pumped on the Drake Chemical site and five extraction wells were being pumped on the ACC property. Pumping rates are listed in table 2. River and stream stage in the West Branch Susquehanna River and Bald Eagle Creek were determined from USGS streamflow-gaging stations and both stages in the model were set to 3.5 ft above the bottom of the river and creek beds.

Table 2. Summary extraction well rates, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

U.S. Geological Survey well identifier	Local identifier	Pumping rate (gallons per minute)
	Drake Chemical site	
CN-388	DPW-02	4.8
CN-389	DPW-03	4.8
CN-390	DPW-04	5.5
	American Color and Chemical property	
CN-431	APW-01	1.0
CN-432	APW-02	.9
CN-433	APW-03	.9
CN-434	APW-04	1.8
CN-435	APW-05	1.8

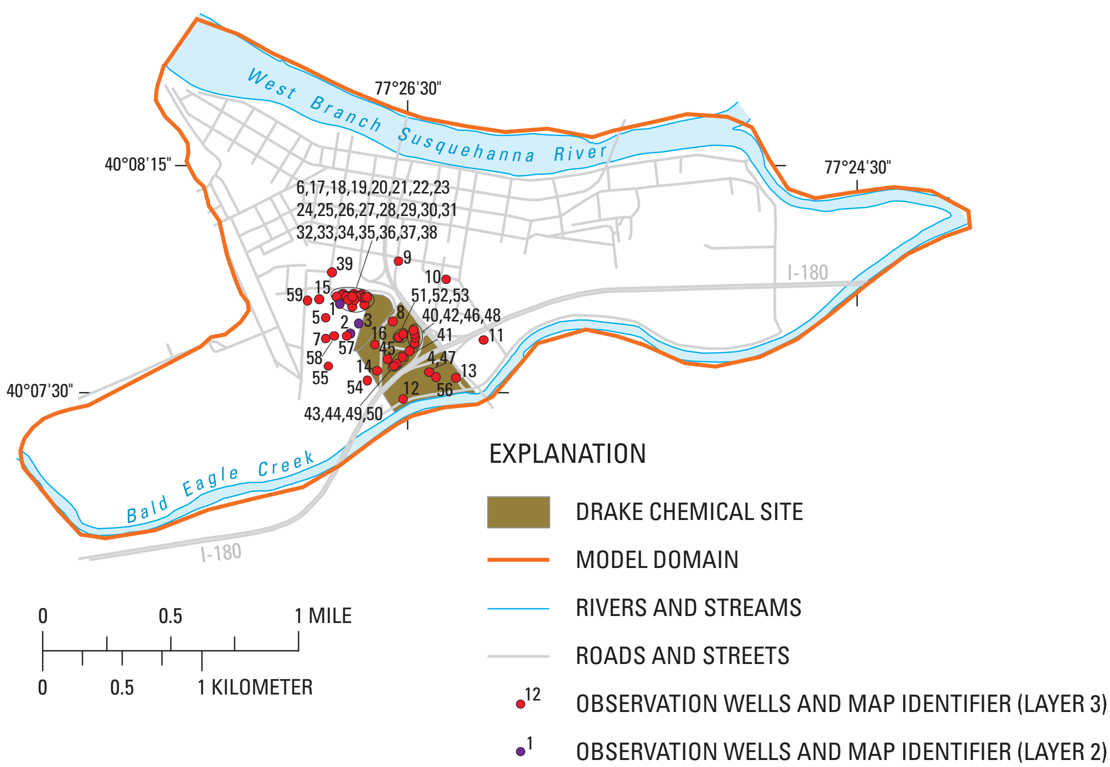

Figure 10. Locations of 59 monitor well observations used in model calibration simulations, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.
(Map identifiers are listed on table 3)

The zonation of hydraulic-conductivity parameters within model layers was done. Two areas were delineated for the model layers on the basis of hydrogeologic data (fig. 11). Area B represented the modeled area in the vicinity of the ACC property where a bedrock high exists. Area A represented the remaining modeled area. Initially, six parameters were used in the parameter-estimation process, four hydraulic conductivities (HK_1_1, HK_1, HK_2, and HK_3), one recharge (Rch_Parm1), and one general-head conductance (GHB_Par3). HK_1_1 was the hydraulic-conductivity parameter for model layer 1 area B. Parameter HK_1 was the hydraulic-conductivity parameter for model layer 1 area A and model layer 2 area B. Parameter HK_2 was the hydraulic-conductivity parameter for model layer 2 area A and model layer 3 area B. Parameter HK_3 was the hydraulic-conductivity parameter for model layer 3 area A.

Results of model simulations showed that the model was not sensitive to the hydraulic-conductivity parameters in layer 1 or to the general-head boundary parameter (fig. 12). Because of the insensitivity of the model to hydraulic conductivity parameters of layer 1 and the general-head conductance parameter, parameters HK_1_1, HK_1, GHB_Par3 were removed from the parameter-estimation process. The hydraulic conductivities for HK_1_1 and HK_1 were set to 1.4 ft/d and 12.2 ft/d, respectively, and the general-head boundary conductance was set to 2.87×10^{-5}.

Simulation results showed that the model was highly sensitive, however, to the recharge and hydraulic-conductivity parameters of layers 2 and 3 (fig. 12). Also, simulation results showed that recharge was highly correlated to the hydraulic-conductivity parameters in layers 2 and 3, suggesting a high probability of a non-unique solution in which an infinite number of combinations of recharge and hydraulic conductivities in layers 2 and 3 are possible and when used could reproduce the observed water-level altitudes in the monitor wells. Therefore, either the recharge or hydraulic-conductivities parameters had to be set and taken out of the parameter-estimation process. Recharge in this area, particularly direct recharge on the alluvial valley deposits, is poorly understood. Hydraulic-conductivity values from on-site aquifer and slug tests were available, however, and comparisons to parameter-estimated results could be done. Therefore, the recharge parameter was taken out of the parameter-estimation process.

The recharge value was set to 5 in/yr. In simulating ground-water flow in Ohio River alluvial aquifers in four areas in West Virginia, Kozar and McCoy (2004) used estimates of recharge ranging from 3 to 12 in/yr. The magnitude of recharge estimates depended on the composition of the alluvial sediments (Kozar and McCoy, 2004). The more silts and clays in

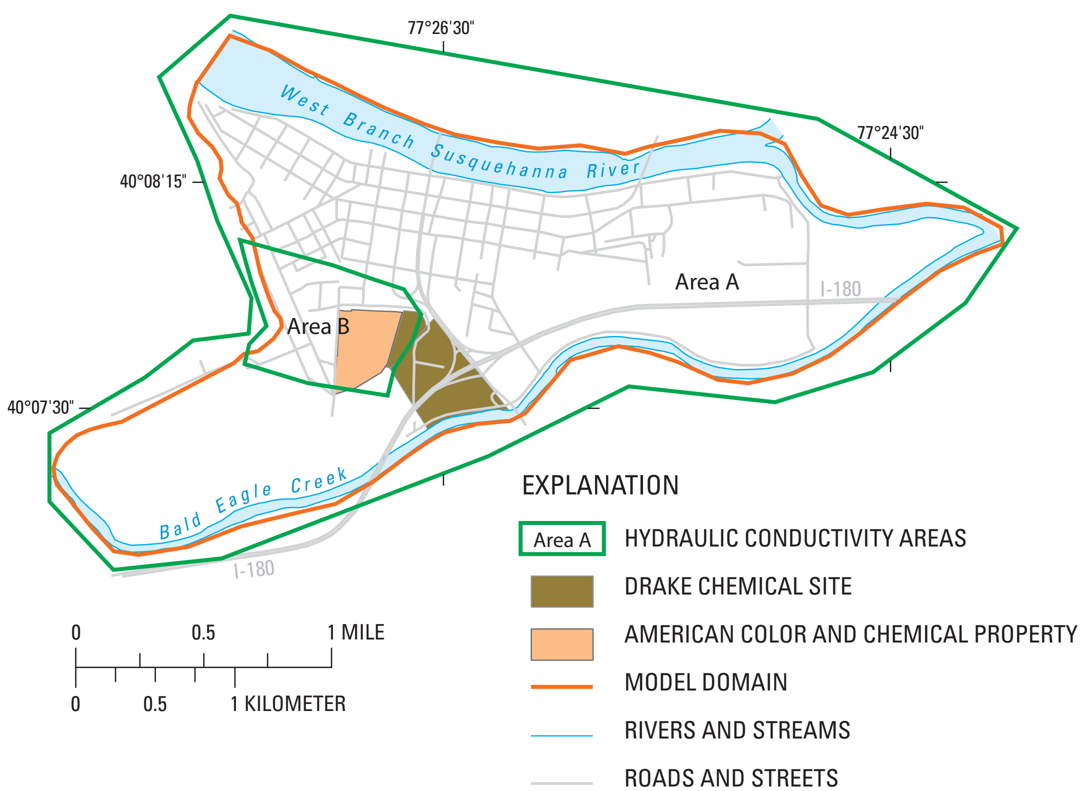

Figure 11. Locations of hydraulic-conductivity areas used in the ground-water flow model, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

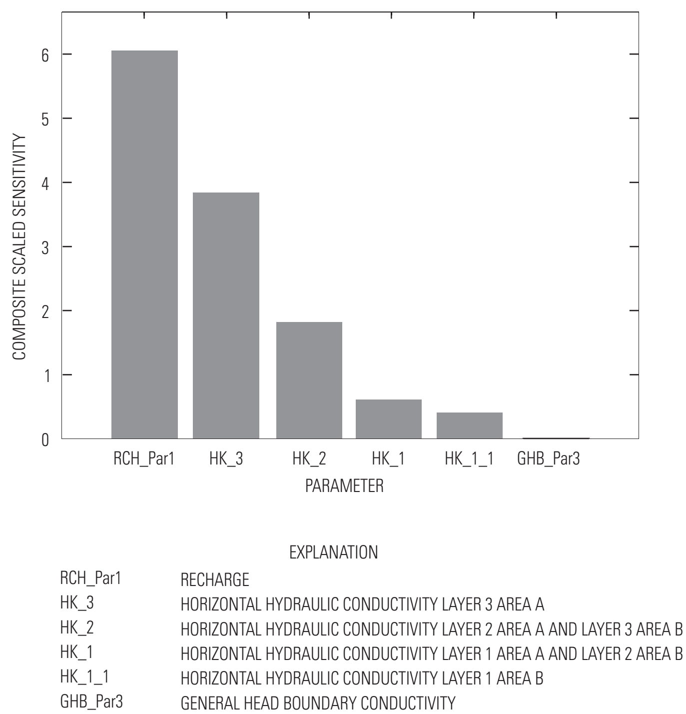

Figure 12. Composite scaled sensitivities for parameters used in model calibrations, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

the alluvial aquifers, the lesser the recharge value. From direct observation, the aquifer material at the extraction wells was made up of highly unsorted alluvial deposits that contained large amounts of silts and clays. Also, large areas of the model domain west and northwest of the Drake Chemical site are urbanized, which could lessen recharge to the area. Roads, streets, and parking lots increase the impervious surface and storm sewer drains are present along streets and parking lots (fig. 13). Also, an impervious cap was installed on an area of the ACC property where disposal lagoons once existed (fig. 13). The recharge to the system is unknown, however, and is a limitation of this model.

Hydraulic-conductivity parameters for model layers 2 and 3 were estimated because those parameters were highly sensitive in the model. Uncertainty of estimated parameters is related to parameter sensitivity and the highly sensitive parameters usually are estimated with a higher level of confidence than those that are not sensitive (Lindsey and Koch, 2004).

Measurements of hydraulic head were all weighted the same. The relation between water-level observations in 59 wells, which were used in the parameter-estimation process, to simulated hydraulic heads are shown in figure 14. Of the observed water-level elevations measured in monitor wells used for calibration, 10 of 59 observations failed to meet the calibration criteria. A cluster of observed head elevations between 545

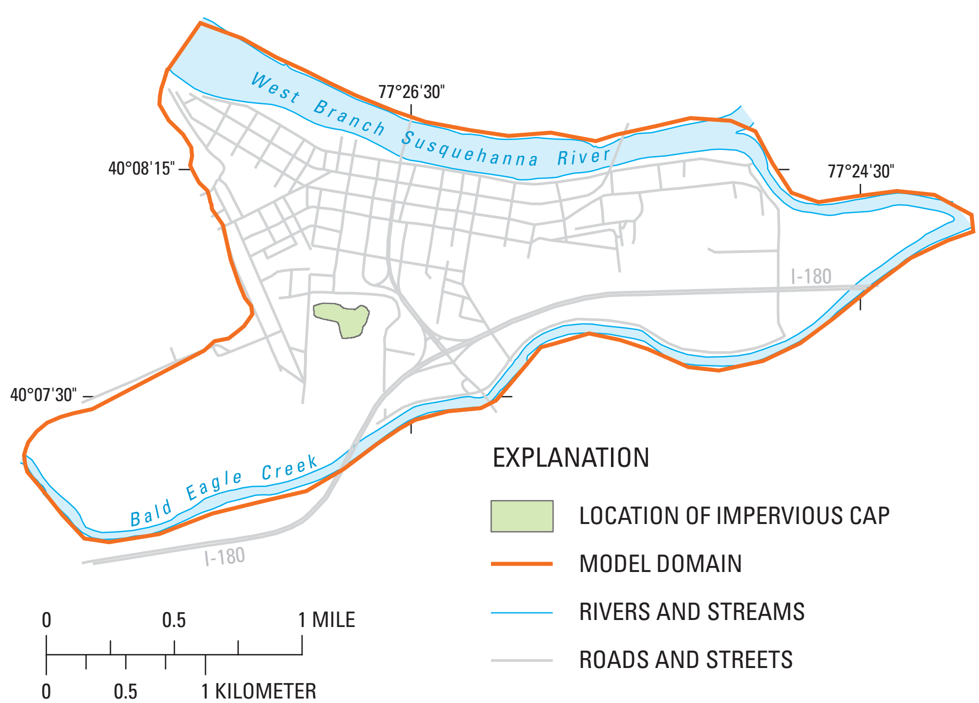

Figure 13. Location of impervious cap on the American Color and Chemical site and roads and streets near the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

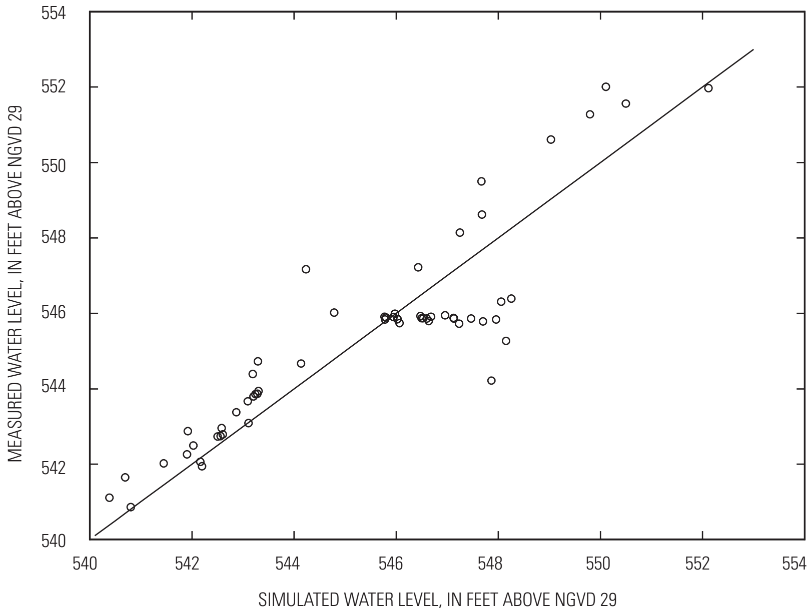

Figure 14. Calibration results showing simulated and measured water-level altitudes, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

and 546 ft above NGVD 29, the flat part of the plot on figure 14, were water-level elevations measured in observation wells on the ACC property that were either actively pumping extraction wells or in close proximity to the extraction wells. The flow model could not simulate the measured water levels in the extraction wells or those in the nearby observation wells. The average residual for all water-level comparisons is 0.009 ft; differences in ground-water levels ranged from -3.65 to +2.94 ft for the steady-state calibration (table 3). The standard error of regression was 1.2069, and the correlation coefficient was 0.90. The sum of squared residuals for this model was 83.0. The largest negative residual was in well APW-02, which is an extraction well on the ACC property, and the largest positive residual was in well MW-M14 (USGS local well identifier Cn-394, appendix fig. 1-1), which is approximately 800 ft west of the Drake Chemical extraction wells. The hydraulic head contour map of the calibration simulation is shown in figure 15. A water-level contour map generated from water-level measurements made on January 13, 2003, is shown on figure 16. A comparison of the simulated hydraulic head contour map and the water-level contour map shows similar configurations.

Results of the simulation indicate that recharge contributed 77 percent of the water to the model, leakage from the rivers contributed 16 percent, head-dependant boundaries contributed 3 percent, and the re-infiltration of treated water contributed 4 percent. Discharge to the rivers totaled 97 percent of the output of water from the model; the remaining 3 percent of output was withdrawals from wells.

Table 3. Measured water levels January 13, 2003, simulated water levels, and the difference between the measured and simulated water levels for the calibration of the ground-water flow model, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

[NGVD 29, National Geodetic Vertical Datum of 1929]

Local identifier	Map identifier (shown on figure 11)	Model layer	Observed water level (feet above NGVD 29)	Simulated water level (feet above NGVD 29)	Difference (feet above NGVD 29)
MW-04R	1	2	545.27	548.16	-2.88
MW-01R	2	2	548.14	547.25	.89
MW-02AR	3	2	547.22	546.43	.79
MW-117A	4	2	542.06	542.16	-.10
MW-07	5	3	552.01	550.11	1.90
MW-18B	6	3	545.99	545.97	.02
MW-25	7	3	551.28	549.79	1.49
MW-M04	8	3	544.67	544.14	.53
MW-M104	9	3	546.02	544.78	1.24
MW-M122	10	3	543.80	543.21	.59
MW-M119	11	3	540.86	540.80	.06
MW-M113	12	3	541.65	540.69	.96
MW-M115	13	3	541.11	540.38	.73
MW-M13	14	3	544.39	543.19	1.20
MW-06	15	3	551.56	550.50	1.06
MW-M14	16	3	547.17	544.23	2.94
P-A2D	17	3	545.91	546.68	-.77
[1]APW-01	18	3	545.80	546.63	-.83
P-A12	19	3	545.90	545.95	-.05
P-A7	20	3	545.85	546.02	-.17
P-A13	21	3	545.87	546.53	-.66
P-A14	22	3	545.86	547.47	-1.61
MW-21	23	3	545.86	547.13	-1.27
P-A10	24	3	545.84	547.96	-2.12
[1]APW-05	25	3	545.84	545.78	.06
[1]APW-02	26	3	544.22	547.87	-3.65
P-A8	27	3	545.87	546.50	-.63
MW-20	28	3	545.85	546.02	-.17
MW-28	29	3	545.95	546.96	-1.01
P-A9	30	3	545.79	547.70	-1.91
P-A11	31	3	546.39	548.26	-1.87
[1]APW-03	32	3	545.73	547.23	-1.50
[1]APW-04	33	3	545.74	546.06	-.32
P-A6	34	3	545.89	545.80	.09
P-A4D	35	3	545.93	546.47	-.54

Table 3. Measured water levels January 13, 2003, simulated water levels, and the difference between the measured and simulated water levels for the calibration of the ground-water flow model, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

[NGVD 29, National Geodetic Vertical Datum of 1929]

Local identifier	Map identifier (shown on figure 11)	Model layer	Observed water level (feet above NGVD 29)	Simulated water level (feet above NGVD 29)	Difference (feet above NGVD 29)
P-A1D	36	3	545.88	547.13	-1.25
P-A3D	37	3	545.86	546.60	-.74
P-A5	38	3	545.91	545.77	0.14
MW-30B	39	3	546.31	548.06	-1.75
[1]DPW-04	40	3	542.88	541.92	.96
[1]DPW-03	41	3	542.26	541.90	.36
P-D8	42	3	542.96	542.58	.38
P-D9	43	3	542.75	542.56	.19
DPW-01	44	3	542.74	542.50	.24
P-D11	45	3	543.09	543.11	-.02
P-D7	46	3	543.38	542.87	.51
MW-117B	47	3	541.94	542.19	-.25
P-D6	48	3	543.67	543.09	.58
P-D10	49	3	542.79	542.60	.19
[1]DPW-02	50	3	542.5	542.03	.47
P-D4D	51	3	543.86	543.24	.62
P-D3D	52	3	543.94	543.30	.64
P-D2D	53	3	543.87	543.28	.59
MW-35B	54	3	544.73	543.29	1.44
MW-14R	55	3	549.5	547.67	1.83
MW-200	56	3	542.02	541.45	.57
ARW-02	57	3	548.62	547.68	.94
ARW-01	58	3	550.61	549.03	1.58
MW-36B	59	3	551.97	552.12	-.15

[1]Active pumping well.

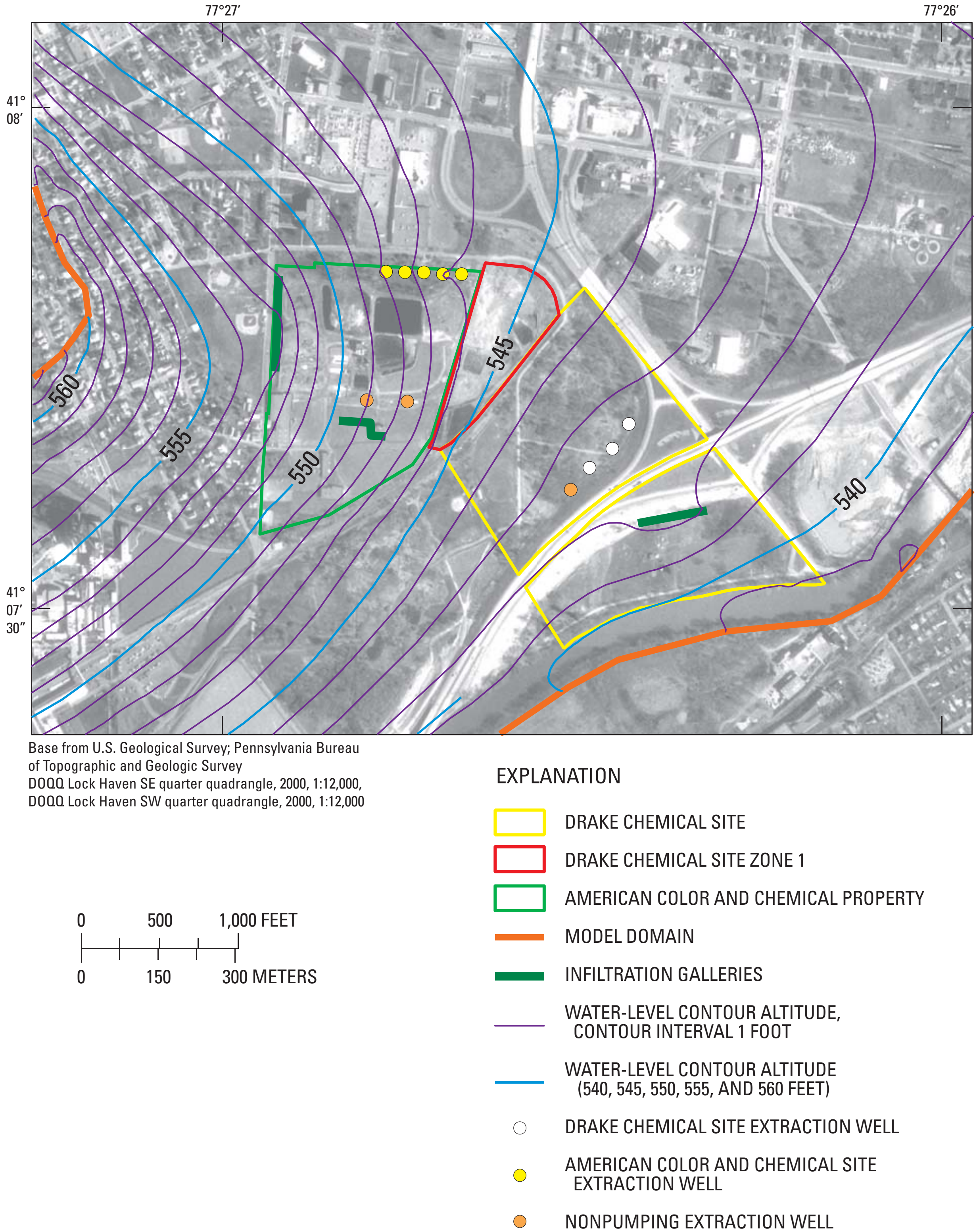

Figure 15. Simulated pumping water-level altitude contours in the vicinity of the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

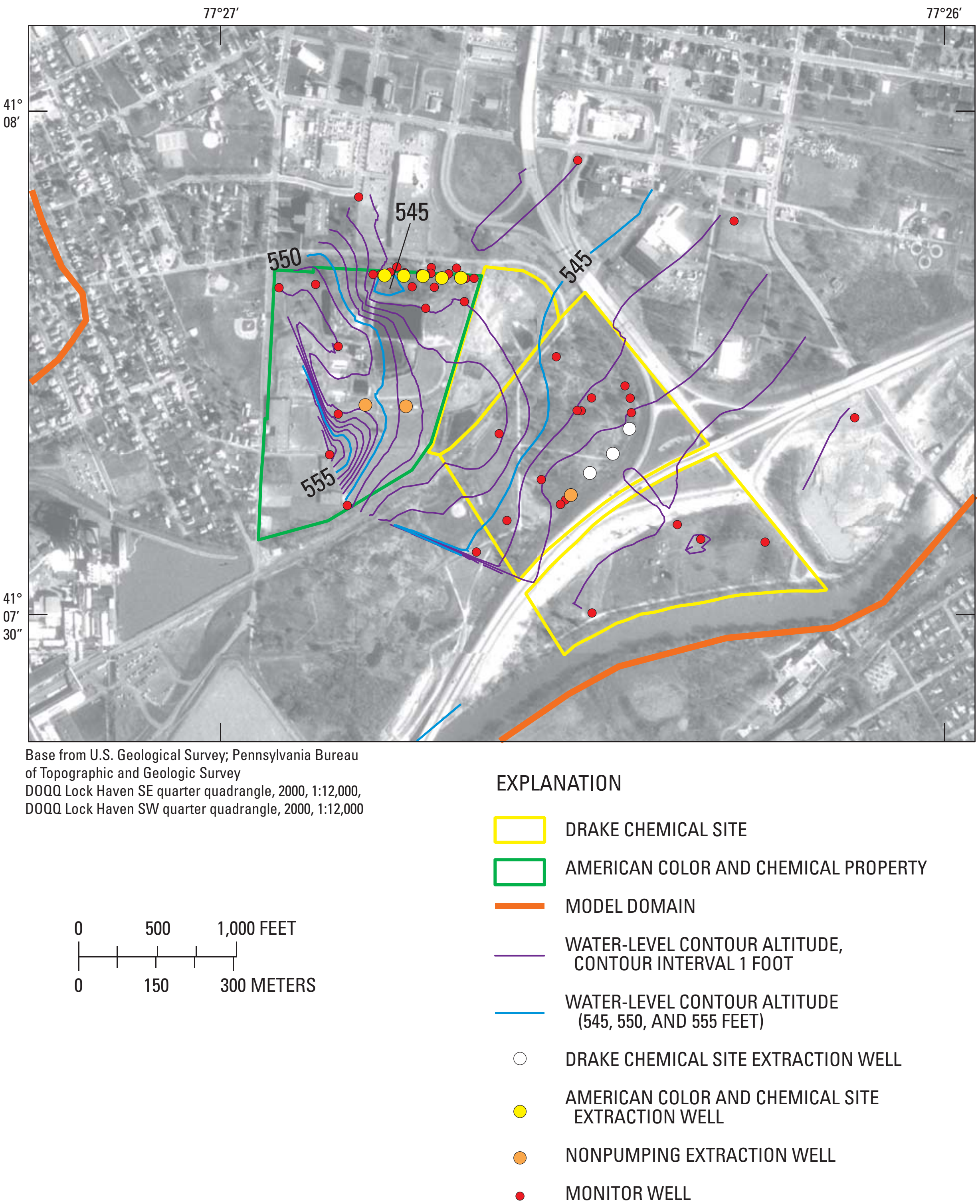

Figure 16. Pumping water-level altitude contours for observations measured January 13, 2003, in the vicinity of the Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

Final calibrated parameter values and the 95-percent confidence intervals for HK_2 and HK_3 are shown in table 4. These values are based on the assumption that the optimization model is linear. A measure of model linearity is the correlation between weighted residuals and the normal order statistics (Hill and others, 2000). This correlation coefficient was 0.97, which is slightly greater than the critical value (0.963) for the 0.05 significance level, indicating the residuals are nearly normally distributed and independent at the 0.05 significance level. Another measure of model linearity is the modified Beale's measure. The model is considered nonlinear if the modified Beale's measure is greater than 0.32, and considered effectively linear if the measure is less than 0.03. The modified Beale's measure for this model was 0.16, which indicates the model is moderately linear and indicates the linear confidence intervals shown on table 5 for the optimized parameters are considered approximate values. The approximate, individual, 95-percent confidence intervals show the hydraulic conductivities for layers 2 and 3 are relatively constrained in the optimization model.

Gannett Fleming (1992) performed a 72-hour pump test of well TW-1 on August 26-29, 1991 (fig. 17). Key Environmental, Inc. (2000), performed a step-drawdown test on a pilot extraction well on February 17, 1999 (fig. 17). Both wells are in zone 2 of the Drake Chemical site and hydraulic-conductivity results are shown in table 5. With recharge set to 5.0 in/yr, the resulting hydraulic conductivities from the parameter-estimation process were similar to hydraulic conductivities estimated from on-site aquifer tests.

Table 4. Optimum and approximate, individual, 95-percent confidence-interval values for hydraulic conductivity of zone A for calibrated simulation of ground-water flow, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

[HK_2, hydraulic conductivity of model layer 2, area A and model layer 3 area B; HK_3, hydraulic conductivity of model layer 3, area A; ft/d, feet per day]

Parameter	Units	Optimum value	Approximate, individual, 95-percent confidence interval	
			Lower value	Upper value
HK_2	ft/d	20.4	11.8	28.9
HK_3	ft/d	34.8	27.6	42.0

Table 5. Summary hydraulic-conductivity values from aquifer tests, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

[ft/d, feet per day; --, not determined; n/a, not applicable]

Local identifier	Hydraulic conductivity from Theis method (ft/d)	Hydraulic conductivity from Theis recovery (ft/d)	Hydraulic conductivity from Thiem-Dupuit method (ft/d)	Hydraulic conductivity from specific-capacity data (ft/d)
PILOT	n/a	n/a	n/a	[1]30.0
TW-1	--	2	--	n/a
OW-1	25	16	17	n/a
OW-2	37	31	18	n/a
OW-3	41	37	--	n/a
MW-M4	287	--	18	n/a
MW-E3	79	--	17	n/a

[1]Calculated from the average of three specific-capacity values determined and an aquifer thickness of 30 feet.

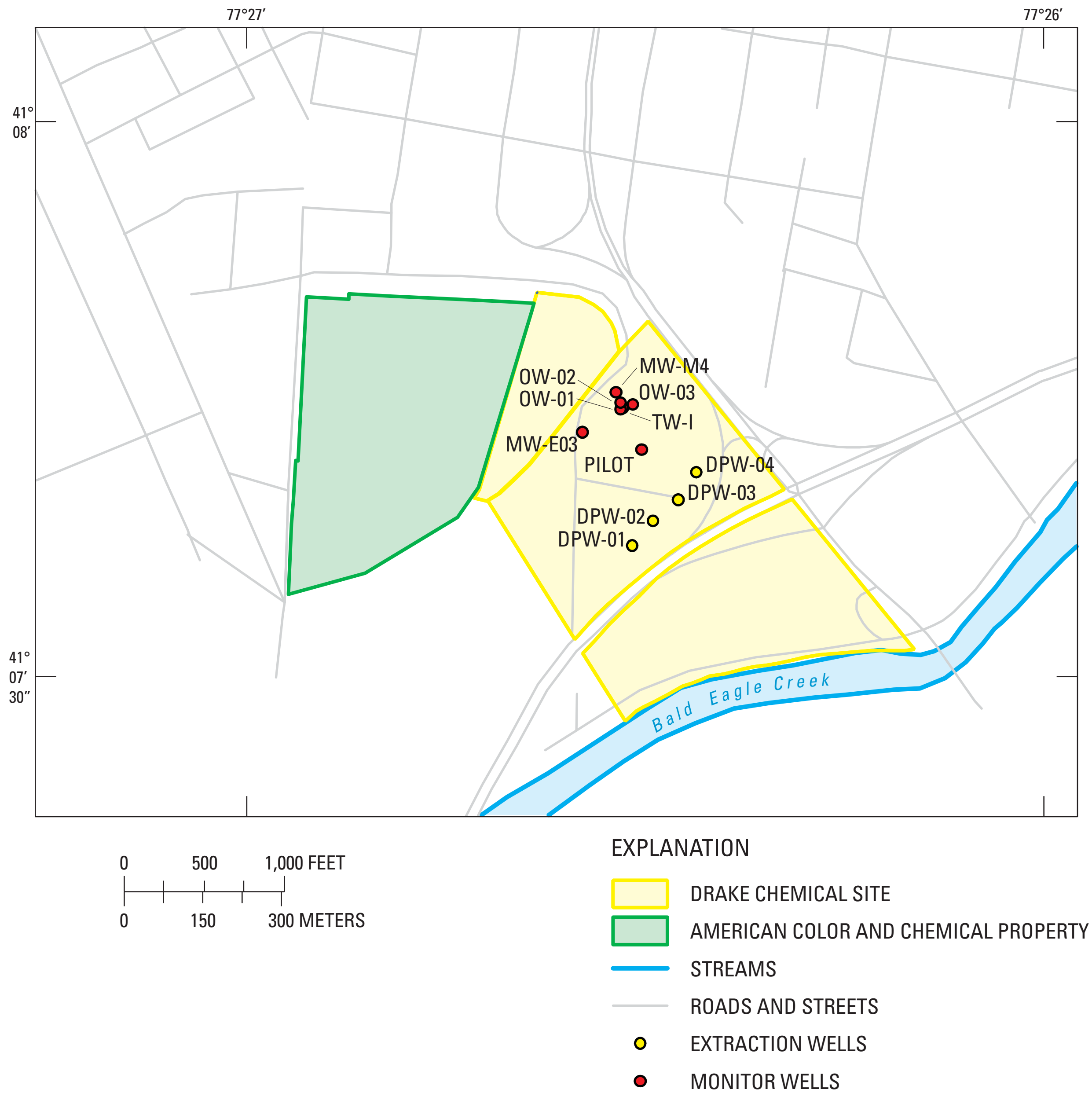

Figure 17. Locations of wells with aquifer test data and extraction wells, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

Model Limitations

The primary intended use of this model is to simulate ground-water flow and estimate areas contributing recharge to three extraction wells on the Drake Chemical site. Most of the data used to calibrate the model were collected on or near the Drake Chemical site and the model should not be used to simulate ground-water flow outside this vicinity.

Even though different hydraulic conductivity zones were used to account for the heterogeneity in hydraulic conductivity of the unconsolidated alluvial system, ground-water flow through the unsorted alluvial system is very complex and assumptions were made that large areas in the model domain were homogeneous with respect to hydraulic conductivity. Also, little or no data were available on the hydraulic conductivity of the fill materials that were present in the top layer of the model.

The recharge rate to the alluvial system in the vicinity of the Drake Chemical Superfund site was estimated to be 5 in/yr. This estimate was made due to the lack of data to determine a recharge rate for the alluvial system in the vicinity of the Drake Chemical site. If recharge is more than the estimated value, to maintain the same extent of the contributing areas for which extraction wells were being pumped at 5 gal/min, extraction wells would have to be pumped at rates greater than 5 gal/min; if recharge is less than the estimated value, pumping rates in the extraction wells could be decreased to maintain the same extent of the contributing areas.

The model was constructed to simulate that the driven sheet pile located in zone 1 of the Drake Chemical site was very permeable to ground-water flow. The sheet pile was installed to stabilize soil, not as a hydraulic barrier. However, if this assumption is flawed, the sheet pile would impede ground-water flow and flow paths would be altered. The flow paths would proceed around instead of through the sheet pile.

Another important assumption incorporated into the model is that ground-water flow from the bedrock into the unconsolidated material of layer 3 is insignificant. If this assumption is flawed and pumping rates are held constant at 5 gal/min, the areas contributing recharge to the extraction wells probably would be smaller in areal extent.

Areas Contributing Recharge to Extraction Wells

The computer program MODPATH (Pollock, 1994), a particle-tracking module linked to MODFLOW that uses hydraulic heads and flows computed by the model, was used to calculate and display the areas contributing recharge to the three extraction wells on the Drake Chemical site. The contributing areas to the extraction wells were determined by a backward-tracking technique that traces particles placed inside the model grid cell of each extraction well. In the particle-tracking program, 2,000 particles were placed in the model grid cell of each of the three extraction wells being pumped on the Drake Chemical site. The particles are tracked backwards either to the land surface, or in the case where model grid cells in layer 1 went dry, to the top of layer 2, which was the uppermost active layer in the model. The areal extent of the plotted particles for each well represented the contributing area for the respective extraction well. The main concern was that ground water migrating from zone 1 area on the Drake Chemical site was being captured by the extent of the contributing areas.

Contributing areas were determined for the calibrated-model simulation on January 13, 2003. The extraction wells were being pumped at approximately 5 gal/min (table 2). Contributing areas also were determined for two other pumping scenarios. For these scenarios, extraction wells were pumped at rates of 2 and 8 gal/min. All other parameters were held constant in these simulations except for the pumping rates. The simulated areal extent of the contributing areas of the three extraction wells pumping at a rate of approximately 5 gal/min on January 13, 2003, is shown on figure 18. The areal extent of the contributing areas encompasses about 92 percent of zone 1 on the Drake Chemical site, and contributing areas for the different wells intersect. A very small area in the southwest part of zone 1 was not covered by the contributing areas of the three extraction wells. However, in the early operation of the remediation system in the fall of 2000 and into 2001, a fourth extraction well, which was located to the southwest of the extraction wells pumped in 2003, was in operation. Pumping from the fourth extraction well was discontinued because the ground water in that area met established performance standards (U.S. Environmental Protection Agency, 1995).

Contributing areas of the extraction wells when the pumping rate was reduced to 2 gal/min are shown on figure 19. The areal extent of the contributing areas does not encompass zone 1 of the Drake Chemical site nor do the contributing areas intersect between wells. Contributing areas of the extraction wells when the pumping rate was increased to 8 gal/min are shown on figure 20. The areal extent of the contributing area does encompass all of zone 1 on the Drake Chemical site, and contributing areas for the different wells intersect.

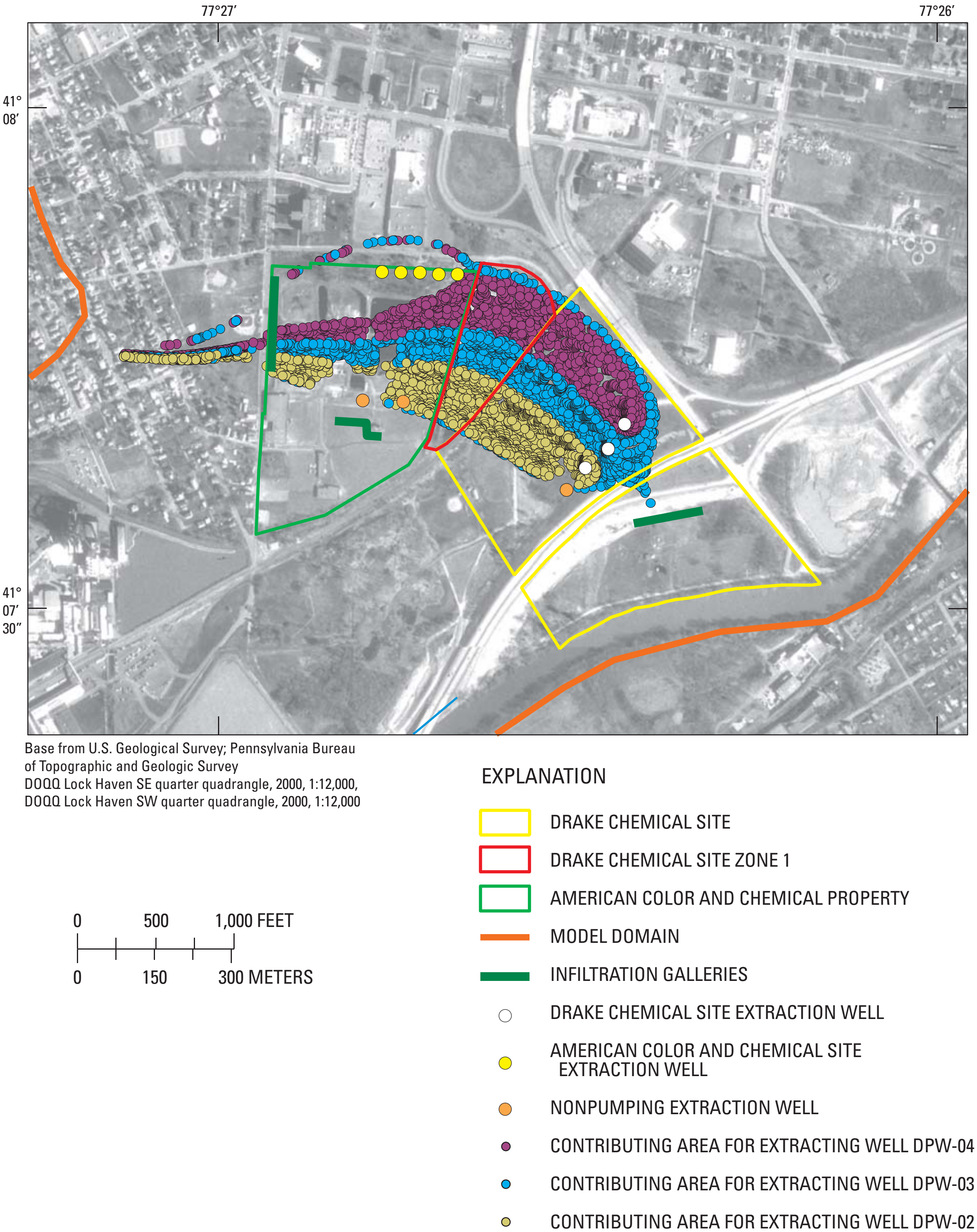

Figure 18. Contributing areas for three extraction wells for pumping on January 13, 2003, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

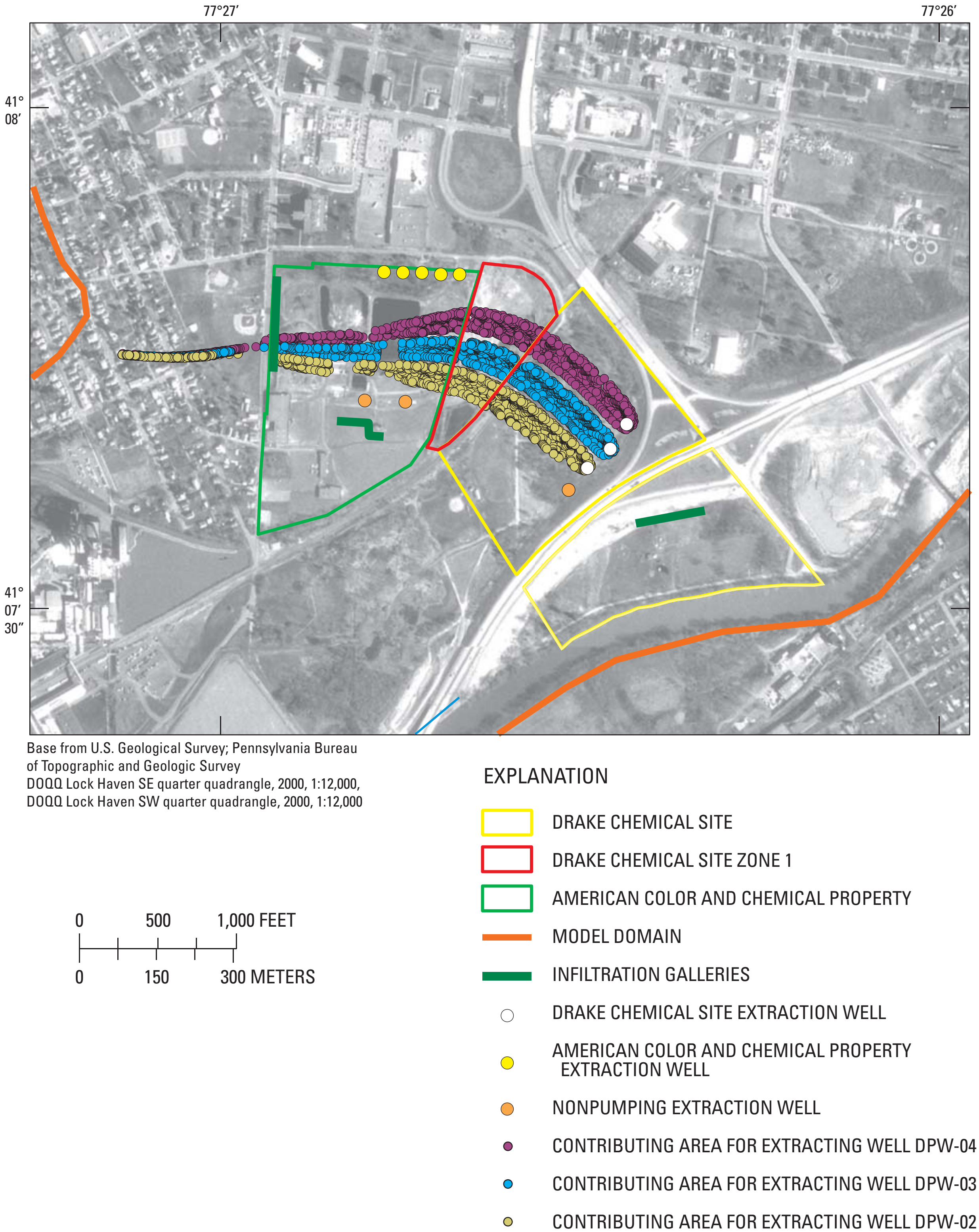

Figure 19. Contributing areas for three extraction wells for pumping at 2 gallons per minute, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

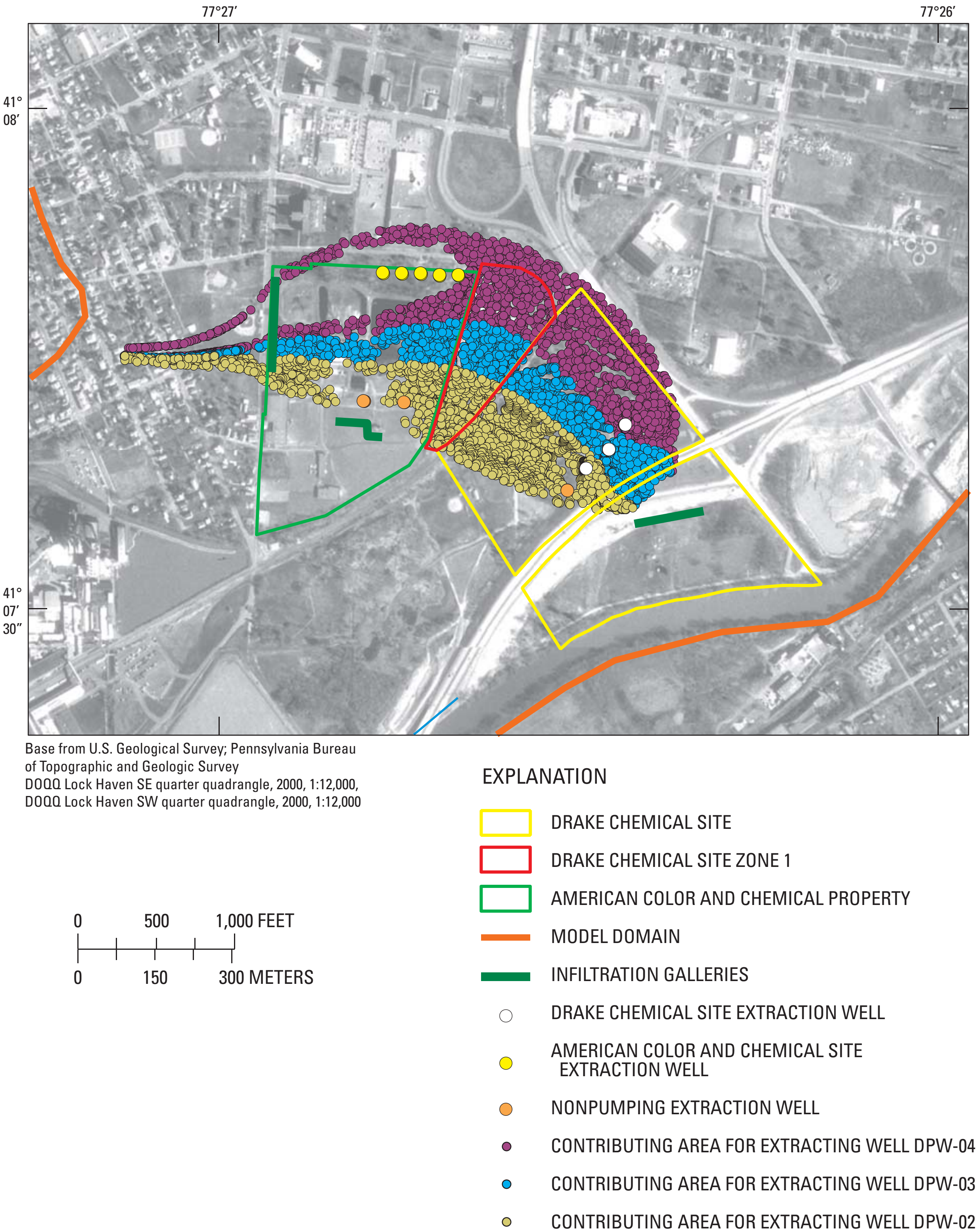

Figure 20. Contributing areas for three extraction wells for pumping at 8 gallons per minute, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

Summary and Conclusions

Ground-water flow in the vicinity of the Drake Chemical Superfund Site was simulated using a three-dimensional finite difference model. The simulation of ground-water flow was based on assumptions of 1) input to the model of evenly distributed areal recharge, 2) flow through homogeneous porous media, and 3) output from the model of ground water discharging to the local river and creek. Also, a general-head boundary was defined to represent a lateral input of ground water and a horizontal-flow barrier was defined to represent a driven sheet pile that was installed on the Drake Chemical site. Steady-state conditions were simulated, which implies the inputs and outputs of water have reached a state of equilibrium and are not changing.

A three-layer model was used to define three poorly sorted alluvial sediment layers. Layer 1 represented silt, clay, fill material, and re-worked soils and had a maximum thickness of approximately 18 ft. Layer 2 represented sand, silt, and some gravel and had a maximum thickness of approximately 18 ft. Layer 3 represented sand, gravel, and cobbles and had a maximum thickness of approximately 26 ft. Underlying consolidated bedrock aquifers were not included in the model.

The model was calibrated using the parameter-estimation process included in MODFLOW-2000. This model was calibrated to hydraulic-head observations only, and all observations were weighted the same. The model was calibrated to 59 water-level observations collected on January 13, 2003. The model was sensitive to hydraulic-conductivity parameters for layers 2 and 3. Results of the parameter-estimation process showed that recharge was highly correlated with hydraulic conductivity of layers 2 and 3. Thus, the recharge parameter was set constant at 5 in/yr for the simulations. The optimal hydraulic conductivities for layers 2 and 3 were 20.4 and 34.8 ft/d, which were in the range of hydraulic conductivities estimated from on-site aquifer-test data.

The calibrated model was used to estimate the land-surface areas contributing recharge to three extraction wells on the Drake Chemical site. At issue was the land-surface plan-view coverage of the contributing areas of the extraction wells. The remedial system was designed so that the contributing areas of the extraction wells were to encompass zone 1 of the Drake Chemical site because zone 1 was assumed to be the source area of the ground-water contamination. Contributing areas of the three extraction wells were estimated using three different pumping rates. Contributing areas were estimated for the pumping rate used on January 13, 2003, which was approximately 5 gal/min, and also were estimated for pumping rates of 2 and 8 gal/min. The estimated contributing areas for the extraction wells encompassed 92 percent of zone 1 at pumping rates of approximately 5 gal/min. A small area in the southwest part of zone 1 was not covered by the contributing areas. The estimated contributing areas for the extraction wells at pumping rates of 2 gal/min only partially encompassed zone 1. The estimated contributing areas for the extraction wells did encompass zone 1 at pumping rates of 8 gal/min and also encompassed a small area north of zone 1. Thus, pumping rates of 5 gal/min or more are estimated to maintain contributing-area coverage of zone 1. However, this estimate depends on a number of assumptions, including recharge. If recharge is more than the set value, pumping rates would have to be increased; if recharge is less than the set value, pumping rates could be decreased. Also, because of the proximity of the site to the Bald Eagle Creek and the direct hydraulic connection of the alluvial ground-water system to the creek, if all model parameters are held constant and the creek stage is changed, the shape and size of the contributing area would change.

Application of the simulation results is limited because the model was calibrated to hydraulic-head observations only. The confidence level in the results would be improved if flow data were included in the parameter-estimation process. Useful flow data are not available nor attainable, however, and the ground-water system in this area is virtually unconstrained. Also, to increase confidence in the applicability of the model, further study is needed to define the recharge rate to the alluvial system in this area. Additional data would better define the hydraulic effect, if any, the sheet pile may have on water levels and ground-water flows in the local alluvial system on the Drake Chemical site.

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Appendix 1—Water-Level Hydrographs

Pressure transducers were installed in monitor wells to measure water-level fluctuations. Appendix 1 shows water-level hydrographs of 15-minute measurements for wells Cn-391, Cn-392, Cn-393, Cn-394, Cn-398, Cn-399, Cn-419, and Cn-445. Pressure transducers were installed in wells, Cn-391, Cn-392, Cn-393, and Cn-394 from November 7, 2000, to September 30, 2001. Pressure transducers were installed in wells Cn-398, Cn-399, and Cn-419 from December 12, 2001, through March 2002 and June 7, 2002, through September 30, 2005. A pressure transducer was installed in monitor well Cn-445 from December 12, 2001, through March 2002 and June 7, 2002, through December 10, 2002.

Fluctuations in water levels were in response to precipitation events and the start-up and shutdown of the remedial extraction system. The fluctuations seen in wells Cn-398 and Cn-399 from June 2002 through October 2002 (figures 1-6, 1-7, 1-10, and 1-11) were due to the start-up and shutdown of the remedial treatment system. Also, water-level fluctuations in wells Cn-445 and Cn-419 were in influenced by the stage of Bald Eagle Creek because of there proximity to the creek (figure 1-1).

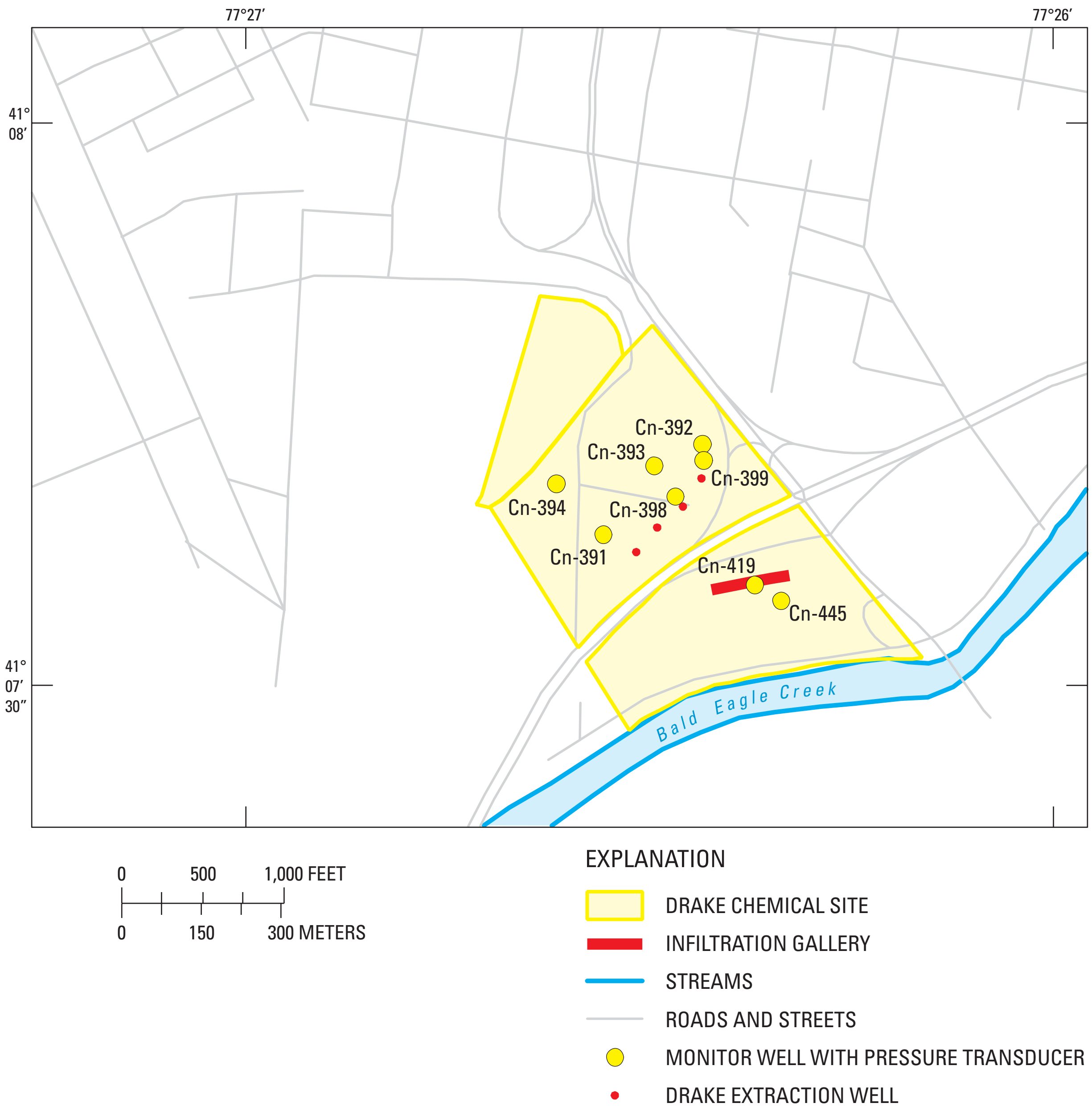

Figure 1-1. Monitor well locations with pressure transducers installed and extraction wells, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa.

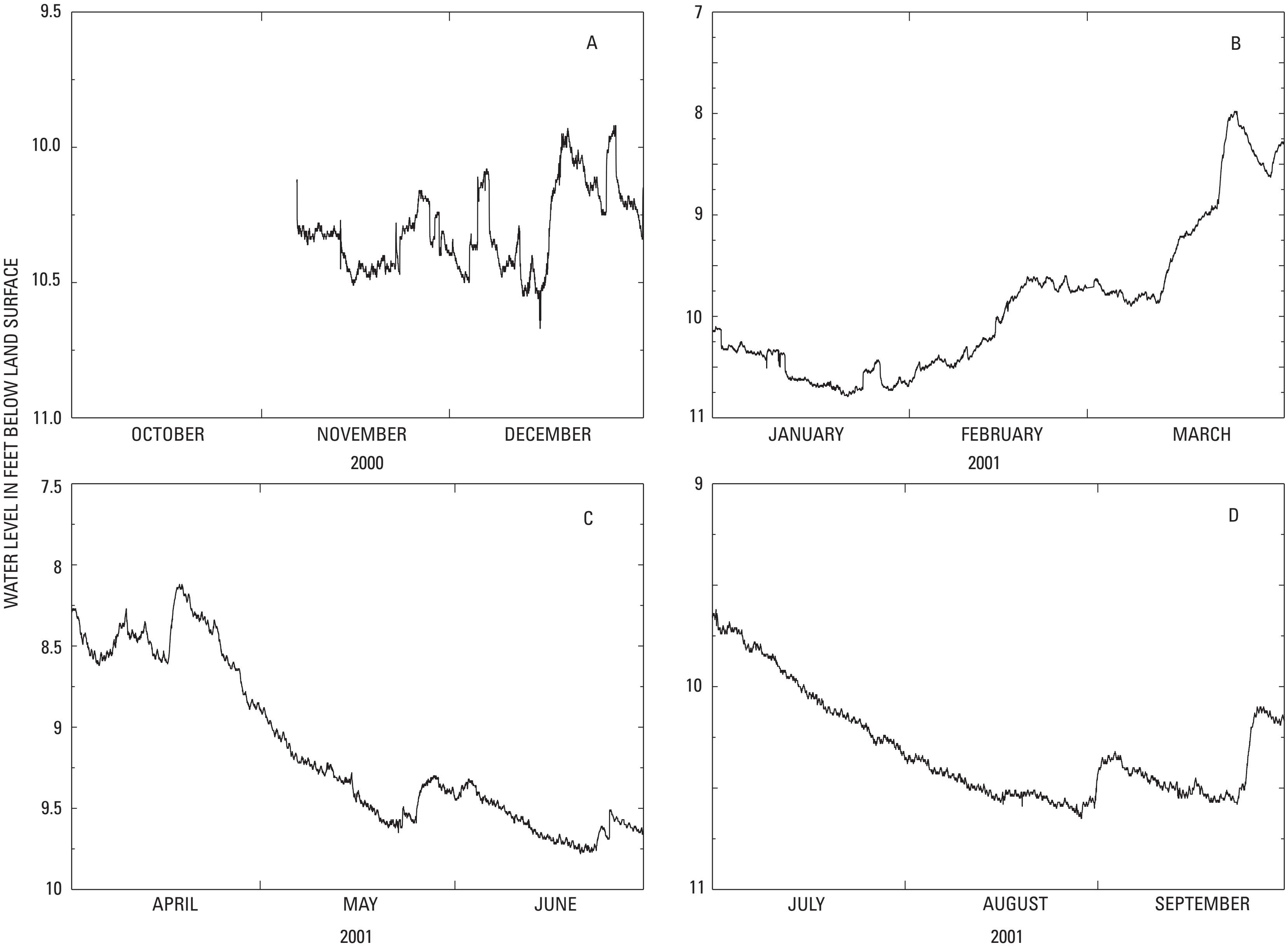

Figure 1-2. Water-level hydrographs for well Cn-391, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: November 7 to December 31, 2000; B: January 1 to March 31, 2001; C: April 1 to June 30, 2001; and D: July 1 to September 30, 2001.

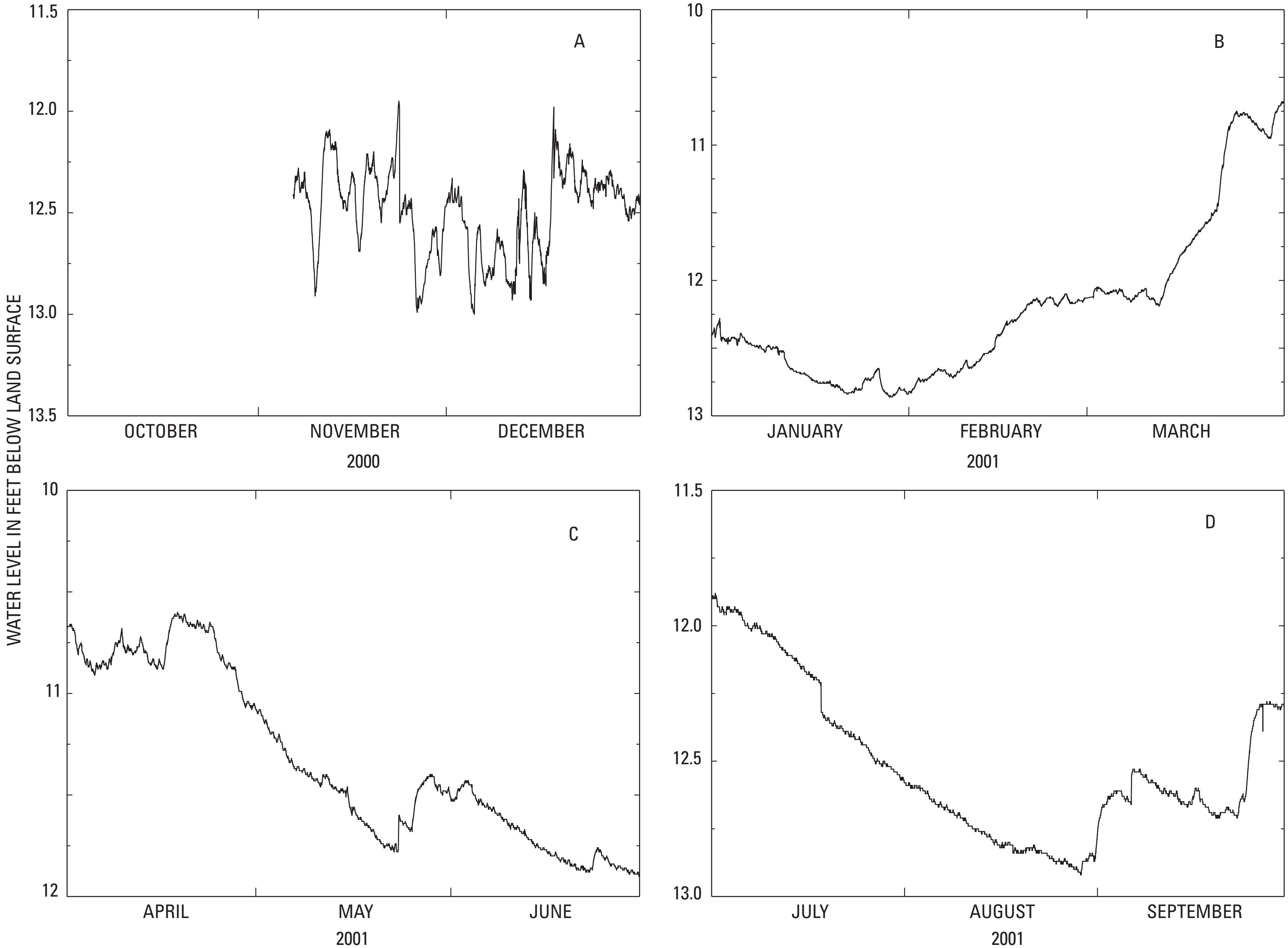

Figure 1-3. Water-level hydrographs for well Cn-392, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: November 7 to December 31, 2000; B: January 1 to March 31, 2001; C: April 1 to June 30, 2001; and D: July 1 to September 30, 2001.

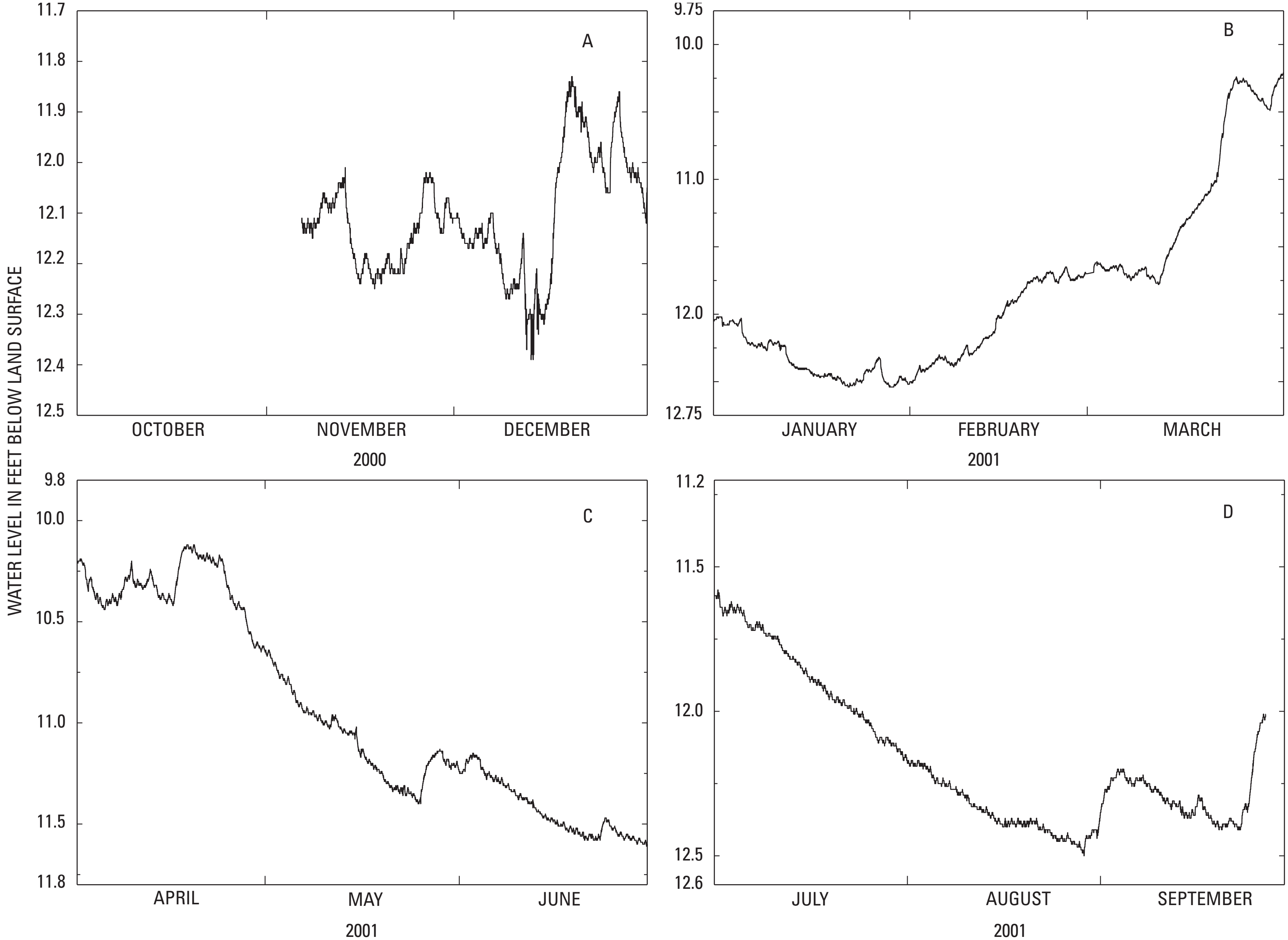

Figure 1-4. Water-level hydrographs for well Cn-393, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: November 7 to December 31, 2000; B: January 1 to March 31, 2001; C: April 1 to June 30, 2001; and D: July 1 to September 30, 2001.

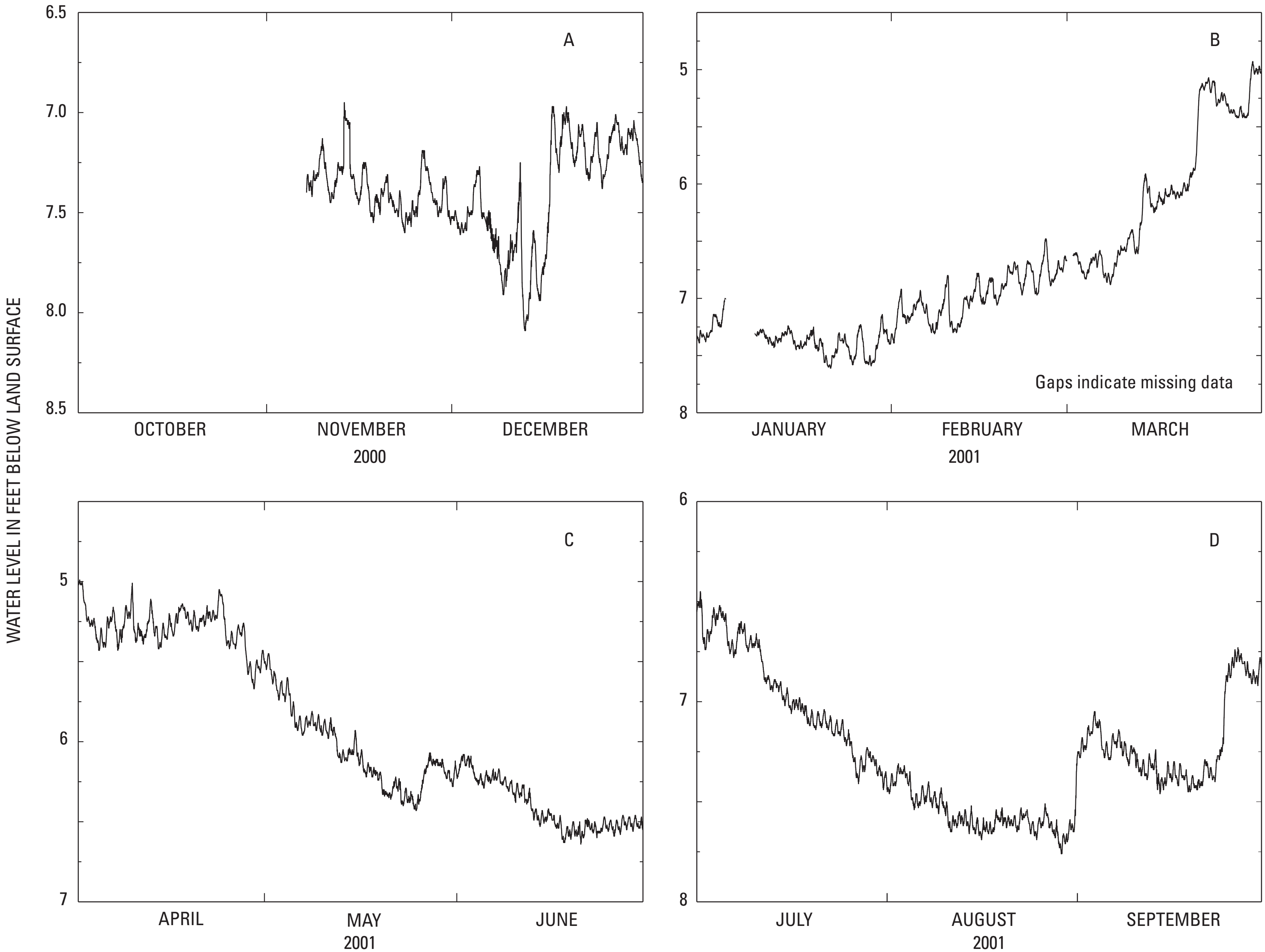

Figure 1-5. Water-level hydrographs for well Cn-394, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: November 7 to December 31, 2000; B: January 1 to March 31, 2001; C: April 1 to June 30, 2001; and D: July 1 to September 30, 2001.

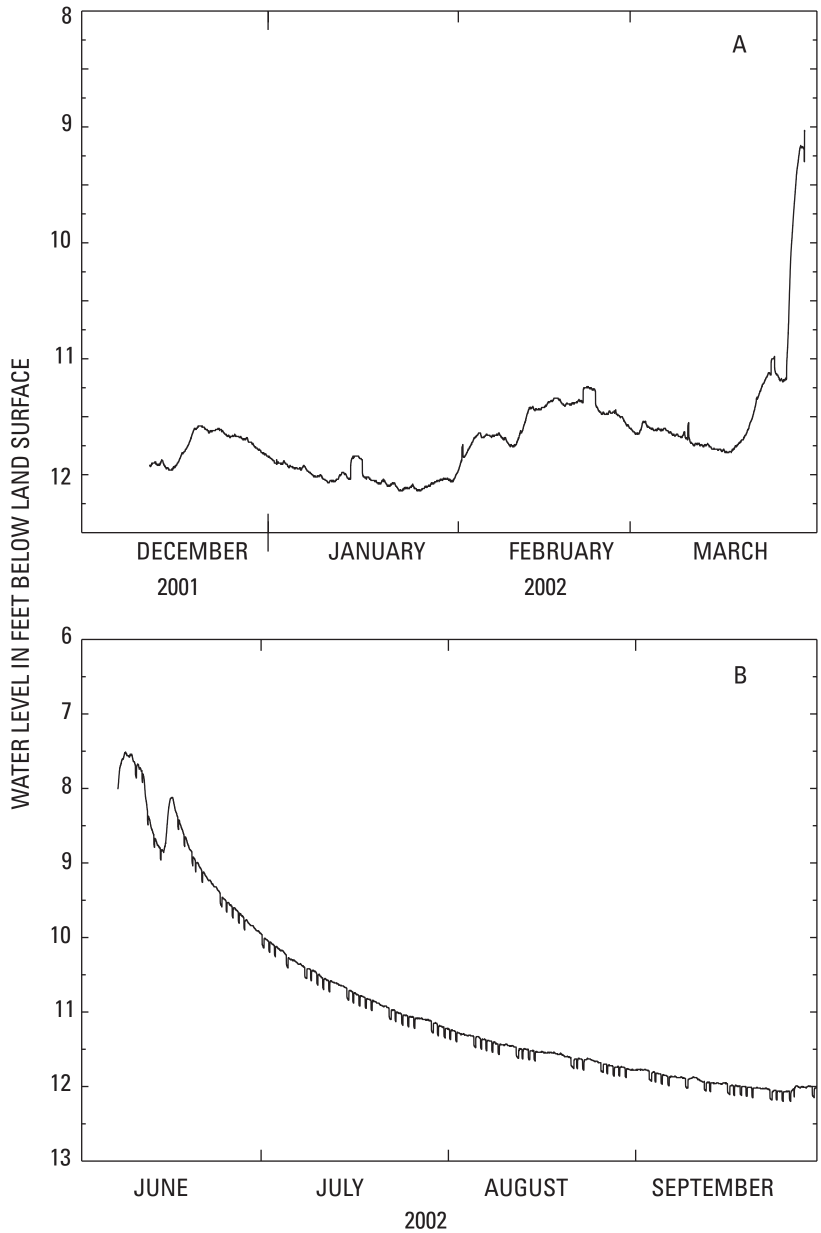

Figure 1-6. Water-level hydrographs for well Cn-398, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: December 12, 2001, to March 29, 2002; and B: June 7 to September 30, 2002.

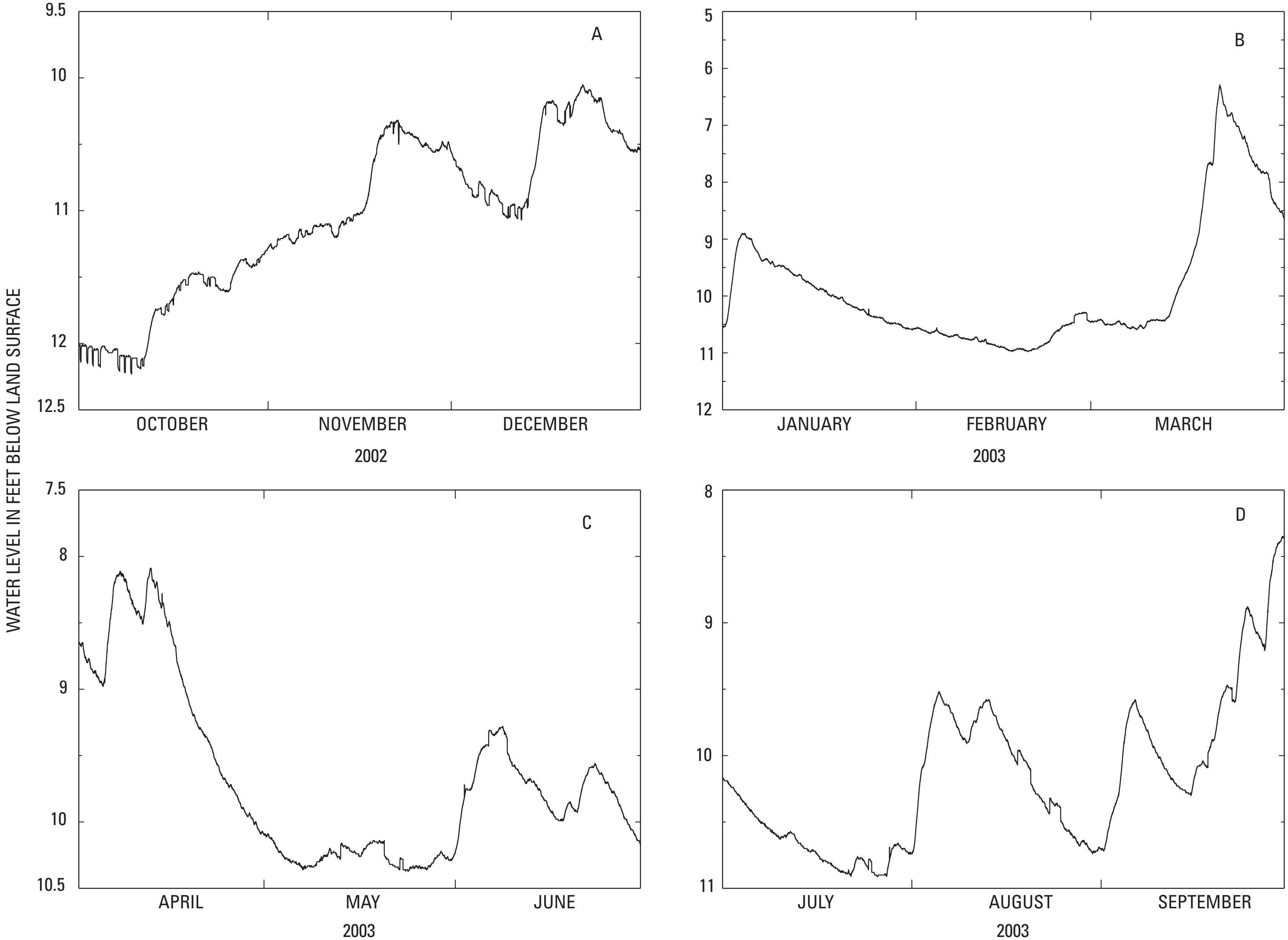

Figure 1-7. Water-level hydrographs for well Cn-398, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2002; B: January 1 to March 31, 2003; C: April 1 to June 30, 2003; and D: July 1 to September 30, 2003.

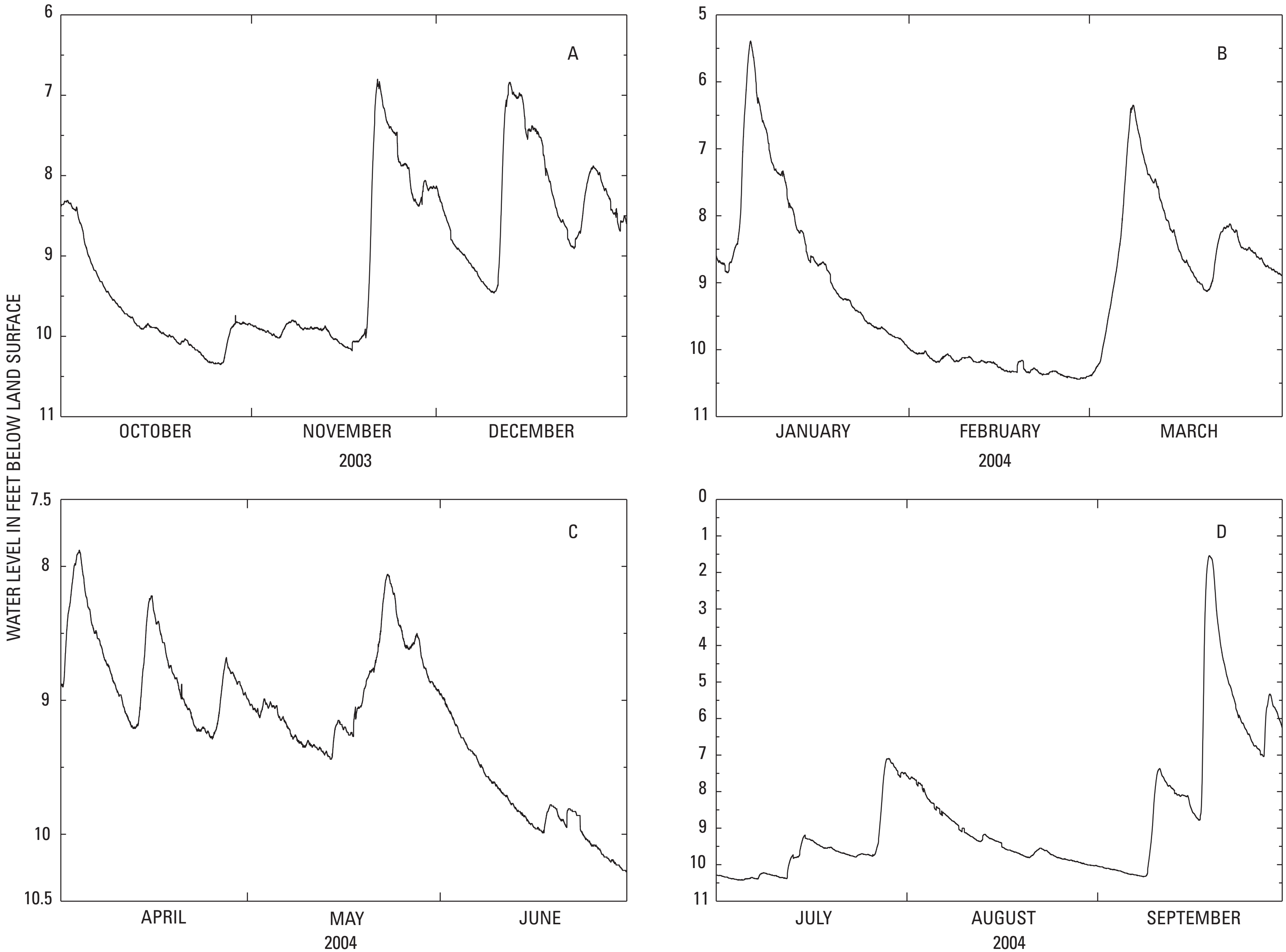

Figure 1-8. Water-level hydrographs for well Cn-398, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2003; B: January 1 to March 31, 2004; C: April 1 to June 30, 2004; and D: July 1 to September 30, 2004.

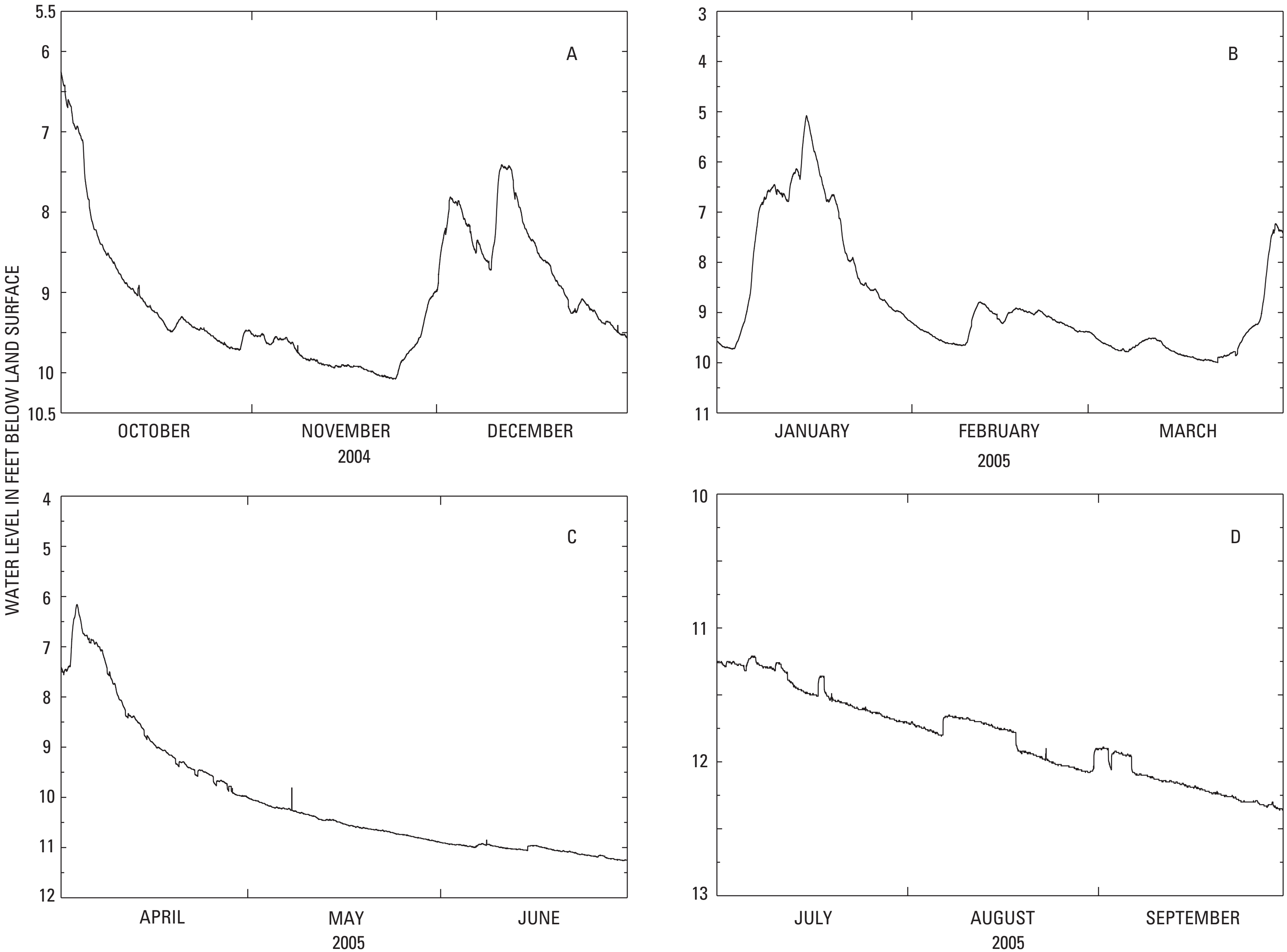

Figure 1-9. Water-level hydrographs for well Cn-398, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2004; B: January 1 to March 31, 2005; C: April 1 to June 30, 2005; and D: July 1 to September 30, 2005.

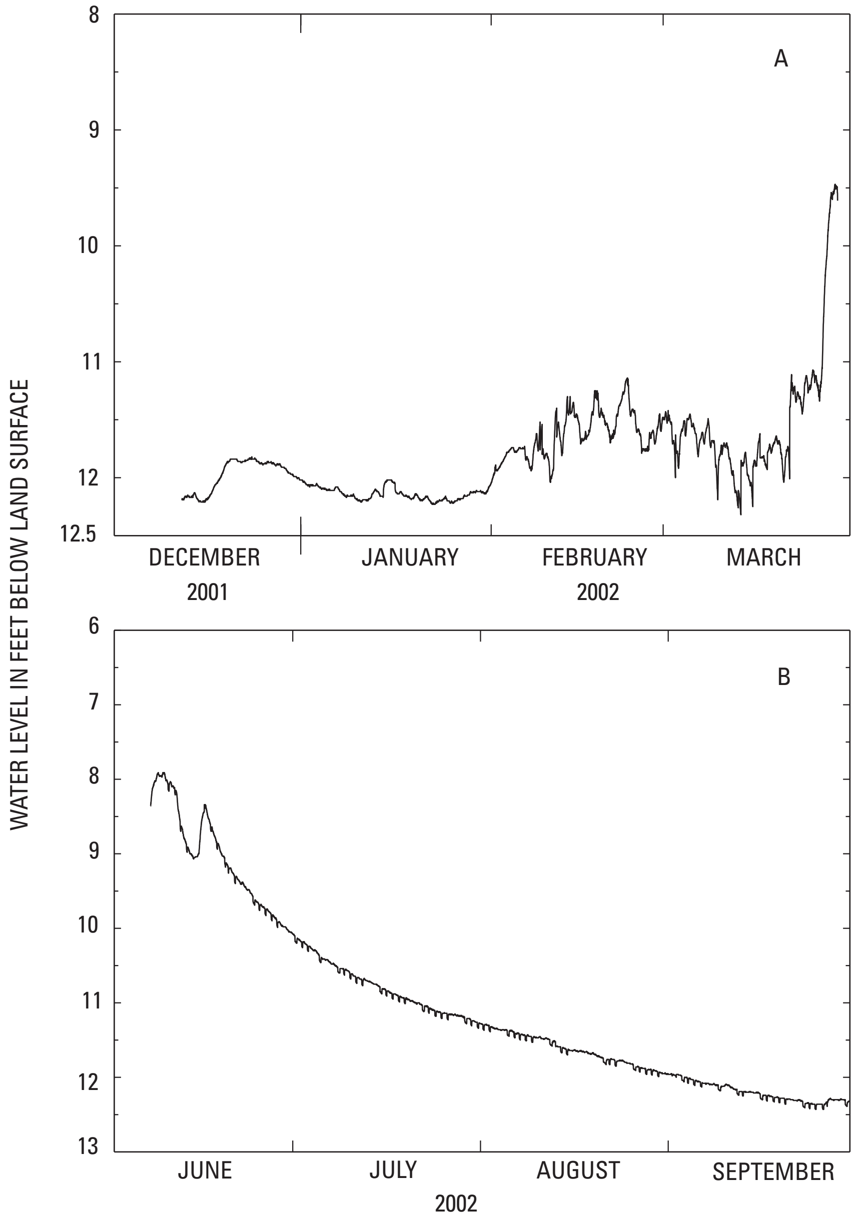

Figure 1-10. Water-level hydrographs for well Cn-399, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: December 12, 2001, to March 29, 2002; and B: June 7 to September 30, 2002.

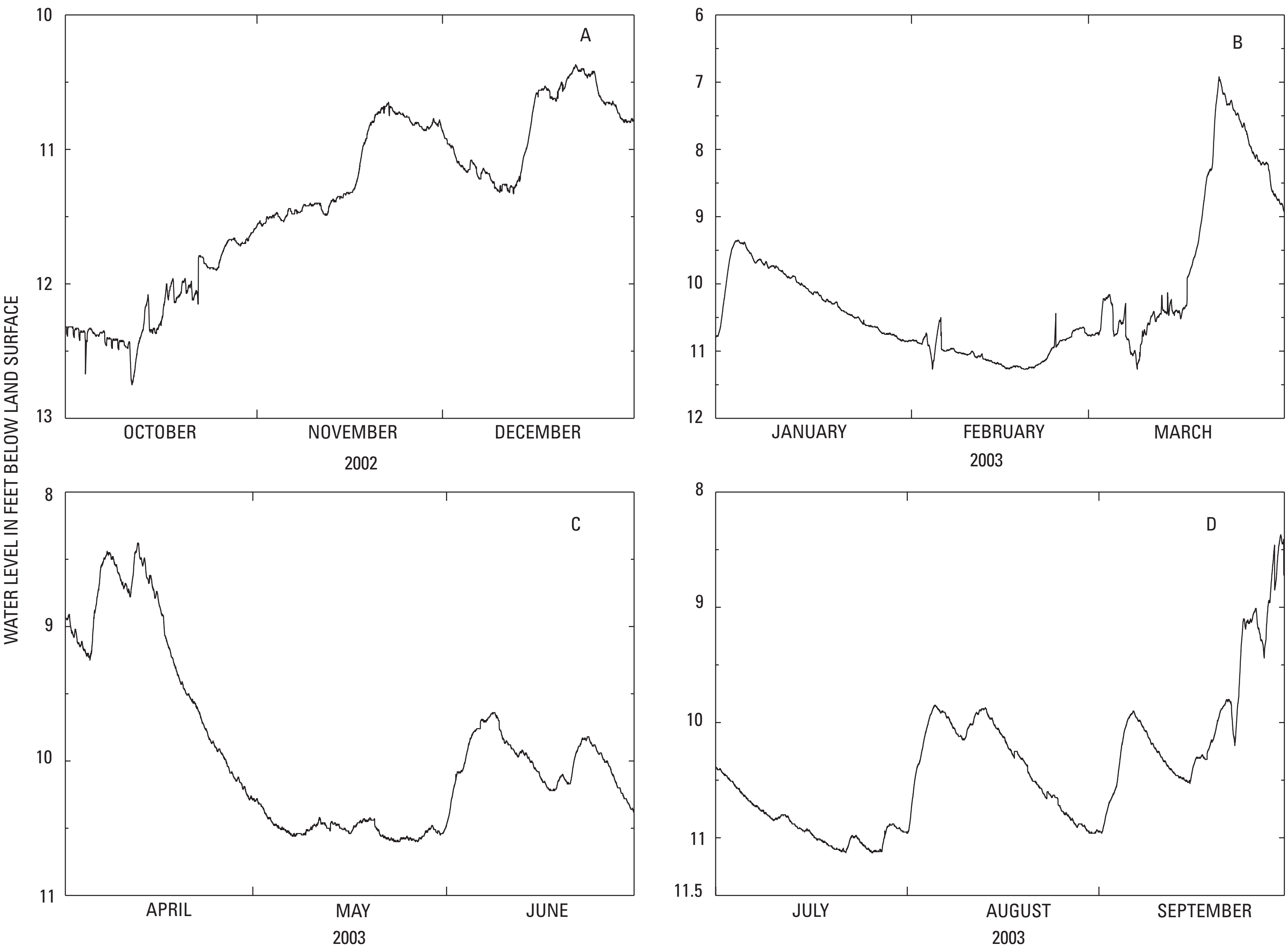

Figure 1-11. Water-level hydrographs for well Cn-399, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2002; B: January 1 to March 31, 2003; C: April 1 to June 30, 2003; and D: July 1 to September 30, 2003.

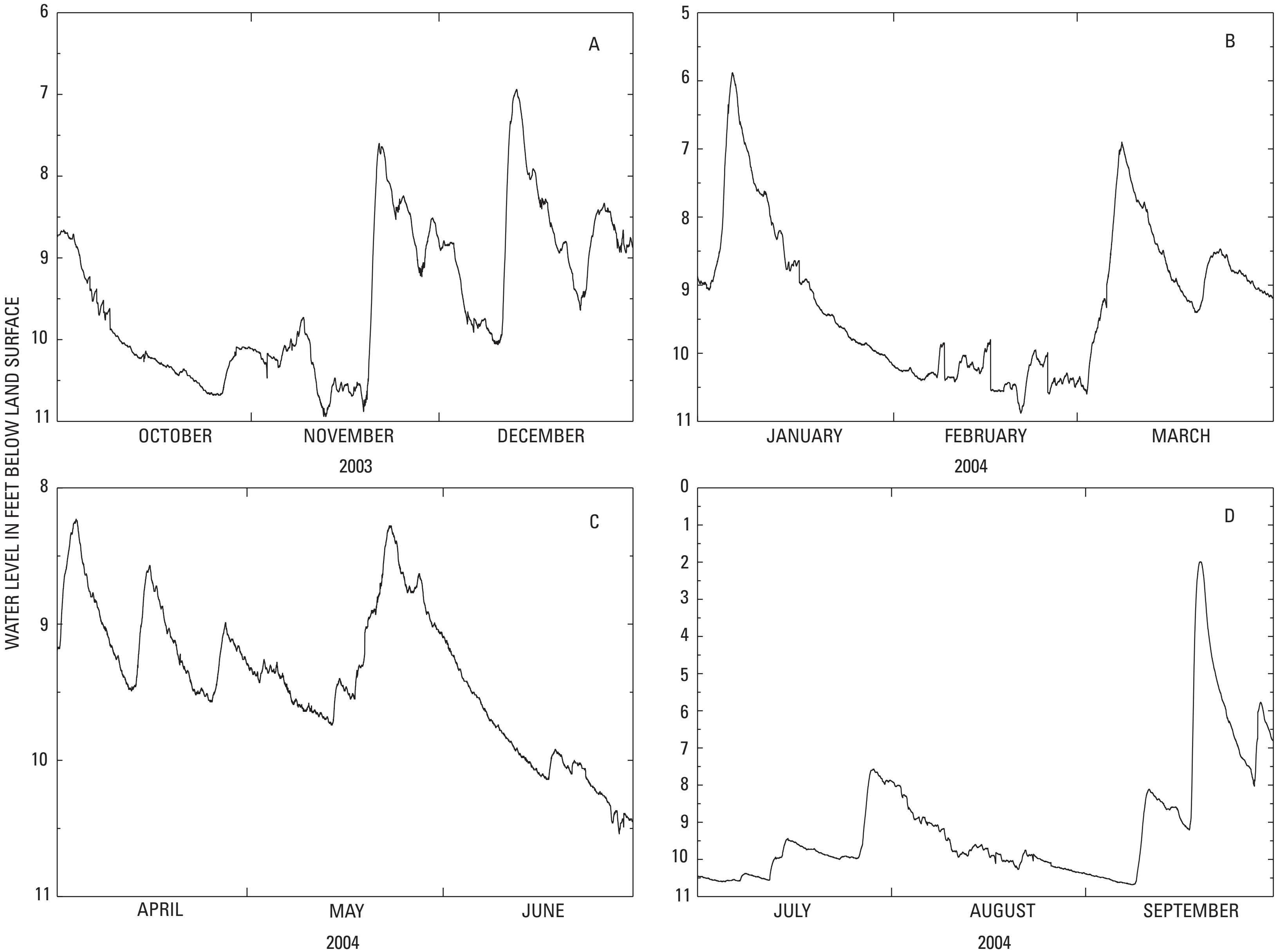

Figure 1-12. Water-level hydrographs for well Cn-399, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2003; B: January 1 to March 31, 2004; C: April 1 to June 30, 2004; and D: July 1 to September 30, 2004.

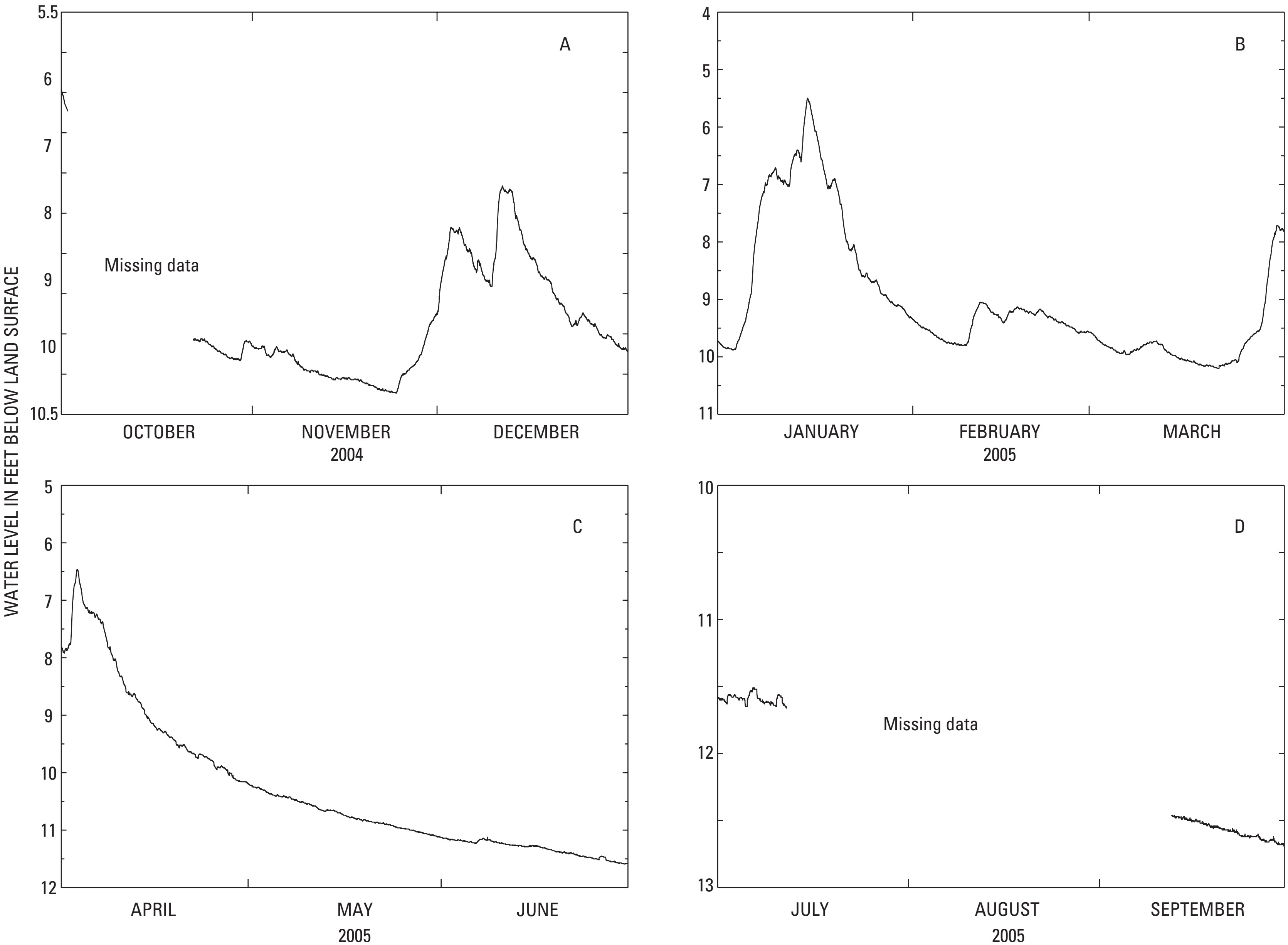

Figure 1-13. Water-level hydrographs for well Cn-399, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2004; B: January 1 to March 31, 2005; C: April 1 to June 30, 2005; and D: July 1 to September 30, 2005.

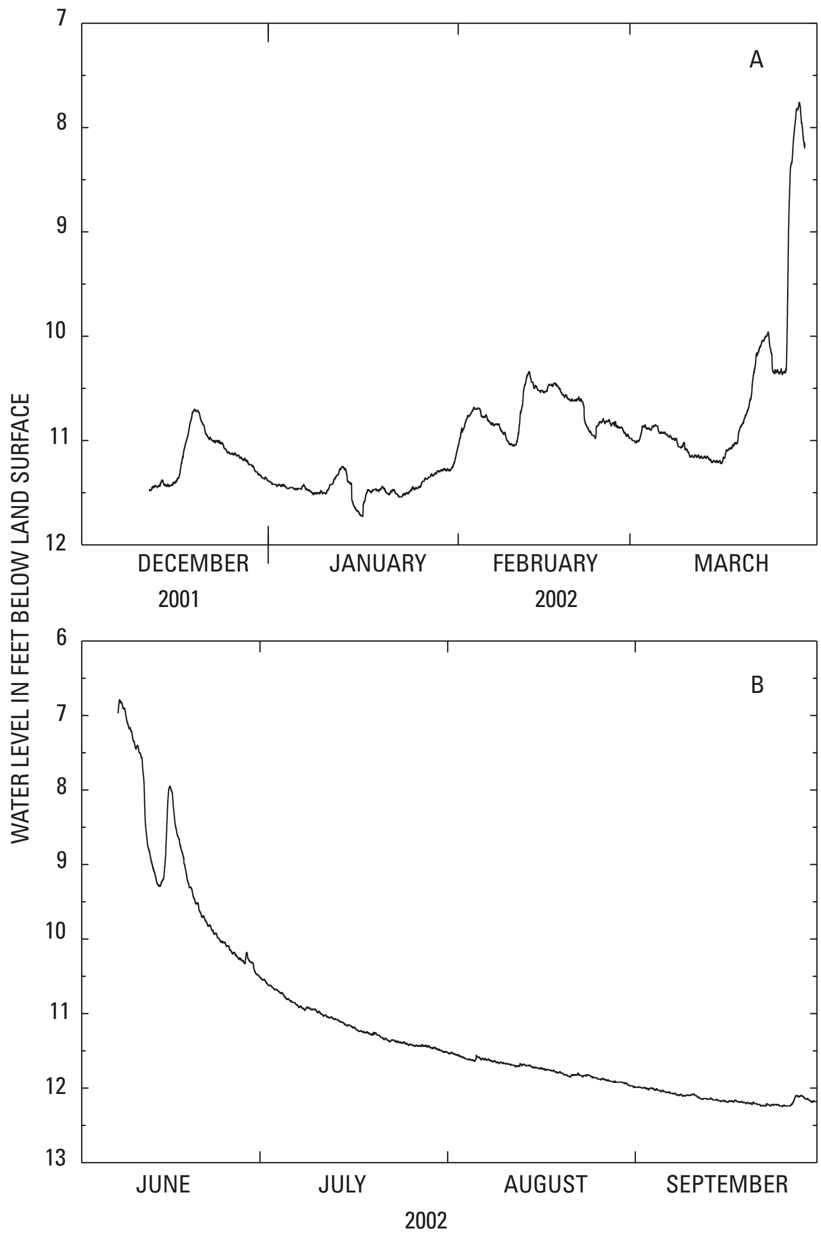

Figure 1-14. Water-level hydrographs for well Cn-419, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: December 12, 2001, to March 29, 2002; and B: June 7 to September 30, 2002.

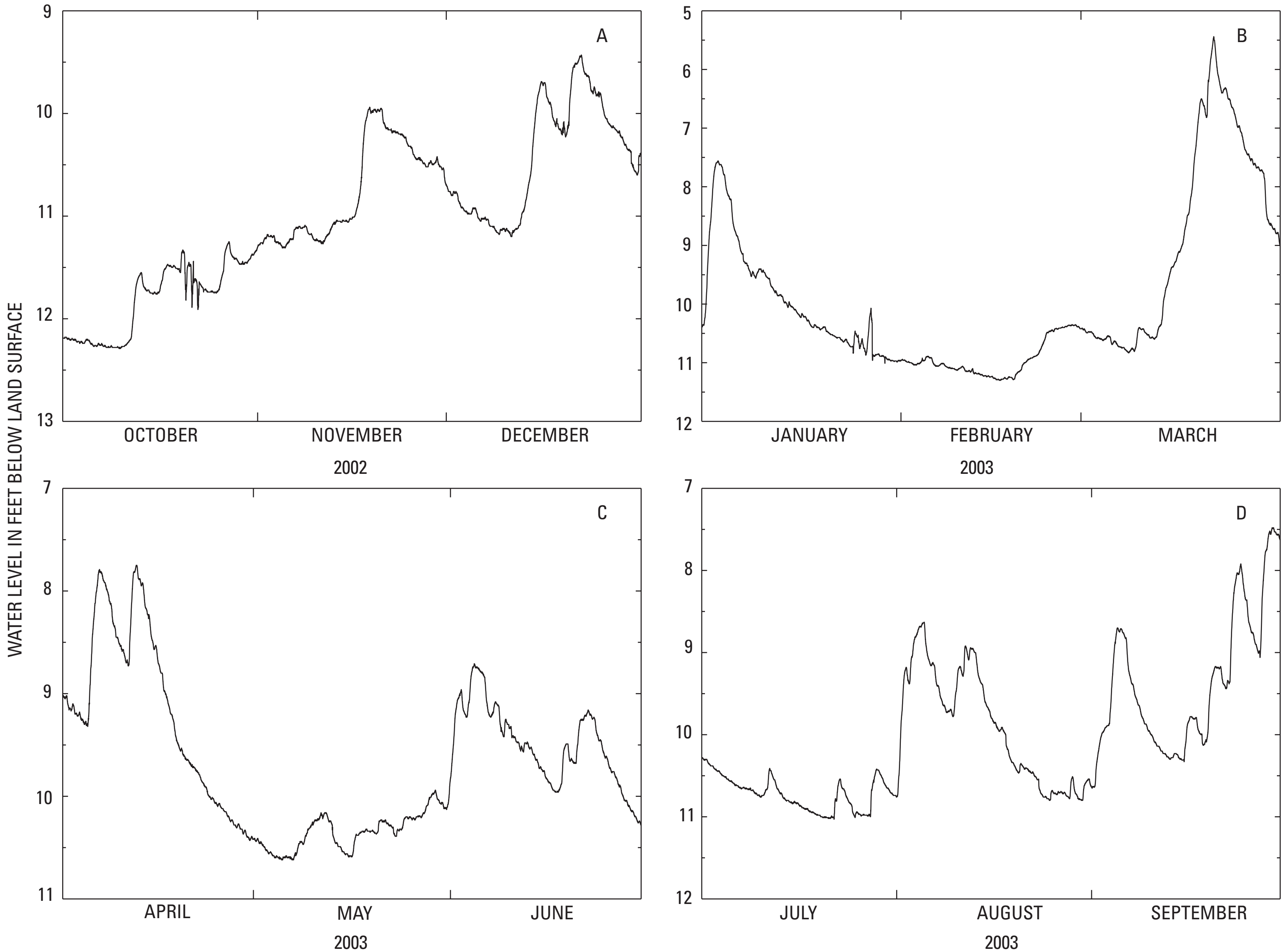

Figure 1-15. .Water-level hydrographs for well Cn-419, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2002; B: January 1 to March 31, 2003; C: April 1 to June 30, 2003; and D: July 1 to September 30, 2003.

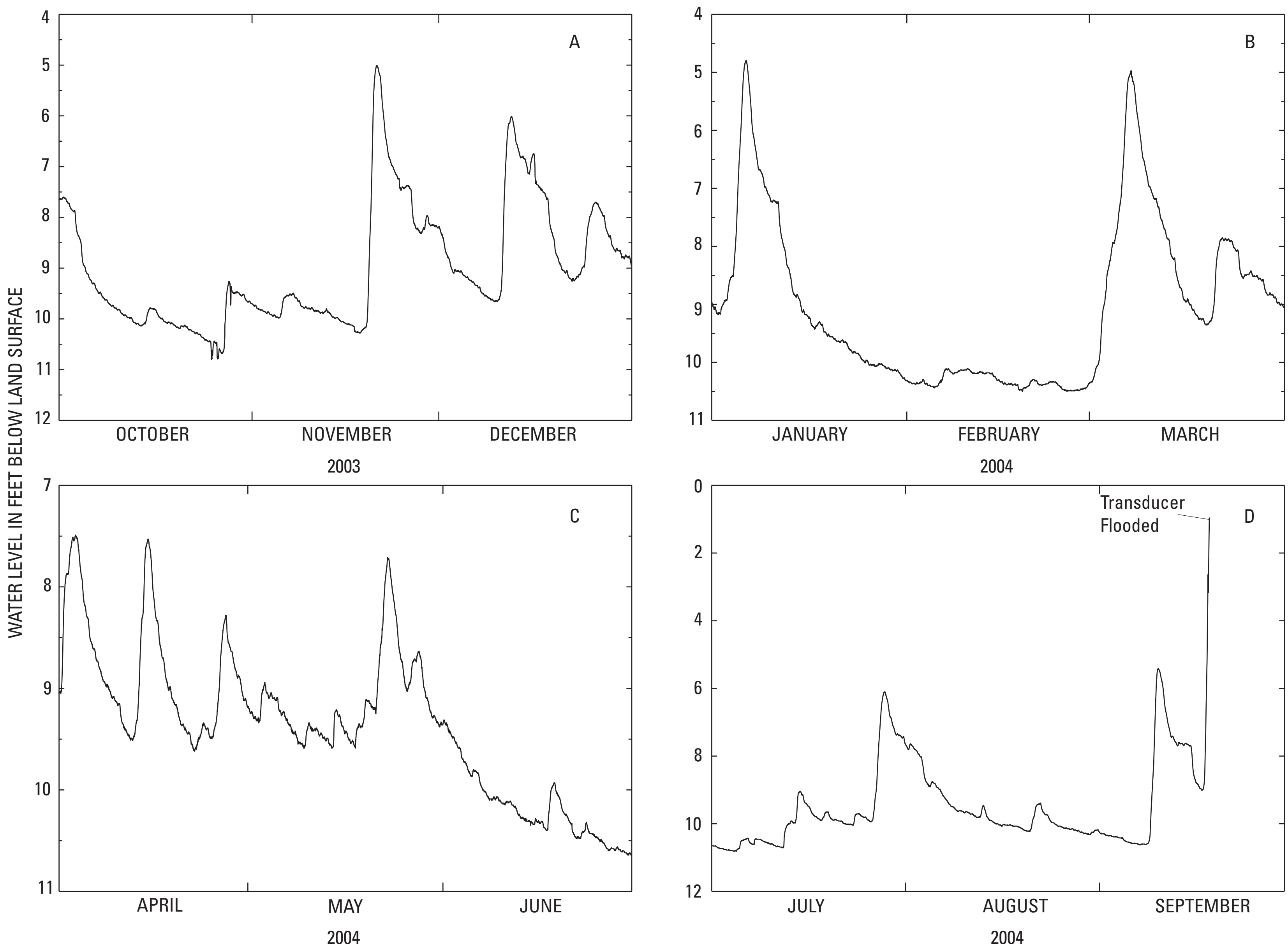

Figure 1-16. Water-level hydrographs for well Cn-419, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2003; B: January 1 to March 31, 2004; C: April 1 to June 30, 2004; and D: July 1 to September 30, 2004.

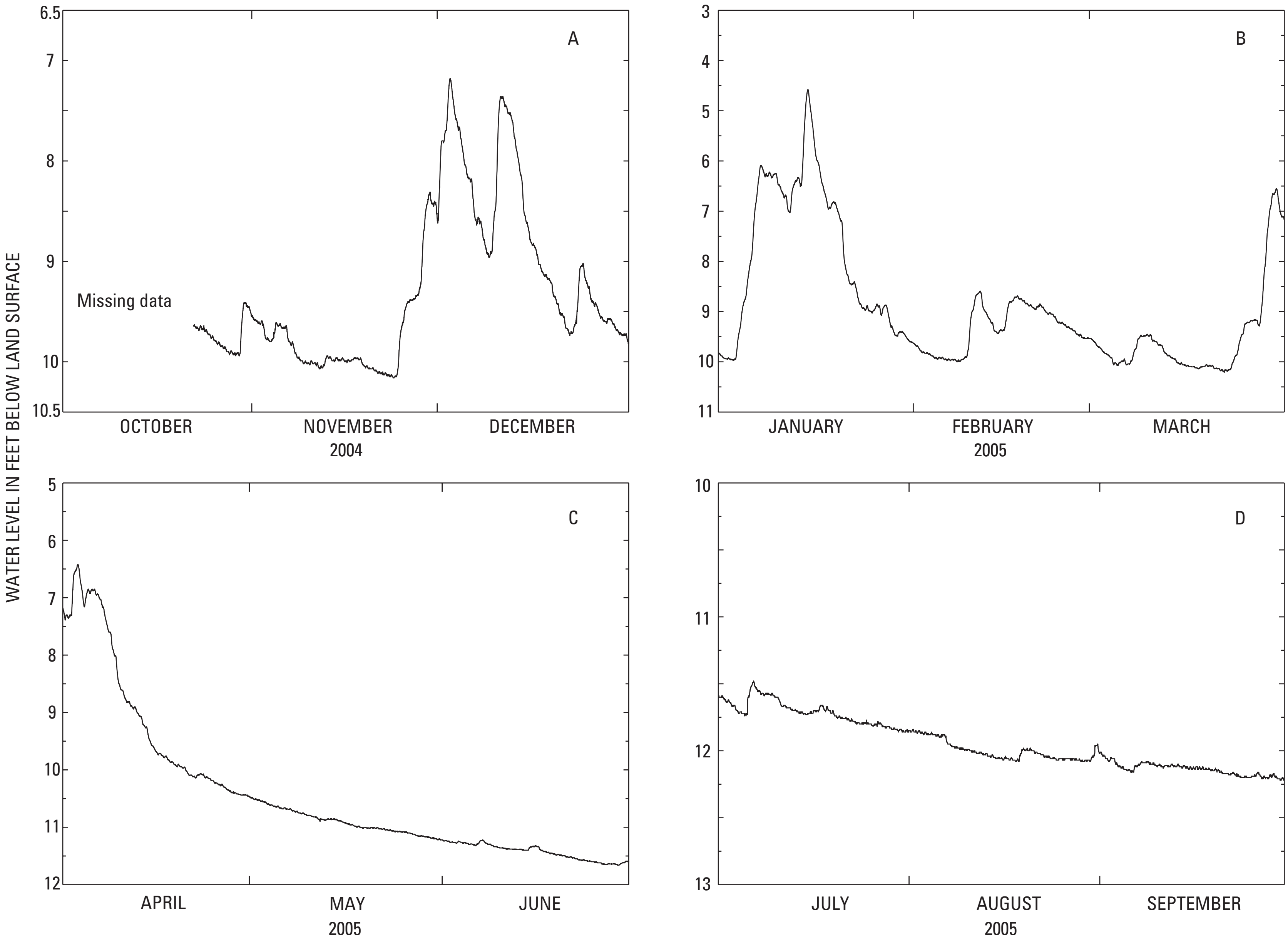

Figure 1-17. Water-level hydrographs for well Cn-419, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: October 1 to December 31, 2004; B: January 1 to March 31, 2005; C: April 1 to June 30, 2005; and D: July 1 to September 30, 2005.

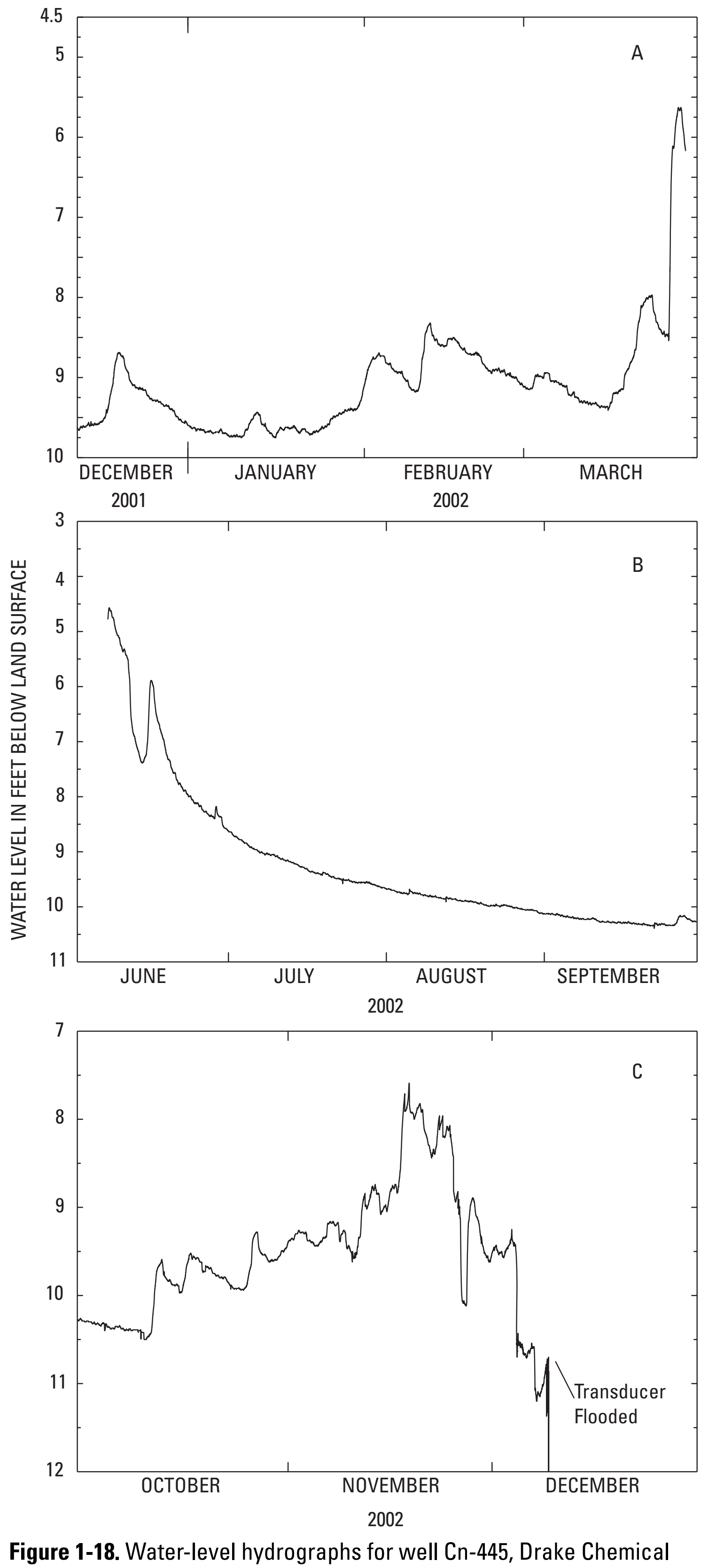

Figure 1-18. Water-level hydrographs for well Cn-445, Drake Chemical Superfund Site, City of Lock Haven and Castanea Township, Pa., A: December 12, 2001, to March 29, 2002; B: June 7 to September 30, 2002; and C: October 1 to December 9, 2002.