Prepared in cooperation with the Indiana Department of Natural Resources, Division of Reclamation

Hydrogeology and Simulation of Groundwater Flow at the Green Valley Reclaimed Coal Refuse Site near Terre Haute, Indiana

Scientific Investigations Report 2011–5116

U.S. Department of the Interior
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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ton	0.001	kilogram (kg)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	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)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88).

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.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Electromagnetic conductivity is given in millisiemens per meter (mS/cm at 25°C).

Other abbreviations or acronyms used in this report:

Acronym or abbreviation	Full name of acronym or abbreviation
Cl	Chloride
Fe	Iron
H	Hydrogen
Mo	Month
O	Oxygen
SO_4	Sulfate
PVC	Polyvinyl chloride
USGS	U.S. Geological Survey

Acknowledgment

The authors are grateful to Mr. Charles Lee, property owner, for access to the site.

Hydrogeology and Simulation of Groundwater Flow at the Green Valley Reclaimed Coal Refuse Site near Terre Haute, Indiana

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Abstract

The Green Valley reclaimed coal refuse site, near Terre Haute, Ind., was mined for coal from 1948 to 1963. Subsurface coal was cleaned and sorted at land surface, and waste material was deposited over the native glacial till. Approximately 2.7 million cubic yards of waste was deposited over 159 acres (92.3 hectares) in tailings ponds and gob piles. During 1993, the Indiana Department of Natural Resources, Division of Reclamation, improved the site by grading gob piles, filling tailings ponds, and covering the refuse with a layer of glacial drift. During 2008, the Division of Reclamation and U.S. Geological Survey initiated a cooperative investigation to characterize the hydrogeology of the site and construct a calibrated groundwater flow model that could be used to simulate the results of future remedial actions. In support of the modeling, a data-collection network was installed at the Green Valley site to measure weather components, geophysical properties, groundwater levels, and stream and seep flow.

Results of the investigation indicate that (1) there is negligible overland flow from the site, (2) the prevailing groundwater-flow direction is from northeast to southwest, with a much smaller drainage to the northeast, (3) there is not a direct hydraulic connection between the refuse and West Little Sugar Creek, (4) about 24 percent of the groundwater recharge emerges through seeps, and water from the seeps evaporates or eventually flows to West Little Sugar Creek and the Green Valley Mine Pond, and (5) about 72 percent of groundwater recharge moves vertically downward from the coal refuse into the till and follows long, slow flow paths to eventual discharge points.

Introduction

The Green Valley reclaimed coal refuse site (Green Valley site) includes approximately 159 acres of reclaimed gob (coarse coal refuse) and tailings (fine coal refuse) (Melchiorre, Dale, and others, 2005). The site was actively mined from 1948 to 1963 (Melchiorre, Dale, and others, 2005). Subsurface mining of Springfield Coal Member of the Petersburg Formation and Seelyville Coal Member of the Staunton Formation produced about 14 million tons of coal (Melchiorre, Dale, and others, 2005). The 2.7 million cubic yards of coarse coal refuse was deposited on the land surface, near the main shaft. The thickness of gob ranged up to 55 ft (Eggert and others, 1981; Melchiorre, Dale, and others, 2005). In the years after site abandonment, three studies documented the degradation of adjacent and downstream groundwater and surface-water resources as a result of acidic mine drainage and sedimentation (Caserotti and Marland, 1974; Eggert and others, 1981; Geosciences Research Associates, Inc., 1985).

In an effort to reduce water-quality degradation and the deposition of eroded refuse in adjacent waterways, the Indiana Department of Natural Resources, Division of Reclamation, made improvements to the Green Valley site during 1993. The gob piles were regraded, and tailings ponds were filled with gob. A thin layer of agricultural lime (less than 1 ft thick) was spread over the refuse surface, and the site was capped with an approximate 3 ft thickness of sandy till that was excavated from the property immediately east of the site (Mark Stacy, Indiana Department of Natural Resources, oral commun., 2009). A berm of sandy till was installed around the top of the largest, centrally located gob pile to limit overland flow. The surface of the capped refuse was plowed to create a corrugated surface to capture precipitation and limit overland flow. Acidophilic trees and grasses were sown into the cap material to stabilize the surface. Channels were installed around the base of the refuse piles and lined with cobble-sized dolostone riprap to chemically neutralize and control the conveyance of runoff and seep discharges.

Post-reclamation studies determined that acid mine drainage was still emanating from groundwater seeps at the Green Valley site and impairing water quality in adjacent waterways (Brake and others, 2001; Amt and others, 2003; Unger and others, 2003; Melchiorre, Dale, and others, 2005; Gibson, 2006). During 2008, the Indiana Department of Natural Resources, Division of Reclamation, and the U.S. Geological Survey (USGS) began a cooperative investigation to characterize the hydrogeology of the Green Valley site. The characterization was accomplished by collecting and analyzing field data, describing the hydrogeology, and using a calibrated computer model to simulate groundwater flow through and beneath the coal refuse deposit. One aspect of the mission of the USGS is to protect and enhance our Nation's water resources for human health, aquatic health, and environmental quality. This investigation supported the USGS mission by characterizing the hydrology of a site that may be adversely impacting water quality, and using data analyses and groundwater models to explore potential ways to improve the quality of water emanating from the site.

Purpose and Scope

This report describes the hydrogeology and hydrologic budget of the reclaimed coal refuse and the adjacent geologic deposits at the Green Valley site (study area in fig. 1). The analysis presents the basic field data, including continuous and periodic groundwater levels, continuous and periodic seep measurements, weather data, and surface and borehole geophysical surveys. The analysis also includes information describing the construction and calibration of a groundwater flow model, steady-state and time-dependent (transient) simulations done with the model, and descriptions of the simulated water table, groundwater-flow paths, and hydrologic budget. The groundwater-flow model was used to simulate the movement of acid mine drainage through the coal refuse and underlying till.

Field data were collected for this investigation from May 2008 through December 2009. The data-collection network was distributed across the entire site and monitored hydrologic conditions in the coal refuse and underlying glacial till. The network consisted of 26 monitoring wells, 5 seep discharges, 2 streamflow sites, and a weather station. Borehole geophysical logs (including gamma, electromagnetic induction, and horizontal flowmeter) were measured in one or more wells at most well sites. A surface electromagnetic induction survey was done around the perimeter of the site and across the center of the refuse. Slug tests were done in four wells to obtain data to compute hydraulic properties.

Previous Investigations

The Green Valley site and nearby waterways have been the subject of various scientific investigations, both before and after reclamation. Geosciences Research Associates, Inc. (1985) assessed the site prior to reclamation and documented the mining history, geologic setting, and hydrogeology. Refuse at the site is the result of operations between 1948 and 1963. The Springfield Coal Member was mined from approximately 313 ft below land surface until 1952. The Seelyville Coal Member was mined from approximately 503 ft below land surface until 1963. Room and pillar mining technique was used. The Springfield Coal Member extent was 380 acres, and the Seelyville Coal Member extent was 3,390 acres (Geosciences Research Associates, Inc., 1985).

Eggert and others (1981) described the geology and water quality of the Green Valley site after mining operations ceased but before reclamation; the analysis was done while assessing energy resources in the remaining coal refuse. Water-quality samples were collected from the reach of West Little Sugar Creek that borders the Green Valley site (upstream and downstream from the site), a tailings pond, a stream that drained the site, and a well located on one of the coal refuse piles (Eggert and others, 1981, p. 144). The quality of West Little Sugar Creek surface-water samples downstream from the Green Valley site was noticeably different from that of samples collected upstream, including a fivefold increase in dissolved solids. Caserotti and Marland (1974) similarly documented the effects of effluent from the Green Valley site on West Little Sugar Creek.

Brake and others (2001), Amt and others (2003), Unger and others (2003), and Gibson (2006) examined water quality in West Little Sugar Creek after reclamation and concluded that water quality in West Little Sugar Creek was not improving and might be getting worse with time. Gibson (2006) concluded that water quality in the creek was directly related to streamflow. Brake and others (2001) and Amt and others (2003) indicated that impairment of water quality and ecological communities in West Little Sugar Creek was the result of elevated concentrations (above background concentrations) of chemical constituents in seep effluent that discharged to the creek. Concentrations of most major and trace elements decreased with increasing distance from the confluences of West Little Sugar Creek and seep channels on the Green Valley site.

Unger and others (2003), Melchiorre, Dale, and others (2005), and Melchiorre, Mills, and others (2005), studied the water quality and mineralogy associated with the seeps. Unger and others (2003) compared constituent concentrations in seeps at the Green Valley site with concentrations in unaffected surface water from nearby waterways and determined that the seeps contained much higher concentrations of various trace elements relative to the other samples. Melchiorre, Mills, and others (2005) documented the occurrence of a relatively rare mineral, xitieshanite [$Fe^{3+}(SO_4)Cl\cdot 6H_2O$], at the Green Valley site. The mineral precipitated at a location where seep water flowed over limestone riprap and glacial till.

Melchiorre, Dale, and others (2005) examined water chemistry and oxygen stable isotopes in samples of groundwater, surface water, and precipitation collected on-site between September 2000 and January 2002 to describe hydraulic properties of the coal refuse at the Green Valley site. Melchiorre, Dale, and others (2005) collected samples from four wells (GV1, GV2, GV3, and GV4); wells GV1, GV2 and GV3 are screened in glacial drift and located around the periphery of the refuse deposit, whereas GV4 is screened in the coal refuse. The specific conductance of water samples from four wells on the site responded almost immediately to rainfall, but a 30-day lag preceded noticeable dilution in water emanating from

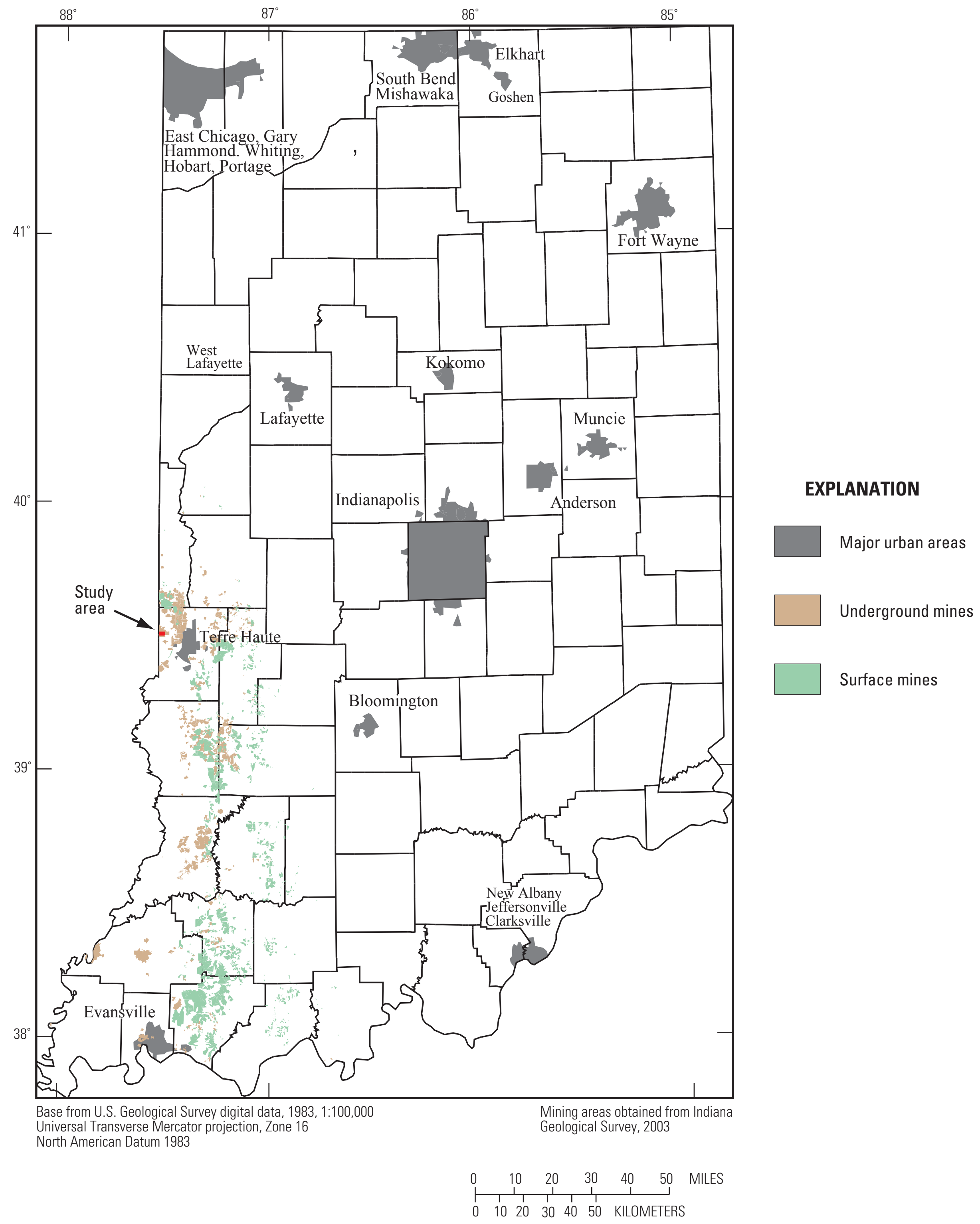


Figure 1. Location of the Green Valley mine site, near Terre Haute, relative to underground and surface coal mines in southwestern Indiana.

the seeps. Oxygen isotope data indicated that precipitation recharged groundwater flowed to wells GV1, GV2, and GV3 in less than 8 days and GV4 in about 27 days. Changes in isotope values data collected at three seeps, including S3 and S4 from this investigation (and a third site that did not seep during this investigation) lagged precipitation inputs by 60, 90, and 105 days, respectively. Hydraulic conductivities computed from these data ranged from 1.05 to 7.37 ft/d in the glacial drift and from 7.37 to 16.44 ft/d in the gob. Melchiorre, Dale, and others (2005) concluded that multiple sources of recharge were required to produce their observations; they hypothesized that one source of water was infiltrating precipitation and that a second source was water expelled from pre-mining karst-like features.

Jennifer Bellamy (Indiana State University, written commun., 2007) examined the effect of the Green Valley site on water and sediment chemistry in adjacent John A. Scott Lake and the Green Valley Mine Pond. John A. Scott Lake was created by the excavation of till that was used to cap the refuse. On the basis of chemical analyses of water and sediment, Jennifer Bellamy (Indiana State University, written commun., 2007) concluded that bank sediments in John A. Scott Lake were not contaminated by mine drainage from the Green Valley site. Seep effluent from the northeastern part of the Green Valley site into the headwaters of Green Valley Mine Pond, however, resulted in elevated concentrations of minor and major elements in the vicinity of the channel mouth.

Hydrologic Setting

The study area is in the Central Wabash Valley physiographic area of the Central Tipton Till Plain region of western Indiana, near the southern limit of Wisconsin glacial deposits (Gray, 2000). Surface topography ranges from nearly flat to gently rolling. Surficial deposits in the surrounding area and beneath the coal refuse deposit are composed of glacial drift. The glacial drift is till that was deposited during the Wisconsin glacial episode, underlain in most places by till deposited during the Illinois glacial episode; the latter appears at land surface only where the former has been severely eroded (Schneider, 1966). The till is generally sandy, with interbedded silty and sandy-till stringers. Streams near the site are underlain with a nominal thickness of relatively younger alluvium than is found at distance from the streams. The thickness of till varied beneath the study area. A test boring done as part of this investigation at site GV8, near the center of the refuse deposit, determined that the thickness of glacial drift was about 50 ft. A boring by Geosciences Research Associates, Inc. (1985), as part of an earlier investigation, struck shale at 45 ft below the natural land surface. A hydrogeologic cross section through the study area, based on well-record information from this investigation and from the Indiana Department of Natural Resources (2002), indicates that the till thickness is varied (fig. 2).

At the Green Valley site, the glacial till is overlain by coal-mining refuse. The refuse deposits consist of gob, tailings, and mining-related rubbish. Gob, created by beneficiation of coal at land surface, was described by Geosciences Research Associates, Inc. (1985), as "rock, mineral and coal fragments that are wastes from the tipple or preparation plant." Tailings include "accumulations of fine gravel, sand, silt and clay size fragments or particles of coal and other materials that are washed out of the coal in the wash or preparation plant" (Geosciences Research Associates, Inc., 1985). Additional wastes deposited at the site may include debris from the mine roof, underclay, and refuse from the tipple and mining equipment. Underclay is a layer of clay beneath a coal bed. A railway grade that formerly crossed the site from northwest to southeast was determined to be composed of soil, gravel, and coal with occasional concrete piers, culverts, and wooden trestles.

Geometry of the deposits is uncertain, but maps constructed prior to reclamation showed the general distribution of gob and tailings (Geosciences Research Associates, Inc., 1985; fig. 3). The land-surface area of the two gob piles was approximately 42 acres. During reclamation, the elevation and slope of gob piles was reduced by moving material from higher elevations into the lower lying areas. Well-driller records generated as part of this investigation indicate that thickness of the coal refuse ranges from zero, at the margins of the site, to as much as 69 ft at GV9 near the center of the Green Valley refuse deposit; the exceptional thickness at GV9 is attributed to the well site's being positioned over a depression in the underlying till.

John A. Scott Lake was created immediately east of the Green Valley site by the excavation of glacial till used to cap the coal refuse. John A. Scott Lake is connected by a short channel to the Green Valley Mine Pond. The level of the pond is maintained by use of an engineered overflow and, as a result, little variability (less than 0.5 ft) in lake or pond-surface water levels was observed during this investigation. Depth of John A. Scott Lake is approximately 45 ft.

The study area is in the Wabash River drainage basin. The Green Valley site drains to West Little Sugar Creek to the west and the Green Valley Mine Pond to the east. West Little Sugar Creek merges with Sugar Creek, which flows into the Wabash River approximately 11 mi downstream from the Green Valley site. The drainage area of West Little Sugar Creek above the Green Valley site is approximately 6.2 mi^2 (*http://water.usgs.gov/osw/streamstats/indiana.html*; accessed February 2, 2010).

West-central Indiana, including the study area, has a continental climate. Temperatures in the study area generally range from an average low of about 18°F in January to an average high about 87°F in July (Midwestern Regional Climatic Center, 2010a), and the average annual temperature is 54°F (Clark, 1980). Rainfall is fairly evenly distributed throughout the year but is typically highest from March to

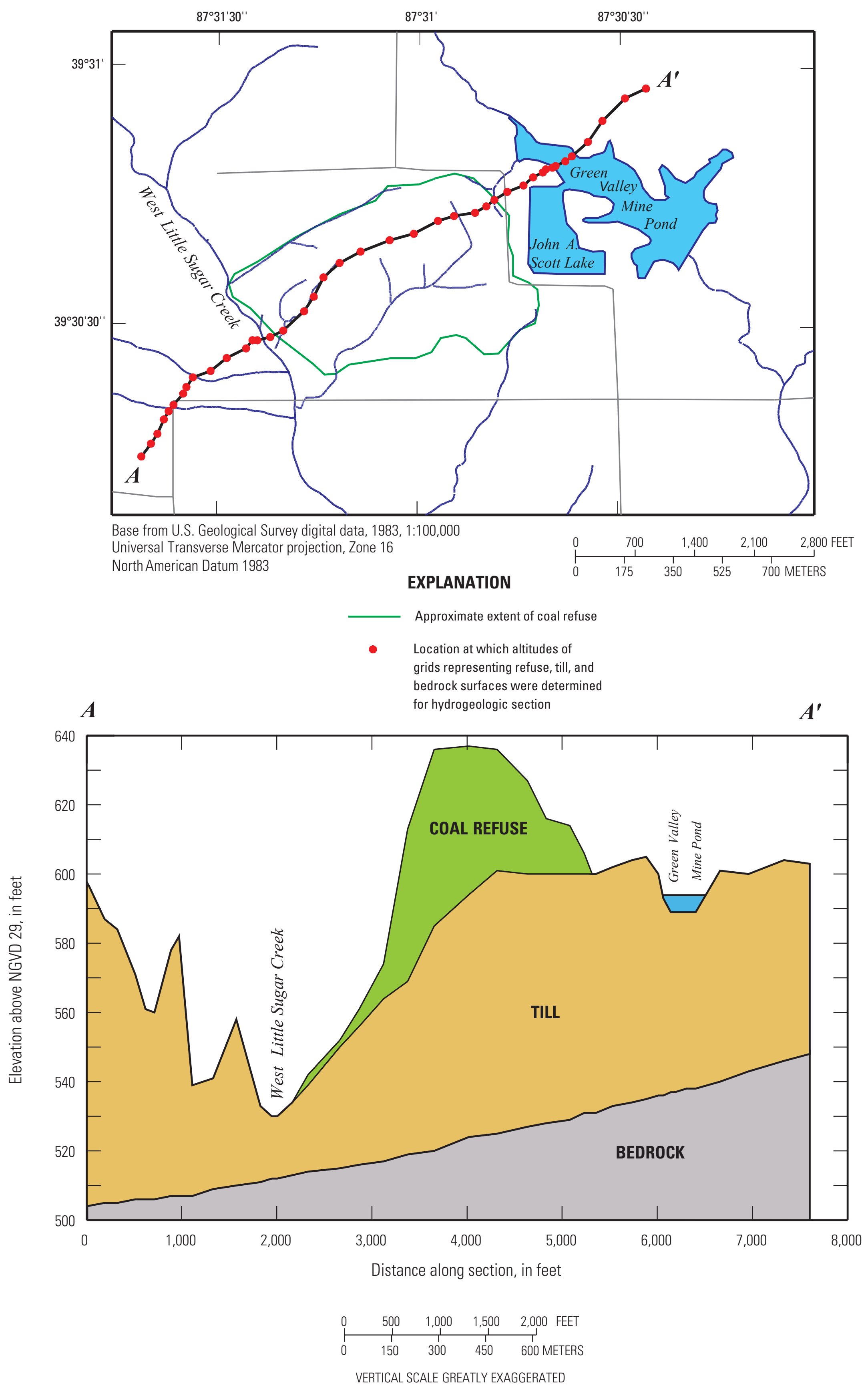


Figure 2. Hydrogeologic section showing the variation in thickness of deposits in the Green Valley mine site, Indiana.

August (averages ranging from 3.68 to 4.46 in./mo) and lowest in September to February (averages ranging from 2.13 to 3.39 in./mo); annual precipitation averages about 42 in. (Midwestern Regional Climatic Center, 2010b). The statewide annual average evapotranspiration is about 69 percent of the net precipitation, and recharge averages 12 in. (Clark, 1980).

Methods of Investigation

A data-collection network was installed at the Green Valley site to measure weather components, geophysical properties, groundwater levels, seep discharge, and streamflow. The installations consisted of a weather station, monitoring wells, a weir, and controlled outfalls. Measurements collected from the data network were used to characterize the site hydrology, create input data and flow and head constraints for the groundwater-flow model, and provide verification data for the simulated water budget. All data were collected, preserved, and reported according to methods that meet the standards of the USGS.

A weather station (Vaisala Model WXT520) was installed at the Green Valley site to collect data that would be used to understand relations between weather and site hydrology. A tipping-bucket rain gage was installed approximately 20 ft from the weather station. The weather instruments were installed in an open, grassy area near the highest elevation at the site and approximately midway between well sites GV4, GV8, and GV9 (fig. 4). Measured weather variables were wind speed, wind direction, humidity, temperature, and

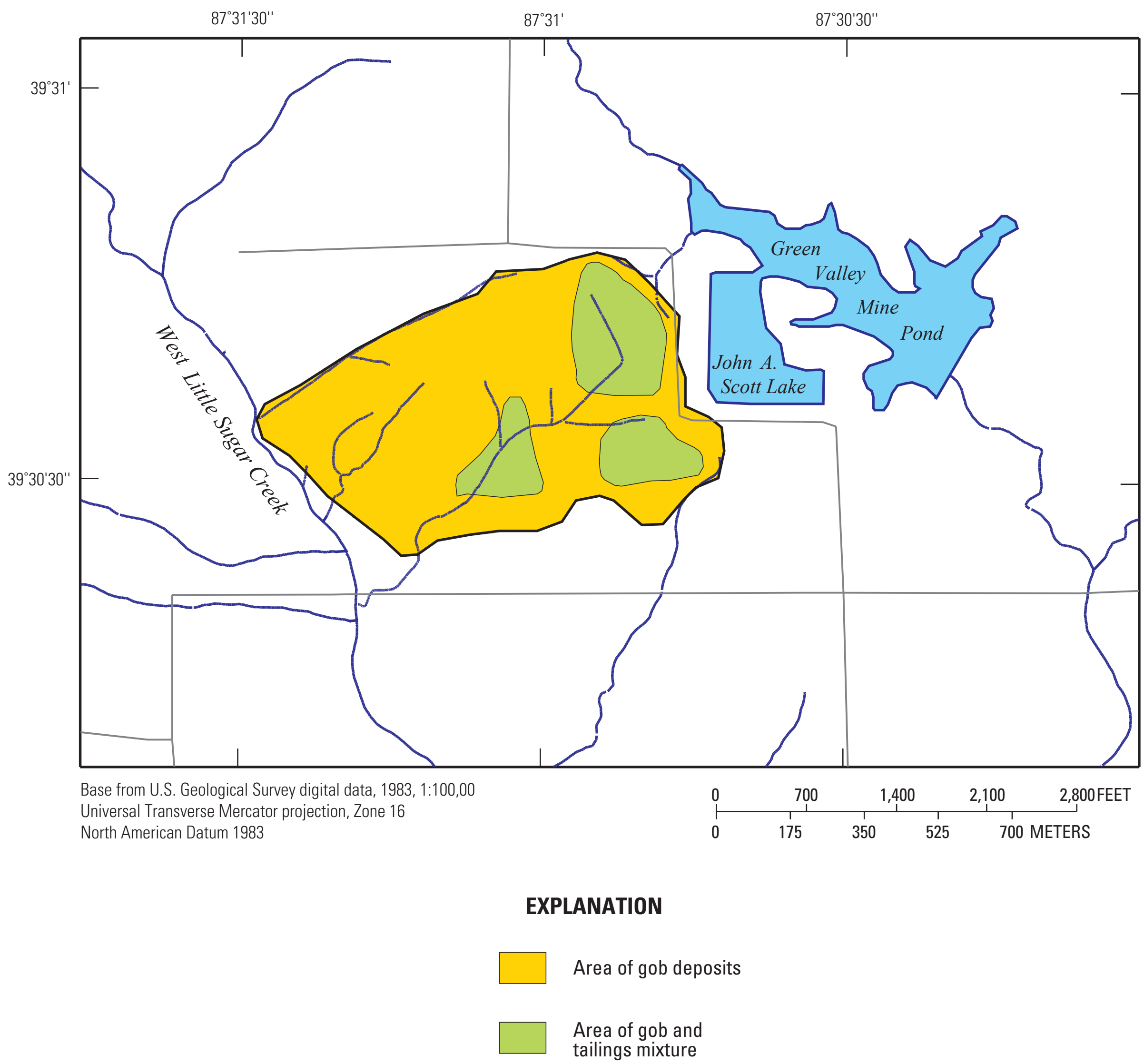


Figure 3. Areal extents of gob and mixed gob and tailings deposits in the coal refuse at the Green Valley mine site, Indiana.

precipitation. Precipitation was measured with an impact sensor and a tipping-bucket gage. Measurements were totaled every 60 minutes and radio-transmitted from the weather station to the USGS Indiana Water Science Center office in Indianapolis every 3 hours. The weather data were archived in the USGS National Water Information System (U.S. Geological Survey, 2010).

Twenty-two monitoring wells were installed at 16 sites, including 2 wells installed at 4 sites and 3 wells installed at one site, during June–August 2008. At each of the 16 sites, a 4-in.-inside-diameter polyvinylchloride (PVC) casing was installed and completed with a 0.010-in. slotted well screen. A filter pack of No. 4 sand was used to fill the annular space to

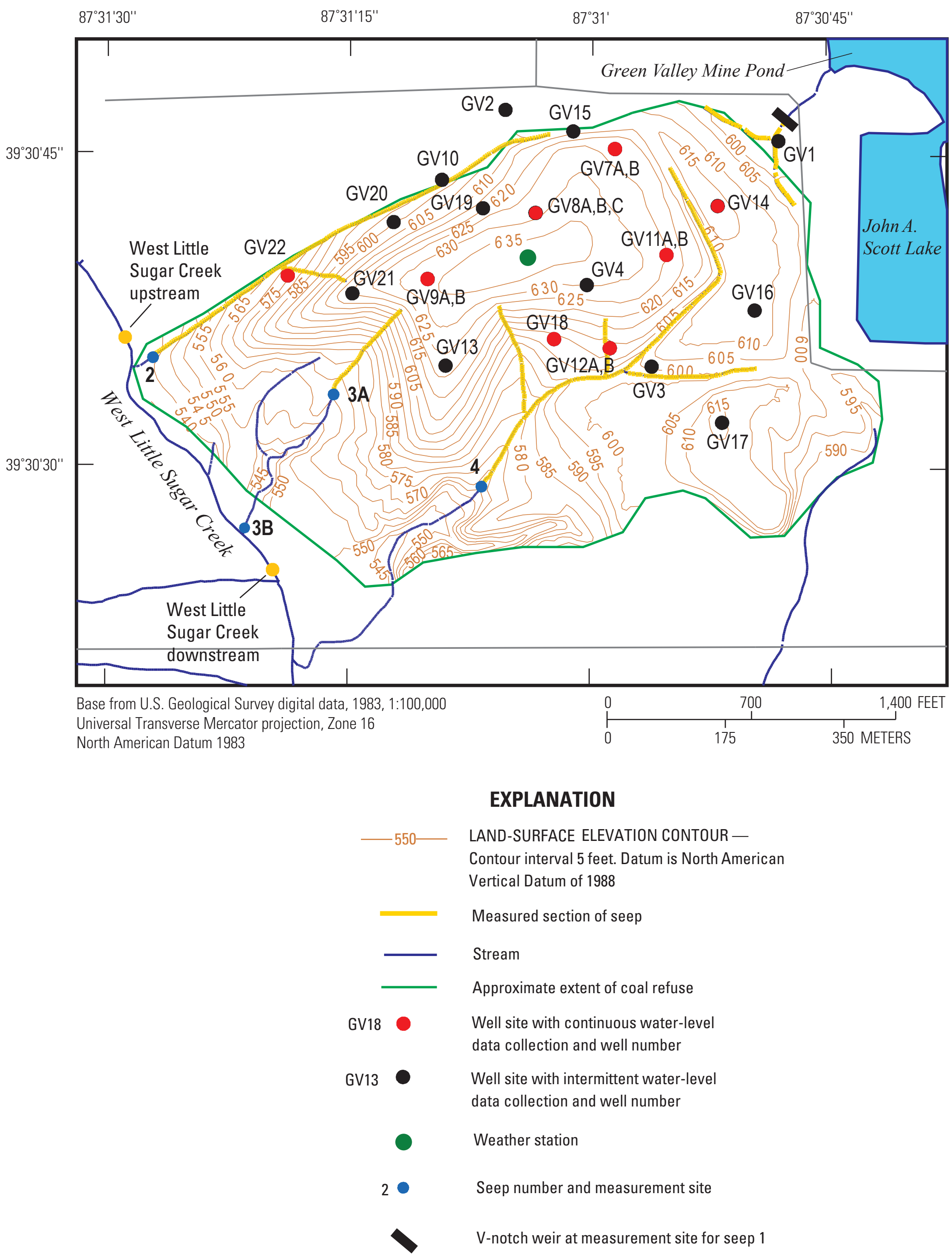


Figure 4. Location of monitoring wells, weather station, and V-notch weir at the Green Valley mine site, Indiana.

1 ft above the screen. The remaining annular space was sealed with bentonite chips to within 2 ft of land surface. A concrete plug and steel well-protector were used to finish the well. Second and third wells at clustered-well sites were constructed from 2-in.-inside-diameter PVC casing and slotted screens. The 2-in. wells were finished in the same fashion as the 4-in. wells. The 4-in. well screens had six columns of slots, and the 2-in. well screens had four columns of slots. Wells were installed by using hollow-stem drilling methods and developed by pumping for a minimum of 1 hour. The latitudes, longitudes, and elevations of measuring points of wells were surveyed by the IDNR using a global positioning system. An IDNR investigation during 2000 installed four additional 2-in. wells that were included in the data-collection network. Those wells were constructed with methods and materials similar to those used during this investigation; however, the bentonite was tremied (rather than poured) into the annular space, and the wells were not completed with a concrete plug and steel well-protector. In total, the groundwater monitoring network has 26 wells at 20 sites (table 1, figure 4).

Twenty-one of the well screens installed during 2008 extended from 0 to 3 ft below the refuse-till interface to about 5 ft below land surface. Screen lengths ranged from 5 to 30 ft. The purpose for long well screens was to accommodate borehole flowmeter measurements. Well GV8C was fully cased except for the bottom 5 ft; this well was screened across the shallowest sandy horizon found in the till beneath the refuse-till interface. The total depths of wells ranged from 14 to 74 ft below land-surface datum. Wells were developed by pumping for a period of 1 hour. Wells GV1–3 were cased entirely through till and screened across sandier zones that were penetrated. All other wells were screened mostly or entirely in coal refuse.

The depth to water was measured in all wells with an electric tape approximately once per month, provided that sites were accessible; during some visits the well-protectors were frozen shut or the water in the well was frozen (Appendix 1). Pressure transducers were installed in nine wells and used to measure the water-level elevation at 60-minute increments from November 2008 through December 2009. Vented transducers were installed in wells GV8C, GV9A, GV11A, and GV18 (In-Situ model Level Troll 500) and in wells GV7A, GV8A, GV12A, GV14, and GV22 (Global Water model WL16). Accuracy of the transducer measurements of water levels was approximately ±0.01 ft. Transducer measurements of water levels were adjusted for mechanical drift by linearly averaging the difference between the transducer and electrical-tape measurements over the period between electrical-tape measurements. Tape-down measurements of groundwater levels were not made during September–December 2009; transducer measurements of water levels during this period were not corrected for mechanical drift. Well-construction records, location, elevation, and water-level measurements for all wells were preserved in the USGS Ground-Water Site-Inventory (GWSI) system.

Borehole and surface geophysical measurements were used to acquire additional information about the hydrogeology at the site. Borehole geophysical measurements were made in the well network at the Green Valley site to gather information about the stratigraphy, water quality, and groundwater flow. Surface measurements of electromagnetic induction were made on transects inside and outside of the property boundaries and across the center of the coal refuse. Borehole geophysical measurements consisted of continuous logs of natural-gamma activity and electromagnetic induction, and discrete measurements of groundwater velocity and direction. Natural-gamma activity was measured through the entire well profile in one well at all 20 well sites (Appendix 2). Electromagnetic induction was measured through the entire well profile in 1 well at 11 sites (Appendix 3). Groundwater flow (rate and direction) measurements were attempted at one or more discrete depths in all 26 wells. Natural-gamma measurements are stable in time, so they were completed as time allowed throughout the course of the investigation. Electromagnetic induction values can change through time, and those logs were measured during May–June 2008. Flowmeter measurements can vary with time and depth, so those measurements were made during June–July 2008 and August–September 2009.

Natural-gamma activity is a measureable quantity created by the spontaneous emission of alpha particles during the radioactive decay of elemental potassium that occurs naturally in some rock and clay minerals (Keys, 1990). At the Green Valley site, the highest gamma values likely indicate clay minerals in the till used to cover the coal refuse, till beneath the refuse deposit, and non-coal rock fragments that were a byproduct of the mining operation and were disposed of and intermingled with the coal refuse. Electromagnetic induction measures the capacity of the geologic materials and groundwater in the vicinity of a well to conduct electricity (Keys, 1990). Geologic materials that increase electromagnetic conductivity include clay minerals and iron-bearing minerals. Electrically conductive rubbish that includes metals and that was buried with the coal refuse would also increase the measured conductivity. Acid mine drainage, documented at the Green Valley site in various studies, is highly conductive relative to groundwater unaffected by mining activity. A comparison of natural-gamma activity and electromagnetic induction logs can be done to identify subsurface intervals where groundwater and pore fluids have relatively high electrical conductivity as compared to other fluids.

Gamma and electromagnetic induction measurements were made by means of a Mt. Sopris MGX logging system fitted with a Mt. Sopris Model 2PGA-1000 gamma tool and a Mt. Sopris Model 2PIA-1000 electromagnetic induction tool. Factory-set parameters were used instead of site-specific calibration of the electromagnetic induction tool. Wells were logged for natural-gamma activity and electromagnetic induction at a rate of 10–15 ft/min. All data were archived according to USGS standards.

Table 1. Selected characteristics for observation wells at the Green Valley mine site, Indiana.

[PVC, polyvinylchloride; N100GLCIAL, glacial till; 111GOB, coal gob; C, confined; U, unconfined]

Local well identifier[1]	Top of well screen below land surface (feet)	Bottom of well screen below land surface (feet)	Well-screen material	Geologic unit	Aquifer type	Land-surface altitude[2]	Begin date for measuring-point use	Measuring-point altitude[3]
GV1	3.35	8.35	PVC	N100GLCIAL	C	593.02	06/19/2008	595.50
GV2	4.47	19.47	PVC	N100GLCIAL	C	609.60	06/02/2008	612.84
GV3	11.71	21.71	PVC	N100GLCIAL	C	601.00	05/22/2008	604.19
GV4	28.23	38.23	PVC	111GOB	U	628.50	05/22/2008	630.27
GV7A	5.22	30.22	PVC	111GOB	U	624.39	06/20/2008	624.39
GV7B	4.97	29.97	PVC	111GOB	U	624.13	10/15/2008	626.12
GV8A	14.78	44.78	PVC	111GOB	U	629.47	06/25/2008	629.47
GV8B	15.11	45.11	PVC	111GOB	U	629.66	10/15/2008	631.52
GV8C	69.35	74.35	PVC	N100GLCIAL	C	629.96	09/04/2008	632.24
GV9A	16.69	66.69	PVC	111GOB	U	632.80	06/25/2008	632.80
GV9B	16.67	66.67	PVC	111GOB	U	632.98	10/15/2008	635.51
GV10	4.50	14.50	PVC	111GOB	U	597.09	06/26/2008	597.09
GV11A	9.69	29.69	PVC	111GOB	U	626.48	06/27/2008	626.48
GV11B	10.18	30.18	PVC	111GOB	U	626.49	10/15/2008	628.86
GV12A	9.86	19.86	PVC	111GOB	U	607.38	06/27/2008	607.38
GV12B	10.21	20.21	PVC	111GOB	U	607.34	10/15/2008	609.41
GV13	8.97	33.97	PVC	111GOB	U	619.98	06/26/2008	619.98
GV14	9.44	24.44	PVC	111GOB	U	618.14	06/26/2008	618.14
GV15	4.56	19.56	PVC	111GOB	U	616.38	09/04/2008	616.34
GV16	4.66	19.66	PVC	111GOB	U	613.67	09/04/2008	613.67
GV17	4.84	19.84	PVC	111GOB	U	615.71	09/04/2008	615.68
GV18	9.75	24.75	PVC	111GOB	U	601.13	09/04/2008	601.11
GV19	8.88	23.88	PVC	111GOB	U	619.10	09/04/2008	619.10
GV20	5.00	20.00	PVC	111GOB	U	598.86	09/04/2008	598.95
GV21	15.12	40.12	PVC	111GOB	U	615.83	09/04/2008	615.83
GV22	4.60	14.60	PVC	111GOB	U	572.29	09/04/2008	572.24

[1] Sites are shown on figure 4.

[2] Horizontal datum is referenced to North American Datum of 1983.

[3] Vertical datum is referenced to North America Datum 1988.

The surface geophysical survey of electromagnetic conductivity was done January 26, 2009, to identify areas where acid mine drainage could be flowing offsite in groundwater. The electromagnetic survey measured the apparent subsurface electrical conductivity (normalized to 25 degrees Celsius), which is affected by a combination of factors including geologic material, anthropogenic influences, and the electrical conductivity of groundwater. A Geophex GEM-2 instrument was used to simultaneously measure conductivity at six settings, corresponding to different depths of penetration; the approximate maximum depth of penetration was 30–65 ft.

Flowmeter measurements in wells were made at 11 sites (11 wells) during relatively wet conditions (from June 2 to July 1, 2008) and at 18 well sites (24 wells) during relatively dry conditions (from August 25 to September 2, 2009). Wells at GV13 and GV19 were dry during the 2009 measurement period. Flowmeter measurements were attempted at multiple depths during 2008 and 2009. Flowmeter measurements made during 2008 were used to provide groundwater-flow direction information that could be used to locate additional well sites in the Green Valley data-collection network. Flowmeter measurements during 2008 and 2009 indicated patterns of groundwater flow near the wells during relatively wet and dry conditions and were used to estimate the hydraulic conductivity of the gob and till.

Two borehole flow meter instruments were applied at the Green Valley site. The Kerfoot Technologies, Inc., Model 200 GEOFLO instrument monitors the transport of a heated parcel of water to measure groundwater-flow rate and direction (Bayless and others, 2011). An AquaVISION Colloidal Borescope measures groundwater-flow rate and direction by digitally tracking optically observed colloids that are transported throughout the well screen (Bayless and others, 2011). In most cases, the technology that was used at a well site during the 2008 measurements was used again during the 2009 measurements.

Streamflow and seep discharge was measured at seven sites (table 2) on two to eight occasions between October 2008 and July 2009. Lack of flow or inaccessibility prevented measurements during some site visits. November measurements could not be made in West Little Sugar Creek because of an equipment malfunction, and January measurements could not be made because ice in the stream was too thick

An acoustic Doppler velocimeter (ADV; SonTek Flowtracker) was used to make streamflow measurements at sites immediately upstream and downstream of the reach of West Sugar Creek that marks the southwestern boundary of the Green Valley site. The velocimeter uses acoustic reflections from entrained sediment to measure flow. The equal-width-increment method was used to measure flow through sections oriented perpendicular to the flow direction. Conditions in West Little Sugar Creek were less than ideal for applying the midsection method to measure streamflow because of irregularities in the streambed profile, narrow stream channels, shallow water depths, and nonuniform velocities (Rantz and others, 1982).

Flow from all seeps except seep 1 was computed by using timed-volume measurements. Temporary dams with outflow pipes were installed at seep 3A and seep 4. Natural dams and outfalls were present at seep 2 and seep 3B. The seep 2 drainage area includes water collected from an engineered channel that extends from West Little Sugar Creek uphill to the vicinity of well site GV15. The discharge from seep 2 was measured immediately above the confluence of the seep channel with West Little Sugar Creek. The discharge at seep 3A was measured near the site where groundwater emerges at land surface on the western side of the refuse deposit. The seep 3B site is in the same channel as seep 3A but further downstream and immediately above the confluence of the seep channel with West Little Sugar Creek. The discharge at seep 3B includes water from the seep channel and water from a private farm and woodland. The seep 4 drainage area includes engineered

Table 2. Selected characteristics for surface-water discharge measurement sites at the Green Valley mine site, Indiana.

[USGS, U.S. Geological Survey; °, degrees; ′ minutes; ″, seconds]

Local site identifier[2]	USGS station identifier	Latitude[1]	Longitude[1]	Flow-measurement method
Seep 1	393047087304701	39°30′39″	87°30′47″	Weir.
Seep 2	393035087312801	39°30′35″	87°31′28″	Pool overflow.
Seep 3A	393035087311401	39°30′35″	87°31′14″	Pipe discharge, dye tracing.
Seep 3B	393027087312101	39°30′27″	87°31′21″	Pool overflow.
Seep 4	393031087310401	39°30′31″	87°31′04″	Pipe discharge.
West Little Sugar Creek, upstream	393036087312801	39°30′36″	87°31′28″	Acoustic Doppler velocimeter.
West Little Sugar Creek, downstream	393025087311901	39°30′25″	87°31′19″	Acoustic Doppler velocimeter.

[1] Horizontal datum is referenced to North American Datum of 1983.

[2] Sites are shown on figure 4.

channels that extend east to the property boundary, northeast to near well site GV15, and north to near well site GV18. Seep 4 discharges to West Little Sugar Creek approximately 0.20 mi southwest from the southwesternmost corner of the Green Valley site. Seep 1 discharge was measured with a V-notch weir. Stage behind the weir was continuously recorded with a pressure transducer. The flow rate of water at seep 1 was computed from the recorded data. Seep 1 discharges to a small channel that flows into the Green Valley Mine Pond.

Aquifer and slug tests were done at the Green Valley site to provide data to compute hydraulic properties of the coal refuse. Two-well aquifer tests were attempted at five sites, and single-well slug tests were done at four sites. Tests were done in wells screened in thin sand lenses within the till and wells screened in the coal refuse. Slug tests were done in well GV2 on July 12, 2009, and in wells GV7A, GV11A, and GV12A between August 27 and September 2, 2009 (Appendix 4). Rising- and falling-head tests were done by introducing and removing a weighted section of PVC pipe to a position immediately above and below the water table, respectively. Groundwater levels were monitored during the test with a pressure transducer that was positioned below the water table. Slug-test data were analyzed with the Bouwer and Rice (1976; Bouwer, 1989), Hvorslev (1951), and KGS (Hyder and others, 1994) methods by using AQTESOLV software (Hydrosolve, 2002). The analyses with the Bouwer and Rice method were generally insensitive to whether a confined or unconfined aquifer model was used, so the unconfined model was used for all slug tests. A set of simplifying assumptions was used in the analysis of slug tests. The vertical anisotropy used in the computations was assumed to be 0.2 for all slug-test analyses; testing indicated that the results were generally insensitive to this parameter. The tested interval at each well screen was assumed to be homogenous and have infinite areal extent. The potentiometric surface for each test was assumed to be initially horizontal.

Hydrogeology of the Green Valley Reclaimed Coal Refuse Site

The precipitation measured with the impact sensor during water year 2009 (October 1, 2008 through September 30, 2009) at the Green Valley site, totaled 47.17 in. and was higher than the average annual precipitation reported for a long-term weather station at Terre Haute, Ind. Precipitation measurements made with the impact sensor and the tipping-bucket rain gages showed strong linear correlation (fig. 5*A*). The tipping-bucket rain gage was not heated and, as a result, could not measure solid precipitation and frequently froze in an arrested position during cold weather. Conversely, the impact sensor measured precipitation year round. For these reasons, the impact-device measured precipitation data were considered to be the precipitation record for the period of this investigation (fig. 5*B*). Air temperature for the period of investigation ranged from 0.2 to 91.50°F (median 52.7°F), and relative humidity ranged from 18.5 to 100 percent, with a median of

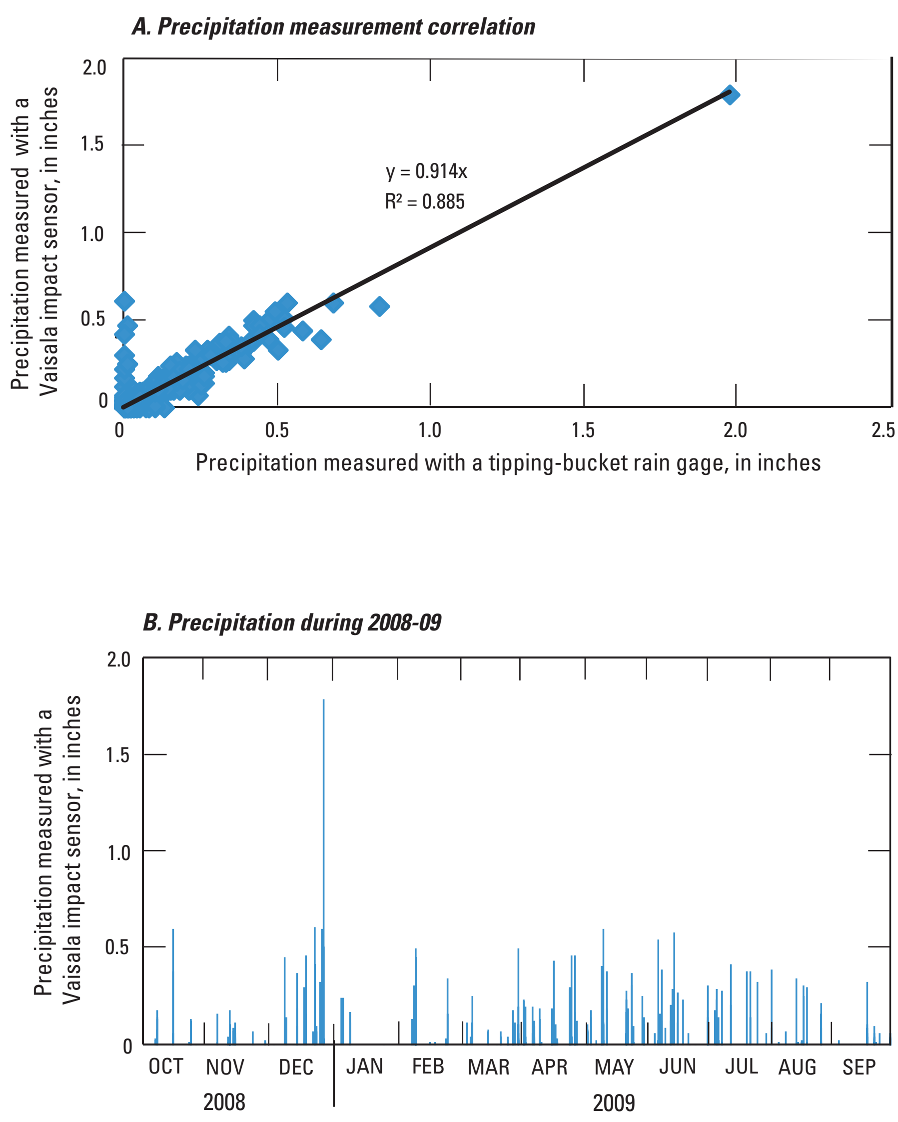


Figure 5. Precipitation at the Green Valley mine site, Indiana. *A*, Amounts of precipitation measured using an impact sensor (Vaisala) showing relation to amounts measured using a tipping bucket gage (measurements during periods when the tipping bucket gage was frozen are not included). *B*, Precipitation measured for water year 2009 by use of the impact sensor.

76 percent (fig. 6). Assuming evapotranspiration was 69 percent of the total precipitation, as proposed by Clark (1980), an evapotranspiration amount of approximately 32.5 in. might be expected for the Green Valley site during water year 2009.

Groundwater levels were annually cyclical. At most sites, groundwater levels were highest during April to July and lowest during September to December (figs. 7 and 8). Groundwater levels in wells at four well sites—GV4, GV8, GV9, and GV18—were distinctly different throughout the year, being highest from June through September and lowest around March. The thickness of the unsaturated zone in wells GV4, GV8, GV9, and GV18 averaged about 9.0 to 50.62 ft during water year 2009 (median: 32.03 ft) compared to 11.10 to 39.35 in the other wells screened in gob (median: 14.04 ft), and may indicate a relation between water-level variability and unsaturated-zone thickness. These data represent the hydrologic conditions present during water year 2009 and may vary from year to year.

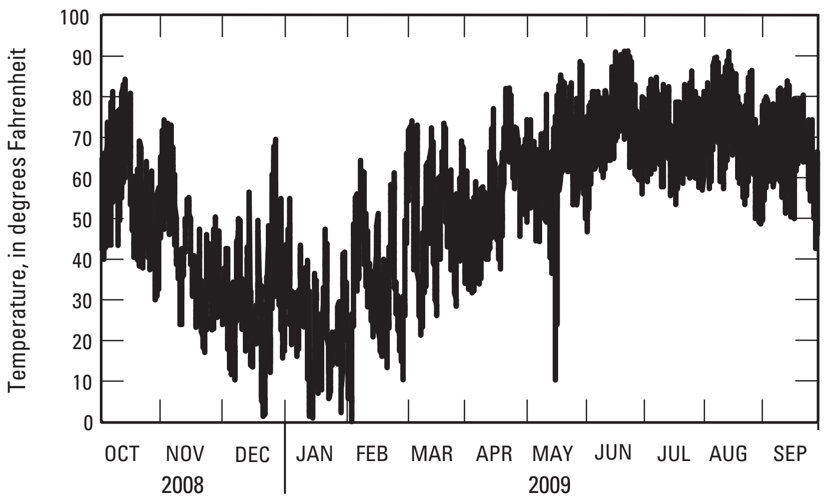


Figure 6. Air temperature measured at the weather station at the Green Valley mine site, Indiana, October 1, 2008, through September 30, 2009.

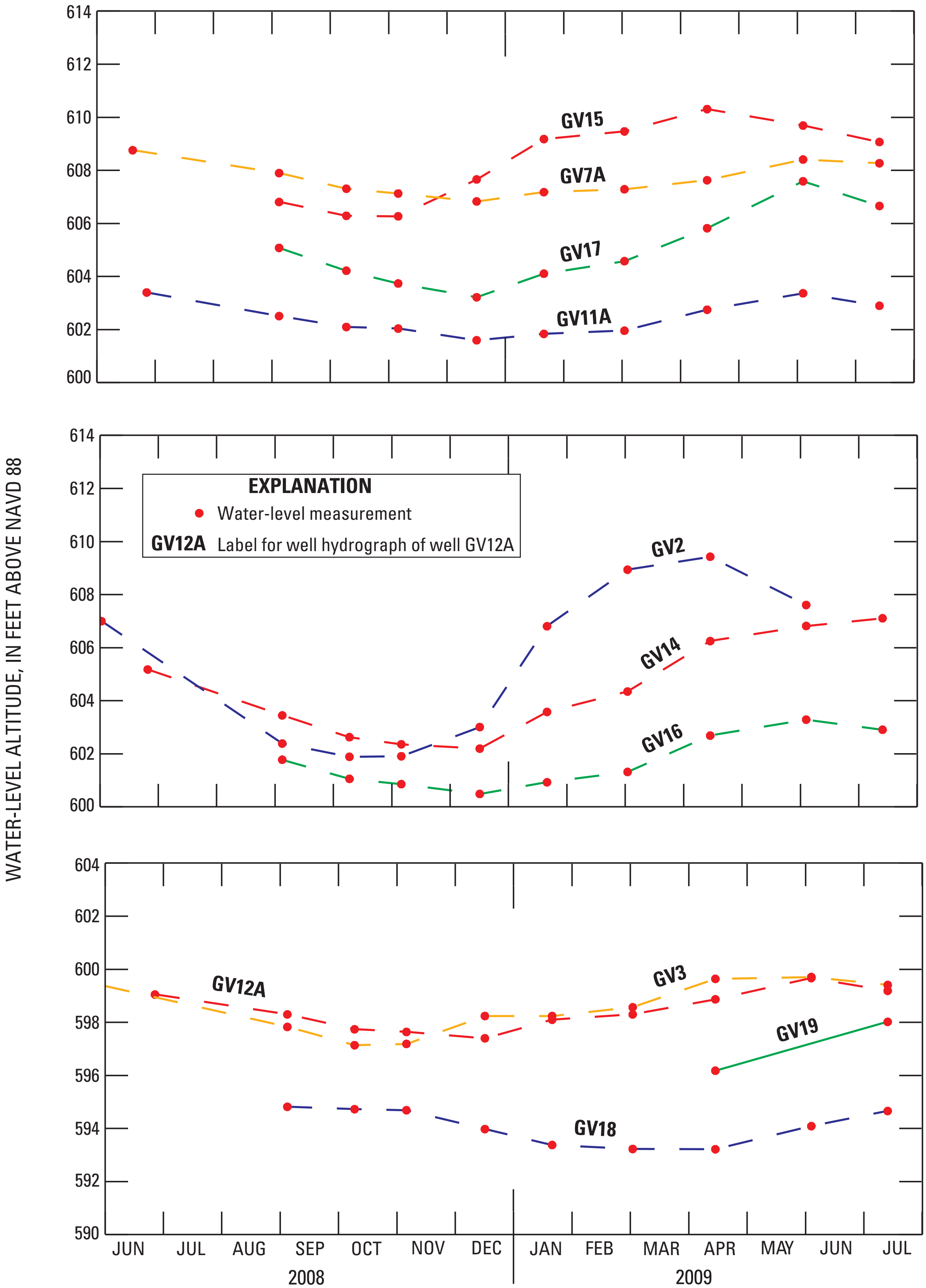


Figure 7. Water-level hydrographs for monthly measurements at 11 wells at the Green Valley mine site, Indiana.

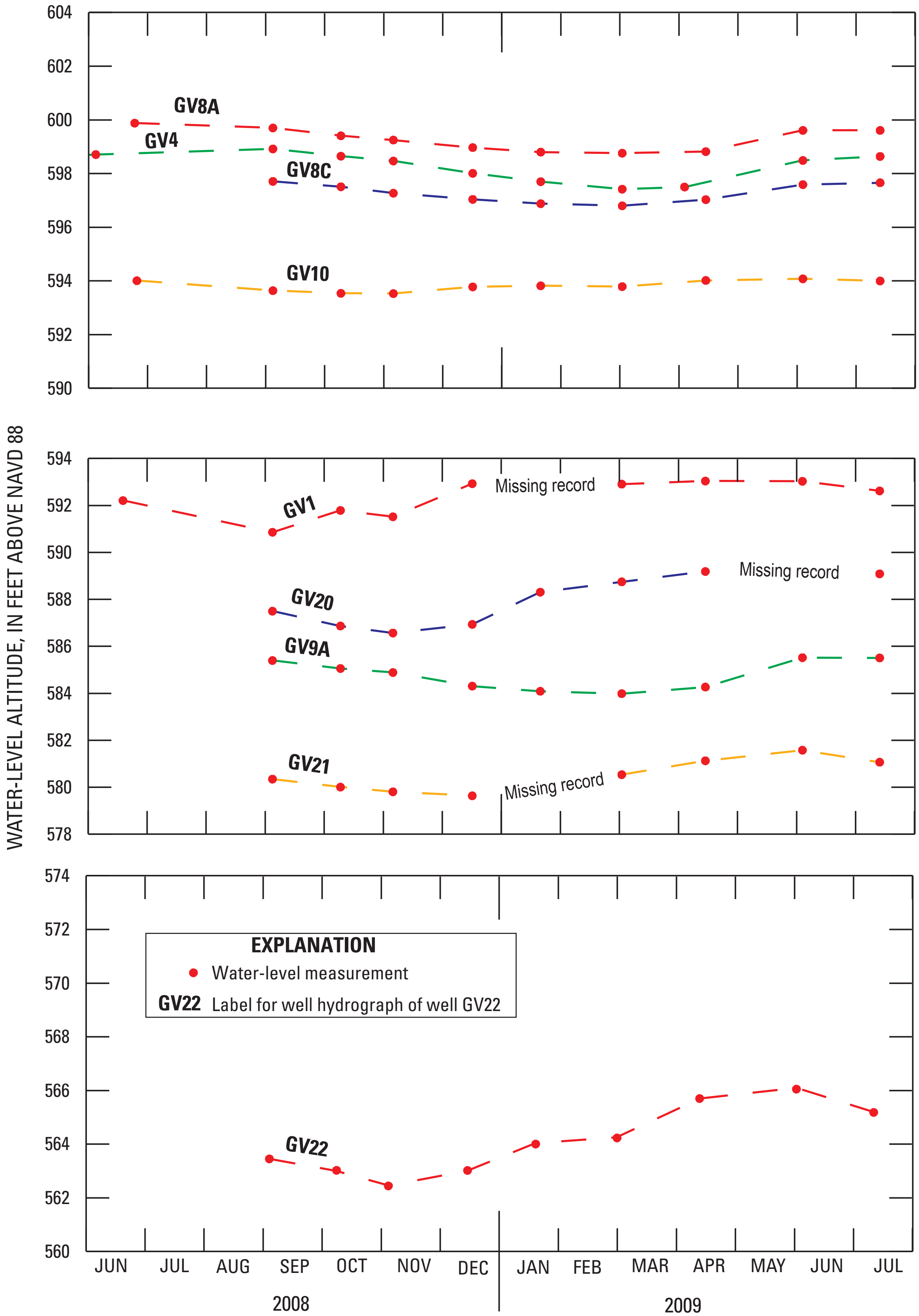


Figure 8. Water-level hydrographs for monthly measurements at nine wells at the Green Valley mine site, Indiana.

Groundwater levels in well GV8A in the gob were consistently higher than in the underlying till (GV8C), indicating that the hydraulic gradient is from the coal refuse into the underlying till (fig. 9). A specific conductance of 4,300 µS/cm of water from well GV8C on August 31, 2009, was higher than would be expected for groundwater unaffected by mine drainage. This conductance may indicate that water from the overlying coal refuse is moving into the underlying till, as suggested by the hydraulic gradient. The distance is 24 ft from the well screen at GV8C to the interface between the coal refuse and the till. A poor annular seal around the well or inadequate well development could also explain the elevated specific conductance of the water in the well. A specific conductance measurement (20,400 µS/cm) was made in water from well GV7A, screened in gob, on June 29, 2009. In the till, historical values of specific conductance were measured in water from two wells about 0.75 mi northeast of the Green Valley site (790 µS/cm, in well 392854087303199, sampled July 18, 1979; and 540 µS/cm, in well 393109087300899, sampled August 13, 1979; U.S. Geological Survey, National Water Information System, 2010). Assuming that these data represent current background water-quality conditions in the till, the higher specific conductance values under the Green Valley site in well GV8C likely indicate that the hydraulic gradients were from the gob into the till.

Continuous groundwater-level data showed similar patterns to the monthly measurements but provided additional detail about water-table fluctuations during the periods between monthly measurements (fig. 10). Some wells, such as GV8A, GV9A, GV11A, and GV18, showed less water-level variability than other wells. Water-level fluctuations in well GV8C, screened in the underlying till, were the most subdued from all of the measured wells. Groundwater-level fluctuations during the study period ranged from 0.55 ft at GV10 to 7.54 ft at GV2. The median fluctuation (minimum to maximum) for all 26 wells was 1.98 ft. In general, water-level fluctuations ranged from approximately 2 ft or less near the center of the refuse deposit and from about 2 to about 7 ft around the margins of the refuse deposit. The observed spatial pattern in annual water-level variability may be related to thickness of the unsaturated zone, proximity of wells to seep zones, thickness of the glacial drift cap over the refuse, the presence of preferential flow paths, or a combination of these factors.

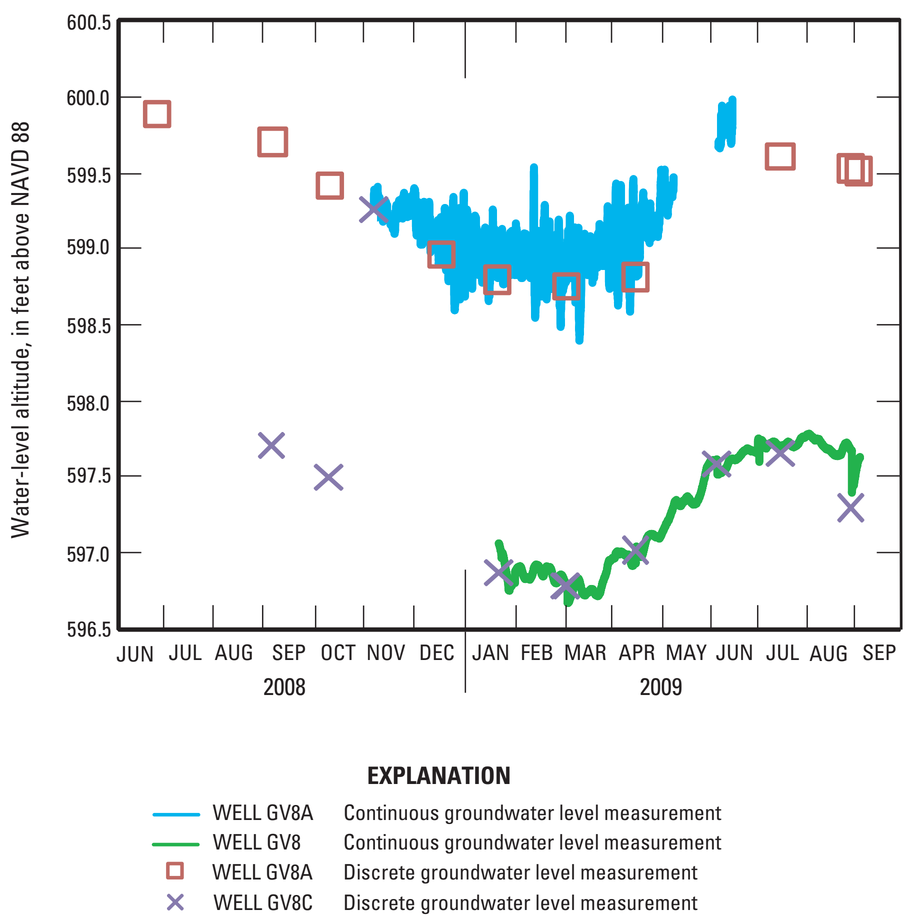


Figure 9. Groundwater levels at the Green Valley mine site, Indiana, indicating a vertical gradient from the coal refuse (well GV8A) into the underlying till (well GV8C).

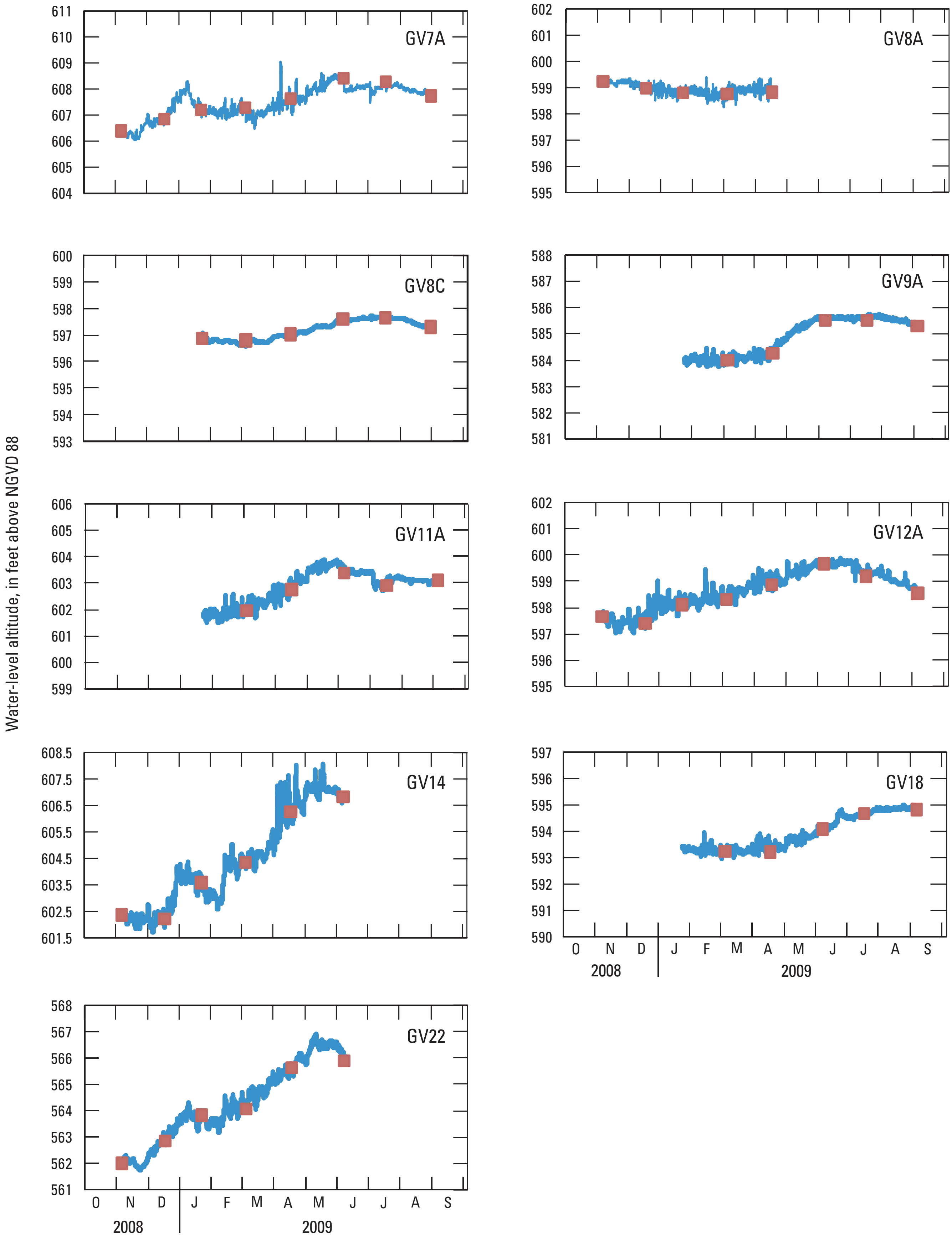


Figure 10. Continuous water levels in selected wells at the Green Valley mine site, Indiana.

In general, distinct depth-related differences in borehole measurements of natural-gamma activity indicate that stratigraphic layering with homogeneous hydraulic properties was not observed (Appendix 1). Some logs indicated higher gamma activity near land surface that probably was caused by the presence of the till cap. Wells GV2 and GV3, completed entirely in glacial deposits, also showed relatively high gamma activity and may indicate a change from clay-rich to sandier till (lower gamma activity) with depth. Many gamma logs appeared to indicate a trend toward decreasing gamma activity with depth; this may be an indication of historic coal-processing techniques or changing source-rock composition. Some wells, including GV4A, GV8C, GV9A, GV11A, GV12A, and GV14, contained a 7- to 12-ft-thick interval near the refuse-till interface with gamma measurements less than 50 counts per second (cps). This interval may represent a common and perhaps hydrologically connected layer of refuse, however, detailed well-driller records and cores were not collected during installation, and a precise interpretation of the gamma logs, in this case, is not possible.

Electromagnetic conductivity varied spatially and with depth at the Green Valley site. At wells screened entirely in till (GV1–3), electromagnetic conductivity values generally were less than 150 mS/m (Appendix 2). Near-surface values at GV1 were slightly higher than 150 mS/cm^2 and probably indicate the infiltration of higher conductivity seep water near the well. The electromagnetic conductivity of the till cap overlying the coal refuse also was generally less than 150 mS/cm^2. The electromagnetic conductivity of coal refuse ranged from 150 mS/cm^2 to greater than 700 mS/cm^2 and, generally, most wells spanned intervals that exceeded 400 mS/cm^2. Near water from some wells, such as GV4 and GV9, higher conductivity appeared to be related to intervals with low gamma activity. For groundwater from most wells, the highest conductivity appeared to be measured in deeper intervals of the wells.

Flowmeter measurements made from June 2 to July 1, 2008, indicated that groundwater flow directions through wells near engineered ditches at the Green Valley site were affected by those structures (table 3; fig. 11). Examples of this observation include measurements made at GV1, GV2, GV3, GV10,

Table 3. Horizontal flowmeter data for the Green Valley mine site, Indiana, June–July 2008.

[bmp, below measurement point; Geologic material, the deposits juxtaposed from the flowmeter measurement interval; CBFM, colloidal borescope flow meter; ft/d, feet per day; NA, not applicable to the measurement; parentheses, a relatively stable subset of the complete dataset was sampled and analyzed for vector properties and is presented in the table; KVA, Kerfoot Technologies, Inc., Model 200 GEOFLO; all times are in Eastern Standard Time]

Local well identifier[1]	Date/time	Depth (bmp)	Measurement Elevation (above vertical datum)	Geologic material in measured interval	Data points collected by CBFM	Duration of CBFM trace	Vector velocity[2] (ft/d)	Vector direction of flow (in compass degrees)	Comments
GV1	6/19/2008 3:40 pm	8.98	586.50	Till	NA	NA	11.7	332.6	
GV2	6/2/2008 5:40 pm	21.00	591.84	Till	NA	NA	12.9	132.2	
GV3	6/5/2008 7:42 pm	16.80	587.39	Till	(462)	(16)	(33.3)	(252)	
GV4	6/12/2008 2:03 pm	36.00	594.27	Coal refuse	NA	NA	3.8	304	
GV7A	6/20/2008	31.90	594.93	Coal refuse	530	26:30	8.4	249	
GV8A	6/25/2008	36.42	595.49	Coal refuse	NA	NA	4.7	223.4	
GV9A	7/1/2008	52.71	582.80	Coal refuse	NA	NA	10.8	258.3	
GV10	6/26/2008	11.50	588.09	Till	NA	NA	4.5	115.7	
GV11A	6/27/2008	29.50	599.48	Coal refuse	NA	NA	NA	NA	Swirling flow with CBFM. Near zero velocity with KVA.
GV12A	6/30/2008	15.00	594.88	Coal refuse	NA	NA	10	151	
GV14	6/30/2008	16.50	604.14	Coal refuse	NA	NA	12.0	281.4	
GV14	6/30/2008	16.50	604.14	Coal refuse	NA	NA	12.0	281.4	

[1] Sites are shown on figure 4.

[2] Flowmeter velocity measurements have not been corrected for borehole acceleration; formation velocities may be less by a factor from 0.1 to 1.0 times the measured borehole velocity.

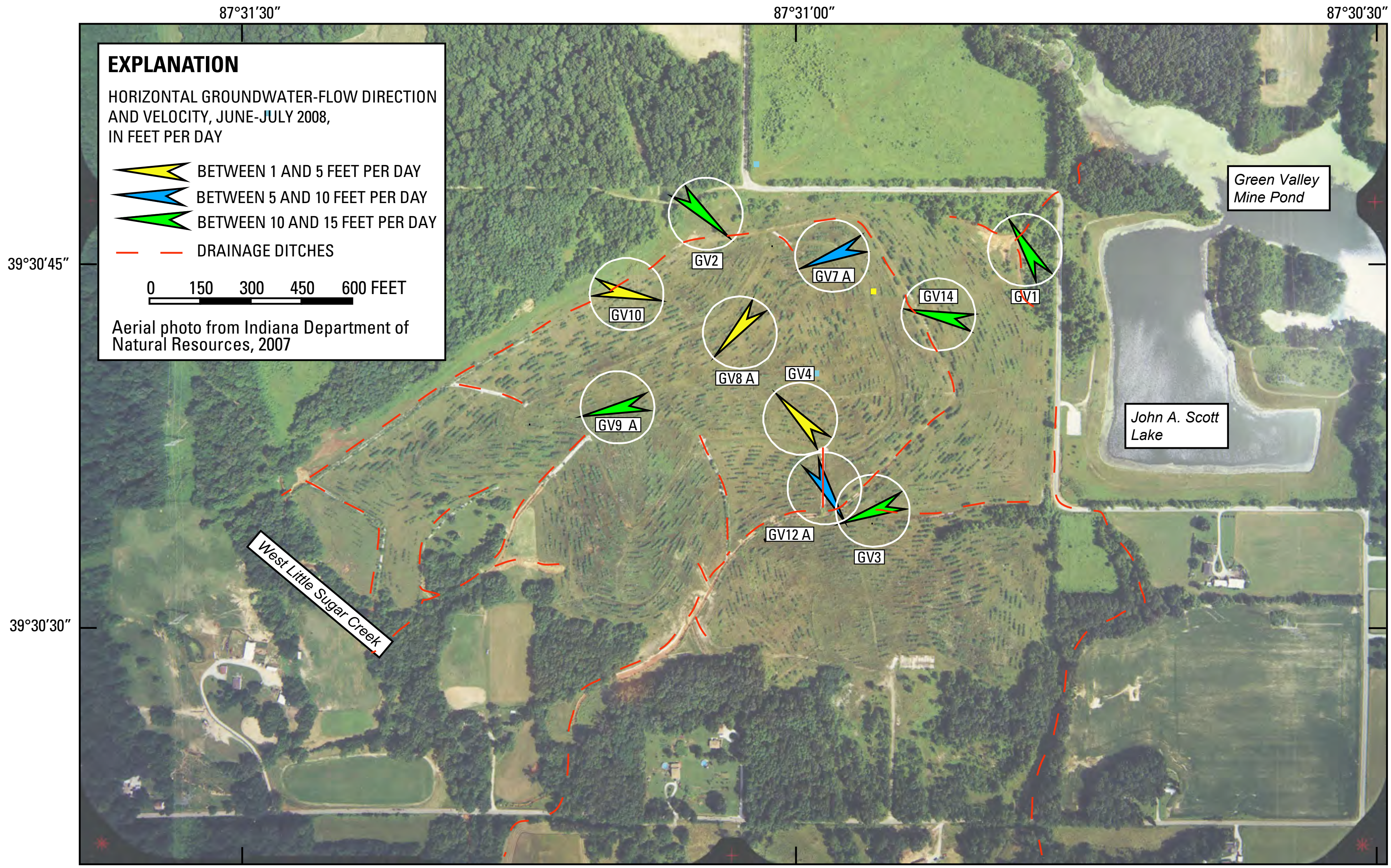


Figure 11. Groundwater flow directions and rates for measurements made at the Green Valley mine site, Indiana, June–July 2008.

GV12, and GV14. Measurements of groundwater flow direction through wells located nearer the center of the refuse pile (GV7, GV8, and GV9), however, were similar to the prevailing hydraulic gradient from northeast to southwest.

In most cases, one interval within each well was determined to have a relatively stable flow direction with a velocity that was notably higher than at the other depths tested. These data indicate that zones of higher hydraulic conductivity are present in the refuse where groundwater-flow rates are relatively faster than other zones in the refuse. The flowmeter-measured velocities, therefore, should be considered in that context and are likely higher than the average groundwater velocity throughout the entire screened interval. Fast flow rates through zones of higher hydraulic conductivity have been observed in other studies where horizontal borehole flowmeters were applied (Kearl, 1997).

Flowmeter velocity measurements indicate the apparent groundwater-flow rate at the depth where the measurement was made. Precise velocity determinations require an adjustment that must be measured in the laboratory. Correction factors for wells that are screened in materials with relatively low hydraulic conductivity, such as the coal refuse at this site, may range from 1 to 10 (Kearl, 1997; Wu and others, 2008) but more commonly range from 1.8 to 4.0 (Drost and others, 1968). Correction factors for the two flowmeter technologies should not be expected to be the same. Laboratory determination of correction factors was beyond the scope of this investigation and, as a result, the velocities reported in tables 2 and 3 have not been corrected.

Interpretation of the flowmeter vectors measured during 2009 is problematic. Despite attempts to measure groundwater-flow vectors at the same depth and with the same technology as used during 2008, the results were notably different. Measured groundwater velocities during August–September 2009 (table 4) were slower and probably indicate the difference in the hydrologic conditions of the site during late summer, compared to the early-summer conditions during 2008 (table 3). In some wells, measurements were made at two depths. Groundwater-flow directions through wells GV3, GV12, GV15, GV17, and GV18 continued to indicate flow towards natural and engineered discharge areas (fig. 12). Flow in wells near the center of the coal refuse, including GV4, GV8, GV9, and GV11, was in a more northwesterly direction during the late-summer measurements. Wells screened all or partly in till and located around the periphery of the site, including GV1, GV2, GV10, GV21, and GV22, showed no consistent trend in flow direction.

Velocities measured with flowmeters and hydraulic gradients estimated from water-level altitudes were used to compute the hydraulic conductivity of the till and refuse. Hydraulic conductivities computed from flowmeter data can be higher than those computed from slug-test data because a slug test evaluates the hydraulic response of the entire screened interval, whereas flowmeter measurements were normally made in zones where the highest groundwater velocities were observed. Hydraulic conductivities were computed from a rearranged form of Darcy's Law: $K_{xy}=v/(\Delta H/|\Delta xy|)$ where K_{xy} is the horizontal conductivity, v is the Darcy groundwater velocity, ΔH is the change in hydraulic head between two points x and y along the groundwater-flow vector, and Δxy is the absolute value of the distance between x and y.

For these computations, x was the well where the flowmeter measurement was made, and y was an upgradient or downgradient water-table contour along a projection of the flowmeter-measured vector. A potentiometric surface based on water-level measurements made during the August–September (2009) flowmeter measurements was used (fig. 13). A correction factor of 5.0 borehole acceleration was applied; a correction factor of 5.0 is probably appropriate where the well is screened in deposits of relatively low permeability. Some data were not used in this analysis. For example, (1) if the flowmeter-measured vector indicated flow from lower to higher water-table altitudes or parallel to the potentiometric contours or, (2) if there were no potentiometric contours because of positioning near water-surface saddles, surface water or refuse-deposit boundaries, then the data were considered poorly suited for calculating hydraulic conductivity and were not used. Hydraulic conductivities computed from the 2009 flowmeter data ranged from 15.7 to 68.0 ft/d in nine wells screened entirely in coal refuse, with a mean value of 47.4 ft/d (table 5). Hydraulic conductivities in three wells screened in till ranged from 44.4 to 83.3 ft/d, with a mean value of 60.6 ft/d; this mean may be biased high by the flowmeter velocity measured in GV3 that gamma logs indicate was measured in a sandy zone within the till.

Little variation in surface-measured electromagnetic conductivity was observed between measurements made at the various frequencies (penetration depths); therefore, results for only one frequency (3,930 mS/m) are depicted (fig. 14). The conductivity in transects measured beyond the boundaries of the site were generally less than 100 mS/m. On the basis of this information, conductivities above 100 mS/m were used to indicate areas where coal refuse or acid mine drainage might be present in the near subsurface. Areas at the Green Valley site with conductivity exceeding 150 mS/m were (1) an underground pipeline on the northern property boundary, (2) the coal refuse pile, (3) the seep 3 and seep 4 channels, (3) the southeastern boundary of the site, and (4) the foundation of a former building in the southeast corner of the site (fig. 14). The survey provided no indication of acidic discharge either to West Little Sugar Creek along the western boundary of the site or to the lakeshore beyond the eastern boundary of the site during December 2008.

Table 4. Horizontal flowmeter data for the Green Valley mine site, Indiana, August–September 2009.

[bmp, below measurement point; Geologic material, the deposits juxtaposed from the flowmeter measurement interval; Center of screen slot, incremented at 90 degrees for 2-inch wells and 60 degrees for 6-inch wells; CBFM, colloidal borescope flowmeter; ft/d, feet per day; NA, not applicable to the measurement; parentheses, a relatively stable subset of the complete dataset was sampled and analyzed for vector properties and is presented in the table; all times are in Eastern Standard Time]

Local well identifier[1]	Date/ time	Depth (bmp)	Measurement elevation (above vertical datum)	Geological material in measured interval	Center of screen slot (in compass degrees)	Data points collected by CBFM	Duration of CBFM trace (minutes)	Vector velocity[2] (ft/d)	Vector direction of flow (in compass degrees)	Comments
GV1	8/26/2009 5:08 pm	9.0	586.50	Till	NA	NA	NA	2.8	124.9	
GV2	8/25/2009 3:15 pm	21.0	591.84	Till	180	NA	NA	2.0	15.3	
GV3	8/27/2009 11:36 am	16.8	587.39	Till	240	(294)	(8)	(11.0)	(257.3)	Stable velocity, moderately stable direction.
GV4	9/01/2009 3:25 pm	32.0	598.27	Coal refuse	135	NA	NA	4.6	280.3	
GV4	9/01/2009 4:48 pm	36.0	594.27	Coal refuse	135	NA	NA	12.6	9.2	
GV7A	8/26/2009 11:47 am	31.9	594.93	Coal refuse	300	115	39	2.3	296.7	Moderately stable velocity, unstable direction.
GV7B	8/26/2009 1:11 pm	NA	NA	Coal refuse	NA	NA	NA	NA	NA	Too turbid for measurement.
GV8A	8/26/2009 12:36 pm	36.40	595.49	Coal refuse	270	NA	NA	1.6	240.0	
GV8B	8/26/2009 10:49 am	35.84	595.68	Coal refuse	120	NA	NA	5.0	44.4	
GV8C	8/26/2009 2:51 pm	NA	NA	Coal refuse	NA	NA	NA	NA	NA	Water levels never returned to pre-insertion values.
GV9A	8/31/2009 2:32 pm	52.71	582.80	Coal refuse	90	NA	NA	7.9	13.4	
GV9B	8/31/2009 3:23 pm	52.47	582.84	Coal refuse	300	NA	NA	2.5	305.7	
GV10	9/02/2009 10:45 am	11.5	588.09	Till	0	NA	NA	2.7	272.5	
GV11A	9/01/2009 12:48 pm	29.50	599.48	Coal refuse	30	NA	NA	6.2	268.2	
GV11B	9/01/2009 11:11 am	29.37	599.49	Coal refuse	315	NA	NA	1.5	236.1	
GV12A	9/01/2009 11:37 am	15.0	594.88	Coal refuse	NA	758	31	3.39	129.50	Moderately stable velocity, moderately stable to variable direction.

Table 4. Horizontal flowmeter data for the Green Valley mine site, Indiana, August–September 2009.—Continued

[bmp, below measurement point; Geologic material, the deposits juxtaposed from the flowmeter measurement interval; Center of screen slot, incremented at 90 degrees for 2-inch wells and 60 degrees for 6-inch wells; CBFM, colloidal borescope flowmeter; ft/d, feet per day; NA, not applicable to the measurement; parentheses, a relatively stable subset of the complete dataset was sampled and analyzed for vector properties and is presented in the table; all times are in Eastern Standard Time]

Local well identifier[1]	Date/ time	Depth (bmp)	Measurement elevation (above vertical datum)	Geological material in measured interval	Center of screen slot (in compass degrees)	Data points collected by CBFM	Duration of CBFM trace (minutes)	Vector velocity[2] (ft/d)	Vector direction of flow (in compass degrees)	Comments
GV12B	9/01/2009 12:45 am	14.50	594.91	Coal refuse	100	(538)	(17)	(7.16)	(261.15)	Stable velocity, moderately stable direction.
GV14	8/27/2009 3:10 pm	19.0	601.64	Coal refuse	315	NA	NA	6.1	150.3	
GV15	8/26/2009 2:35 pm	13.0	605.97	Coal refuse	225	(123)	(4)	(21.20)	(89.00)	Stable velocity, stable direction.
GV15	8/26/2009 4:40 pm	17.0	601.97	Coal refuse	225	(359)	(12)	(7.95)	(230.99)	Stable velocity, stable direction.
GV16	8/27/2009 2:16 pm	16.0	600.22	Coal refuse	0	(92)	(4)	(8.51)	(217.75)	Stable velocity, moderately stable to variable direction.
GV17	8/27/2009 12:05 pm	13.5	604.70	Coal refuse	60	NA	NA	9.7	114.3	
GV18	9/01/2009 3:01 pm	12.0	591.44	Coal refuse	160	(250)	(9)	(6.99)	(245.8)	Stable velocity, stable to moderately stable direction.
GV18	9/01/2009 4:55 pm	25.31	578.13	Till	160	262	28	7.67	198.3	Stable velocity, stable direction.
GV20	8/25/2009 1:14 pm	16.5	584.92	Coal refuse	60	(153)	(11)	(5.92)	(67.01)	Stable velocity, moderately stable direction.
GV21	8/31/2009 12:56 pm	41.5	578.33	Till	315	(165)	(6)	(6.63)	(82.40)	Stable velocity, moderately stable direction.
GV22	8/31/2009 2:40 pm	13.0	561.85	Till	300	(257)	(9)	(5.43)	(182.05)	Stable velocity, moderately stable direction.

[1] Sites are shown on figure 4.

[2] Flowmeter velocity measurements have not been corrected for borehole acceleration; actual velocities may be less by a factor of 0.1 to 1.0 times the measured borehole velocity.

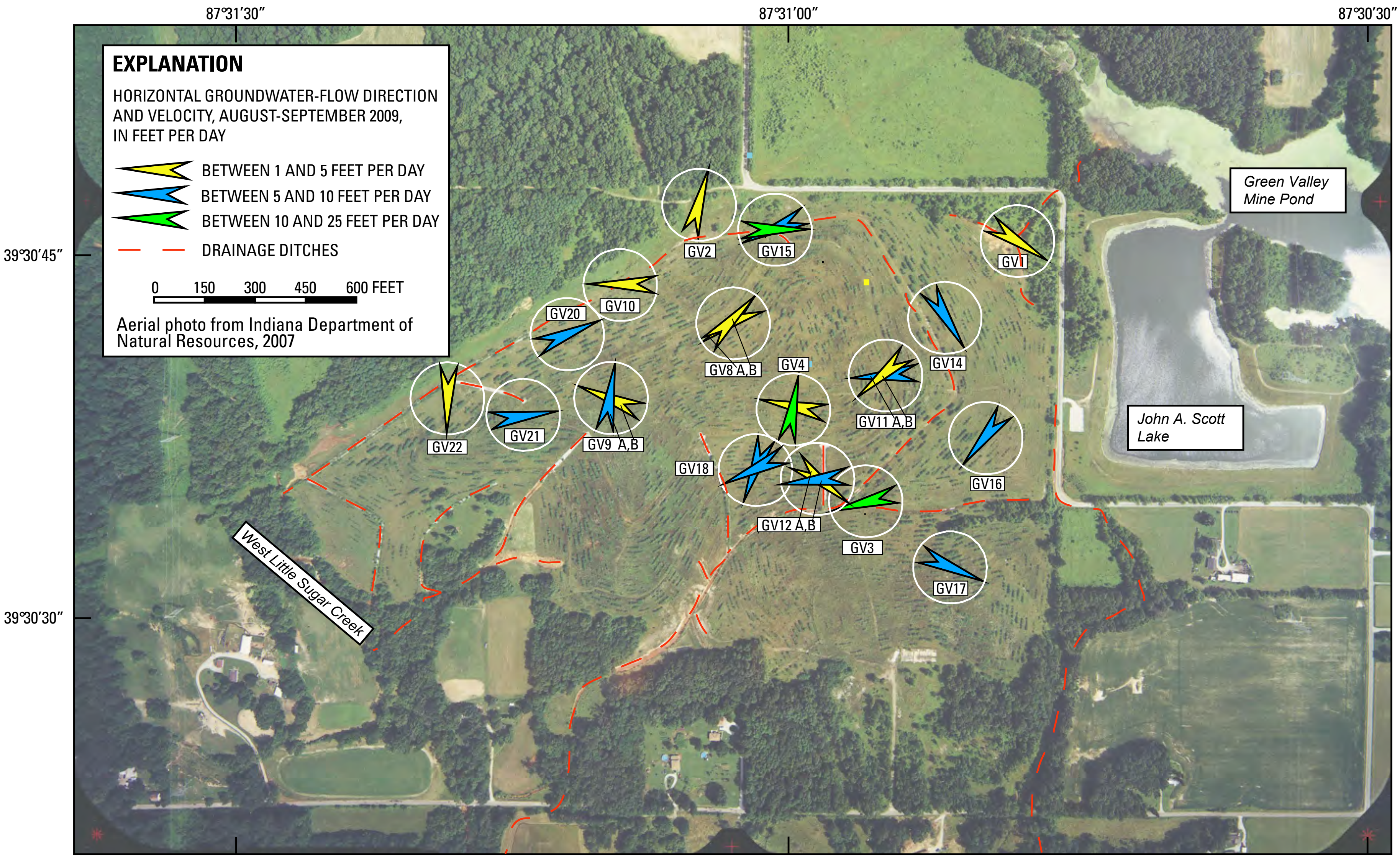


Figure 12. Discrete seep-discharge and streamflow measurements at the Green Valley mine site, Indiana, 2008–9.

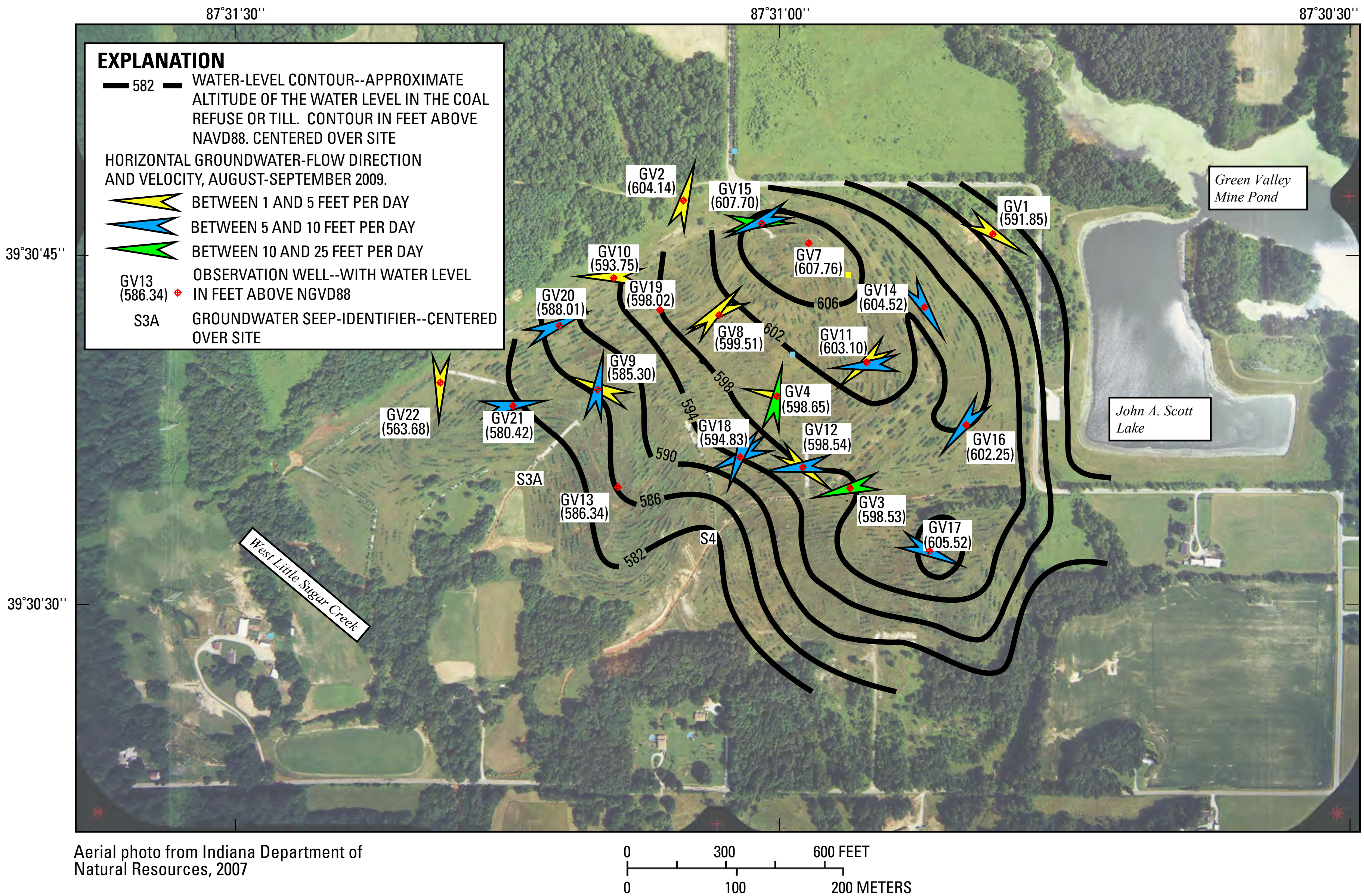


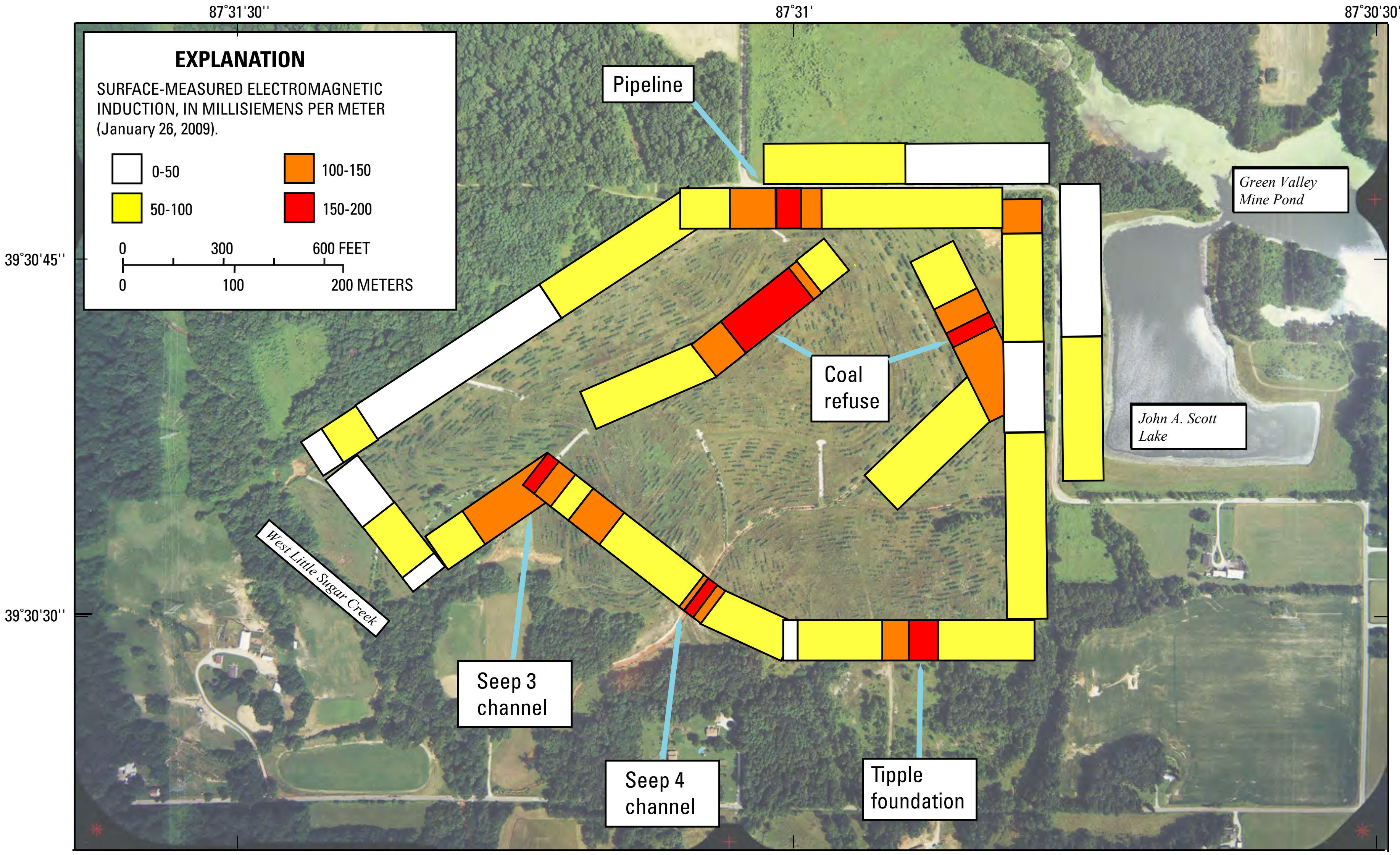
Figure 13. Potentiometric-surface map for August–September 2009 used to (1) show the configuration of the water table at the Green Valley mine site, Indiana, and (2) estimate hydraulic conductivities from flowmeter data.

Table 5. Hydraulic conductivities computed from flowmeter-measured velocities, hydraulic gradients computed from measured groundwater elevations, and an assumed correction factor (a=5.0) for borehole acceleration, Green Valley mine site, Indiana.

[ft, feet; d, day; v, velocity; *, according to Geosciences Research Associates (1985); —, not enough data or poorly suited for use in the calculations]

Local well identifier[1]	Upgradient water-level elevation (ft above vertical datum)	Downgradient water-level elevation (ft above vertical datum)	Distance between upgradient and downgradient water levels (ft)	Hydraulic gradient (ft/ft)	Flowmeter measured velocity (ft/d)	Corrected velocity for an assumed correction factor= 5.0 (ft/d)	Estimated hydraulic conductivity = v/gradient (ft/d)	Geologic material at depth of flowmeter measurement
GV1	595.00	591.85	250	0.0126	2.80	0.56	44.4	Till.
GV2	—	—	—	—	—	—	—	Till.
GV3	598.53	598.00	20	.0265	11.04	2.21	83.3	Till.
GV4	602.00	598.65	210	.0159	3.90	.78	49.0	Tailings.
GV7A	607.76	606.00	190	.0093	2.25	.45	48.3	Tailings.
GV8A	599.51	598.00	135	.0112	1.60	.32	28.5	Tailings.
GV9A	590.00	585.30	150	.0313	7.90	1.58	50.4	Gob.
GV10	594.00	593.75	25	.0100	2.70	.54	54.0	Till.
GV11B	603.10	602.00	110	.0100	6.20	1.24	68.0	Tailings.
GV12B	598.54	594.00	105	.0432	3.39	.68	15.7	Gob.
GV14	—	—	—	—	—	—	—	Tailings.
GV15	607.70	605.00	65	.0415	12.09	2.42	58.3	Gob.
GV16	—	—	—	—	—	—	—	Tailings.
GV17	605.52	602.00	100	.0352	9.70	1.94	55.1	Tailings.
GV18	598.00	594.83	110	.0288	7.67	1.53	53.1	Gob.
GV20	—	—	—	—	—	—	—	Gob.
GV21	—	—	—	—	—	—	—	Gob.

[1] Sites are shown on figure 4.



Aerial photo from Indiana Department of Natural Resources, 2007

Figure 14. Transects used for surface survey of apparent subsurface electrical conductivity at the Green Valley mine site, Indiana, December 2008.

In general, the upstream and downstream streamflow measurements made on West Little Sugar Creek rarely differed by an amount that exceeded the expected measurement error (Sauer and Meyer, 1992). This difference indicates that the combined contributions of base flow, runoff, and seep discharges to the creek are a relatively small percentage of the total flow in West Little Sugar Creek. Visual inspection reveals that a limited amount of mine drainage reaches the stream and causes mineral precipitation that colors the streambed and lithifies bed sediments along the eastern streambank. Discrete seep-discharge measurements at the Green Valley site ranged from 0.00 to 0.0371 ft^3/s (table 6; fig. 15). Continuous stage recordings at seep 1 provided data to compute the annual discharge of 427,000 ft^3/yr at seep 1 for the period November 6, 2008, to November 5, 2009 (fig. 16).

Table 6. Discrete seep-discharge and streamflow measurements at the Green Valley mine site, Indiana, 2008–9.

[ft^3/s, cubic feet per second; mm/dd/yyyy, month/day/year; —, not measured or determined]

Local site identifier[1]	Flow (ft^3/s)							
	10/09/2009	11/05/2008	12/16/2008	01/20/2009	03/04/2009	04/16/2009	06/05/2009	07/13/2009
Seep 1, continuous data								
Seep 2	—	—	0	—	0.0032	0.0046	0	0
Seep 3A	—	0.0056	—	—	.0119	.0050	0.0084	0.0064
Seep 3B	—	—	—	—	.0150	.0198	.0155	—
Seep 4	—	—	—	—	—	.0371	.0183	.0107
West Little Sugar Creek, upstream	0.0343	—	2.66	—	4.06	9.356	2.45	—
West Little Sugar Creek, downstream	.0703	—	3.12	—	6.47	9.425	2.59	—

[1] Sites are shown on figure 4.

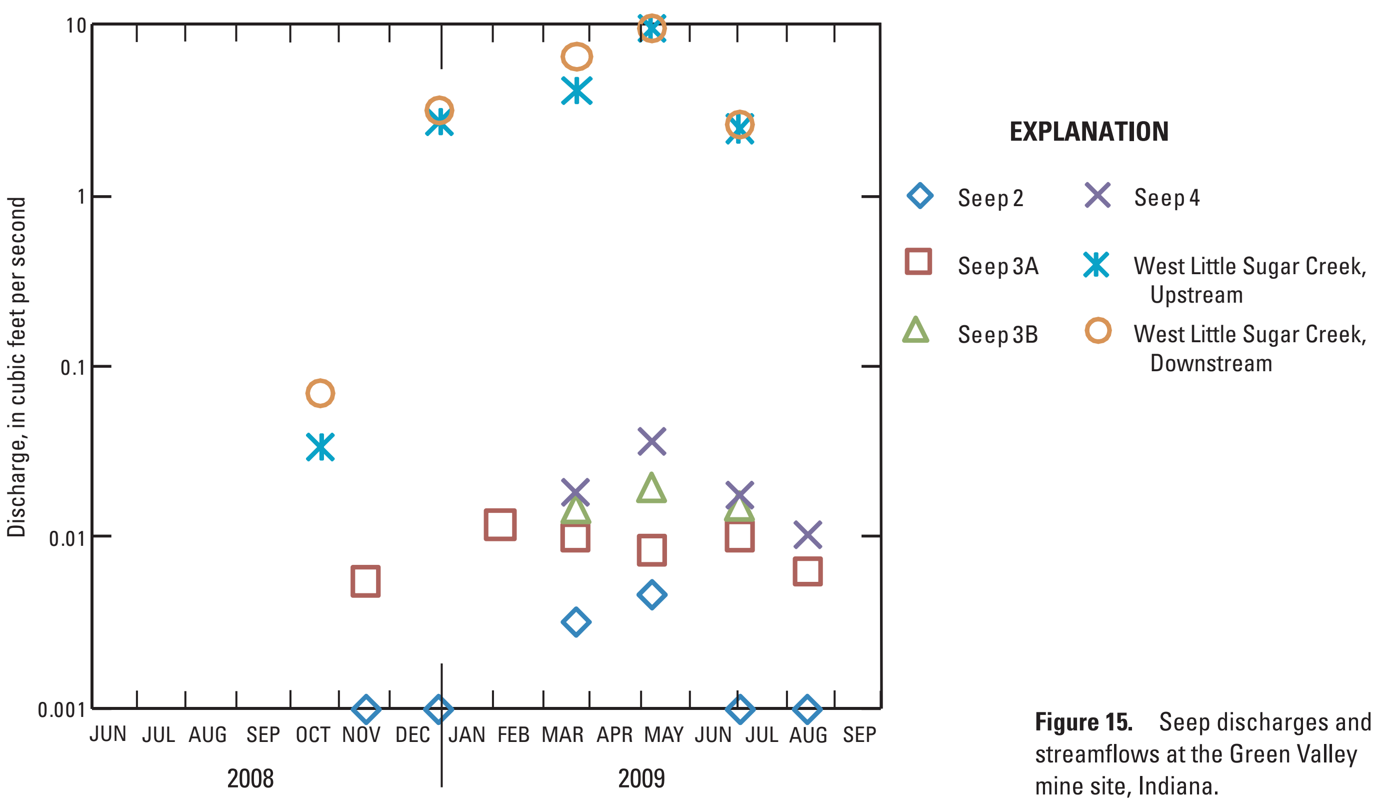


Figure 15. Seep discharges and streamflows at the Green Valley mine site, Indiana.

Two-well aquifer tests were largely unsuccessful. Aquifer tests were attempted in wells at sites GV7, GV8, GV9, GV11, and GV12 between June 20 and July 2, 2009. At site GV7, well GV7A was pumped at a rate of about 0.5 gal/min, and it went dry (12.5 ft drawdown) after 37 minutes; drawdown in the adjacent well GV7B was 0.181 ft when GV7A went dry. At site GV8, pumping of well GV8A at approximately 3 gal/min for 130 minutes created approximately 0.45 ft of drawdown in the adjacent well GV8B. At site GV9, high concentrations of particulates in the water repeatedly caused the pumps to jam and prematurely ended the tests. At site GV11, pumping of well GV11A at a rate of about 0.4 gal/min for 69 minutes created 0.06 ft of drawdown in the adjacent well GV11B. At GV12, well GV12A was pumped at a rate of about 0.3 gal/min for 125 minutes, and approximately 0.10 ft drawdown resulted in the adjacent well GV12B. At sites GV8, GV11, and GV12, two-well aquifer test data yielded abnormal time-drawdown curves that could not be reliably analyzed with AQTESOLV software (Hydrosolve, 2002). In summary, results of the two-well aquifer tests indicated that the coal refuse may have a hydraulic conductivity that is too low to be measured by a two-well aquifer test and that slug testing might be a more appropriate technique.

Slug tests provided useful data at wells GV2, GV7A, GV11A, and GV12A. Water levels from rising-head tests in wells GV7A and GV11A and from a falling-head test in well GV12A were analyzed (table 7). The falling-head tests indicated oscillating water levels in wells GV7A and GV11A and, as a result, those data were not used to compute hydraulic properties. The hydraulic conductivity computed for the till at well GV2 was 0.10 ft/d; in the coal refuse at wells GV7A, GV11A, and GV12A, hydraulic conductivity ranged from 0.03 to 0.83 ft/d (table 7). Results were approximately the same regardless of the method used to analyze the data in this investigation.

The hydraulic conductivities computed from slug-test data were notably lower than the values estimated by other methods for the coal refuse at the Green Valley site. Melchiorre, Dale, and others (2005) estimated hydraulic conductivity of till at 1.11 to 7.37 ft/d and of the gob at 7.37 to 16.4 ft/d. Hydraulic conductivities estimated from flowmeter data ranged from 44.4 to 83.3 ft/d in till and from 15.7 to 68.0 ft/d in coal refuse. Hydraulic conductivities estimated from tracer and flowmeter data commonly indicate relatively high values because they generally are a measure of flow through preferential-flow zones or features, in comparison to methods that consider the entire screened interval (Kearl, 1997).

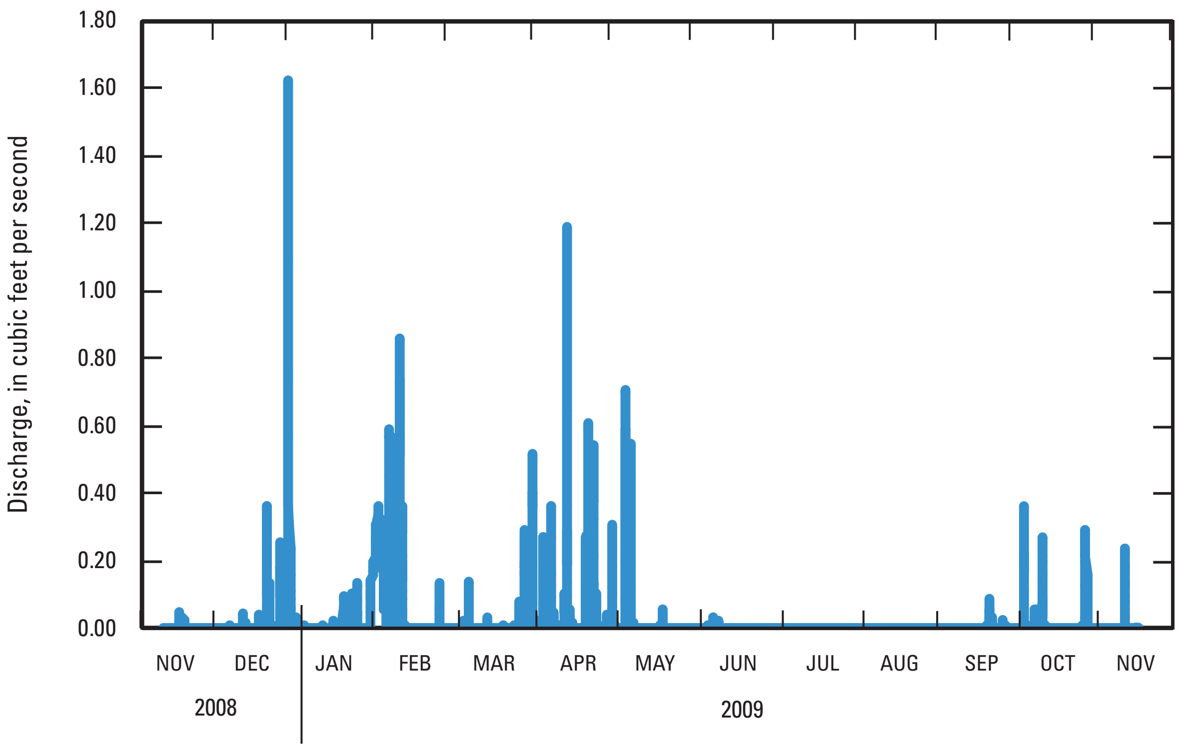


Figure 16. Discharge from seep 1 at the Green Valley mine site, Indiana.

Table 7. Horizontal hydraulic conductivities computed from slug-test data collected at the Green Valley mine site, Indiana, August–September 2009.

[ft/d, feet per day; —, no computation made]

Local well identifier[1]	Geologic material	Horizontal hydraulic conductivity (ft/d)		
		Bouwer and Rice method (unconfined aquifer model)	Hvorslev method (unconfined aquifer model)	Kansas Geological Survey (unconfined aquifer model)
GV2	Glacial till	—	—	0.10
GV7A	Coal refuse	0.23	0.36	—
GV11A	Coal refuse	.49	.83	—
GV12A	Coal refuse	.03	.04	—

[1]Sites are shown on figure 4.

Table 8. Description of geologic materials and model layers used to represent the hydrogeologic system at the Green Valley mine site, Indiana.

Descriptions of geologic materials	Hydrogeologic framework	
	Model layer	Aquifer system equivalent (Grove, 2009)
Gob, plus gob and tailings mixture	Layer 1	None.
Till	Layer 2 Layer 3 Layer 4	Dissected Till Residuum/Till Veneer (DTR) aquifer system and the Central Wabash Valley/Wabash Lowland Till (CWV) aquifer subsystem.
Shale	No-flow boundary	McLeansboro Group Aquifer aquifer system.

Simulated Groundwater Flow

A computer-based groundwater model was developed to gain a more complete understanding of the groundwater-flow system in and near the coal refuse and to improve understanding of how remediation-related changes to the site hydrology could affect flow of groundwater and seepage to surface water. The improved understanding of the flow system may lead to specific remediation scenarios that otherwise would have not been considered. Because remediation scenarios may incorporate transient actions, such as intermittent pumping, a transient model was constructed and calibrated in addition to a steady-state model. This section describes the computer model chosen for the analysis, the conceptual hydrogeologic framework used to guide model construction, the calibration of the model to observations and simulated results, the sensitivity of simulation results to model input, and the model limitations and qualifications. The numerical model was calibrated so that the simulated water levels and flows were a reasonable representation of measured water levels and flows, The calibration was also done so that the residuals, the differences between measured and simulated water levels and flows, were normally distributed and spatially and temporally unbiased. The model will provide a platform to assess new data as they are collected and to examine possible remediation scenarios.

The model used for this investigation is based on the three-dimensional, finite-difference computer code of Harbaugh and others (2000) called MODFLOW-2000. An iterative procedure is used in the model simulation to solve a finite-difference version of the continuity equation for steady flow in an anisotropic, heterogeneous, multilayer groundwater-flow system. The automated parameter-estimation process incorporated into MODFLOW-2000 is used to determine model-parameter values (Hill and others, 2000).

Simplifying Assumptions

A set of simplifying assumptions was used in the construction of the groundwater model. The choice of assumptions was influenced by the data available to define the different components of the groundwater-flow system. The framework of geologic materials and model layering used for the steady-state and transient groundwater-flow models is summarized in table 8 and illustrated in figure 17.

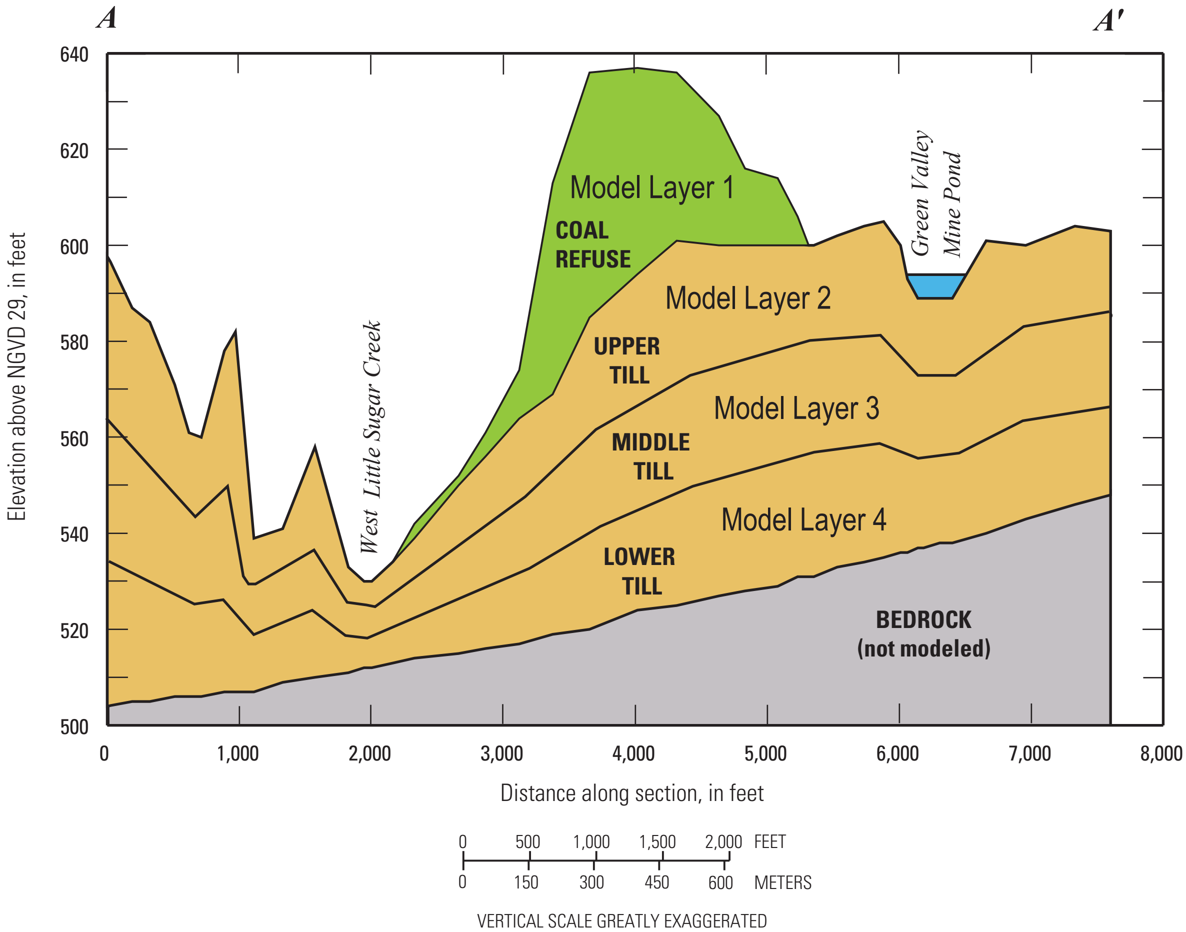


Figure 17. Layering design for the model of the Green Valley mine site, Indiana. (Trace of section is shown in fig. 2).

The following assumptions pertain to the geometry, hydraulic properties, and other characteristics of the groundwater-flow system underlying the area modeled in this investigation:

- The deposits in the coal refuse are represented by a single model layer, and the till deposits are represented by three layers that evenly divide the overall thickness of the till. Three layers were chosen for the till so that simulated water levels for the middle of the three layers would coincide with water levels from an observation well screened in the middle of the till.
- The hydraulic properties of the coal refuse represented by model layer 1 are defined by two zones within the layer. The first zone represents an area of coal gob deposits. The second zone represents areas where coal tailings were mixed with the gob.
- The hydraulic properties of the till are uniform throughout the three layers. The study area is near the approximate boundary of two till aquifer systems the Dissected Till Residuum/Till Veneer aquifer system and the Central Wabash Valley/Wabash Lowland Till aquifer subsystem (Grove, 2009). The Dissected Till Residuum/Till Veneer aquifer system contains few sand lenses within the till; however, the Central Wabash Valley/Wabash Lowland Till aquifer subsystem can contain some intertill lenses of sand and gravel that are generally less than 5 ft thick.
- The shale bedrock beneath the till is considered a no-flow boundary. The shale bedrock under the site is a low permeability part of the Pennsylvanian age Patoka Formation of the McLeansboro Group (Cable and others, 1971, plates 1 and 2). Five borings drilled into bedrock within about 1.5 miles of the Green Valley mine site encountered from about 16 to 37 ft of non-water-bearing shale (Indiana Department of Natural Resources, 2002). Most of the McLeansboro Group is composed of fine-grained geologic materials that limit the movement of groundwater (Grove, 2009). Based on the local drilling record, and the dry conditions encountered, the shale bedrock unit is considered to have a significantly lower horizontal and vertical

hydraulic conductivity relative to that of the local till and coal refuse. The shale bedrock is therefore considered a no-flow boundary at the base of the model.

- The thickness of all simulated streambeds is 1 ft. The calibrated value of streambed vertical hydraulic conductivity is based on a 1-ft streambed thickness.

Model Design

The computer model is based on a 1.6- by 1.1-mi rectangular, block-centered grid network that extends about 500 ft beyond West Little Sugar Creek to the west and the Green Valley Mine Pond to the east (fig. 18). The grid was composed of 28,032 blocks over four layers that ranged in size from 50 ft by 50 ft in the central part of the modeled area to 720 ft by 350 ft at the corners. The finer grid size was generally in the area of the coal refuse so that more detailed simulations could be made for the area of greatest interest.

River and drain cells (Harbaugh and others, 2000) were used in the model to represent local streams. A total of 338 river cells were used to simulate the Green Valley Mine Pond, including the attached borrow area pond (John A. Scott Lake). River cells essentially act as large streams that can supply substantial water to the groundwater-flow system when the

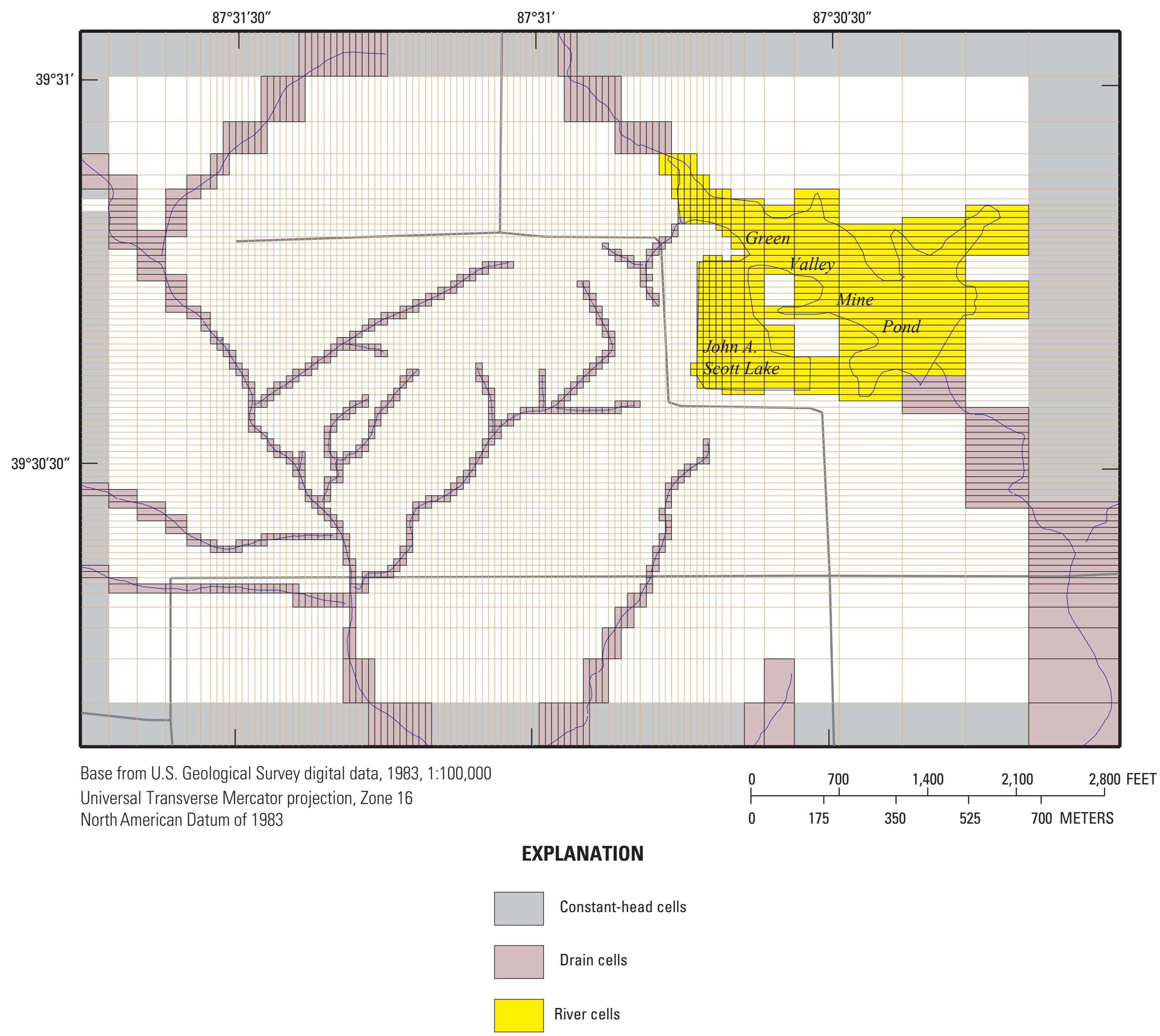


Figure 18. Model grid discretization and river, drain, and constant-head cells used in the simulation of groundwater flow at the Green Valley mine site, Indiana.

water table declines below the bottom of the stream. A total of 620 cells were used to simulate all streams. Drain cells receive groundwater discharge but do not recharge the groundwater system, as can river cells. Drain cells represent streams that cease to flow when the water table declines below the bottom of the stream. All streams, including West Little Sugar Creek, were designated as drain cells because observations during the investigation indicated they can go dry (no flow).

Thicknesses of model layers were based on data from several sources. Total thickness of the till was calculated by subtracting a grid of bedrock-surface altitude from a grid of land-surface altitude. The grid of bedrock-surface altitude was estimated from 104 point values of bedrock-surface altitude obtained from water-well driller logs furnished by the Indiana Department of Natural Resources (2002). A bedrock-surface-altitude grid was generated by using the point values of bedrock altitude as input to the inverse-distance-weighting (IDW) surface-interpolation method available in Arc Info software (Environmental Systems Research Institute, 2003). The grid of land-surface altitude was calculated by using 10-ft land-surface contours (U.S. Geological Survey, 2008) as input to the TOPOGRID command in Arc Info. Thickness of the coal refuse deposits was calculated by subtracting a grid of land-surface altitude for the coal refuse from the grid of land-surface altitude for the till. The grid of land-surface altitude for the coal refuse was obtained by using 2-ft contours from the Indiana Department of Natural Resources, Division of Reclamation, as input to the TOPOGRID command.

Boundary conditions in the groundwater-flow model were selected so that the type and location of the boundary would have a minimal effect on simulated conditions in the center of the model. Model boundaries were defined just beyond West Little Sugar Creek and the Green Valley Mine Pond to incorporate their potential effects as hydrologic boundaries. Constant-head boundaries were placed on all four sides of model layers 2 through 4. Constant-head cells, however, were not used where a river or drain cell was at the edge of the model. Generally, constant-head cells are useful to simulate the flow of water across the edge of the model (in or out of the model) and to help stabilize the iterative solution process in the computer code of the model. A no-flow boundary was defined around layer 1 (the coal refuse) to represent the thinning out to zero thickness of the coal refuse deposits. A no-flow boundary also was assumed below the bottom layer of the model to simulate the low-permeability shale at the base of the glacial sediments. A variable-flux boundary was used at the top of the model to represent recharge from precipitation. Recharge was applied to the uppermost active model layer, which is layer 1 in the area of the coal refuse and layer 2 (the top layer of till) outside of the coal refuse. A single recharge rate was used for the till, and two recharge rates were used for the coal refuse. Areas where the two recharge rates were used for the coal refuse correspond to the areas of gob and of a gob and tailings mixture (Indiana Geological Survey, 2003; fig. 3). Details on estimating the initial values of recharge rates are given later in this report in the section describing model parameters.

Initial water-level values for model simulations were required for the coal refuse deposits and the till. Initial water levels in the coal refuse deposits were assumed to be 10 ft higher than the bottom of the coal refuse deposits (also the top of till), which is approximately the average saturated thickness measured in the coal refuse deposits by this investigation. Initial water levels for the till were estimated from computerized well-log records of water levels. The estimation of reasonable initial water levels in the till was important for the assignment of constant-head values around the model boundaries. Water levels from water-well-driller logs submitted to the Indiana Department of Natural Resources (2002) were used to obtain groundwater levels in the till. Because only 62 water levels were available in or near the study area, a water-level surface for the model layers of till (layers 2–4) could not be estimated directly from the well-log water-level data. Instead, a relation was determined between the available water-level data and land-surface altitude. The correspondence between land-surface altitude and groundwater altitude has long been recognized (Desbarats and others, 2002, p. 26), and equations have been used to establish a relation between the two variables (Kuniansky and others, 2009, p. 99). Of the equations tested, the most appropriate equation to establish the land-surface/water-level relation in the study area is a polynomial equation of the following form:

$$wl = 722.1839 - 1.6874 * ls + 0.0024 * ls^2, \qquad (1)$$

where

wl is the groundwater-level altitude, in feet above land-surface datum, and

ls is land-surface altitude, in feet above land-surface datum.

The resulting polynomial curve follows the data points more closely than the other curves; the relation between the curve and the data points is shown in fig. 19. The coefficient of determination (0.95) indicates a high degree of correlation between the two variables of land surface and water level. The correspondence between the polynomial equation and the data is greatest above 600 ft, which includes the coal refuse and upland around the refuse. The equation was used to process digital data with 10-ft land-surface contours (U.S. Geological Survey, 2008) to generate a continuous surface of initial water-levels values from which average values for each model cell were assigned.

Initial water levels generated from the previous process introduced a small but acceptable error to model analysis. The water levels from well-driller logs and land-surface altitudes from 10-ft land-surface contours are based on the National Geodetic Vertical Datum of 1929, whereas the water levels used to calibrate the model are based on the North American Vertical Datum of 1988. In the study area, NGVD 29 altitudes are 0.32 ft higher than NAVD 88 altitudes. The difference is considered insignificant relative to the error associated with the polynomial equation and error associated with subsequent model calibration.

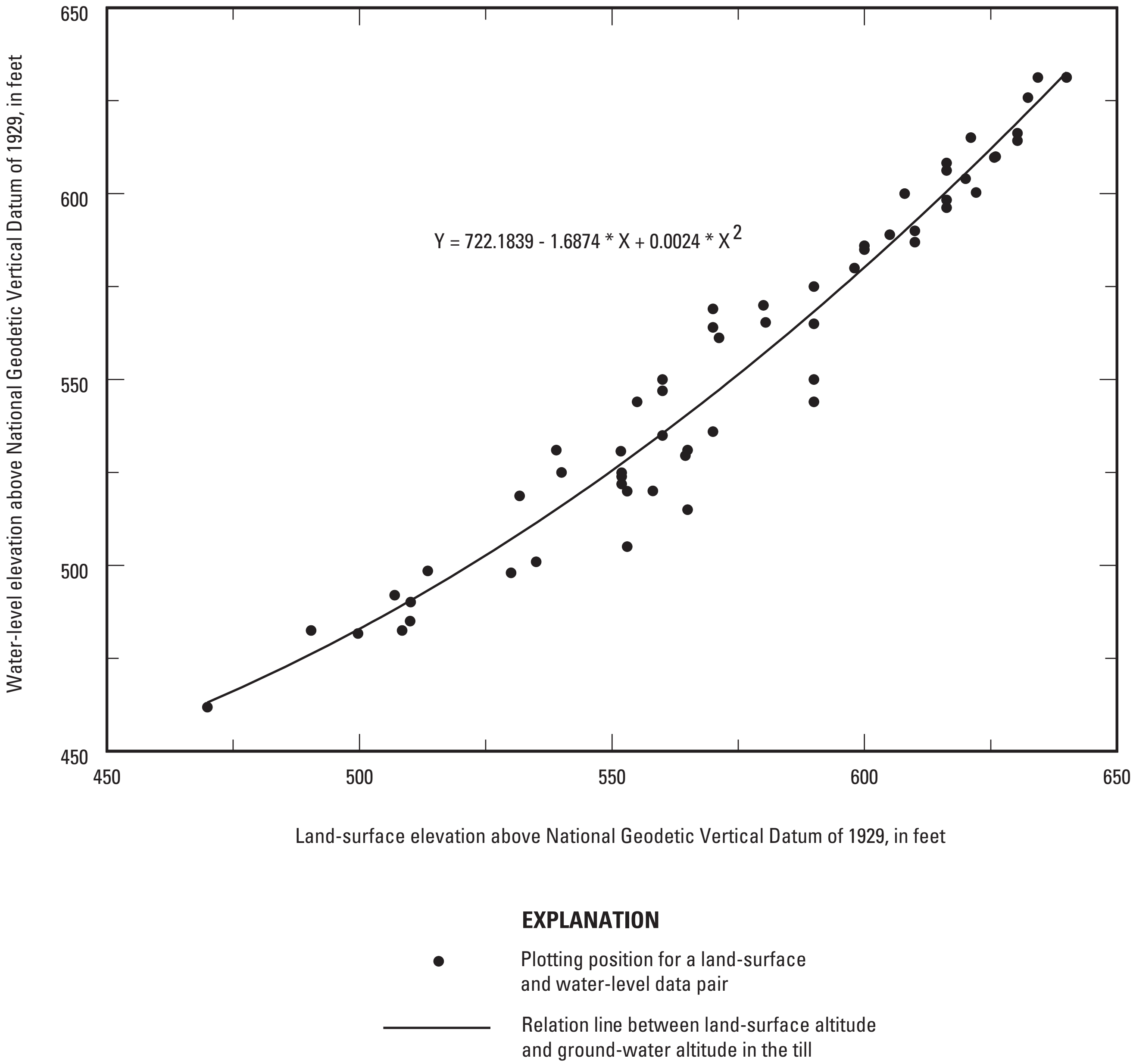


Figure 19. Relation between land-surface altitude and groundwater-level altitude at water-well sites in and near the Green Valley mine site, Indiana.

Model Calibration

Model calibration is the process of adjusting the model input variables, also called parameters, to produce the closest match between simulated and measured streamflow and water levels in the model layers. During calibration, parameters representing hydraulic properties over specified areas were adjusted by automatic parameter-estimation techniques to match measured water levels in wells and measured streamflow. MODFLOW-2000 includes a parameter-estimation feature (Hill and others, 2000) that uses a nonlinear least-squares regression method to calculate unbiased estimates of hydraulic properties and to evaluate model fit. The parameters estimated in the calibration process represent the hydraulic properties distributed as constant values over model areas or over extended linear features, such as rivers, and therefore are not intended to represent specific values of field tests at individual points.

The automated parameter-estimation process involves several components. In the process, parameters are selected to represent the major features of the flow system, and sensitivity analysis is done to determine whether unique parameter values for model features can be estimated. The process includes assigning weights to calibration data (observations) to reflect their accuracy. The numerical difference between measured and observed values is called a residual, and the procedure minimizes the sum of squared weighted residuals, called the objective function (Hill, 1998, p. 4). The final component is an evaluation of model fit to the observations and a representation of the groundwater-flow system as simulated with the model.

Selection and Sensitivity Analysis of Model Parameters

In the model, grid cells that were assumed to have similar hydrologic properties were grouped together as a parameter zone and assigned a parameter value that can be adjusted during the calibration process. The steady-state and transient model calibrations required a set of parameters. The steady-state simulation required 16 different parameters, 6 of which were estimated automatically by the model, and the transient simulation required 41 parameters, 7 of which were estimated automatically. The names of the parameters and the model component that the parameter represents for both calibrations are listed in tables 9 and 10.

Although the initial values for horizontal hydraulic conductivity of the till and coal refuse differ somewhat from the final calibrated values, the initial and final values are similar to those obtained by this investigation from slug tests. For example, the initial hydraulic conductivity value of 0.5 ft/d for till in the steady-state simulation was only slightly higher than the hydraulic conductivity estimate of 0.1 ft/d for till from the slug test of well GV2. The initial hydraulic conductivity value

Table 9. Model parameters used in the steady-state model of the Green Valley mine site, Indiana (June 2009), their initial values, and indication of whether a parameter value was estimated.

[ft/d, foot per day; in/yr, inch per year]

Parameter name	Model component represented	Initial parameter value	Parameter estimated
k.tail	Horizontal hydraulic conductivity of the gob and tailings mixture	0.3 ft/d	Yes.
k,gob	Horizontal hydraulic conductivity of the gob	15.0 ft/d	Yes.
k.till	Horizontal hydraulic conductivity of the till	0.50 ft/d	Yes.
kv.tail	Vertical hydraulic conductivity of the gob and tailings mixture	0.01 ft/d	No.
kv.gob	Vertical hydraulic conductivity of the gob	3.0 ft/d	No.
kv.till	Vertical hydraulic conductivity of the till	0.001 ft/d	Yes.
stream	Hydraulic conductivity of the streambed for small streams in the till	1.0 ft/d	No.
seep	Hydraulic conductivity of the streambed for small streams in the coal refuse and upstream of a flow-measurement point	1.0 ft/d	No.
ds.gob	Hydraulic conductivity of the streambed for small streams in the coal refuse and downstream of a flow-measurement point	1.0 ft/d	No.
river	Hydraulic conductivity of the streambed for West Little Sugar Creek	1.0 ft/d	No.
lake	Hydraulic conductivity of the lakebed for Green Valley Mine Pond	1.0 ft/d	No.
ground	Hydraulic conductivity controlling seepage of water from the soil to the land surface west of the coal refuse	1.0 ft/d	No.
rech.tail	Recharge rate to the areas of gob and tailings mixture	2.6 in/yr	Yes.
rech.gob	Recharge rate to the areas of gob	4.3 in/yr	Yes.
rech.till	Recharge rate to the till	2.6 in/yr	No.
rech.lake	Recharge rate to the area beneath Green Valley Mine Pond	0.0 in/yr	No.

Table 10. Model parameters used in the transient model of the Green Valley mine site, Indiana (June 2009), their initial values, and indication of whether a parameter value was estimated.

[ft/d, foot per day; in/yr, inch per year; ft^{-1}, 1/feet]

Parameter name	Model component represented	Initial parameter value	Parameter estimated
k.tail	Horizontal hydraulic conductivity of the tailings and gob mixture	0.75 ft/d	Yes.
k,gob	Horizontal hydraulic conductivity of the gob	0.032 ft/d	Yes.
k.till	Horizontal hydraulic conductivity of the till	0.43 ft/d	Yes.
kv.tail	Vertical hydraulic conductivity of the gob and tailings mixture	0.01 ft/d	No.
kv.gob	Vertical hydraulic conductivity of the gob	3.0 ft/d	No.
kv.till	Vertical hydraulic conductivity of the till	0.0019 ft/d	No.
Stream	Hydraulic conductivity of the streambed for small streams in the till	1.0 ft/d	No.
Seep	Hydraulic conductivity of the streambed for small streams in the coal refuse and upstream of a flow-measurement point	1.0 ft/d	No.
ds.gob	Hydraulic conductivity of the streambed for small streams in the coal refuse and downstream of a flow-measurement point	1.0 ft/d	No.
River	Hydraulic conductivity of the streambed for West Little Sugar Creek	1.0 ft/d	No.
Lake	Hydraulic conductivity of the lake bed for Green Valley Mine Pond	1.0 ft/d	No.
ground	Hydraulic conductivity controlling seepage of water from the soil to the land surface west of the coal refuse	1.0 ft/d	No.
rech.lake	Recharge rate to the area beneath Green Valley Mine Pond	0.0 in/yr	No.
till.jun08	Recharge rate to the till during the month of June 2008	5.64 in/yr	No.
till.jul08	Recharge rate to the till during the month of July 2008	3.72 in/yr	No.
till.aug08	Recharge rate to the till during the month of August 2008	1.20 in/yr	No.
till.sep08	Recharge rate to the till during the month of September 2008	0.48 in/yr	No.
till.oct08	Recharge rate to the till during the month of October 2008	0.36 in/yr	No.
till.nov08	Recharge rate to the till during the month of November 2008	0.60 in/yr	No.
till.dec08	Recharge rate to the till during the month of December2008	3.12 in/yr	No.
till.jan09	Recharge rate to the till during the month of January 2009	3.48 in/yr	No.
till.feb09	Recharge rate to the till during the month of February 2009	4.20 in/yr	No.
till.mar09	Recharge rate to the till during the month of March 2009	3.60 in/yr	No.
till.apr09	Recharge rate to the till during the month of April 2009	6.84 in/yr	No.
till.may09	Recharge rate to the till during the month of May 2009	7.32 in/yr	No.
till.jun09	Recharge rate to the till during the month of June 2009	4.56 in/yr	No.
mnd.jun08	Recharge rate to the tailings and gob mixture during the month of June 2008	6.43 in/yr	No.
mnd.jul08	Recharge rate to the tailings and gob mixture during the month of July 2008	4.24 in/yr	No.
mnd.aug08	Recharge rate to the tailings and gob mixture during the month of August 2008	1.36 in/yr	No.
mnd.sep08	Recharge rate to the tailings and gob mixture during the month of September 2008	0.55 in/yr	No.
mnd.oct08	Recharge rate to the tailings and gob mixture during the month of October 2008	0.41 in/yr	No.
mnd.nov08	Recharge rate to the tailings and gob mixture during the month of November 2008	0.68 in/yr	No.
mnd.dec08	Recharge rate to the tailings and gob mixture during the month of December 2008	3.56 in/yr	Yes.
mnd.jan09	Recharge rate to the tailings and gob mixture during the month of January 2009	3.97 in/yr	Yes.
mnd.feb09	Recharge rate to the tailings and gob mixture during the month of February 2009	4.79 in/yr	Yes.
mnd.mar09	Recharge rate to the tailings and gob mixture during the month of March 2009	4.10 in/yr	No.
mnd.apr09	Recharge rate to the tailings and gob mixture during the month of April 2009	7.80 in/yr	Yes.
mnd.may09	Recharge rate to the tailings and gob mixture during the month of May 2009	8.34 in/yr	Yes.
mnd.jun09	Recharge rate to the tailings and gob mixture during the month of June 2009	5.20 in/yr	No.
sy.gob	Specific yield of the coal refuse	0.06	Yes.
ss.till	Specific storage of the till	0.00017 ft^{-1}	Yes.

of 0.3 ft/d used for the gob and tailings mixture was within the range of hydraulic conductivity values (0.03 to 0.83 ft/d) computed for tests in wells GV7A, GV11A, and GV12A in the coal refuse. To reduce the number of parameters to be estimated in the transient calibration (a total of 41 parameters), the horizontal and vertical hydraulic conductivities of the till and coal refuse estimated from the steady-state calibration were used in the transient calibration and not re-estimated (see the table 10).

A relatively large hydraulic conductivity value of 15 ft/d was used as the initial value for the gob in the steady-state simulation to represent the possibility of more conductive deposits of coal refuse in the reclaimed area. That value was near the higher part of the range of hydraulic conductivity (7.37 to 16.4 ft/day) estimated for gob deposits by Melchiorre and others (2005). The final calibrated hydraulic conductivity of gob in the steady-state model of 0.032 ft/d was similar to the smallest values for gob plus tailings that were derived from slug testing. The larger estimates of hydraulic conductivity by Melchiorre and others (2005) may have represented relatively rapid transport of precipitation-affected water through a partially fractured saturated surface soil to seeps and not the bulk permeability of the coal refuse.

The degree of detail used to represent the flow system in the model parameters is limited not only by the sensitivity of model parameters but also by the availability and distribution of observation data (water levels and streamflow flux). For example, only one model parameter represented the horizontal hydraulic conductivity of the till because few observation water levels were located in the till. In contrast, two parameters represented the horizontal hydraulic conductivities in the much smaller area of the model containing coal refuse because of the abundance of observation water levels in the coal refuse. Multiple stream parameter zones were created to provide the opportunity to vary streambed hydraulic conductivity areally in the model, but the response of the model to all streambed parameters was found to be insensitive (tables 9 and 10). All but the recharge parameters from the steady-state simulation in table 9 are repeated for the transient state simulation in table 10. The additional parameters in the transient simulation (table 10) are the recharge parameters for each month of the 13-month simulation and the storage parameters for the till and coal refuse.

The decision to estimate a specific parameter was based on the sensitivity of simulated water levels and flows to changes in model parameters. Sensitivities of various parameters were calculated by using the sensitivity equation method (Hill and others, 2000, p. 67). Composite scaled sensitivities (CSS) were calculated for each parameter. CSS aid in determining whether there is adequate information in the calibration data to estimate a particular parameter. CSS less than about 0.01 times the largest CSS of all the parameters indicate that the nonlinear regression method may not be able to estimate that parameter (Hill, 1998, p. 38). The recharge rate to the till could be estimated in the steady-state simulation, but not in the transient. The few water-level observations in the till and the small change in till water level from month to month may have limited the model's ability to estimate till recharge. The only recharge parameters that could be estimated for the transient simulation were for the coal refuse during months of high recharge, which caused large changes in water levels.

Initial values of recharge rate to the till were estimated by using a base-flow separation technique (Rutledge, 1998). The study area is not within a gaged drainage basin; therefore, a gaged basin with similar geologic deposits (the North Fork Embarras River near Oblong, Illinois) was used to compute monthly recharge estimates as initial estimates of recharge to till in the study area. The 68-year streamflow record (1941–2009) from the USGS gage on the North Fork Embarras River near Oblong, Illinois (station number 03346000; U.S. Geological Survey, 2010), was used for the recharge estimate. The drainage basin for the gage encompasses 318 mi^2 and lies 20 mi west of the study area. Loamy till deposits are present in both the Embarras River drainage basin and in the study area. The base flow is calculated from the total flow record and is then reported monthly, yearly, and as a long-term average. The base flows are assumed equivalent to groundwater recharge and, therefore, are used as estimates for recharge in model simulations.

The monthly estimates of recharge to the till also were used to calculate a recharge rate to the areas of gob and tailings mixture in the coal refuse. The initial estimates for recharge rate to the areas of gob and tailings mixture for the transient simulation were based on a ratio of recharge rates obtained from the steady-state calibration. The ratio was calculated by dividing the steady-state calibrated recharge rate to the area of tailings by the steady-state calibrated recharge rate to the till. The initial estimates for transient recharge rate to the areas of gob and tailings mixture were calculated by multiplying the ratio by the initial estimates of monthly recharge to the till. The estimates are based on the assumption that the steady-state ratio of recharge to the two areas of gob and tailings mixture divided by the rate of recharge to the till is constant through the period of transient simulation.

The calculation described in the previous paragraph provided an estimate for transient recharge rate to the areas of gob and tailings mixture, but not to the area of gob. To obtain an estimate for transient recharge rate to the area of gob, the ratio between recharge rate to the gob and recharge to the area of gob and tailings determined from the steady-state calibration was used. The value of the ratio was calculated by dividing the calibrated steady-state recharge rate for the area of gob by the steady-state rate for the areas of gob and tailings mixture. The ratio between the two recharge rates was assumed to be the same in the transient simulation as in the steady-state simulation. The recharge rate to the area of gob was calculated by multiplying the ratio by the estimated recharge rate to the areas of gob and tailings mixture.

Estimating a recharge rate to the areas of gob and tailings mixture and then using a ratio to estimate the recharge rate to the area of gob reduced the number of estimated recharge rates for the coal refuse from two to one. The number of recharge parameters was reduced to decrease the overall number of estimated parameters. The transient calibration required a large increase in parameters to represent the system; specifically, 13 monthly recharge parameters for the till and 13 for the coal refuse. Increasing the number of parameters to be estimated decreases the capacity of the parameter-estimation process to solve for unique values of the parameters from a limited number of water-level and streamflow-flux observations.

The initial estimates for the storage parameters used in the transient calibration were based on literature values and on texture observations. The specific storage estimate for the till (0.00017 ft^{-1}) was assumed to be the same as an average, calculated by Shaver (1998, p. 552), of 107 till samples. The specific yield for the coal refuse was assumed to be the same as the average of 11 values for silt till reported by Morris and Johnson (1967). The specific yield of silt till (0.06) was chosen to estimate the specific yield of the coal refuse because of the similarity in textures of the two deposits (both silt-sized material). Because of lack of data, no attempt was made to distinguish a difference in storage properties between the gob and the gob and tailings mixture.

Storage for the top layer of till was represented by a specific storage parameter and not a specific yield parameter. When a specific yield parameter was estimated, the value calculated by parameter estimation was extremely low (0.0098). Although the observed water levels were from the top layer of till, the observed data usually were measuring a depth within the till that indicated that the material near the well screen behaved as though it was confined. Therefore, a specific storage term was used for the top layer of till, and the calibrated value for specific storage mostly represents the confined part of the layer. Available data were insufficient to justify a thin model layer along the top of the till for which a specific yield would actually apply.

The steady-state calibration of the numerical model was accomplished using water levels measured during the period of highest water levels in June 2009. During periods of annual high or low groundwater levels, storage processes are inactive and the steady-state equation can be applied to calibrate the model. The model, when calibrated using high water levels, such as during long-term wet conditions, will reflect the higher recharge needed to maintain that condition (Anderson and Evans, 2007, p.505). Groundwater levels in the Green Valley wells were almost at their highest level during June 2009 but were not in phase with each other throughout other parts of the year. In addition, most seeps and West Little Sugar Creek were flowing during June 2009; this set of discharge measurements was available to compare with simulated seep and surface-water flows computed by the calibrated groundwater model. The recharge values obtained by calibrating to the high groundwater level condition enabled the model to provide simulation results more useful to evaluate the water budget under conditions when higher volumes of groundwater flow and seepage were generated from the coal refuse.

The initial water levels for the transient simulation were obtained from the steady-state calibration for June 2009. Water levels for June 2009 were generally close to their values observed in June 2008, when the transient simulation begins. Matching measured water levels throughout the year during the transient calibration provided an opportunity to calibrate the model to all water-level conditions, including average conditions.

Observations and Observation Weights

The observations used for model calibration consisted of 152 water-level observations from 18 wells and 19 streamflow measurements from 4 stream locations, all made from June 2008 to June 2009. The locations of the observation points are shown in figure 20. Four of the wells are screened in the upper part of the till, and one (GV8C) is located in the center of the coal refuse and screened in the middle of the till. Observations from well GV8A, in the coal refuse, and adjacent well GV8C, in the till, were used to estimate the vertical hydraulic conductivity of the till.

The purpose of weighting the observations used in model calibration is twofold. First, weighting reduces the effect of observations that are known to be less accurate and increases the effect of observations that are known to be more accurate. Second, weighting produces weighted residuals (a measure of the difference between the observation and its simulated equivalent) that have the same units, whether the residual is for water level or streamflow flux (gain/loss observations). Having water-level and streamflow flux residuals in the same units allows both residuals to be included in the sum of squared errors to be minimized in model estimates of the parameters. Weights on observation data account for measurement error associated with the accuracy of the sampling device, method of determining land surface, effects of recent pumping, unknown screened intervals of wells, and other sources of uncertainty. In theory, weighted observations used in the regression procedure can be calculated from estimates of the variance of measurement error (Hill, 1998, p. 45–47). The weights are proportional to 1 divided by the variance of the measurement errors for the observation. To estimate these variances, MODFLOW-2000 reads statistics on measurement error (supplied by the user) from which the variances of the observation errors and the weights are calculated. The standard deviation of the measurement error was used to estimate the weights for water-level observations, and the coefficient of variation was used to estimate the error for the streamflow-flux observations. The calculations of the statistics are described in Hill (1998, p. 46–47).

Weights for the water-level observations were based on the assumption that 95 percent of the measurements were within the measurement error, which was considered to be 0.03 ft. Statistical theory for normally distributed populations

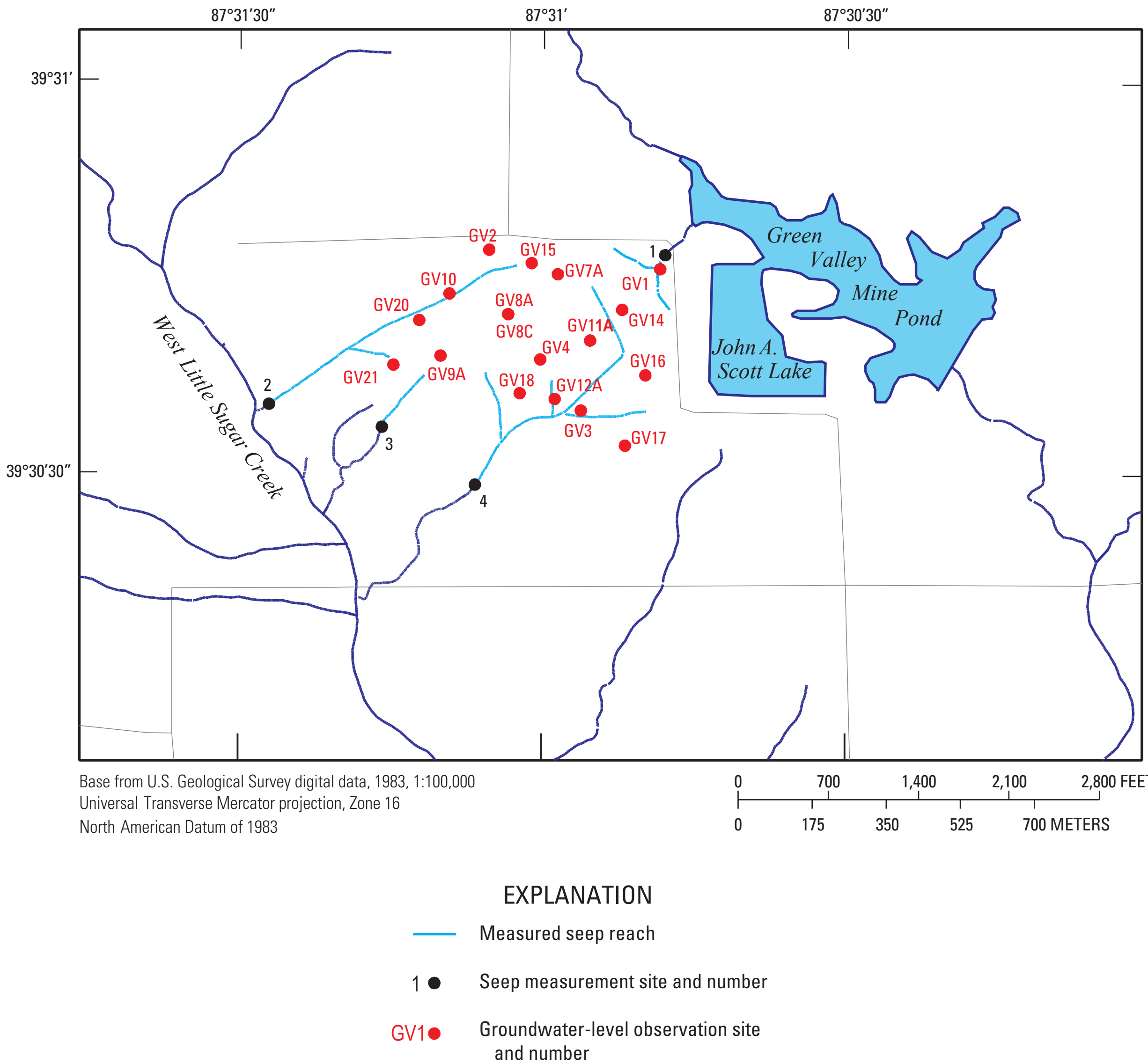


Figure 20. Location of sites used to provide observations of streamflow flux (gain/loss) and groundwater levels at the Green Valley mine site, Indiana.

states that for the 95-percent confidence interval, the measurement error should be 1.96 times the standard deviation of the measurement error (Cooley and Naff, 1990, p. 44). The standard deviation of the measurement error is, therefore, equal to 0.0153 (0.03 divided by 1.96); the standard deviation of the measurement error is used as an input to MODFLOW-2000 for calculating water-level weights.

Weights for streamflow observations were calculated by taking the inverse of the product of streamflow and the coefficient of variation associated with the difference in streamflows between two points on the stream. The coefficient of variation is calculated by finding the standard deviation of both the upstream and downstream streamflow errors, then squaring each standard deviation to obtain variances for each streamflow error. The variance of the gain or loss is then calculated by adding the two variance values associated with each measurement. The coefficient of variation is determined by dividing the square root of the summed variances of the gain or loss (a standard deviation) by the gain or loss in the stream segment (Hill, 1998, p. 47).

Changes in the Design of the Model During Calibration

Groundwater in the coal refuse appeared to be under water-table conditions, but attempts at water-table simulations resulted in unstable solutions, as evidenced by excessive iterations. The large number of iterations was caused by model cells changing from active to inactive. To improve the stability of model solutions, all layers were simulated as confined. The confined thickness of layer 1 was set to approximate the saturated thickness within the coal refuse so that the transmissivity for a confined layer 1 approached that for a water-table layer. A confined steady-state simulation for June 2009 was achieved, and the simulated water levels for layer 1 were used to define the top of layer 1. This approximation of the actual water-table surface likely would not impair the estimation of representative model-parameter values for the coal refuse because estimated parameter values were insensitive to the change in layer 1 thickness. Parameter estimation simulations using land surface as the top of layer 1 resulted in horizontal hydraulic conductivities that were similar to those obtained using the approximate water-table surface as the top of layer 1. For example, horizontal hydraulic conductivities in the coal refuse estimated by both conceptual models were near 0.1 ft/d.

An additional parameter was added during calibration. The steady-state model was simulating water levels to be above land surface just west of the coal refuse. Also, during field visits to the study site, USGS personnel noted that the land surface just west of the coal refuse was occasionally bare and covered with orange stains, apparently from groundwater with high iron concentrations seeping out from the soil. To simulate this process, an area of drain cells with altitudes equal to land-surface altitude was added to the model from the western edge of the coal refuse to the first gully west of the refuse (fig. 21). These drain cells allowed groundwater to discharge from the model if the water surface rose above

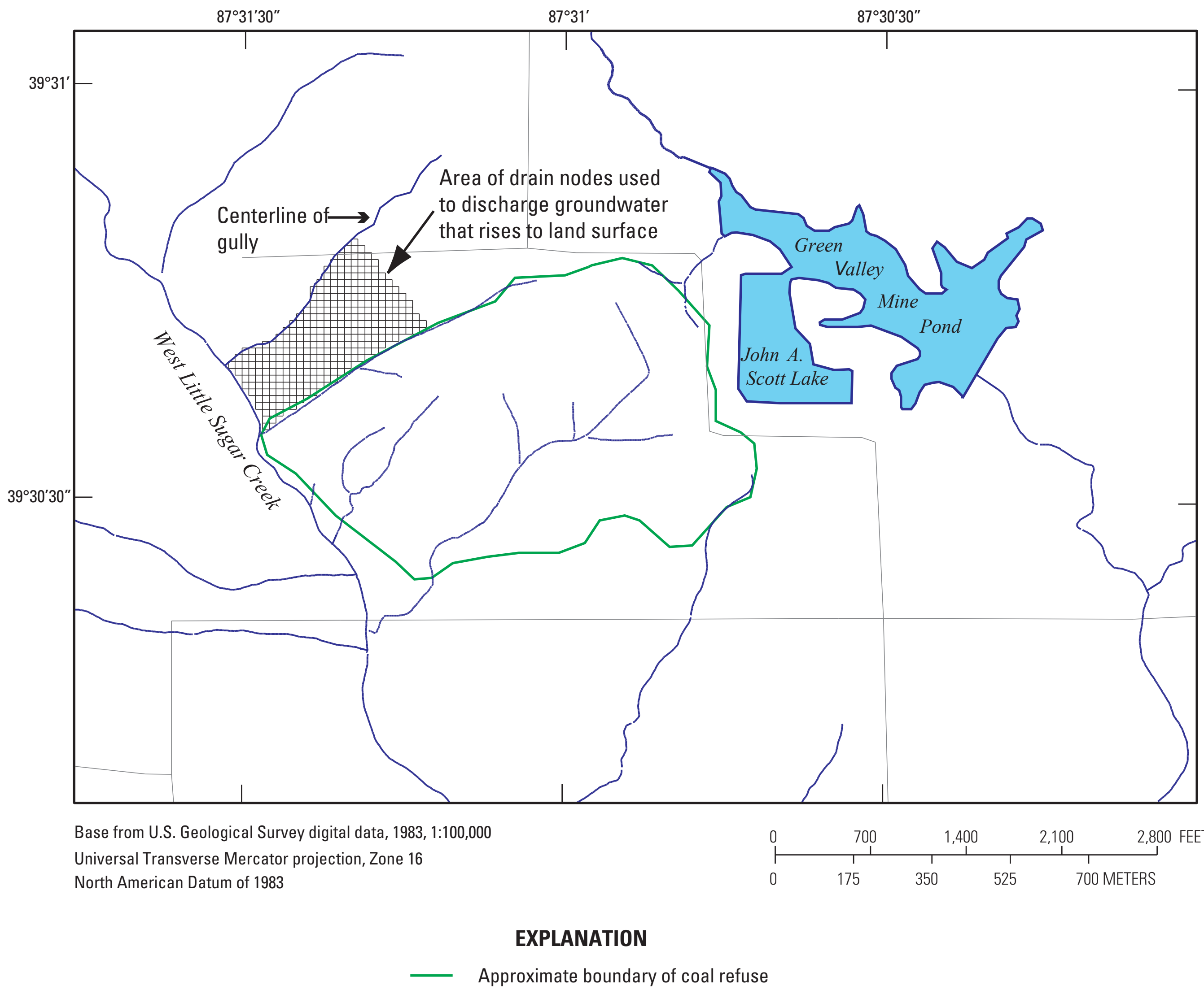


Figure 21. Location of drain cells in simulation used to discharge groundwater that reaches land surface at the Green Valley mine site, Indiana.

the land surface, as well as allowed groundwater to discharge to the gully. No discharge results where groundwater level is below the land surface. Although simulated water levels are not allowed to be higher than actual, the simulated flux rate to land surface may or may not be similar to the actual rate. Any error in the flux rate should not affect overall model results because the area of observed land-surface seepage is small relative to the entire model area.

Other adjustments and approximations to actual hydrogeologic conditions were made during calibration. The estimated water levels from the June 2009 simulation were below the bottom of layer 1 in some areas; therefore, cells for these areas were simulated as no flow. The thickness of the till was not adjusted to its saturated thickness because (1) the unsaturated part of the till is a small percentage (about 5 percent) of the overall till thickness and (2) the till is outside the area of primary interest, which is the coal refuse. Use of a single recharge rate to the coal refuse and horizontal hydraulic conductivity of the coal refuse was separately tested, but the agreement between simulated and observed water levels worsened. Two recharge rates and corresponding horizontal and vertical hydraulic conductivities were maintained for all simulations.

Calibration Results

This section includes the calibrated values for model parameters, indications of how well the model simulates observed water levels and streamflow with the calibrated parameters, and a description of the groundwater-flow system as simulated by the model. The flow system is described by a presentation of the simulated model budget, water-level contours, and groundwater-flow paths.

Calibrated Parameter Values

The calibrated parameter values are listed in table 11. The calibrated parameter values are listed only for the transient simulation because that list includes the steady-state parameter values. Calibrated parameter values for the steady-state simulation are the same as listed in table 11.

Some observations on the calibrated values are listed below:

1. The horizontal hydraulic conductivities and recharge rates for the coal refuse are similar to those for the till. The similarity implies that the coal refuse is low in permeability and does not transmit large amounts of groundwater. The low volume of water flowing through the coal refuse limits the production of acid mine drainage.

2. Aquifer-test and model-calibration estimates of horizontal hydraulic conductivity are similar. The calibrated value for horizontal hydraulic conductivity of the gob and tailings mixture is 0.75 ft/d, and the value derived from the slug test at GV11A (in an area of gob and tailings) is 0.83 ft/d based on the Hvorslev analysis (1951). The calibrated value for horizontal hydraulic conductivity of the gob is 0.03 ft/d, and the value derived from the slug test at GV12A (located in an area of gob) is 0.04 ft/d based on the Hvorslev analysis (1951). The gob and tailings mixture might be expected to be fine-grained material that would have a lower horizontal hydraulic conductivity than that for the gob, but areas of the gob and tailings mixture have been described as a mixture of coarse- and fine-grained material. A feasibility investigation by Geosciences Research Associates (1985, p. 8) described tailings as a mixture of fine gravel, sand, silt, clay, and particles of coal. The sand- and gravel-sized particles within the gob and tailings mixture apparently create a zone of higher horizontal hydraulic conductivity than is present in the gob.

3. The calibrated value of specific storage for the till is high compared to values given by Shaver (1998, p. 552). As explained in the section on the choice of model parameters, the calibrated value for specific storage was higher than expected for till. The observed water levels within the till were to some degree affected by release of water from gravity drainage. As a result, the calibrated specific storage is higher to reflect that release of water. The approximation of two parameters (specific storage and specific yield) by one parameter is not expected to substantially affect model simulations. The approximation applies to till and not to the coal refuse, the model component of interest.

Table 11. Calibrated parameter values obtained for the groundwater model of the Green Valley mine site, Indiana.

[ft/d, feet per day; in/yr, inches per year; ft^{-1}, per foot]

Parameter name	Model component	Calibrated parameter value
k.tail	Horizontal hydraulic conductivity of the gob and tailings mixture	0.75 ft/d
k,gob	Horizontal hydraulic conductivity of the gob	0.03 ft/d
k.till	Horizontal hydraulic conductivity of the till	0.43 ft/d
kv.tail	Vertical hydraulic conductivity of the gob and tailings mixture	0.07 ft/d
kv.gob	Vertical hydraulic conductivity of the gob	0.003 ft/d
kv.till	Vertical hydraulic conductivity of the till	0.0019 ft/d
Stream	Hydraulic conductivity of the streambed for small streams in the till	1.0 ft/d
Seep	Hydraulic conductivity of the streambed for small streams in the coal refuse and upstream of a flow-measurement point	1.0 ft/d
ds.gob	Hydraulic conductivity of the streambed for small streams in the coal refuse and downstream of a flow-measurement point	1.0 ft/d
River	Hydraulic conductivity of the streambed for West Little Sugar Creek	1.0 ft/d
Lake	Hydraulic conductivity of the lakebed for Green Valley Mine Pond	1.0 ft/d
ground	Hydraulic conductivity controlling seepage of water from the soil to the land surface west of the coal refuse	1.0 ft/d
rech.lake	Recharge rate to the area beneath Green Valley Mine Pond	0.0 in/yr
till.jun08	Recharge rate to the till during the month of June 2008	4.45 in/yr
till.jul08	Recharge rate to the till during the month of July 2008	3.72 in/yr
till.aug08	Recharge rate to the till during the month of August 2008	1.20 in/yr
till.sep08	Recharge rate to the till during the month of September 2008	0.48 in/yr
till.oct08	Recharge rate to the till during the month of October 2008	0.36 in/yr
till.nov08	Recharge rate to the till during the month of November 2008	0.60 in/yr
till.dec08	Recharge rate to the till during the month of December 2008	3.12 in/yr
till.jan09	Recharge rate to the till during the month of January 2009	3.48 in/yr
till.feb09	Recharge rate to the till during the month of February 2009	4.20 in/yr
till.mar09	Recharge rate to the till during the month of March 2009	3.60 in/yr
till.apr09	Recharge rate to the till during the month of April 2009	6.84 in/yr
till.may09	Recharge rate to the till during the month of May 2009	7.32 in/yr
till.jun09	Recharge rate to the till during the month of June 2009	4.56 in/yr
mnd.jun08	Recharge rate to the tailings and gob mixture during the month of June 2008	3.14 in/yr
mnd.jul08	Recharge rate to the tailings and gob mixture during the month of July 2008	4.24 in/yr
mnd.aug08	Recharge rate to the tailings and gob mixture during the month of August 2008	1.37 in/yr
mnd.sep08	Recharge rate to the tailings and gob mixture during the month of September 2008	0.55 in/yr
mnd.oct08	Recharge rate to the tailings and gob mixture during the month of October 2008	0.41 in/yr
mnd.nov08	Recharge rate to the tailings and gob mixture during the month of November 2008	2.00 in/yr
mns.dec08	Recharge rate to the tailings and gob mixture during the month of December 2008	2.53 in/yr
mnd.jan09	Recharge rate to the tailings and gob mixture during the month of January 2009	4.54 in/yr
mnd.feb09	Recharge rate to the tailings and gob mixture during the month of February 2009	3.89 in/yr
mnd.mar09	Recharge rate to the tailings and gob mixture during the month of March 2009	2.50 in/yr
mnd.apr09	Recharge rate to the tailings and gob mixture during the month of April 2009	10.3 in/yr
mnd.may09	Recharge rate to the tailings and gob mixture during the month of May 2009	5.86 in/yr
mnd.jun09	Recharge rate to the tailings and gob mixture during the month of June 2009	3.50 in/yr
sy.gob	Specific yield of the coal refuse	0.013
ss.till	Specific storage of the till	0.00197ft^{-1}

Analysis of the Residuals

The degree of fit between field-measured and model-simulated values is an indication of how well the model represents the actual groundwater-flow system. Model fit can be assessed by means of multiple indicators, including plots of measured water levels in relation to simulated water levels, the correlation coefficient between those values, and water-level residuals. Residuals can be analyzed in terms of their distribution and degree of bias.

Ideally, simulated values should be close to measured values such that when weighted observations are plotted against weighted simulated values, the residual values fall close to a line with slope equal to 1 and intercept of zero. The plot of weighted measured water levels in relation to weighted simulated water levels for the steady-state calibration is shown in figure 22*A*, and a similar plot for the transient calibration is shown in figure 23*A*. The correlation coefficient between weighted observations and weighted simulated equivalents reflects how well the values follow the 1:1 line. A correlation coefficient greater than 0.90 is desirable (Hill, 1998, p. 22) and the model calibration resulted in a value of 0.99996 and 0.99993 for the steady-state and transient calibrations, respectively.

Valid parameter estimation is expected to result in normally distributed weighted residuals. The weighted residuals are plotted according to their position in an assumed normal distribution. The plotting positions for the steady-state calibration are shown in figure 22*B*. The plotting positions for the transient calibration are shown in figure 23*B*. If the residuals are normally distributed, then the residuals should plot along a straight line. The statistic that measures the linearity of the plot and the independence of one residual to another is called the correlation between ordered weighted residuals and normal order statistics. This correlation coefficient should be near 1; the value associated with the residuals from the model calibration is 0.98 for both the steady-state and transient calibrations and is sufficiently close to 1 that the residuals approximate a normal distribution.

Weighted residuals and their weighted simulated values for the steady-state and transient calibrations were used to evaluate positive or model bias (figs. 22*C* and 23*C*). Ideally, the weighted residuals should be evenly distributed around a mean of zero and not biased positively or negatively. Also, the size of the weighted residuals should not be related to the magnitude of the weighted simulated values; for example, large residuals (relative to the mean residual) associated with lower simulated values. These requirements were generally satisfied in both model calibrations.

The residual plots do not show the residuals associated with measured streamflow. The plotting position for the streamflow flux residuals are near the origin of the axis, whereas the water-level residuals are far from the origin. The relative plotting positions reflect the difference in magnitude of the sum of squared residuals for each type of observation. For the steady-state calibration, the sum of squared streamflow

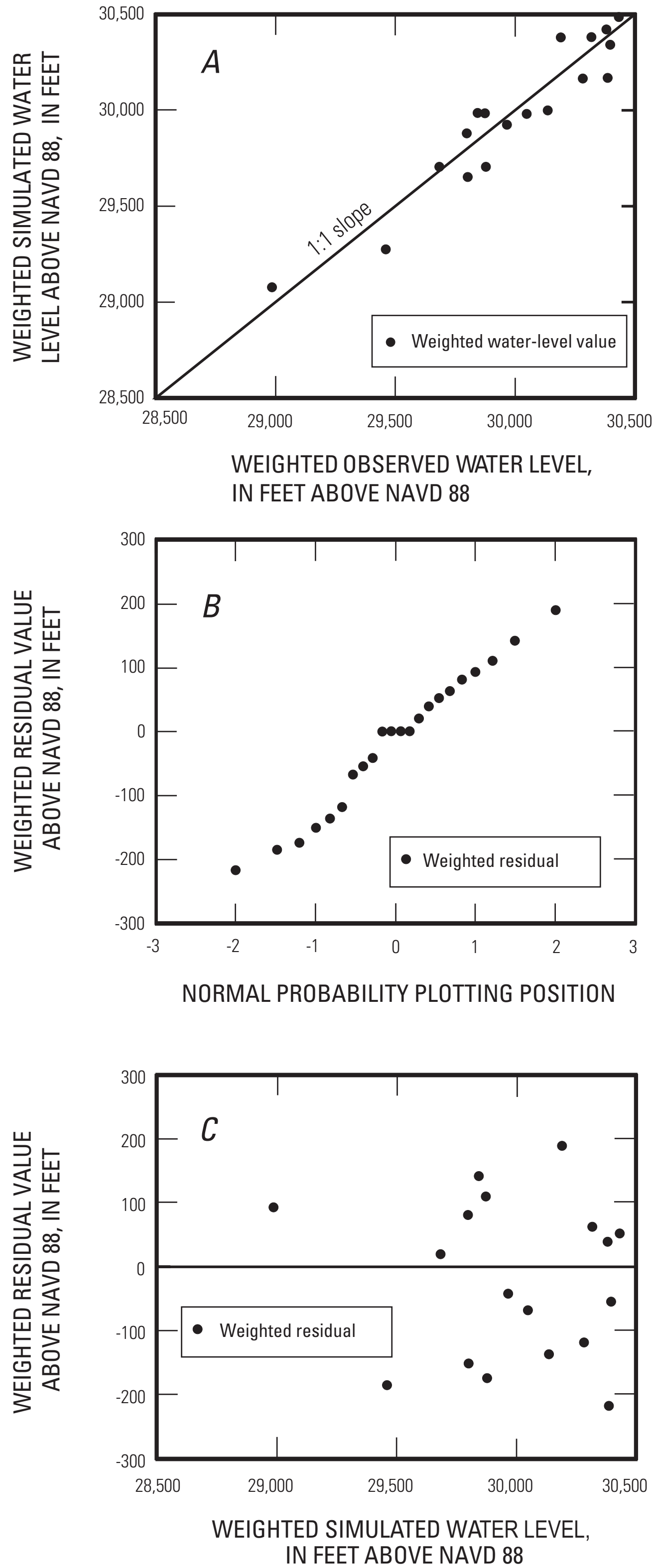


Figure 22. Graphical analysis of the steady-state model fit for the area of coal refuse at the Green Valley mine site, Indiana. *A*, Weighted simulated and weighted observed water levels. *B*, Normal probability plot of weighted residuals. *C*, Weighted residuals and weighted simulated water levels.

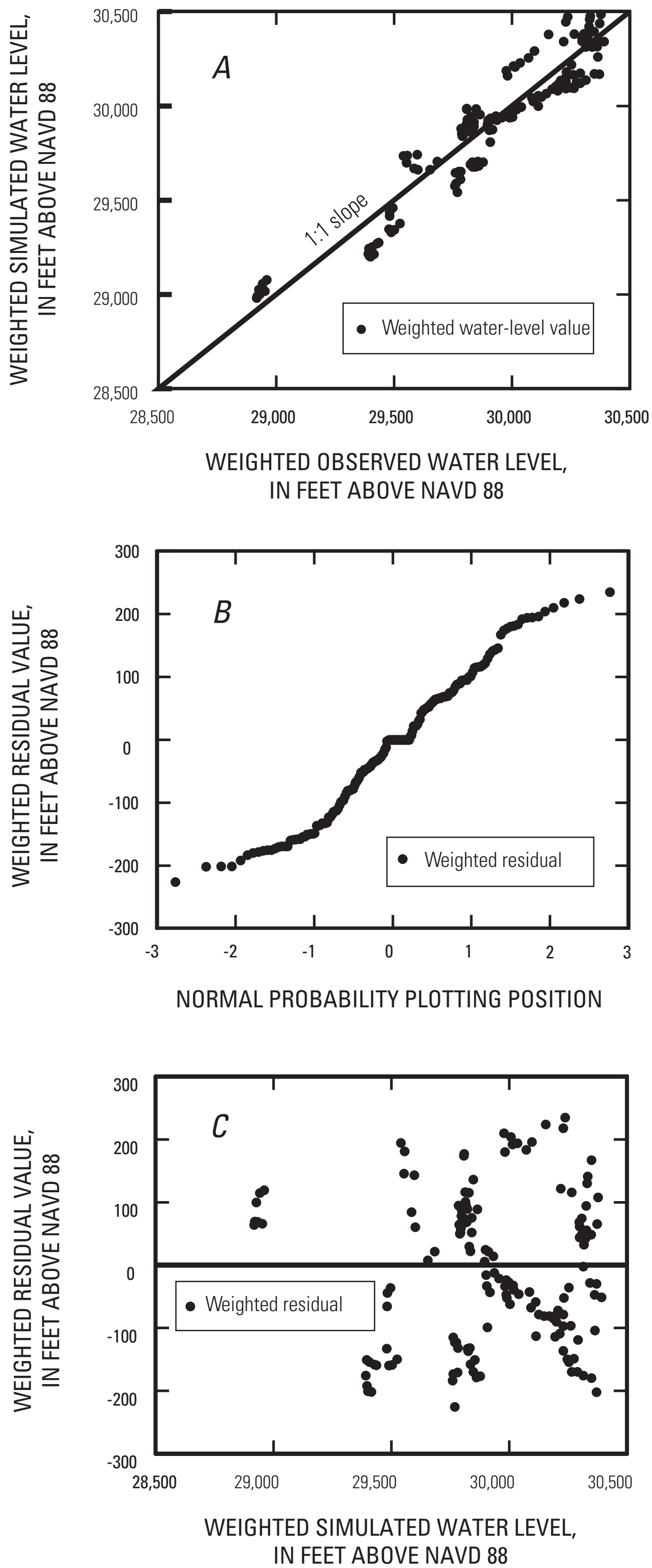


Figure 23. Graphical analysis of the transient model fit for the area of coal refuse at the Green Valley mine site, Indiana. *A*, Weighted simulated and weighted observed water levels. *B*, Normal probability plot of weighted residuals. *C*, Weighted residuals and weighted simulated water levels.

flux residuals is 0.16, and the sum of squared water-level residuals is 267,840. Plotting all residuals on the same graph would result in the water-level residuals plotting so close together that details of the distribution of the water-level residuals would be obscured. To display the more important error associated with the simulated water levels, the axes on the residual plots were chosen to show only the water-level residuals. The streamflow flux residual data for the steady-state and transient calibrations are presented in tables 12 and 13, respectively. The streamflow flux residuals do not generate substantial model error because they plotted near the 1:1 line in figures 22*A* and 23*A* and near the zero line in figures 22*C* and 23*C*.

Although the streamflow flux residuals do not generate substantial model error as compared to water-level residuals, the flux residuals are sometimes a significant percentage of the measured flow. An elaboration on this error is given in the text associated with tables 14 and 15, which present basic statistical measures for all residuals. Residuals also can be analyzed by their areal distribution and magnitude. The map of water-level residuals for all model layers from the steady-state calibration shows a random distribution of positive and negative residuals over the model area (fig. 24), which is characteristic of an adequately calibrated model (Anderson and Woessner, 1992, p. 242). Positive residuals indicate that the model overpredicts a water level. A map of water-level residuals from the transient calibration is not shown because the patterns, signs, and magnitudes of residuals are similar to those for the steady-state calibration. The difference between simulated and observed water levels for the transient simulation can be observed in a set of simulated and observed hydrographs.

The degree to which simulated water levels represent the fluctuations in observed water levels can be seen in figure 25. The simulated fluctuations are affected by the calibrated values for recharge rates, storage properties, and hydraulic conductivity. The hydrographs in figure 25, which are representative examples of all the hydrographs, show observed and simulated water-level fluctuation in the till (at well GV10), in the areas of gob and tailings mixture (at wells GV14 and 17), and in the area of gob (at wells GV21, GV4, and GV7A). Typically, simulated water levels that were above or below the observed value in the steady-state calibration remained the same throughout the transient simulation. Although the simulated water levels differ moderately from the observed values, the range of fluctuation in the simulated water level is usually about the same as that for the observed water levels. The rise in observed water levels at well GV4 begins later than the rise in the simulated water levels. The reason for the delayed rise is unknown, but it is not considered to be caused by a longer time for recharge to travel from the land surface to the water table at site 4 compared to other sites. A delayed rise also occurs at site 18, but only 8 ft of unsaturated coal refuse lies above the water table at that site. Also, all observed water levels attain their highest level in or near June, indicating timing of the recharge process is similar for all sites. The agreement between simulated and observed hydrographs is considered

Table 12. Unweighted streamflow flux residuals for the steady-state calibration of June 2008 for the model of the Green Valley mine site, Indiana.

[(ft3/s), cubic feet per second]

Seep-measurement site[1]	Observed flow (ft^3/s)	Simulated flow (ft^3/s)	Unweighted streamflow flux residual (simulated–observed) (ft^3/s)
1	0.000	0.0034	0.0034
2	.0000	.0006	.0006
3	.0102	.0002	-.0100
4	.0183	.0067	-.0116

[1] Site locations shown in figure 20

Table 13. Unweighted streamflow flux residuals for the transient calibration from June 2008 to June 2009 from the model of the Green Valley mine site, Indiana.

[(ft3/s), cubic feet per second]

Seep-measurement site[1]	Measurement date	Observed flow (ft^3/s)	Simulated flow (ft^3/s)	Unweighted streamflow flux residual (simulated–observed) (ft^3/s)
1	November 2008	0.0000	0.0020	0.0020
2	November 2008	.0000	.0001	.0001
3	November 2008	.0056	.0001	-.0055
1	December 2008	.0000	.0020	.0020
2	December 2008	.0000	.0001	.0001
3	December 2008	.0000	.0001	.0001
3	January 2009	.0119	.0002	-.0117
1	March 2009	.0063	.0023	-.0040
2	March 2009	.0032	.0001	-.0031
3	March 2009	.0050	.0001	-.0049
4	March 2009	.0186	.0040	-.0146
1	April 2009	.0047	.0027	-.0020
2	April 2009	.0046	.0003	-.0043
3	April 2009	.0084	.0002	-.0082
4	April 2009	.0371	.0067	-.0304
1	June 2009	.0000	.0032	.0032
2	June 2009	.0000	.0003	.0003
3	June 2009	.0102	.0002	-.0100
4	June 2009	.0183	.0059	-.0124

[1] Site locations shown in figure 20

Table 14. Statistical summary for the residuals from the steady-state calibration of the model for the Green Valley mine site, Indiana.

[ft, feet; ft^3/s, cubic feet per second]

Type of residual	Minimum residual	Mean residual	Maximum residual	Standard deviation of the residuals	Mean absolute error	Percent mean absolute error (percent)	Median error	Bias
Water level (ft)	-4.34	-0.39	3.78	2.48	2.15	7.6	-0.22	-0.39
Streamflow (ft^3/s)	-0.011	-0.004	0.003	0.007	0.006	33.3	0.004	-0.004

Table 15. Statistical summary for the residuals from the transient calibration of the model for the Green Valley mine site, Indiana.

[ft, feet; ft³/s, cubic feet per second]

Type of residual	Minimum residual	Mean residual	Maximum residual	Standard deviation of the residuals	Mean absolute error	Percent mean absolute error (percent)	Median error	Bias
Water level (ft)	-4.52	-0.20	4.70	2.38	2.10	7.0	-0.50	-0.20
Streamflow (ft^3/s)	-0.03	-0.006	0.003	0.008	0.006	16.2	-0.004	-0.006

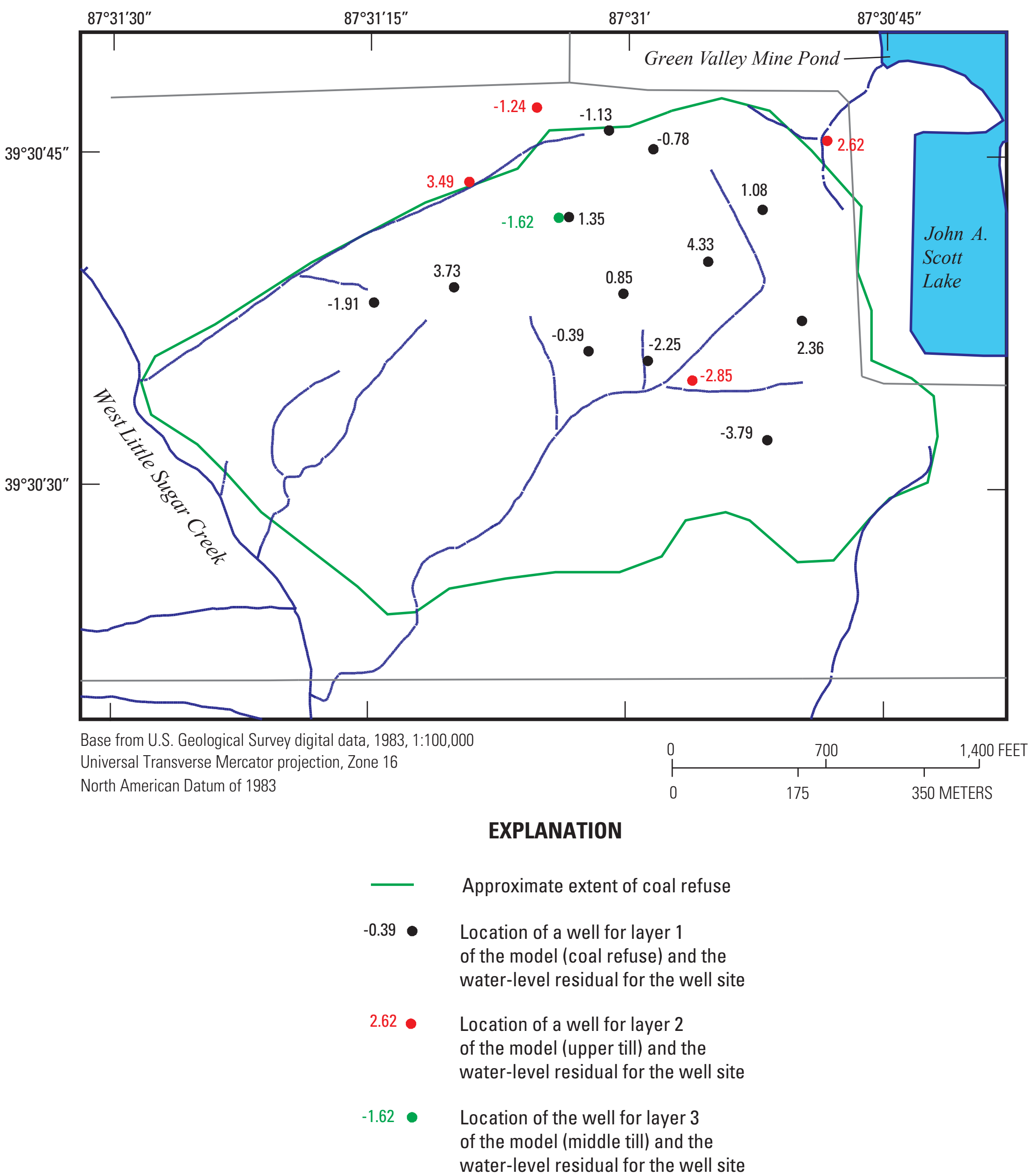


Figure 24. Distribution of positive and negative unweighted water-level residuals for the steady-state calibration of the model for the Green Valley mine site, Indiana..

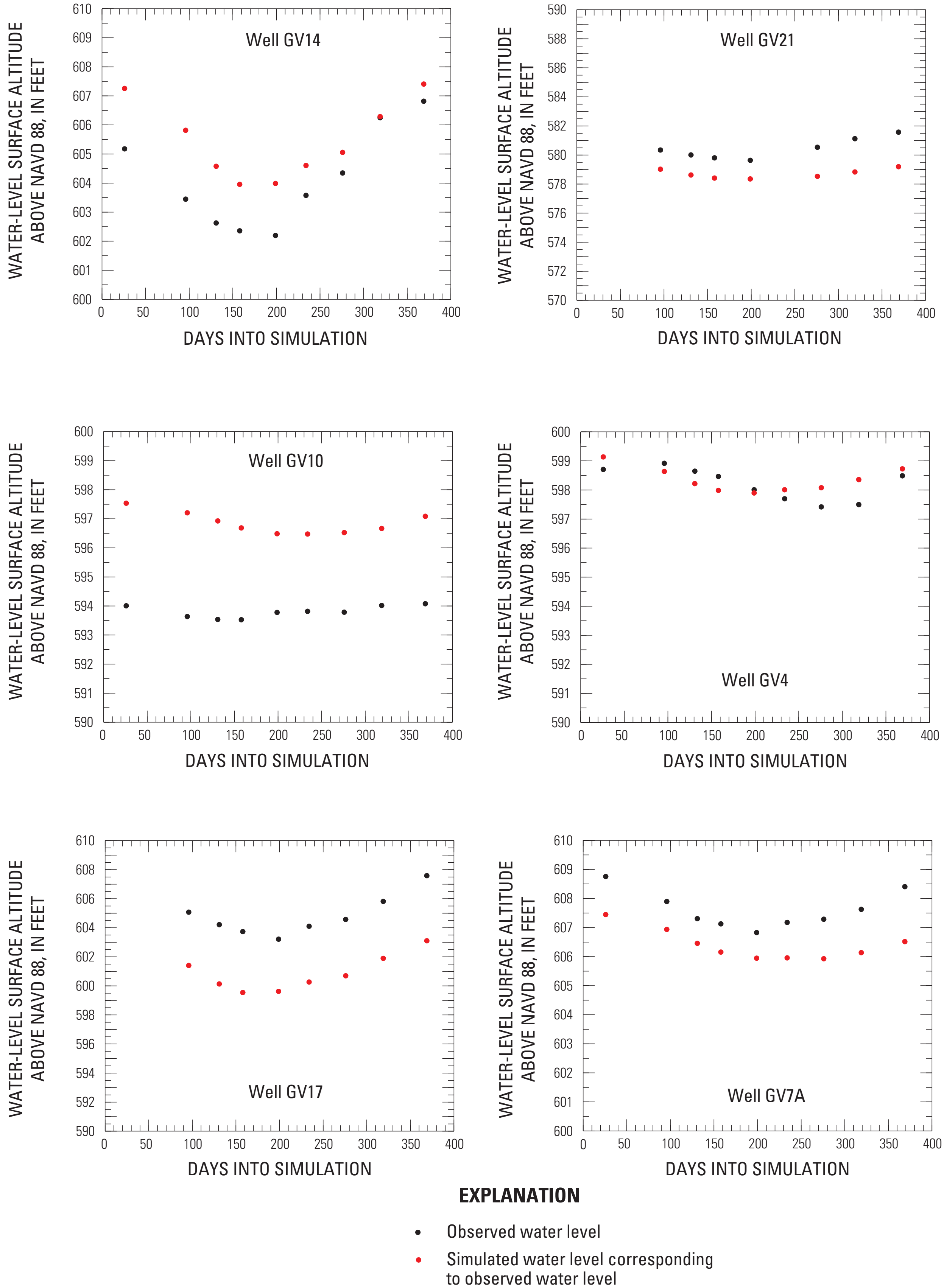


Figure 25. Simulated and observed hydrographs from the transient calibration of the model for the Green Valley mine site, Indiana (well locations shown in fig. 20).

acceptable, especially considering that only one specific yield parameter was used to simulate all deposits in the coal refuse. Using one specific yield for the area containing the gob and tailings mixture and another for the area for the gob only was not considered because of the lack of field data to help define these parameters.

Finally, the residuals were examined by basic statistical measures, such as mean absolute error and bias (tables 14–15). The statistics for the steady-state and transient calibrations are similar, indicating a similar level of accuracy in the two calibrations. Percent mean absolute error is calculated by dividing the mean absolute error by the range in observation values in the study area; the calculation provides a measure of the accuracy of the simulation. For example, a 1-ft mean absolute error may appear to be representing an accurate simulation unless the range in observations is 2 ft, in which case, the percent error would be 50 percent. The percent mean absolute errors for the streamflow flux residuals from the steady-state and transient calibrations are high (33 and 16 percent, respectively), but they may be a reflection of the small absolute values of flux. When the absolute values are small, a small error in model-simulated flux can still show a large percent mean absolute error. The high values for percent mean absolute errors for the streamflow flux residuals can also indicate a limitation of the model to simulate all flow to the seeps. A field observation during August 2008 near seep 3 indicated the existence of a preferential flow path to that seep. Preferential flow paths can serve as alternative flow path to the seeps in addition to normal porous media flow. Additional field data would be needed to confirm and characterize preferential flow paths elsewhere. The bias data are calculated as the sum of residuals divided by the number of observations so that bias represents the average amount that the model overpredicts or underpredicts water levels and fluxes. The negative bias (underprediction) for streamflow flux of 0.004 ft^3/s is 12 percent of the total flow from the gob (table 16), indicating that the error in simulated flow to the seeps is relatively small compared to the overall flow out of the gob (model layer 1).

Model Budget

Some insights into the groundwater-flow system can be gained by analyzing the simulated groundwater-flow budget. Understanding the magnitude and direction of flow can aid in developing remediation strategies. The calibrated, steady-state water budget is listed in table 17. The simulated transient water budgets are similar to the steady-state budget in terms of flow rates except that the transient budgets include flow in and out of storage. The only flow component in the transient budget that varies noticeably from the steady-state budget is recharge. Recharge rates vary throughout the year from 0.0320 to 0.0636 ft^3/s; flows in and out of storage compensate for the recharge-rate variation. For the steady-state budget in Table 17, most of the inflow (83 percent) is from precipitation

Table 16. Simulated steady-state water budget for layer 1 of the model (the coal refuse), Green Valley mine site, Indiana, June 2009.

[ft^3/s, cubic feet per second]

Source of Inflow to model	Inflow rate (ft^3/s)	Outflow from layer 1	Outflow rate (ft^3/s)
Recharge	0.0302	Flow to seeps	0.00915
Flow from the till to the coal refuse	0.00222	Flow from the coal refuse to the till	0.0233
Total inflow	0.0324	Total outflow	0.0325

Table 17. Simulated steady-state water budget in June 2009 for the model of the Green Valley mine site, Indiana.

[ft^3/s, cubic feet per second]

Inflow to model	Inflow rate (ft^3/s)	Outflow from model	Outflow rate (ft^3/s)
Constant-head boundaries	0.0776	Constant-head boundaries	0.142
		Drains	0.290
Leakage from Green Valley Mine Pond	0.00430	Leakage into Green Valley Mine Pond	0.0558
Recharge	0.406		
Total inflow	0.488	Total outflow	0.488

recharge, and most of the outflow (71 percent) is to the drains (the seeps in the coal refuse, water seeping to the land surface, and local streams) and the Green Valley Mine Pond.

The flow budget is further examined by presenting the budget flow rates between layer 1, the coal refuse, and layer 2, the top layer of till (table 16). Most of the discharge outflow from the coal refuse (72 percent) is downward leakage into the till and is not out of the seeps. The seeps are fed mostly by precipitation recharge occurring over the coal refuse; however, a large amount of seepage (24 percent) comes from the till. If the seeps were not present, water from the till currently flowing out to the seeps would discharge as flow elsewhere, such as vertically downward deeper into the till.

Simulated Water Levels

The directions of groundwater flow in the model are illustrated by contours that depict water-level-altitude data and from which direction of flow can be inferred. Water-level contours from the steady-state calibration for the coal refuse (layer 1) are shown in figure 26 and for the middle of the till (layer 3) are shown in figure 27. Contours from the transient calibration are similar to those for the steady-state ones because of the small fluctuation in water levels over the year. A mostly southwesterly groundwater-flow direction can be seen in each contour map; a downward flow direction can be seen by observing generally higher water levels in the coal

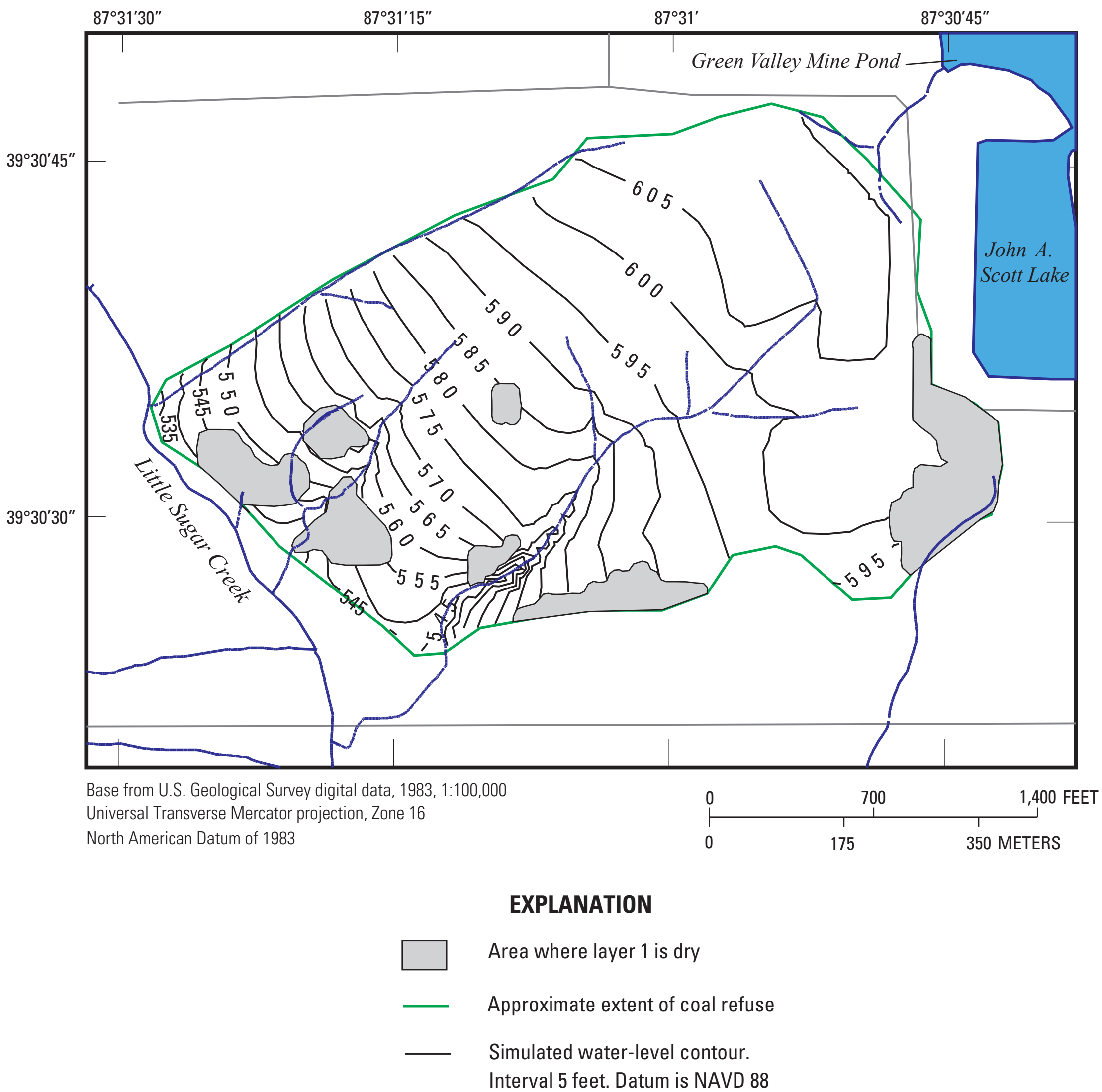


Figure 26. Model-simulated water levels for the coal refuse (model layer 1) of the model, Green Valley mine site, Indiana.

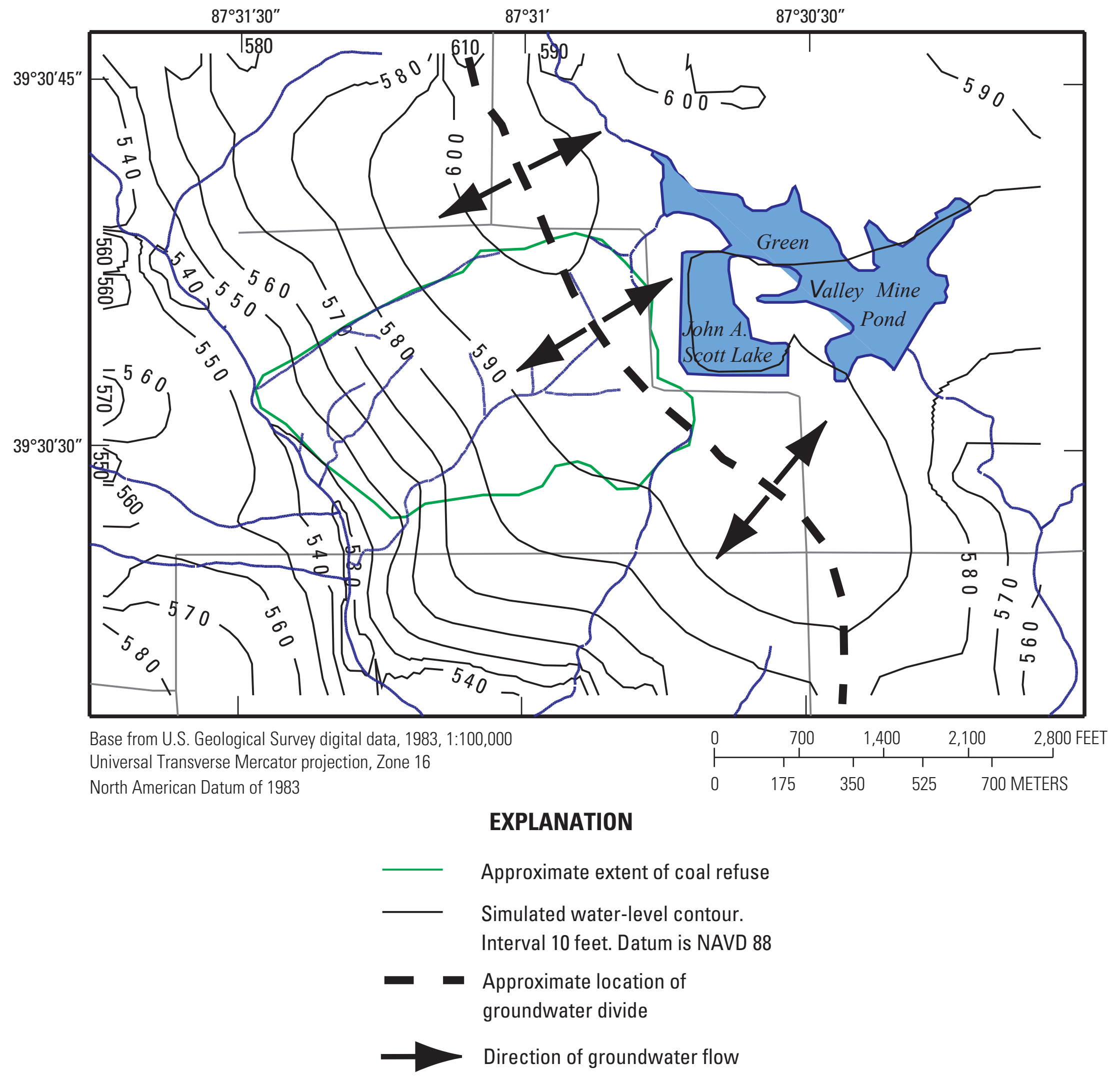


Figure 27. Model-simulated water levels for the middle of the till (model layer 3) of the model, Green Valley mine site, Indiana.

refuse (fig. 26) and lower ones in the till (fig. 27). The horizontal flow direction is towards West Little Sugar Creek. There is an approximate 5-ft vertical downward gradient between the coal refuse and the middle of the till. The water levels in the coal refuse and till also indicate some discharge to the seeps, but the area contributing that water is immediately adjacent to the seep channels. An approximate groundwater divide is shown on figure 27 and indicates that groundwater in a small area of the coal refuse flows to the northeast, toward Green Valley Mine Pond and John A. Scott Lake.

Simulated Flow Paths

Groundwater-flow paths provide useful information about the source, distribution, and discharge flow of ground water in the model area. Both steady-state and transient simulations can be used to generate flow-path information, but the steady-state simulation for June 2009 is used here. Calculations for steady-state simulations are easier to compute, and the flow-path information (the location of the path and the path endpoint) is essentially the same as for a transient simulation. Flow paths can be shown for any area in the model, but a useful set of groundwater flow paths for illustration is the paths taken by water discharging from the coal refuse. Those paths will also show the ultimate discharge for acidic water emanating from the coal refuse. Evenly distributed points of recharge (the small black dots) over the area of coal refuse are shown in figure 28. The ultimate discharge endpoints for these recharge points are shown as red dots, and the red dots cluster at four major discharge areas: West Little Sugar Creek, Green Valley Mine Pond, the downstream part of seep 4, and downgradient streams. Data on how many of the flow paths end in each major discharge area and on travel time to those discharge areas are given in table 18. The discharge area receiving the

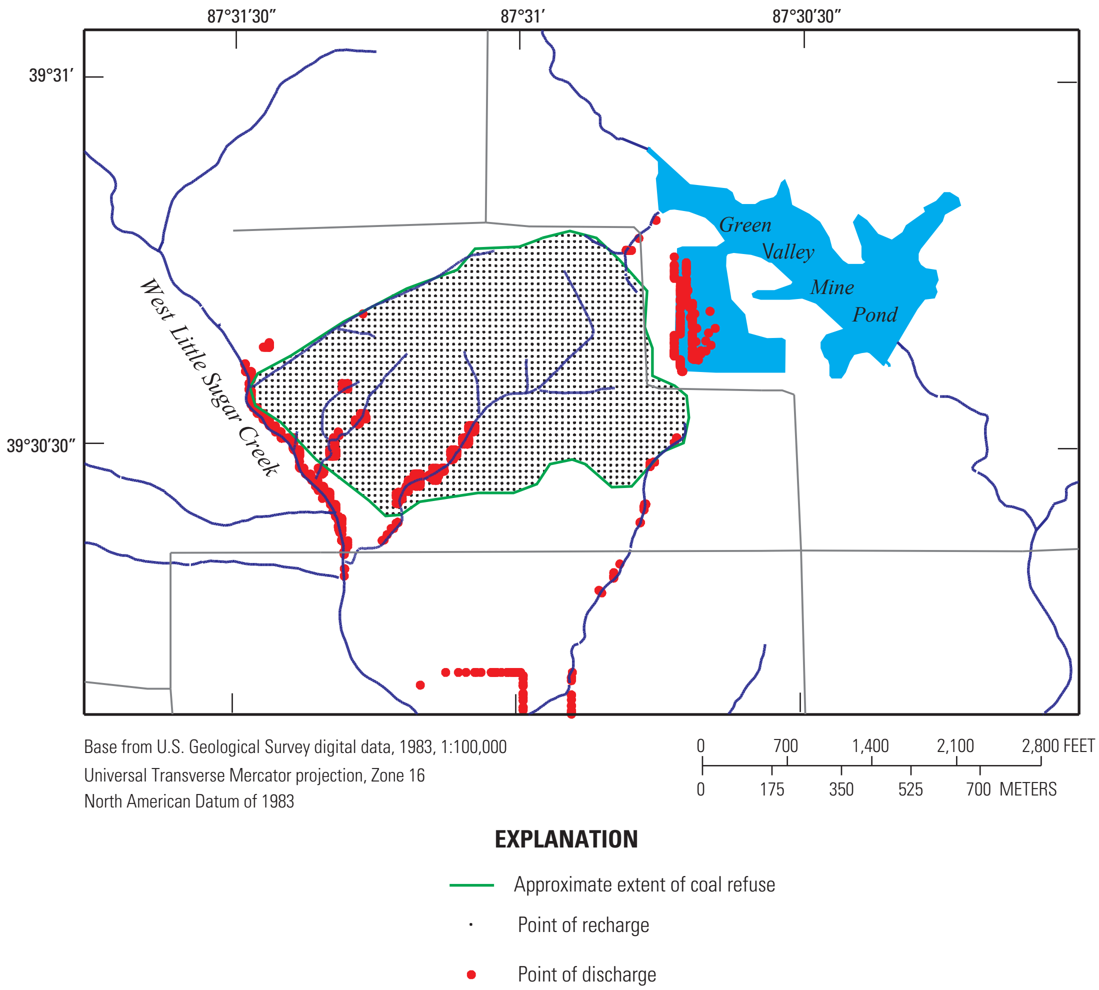


Figure 28. Simulated flow paths from points of recharge in the area of coal refuse (model layer 1) to points of discharge areas, Green Valley mine site, Indiana.

Table 18. Percentage of flow paths discharging to the major discharge areas and travel time statistics for the flow paths, Green Valley mine site, Indiana.

Discharge ouflow area of the model	Percentage of flow paths flowing to area (percent)	Minimum traveltime (years)	Mean traveltime (years)	Maximum traveltime (years)	Maximum traveltime (years)
West Little Sugar Creek	24	5	152	835	150
Green Valley Mine Pond	9	20	140	827	155
Seep 4	32	0	84	423	83
Streams downgradient from coal refuse	7	20	231	1,101	242

most flow paths is the downstream part of seep 4 (32 percent), followed by West Little Sugar Creek (24 percent). Average travel time along the flow paths is long (from 84 to 152 years), allowing substantial time for acidic water to interact with the low-permeability sediments and undergo chemical changes. Travel times are shorter if the recharge points are close to the major discharge area, and can be zero—like at the downstream part of seep 4. In that case, the recharge point is placed on the seep, resulting in no travel time to the discharge point. Travel times can be shorter than those in table 18 if continuous fractures or extensive zones of sand and gravel are present in the till, creating high-permeability zones. The longest travel times are associated with the red discharge points along the bottom center of figure 28 because those discharge points are farthest from the coal refuse. The flow paths discharging to the bottom center of the figure represent paths in the model that would eventually discharge flow to streams further south of the modeled area.

To show the vertical characteristics of the flow paths, a cross-sectional view of flow paths through the coal refuse is shown in (fig. 29). Various recharge points over the center of the coal refuse were selected (part *A* of fig. 29), and the associated flow paths are shown (part *B* of fig. 29). Fewer recharge points were chosen for figure 29 compared to figure 28 for clarity; if all of the flow paths associated with the recharge points in figure 28 were shown, then the high density of flow lines would reduce the ability to observe vertical flow patterns. The flow paths in figure 29 show groundwater from the coal refuse flowing vertically downward into the till, then eventually horizontally to West Little Sugar Creek and the Green Valley Mine Pond. The almost completely downward vertical flow in the coal refuse would indicate that a remediation technique using flow barriers to channel subsurface flow would probably be ineffective. The flow paths are shown along the cross section row 34 of the model (see fig. 29*A* for location) to help explain flow patterns. None of the flow paths flow entirely along row 34 of the model; instead, the flow paths are projected onto the cross section for the purposes of this figure. Because groundwater is not flowing exactly along row 34, the flow paths do not appear to discharge into West Little Sugar Creek and the lakes, but they actually do at another row position. The projected flow paths show the general pattern of flow against model features. For example, most flow paths discharge end at West Little Sugar Creek but some discharge to the Green Valley Mine Pond. The vertical component to the flow paths in the coal refuse and till contributes to the decades-long travel times within these units.

Model Limitations and Qualifications

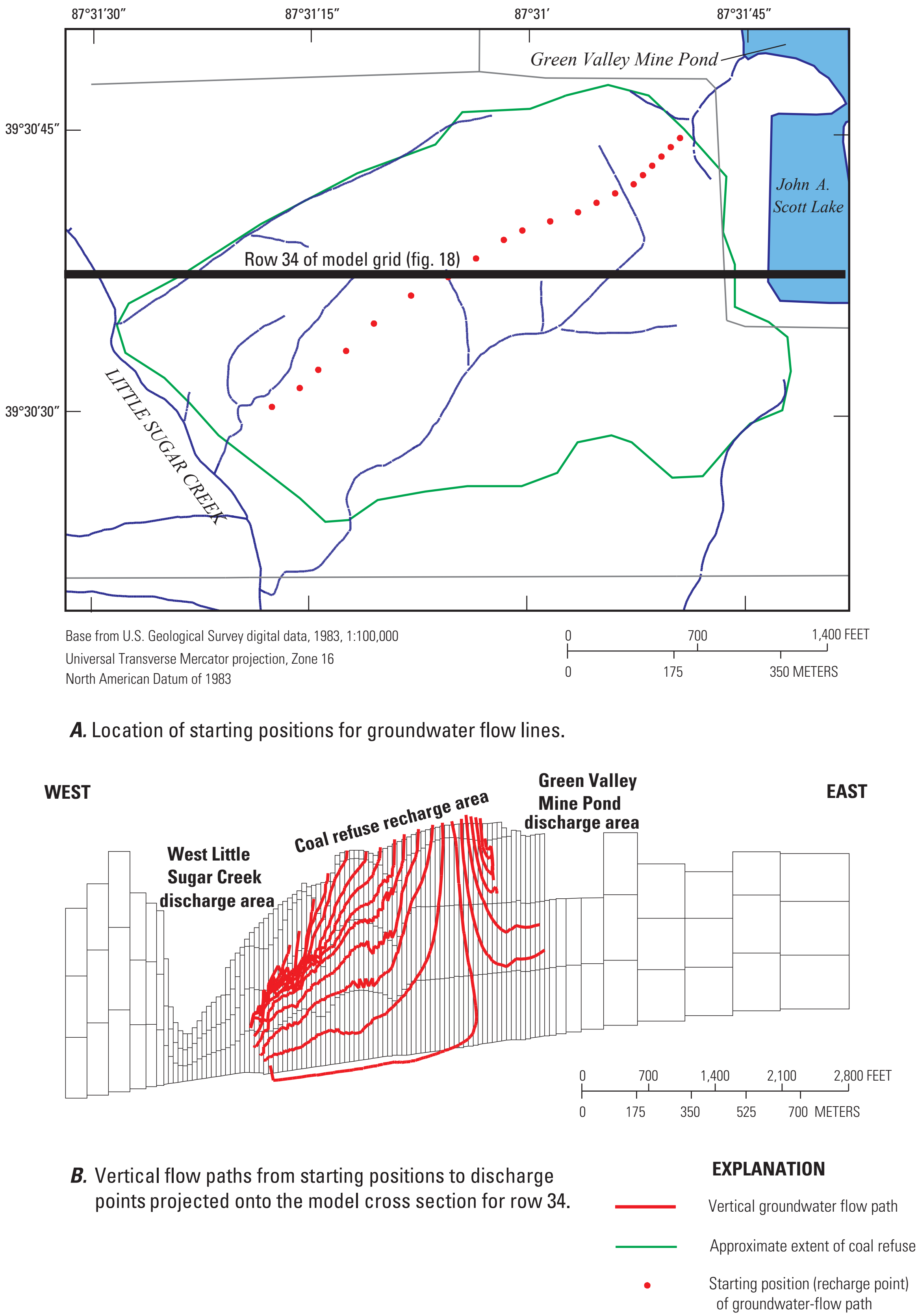
Predictive simulations by the groundwater model should be evaluated and qualified on the basis of model reliability (Anderson and Woessner, 1992, p. 284). The reliability of the calibration is dependent upon the assumptions used in construction of the model. The simplifying assumptions used in the development of this model were previously discussed, but included hydraulic uniformity within model layers and no-flow into or out of the shale bedrock. Although these assumptions were in some ways tested and described within this report, more data may be required to fully evaluate these and other assumptions. The following factors should be considered when evaluating this model and predictive simulations that this model may produce:

1. The model is best used to simulate groundwater flow in the area of the coal refuse because almost all of the observations used to calibrate the model are from the area of coal refuse. The positions and times of simulated groundwater-flow paths outside the area of coal refuse are considered to be less accurate than those in or near the refuse.

2. Sand-and-gravel lenses and fractures in the till were not modeled specifically. The existence of fractures and sand-and-gravel lenses can shorten groundwater travel times considerably. The error in predicted travel times is unknown but is probably related to the abundance of these features. Notations of sand-and-gravel lenses were not abundant in the few well-driller logs available to this investigation, and therefore, the travel time errors are expected to be small.

3. Direct measures of recharge rates to the simulated deposits were not possible. Estimates of recharge from model calibration were influenced by a base-flow separation technique and by measurements of flow in the seeps. The base-flow separation technique determined recharge rates to the till, and ratios of steady-state recharge rates in the till to those in the coal refuse were used to estimate monthly recharge rates to the refuse. Actual ratios are not known, but the recharge estimates should be adequate because of two observations. First, the calibrated horizontal hydraulic conductivities are similar to the values derived from the aquifer tests. If the calibrated horizontal hydraulic conductivities are near actual values, then recharge rates must be near actual values. If recharge rates are too high and horizontal hydraulic conductivities are near actual values, simulated water levels would be biased high, which is not the case. Second, the estimated ratios of recharge rate in the till to that in the coal refuse did not create areal bias in water-level residuals. Positive and negative residuals are evenly distributed in both the area of gob and in the area of the gob and tailings mixture.

4. The model was constructed using two hydraulic conductivity zones within the coal refuse. The boundary of those zones may be incorrect and the presence of additional zones is possible. Regardless of the



A. Location of starting positions for groundwater flow lines.

B. Vertical flow paths from starting positions to discharge points projected onto the model cross section for row 34.

Figure 29. Simulated flow paths projected from points of recharge to row 34 near the center of the coal refuse to points of discharge, Green Valley mine site, Indiana.

inaccuracies in zone boundaries, the actual hydraulic conductivity of the coal refuse in any zone is low, and the calibrated hydraulic conductivities should be similar to actual ones. As such, any simulation is expected to adequately reflect the system response.

5. The shale bedrock was assumed to be a no-flow boundary. If the shale was actually capable of transporting water, then the travel time to the discharge points would increase. The increased travel times would further increase the potential for chemical changes in the effluent from the coal refuse.

Summary and Conclusions

A four-layer, finite-difference computer model of the area near the Green Valley reclaimed coal refuse site was constructed to simulate groundwater flow in the coal refuse and in the till beneath and near the refuse. The coal refuse is represented by one model layer, and the till deposits are represented by three layers that evenly divide the overall thickness of the till. The hydraulic properties of the till are uniform throughout the three till layers.

The hydraulic properties of the coal refuse are defined by two zones; the first zone is the area of coal gob, and the second is areas where coal tailings were mixed with the gob. Thickness of the till was determined by creating surfaces for the top of bedrock (based on water-well log data) and for land surface (based on 10-ft land-surface contours), then subtracting the two surfaces. The thickness of the coal refuse was determined by creating a surface for the top of the coal refuse (based on 2-ft contours) and subtracting the land surface from the surface of the coal refuse. Model calibration consisted of 152 water-level measurements from 18 wells and 19 streamflow measurements from four stream sections over 13 months. The calibrated horizontal hydraulic conductivities for the area of gob and the area of gob and tailings are low, 0.75 and 0.03 ft/d, respectively. The transient simulation with the calibrated model estimated water levels within an average of 2.10 ft of actual values.

Some geophysical measurements indicated that groundwater flow directions were affected by engineered ditches. Horizontal flowmeter measurements in 2008 indicated that groundwater flow directions through wells near engineered ditches were affected by those structures. Flowmeter measured directions through wells nearer to the center of the refuse followed the prevailing hydraulic gradient from northeast to southwest. Results of a surface electromagnetic induction survey indicated that higher conductivity values coincided with engineered ditches—a possible indication of conductive acidic drainage. Some geophysical measurements indicated that groundwater flow directions were affected by engineered ditches. Horizontal flowmeter measurements in 2008 indicated that groundwater flow directions through wells near engineered ditches were affected by those structures. Flowmeter measured directions through wells nearer to the center of the refuse followed the prevailing hydraulic gradient from northeast to southwest. Results of a surface electromagnetic induction survey indicated that higher conductivity values coincided with engineered ditches—a possible indication of conductive acidic drainage, and with subsurface utilities or foundations of former on-site buildings.

The calibrated model provided information about groundwater-flow rates, sources, directions, and travel times. The most reliable predictions are in the area of the coal refuse because almost all of the observations used to calibrate the model are from the area of coal refuse. Most of the discharge from the coal refuse (72 percent) is downward leakage into the till and not to the seeps. The seeps are fed mostly by precipitation recharge that infiltrates the coal refuse; however, a significant amount of seep discharge (24 percent) originates as flow from the till. Contours from the two layers in the area of coal refuse and groundwater flow paths indicate a mostly southwesterly and downward groundwater-flow direction. The horizontal flow direction through most of the coal refuse is towards West Little Sugar Creek. An approximate 5-ft vertical downward gradient is present between the coal refuse and the middle of the till. The water-level contours in the coal refuse and till also indicate some discharge to the seeps, but the area contributing that water is immediately adjacent to the seep channels. A groundwater divide trends northwest to southeast across the northeast corner of the coal refuse, and groundwater in that area flows to the northeast towards the Green Valley Mine Pond. Recharge to the coal refuse ultimately discharges to four major areas: West Little Sugar Creek, Green Valley Mine Pond, the downstream part of seep 4, and streams downgradient of the model area. Average travel time to these discharge areas ranges from about 80 to 150 years. A typical flow path from the coal refuse is vertically downward in the coal refuse, then more horizontal in the till deposits.

Model simulations provided insights into the flow system useful in guiding on-site reclamation, as well as reclamation at other sites. Results of the model simulations indicated that most of the discharge from the coal refuse (72 percent) is downward leakage into the till and not to the seeps. Twenty-four percent of the simulated flow is discharged from the till and to the seeps. Very little of the seep discharge comes from the coal refuse.

References Cited

Amt, Erica; Houston, Christina; Turner, Andrew; Jerz, J.K.; and Gourley, B.L., 2003, West Little Sugar Creek is recovering but still impacted by acid drainage from the abandoned Green Valley Mine in southwest Indiana [abs.], *in* Geological Society of America 2003 annual meeting, Seattle, Wash., November 2–5, 2003: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 239.

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Academic Press, 381 p.

Anderson, W. P., Evans, D. G., 2007, On the interpretation of recharge estimates from steady-state model calibrations: Ground Water, v.45, no. 4, p. 499–505.

Bayless, E.R., W.A. Mandell, and Ursic, J.R., 2011, Accuracy of flowmeters measuring groundwater flow in an unconsolidated aquifer simulator: Groundwater Monitoring and Remediation, v. 31, no. 2, Spring 2011, p. 48-62.

Bouwer, Herman, 1989, The Bouwer and Rice slug test—An update: Ground Water, v. 27, no. 3, p. 304–309.

Bouwer, Herman, and Rice, R.C., 1976, A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423–428.

Brake, S.S., Connors, K.A., and Romberger S.B., 2001, A river runs through it—Impact of acid mine drainage on the geochemistry of West Little Sugar Creek pre- and post-reclamation at the Green Valley coal mine, Indiana, USA: Environmental Geology, v. 40, p. 1,471–1,481.

Cable, L.W., Watkins, F.A. Jr., Robison, T.M., 1971, Hydrogeology of the principal aquifers in Vigo and Clay Counties, Indiana, Indiana Department of Natural Resources Bulletin 34, 34 p., 3 plates, accessed June 15, 2011 at *http://www.in.gov/dnr/water/files/531_all.pdf#Anchor-11640*.

Caserotti, P.M., and Marland, G., 1974, Impact of coal mine-waste runoff on a small stream: Proceedings of the Indiana Academy of Science, v. 83, p. 239–240.

Clark, G.D., ed., 1980, The Indiana water resource—Availability, uses, and needs: Indiana Department of Natural Resources, 508 p.

Cooley, R.L., and Naff, R.L., 1990, Regression modeling of ground-water flow: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. B4, 232 p.

Desbarats, A.J., Logan, C.E., Hinton, M.J., and Sharpe, D.R., 2002, On the kriging of water table elevations using collateral information from a digital elevation model: Journal of Hydrology, v. 255, p. 25–38.

Drost, Walter; Klotz, Dietmar; Koch, Arnd; Moser, Heribert; Neumaier, Ferdinand; and Rauert, Werner, 1968, Point dilution methods of investigating groundwater flow by means of radioisotopes: Water Resources Research, v. 4, no. 1, p. 125–146.

Eggert, D.L., Hailer, J.G., Irwin, P.N., and Miller, L.V., 1981, Energy content, composition, and associated water chemistry of the wastes in the coal-preparation plant of the Green Valley-Wabash Mine, Vigo County, Indiana, *in* Symposium of Surface Mining Hydrology, Sedimentology and Reclamation, University of Kentucky, Lexington, Ky., December 7–11, 1981: p. 143–149.

Environmental Systems Research Institute, 2003, Arc Info, version 8.3: Redlands, Calif.

Geosciences Research Associates, Inc., 1985, Feasibility study for reclamation of the Green Valley Mine Site, Vigo County, Indiana—Project E23-210: Prepared for the State of Indiana Department of Administration and Department of Natural Resources, 94 p.

Gibson, J.L., 2006, The impact of acid mine drainage on West Little Sugar Creek, Vigo County, Indiana: Terre Haute, Ind., Indiana State University, Department of Geography, Geology and Anthropology, Master's thesis, 65 p.

Gray, H.H., 2000, Physiographic divisions of Indiana: Bloomington, Indiana, Indiana Geological Survey, Special Report 61, 15 p., 1 plate.

Grove, G.E., 2009, Unconsolidated and bedrock aquifer systems of Vigo County, Indiana:, Indiana Department of Natural Resources, Division of Water, Aquifer Systems Maps 66–A and 66–B, 2 plates, 2 files with additional text, accessed July14, 2010, at *http://www.in.gov/dnr/water/5774.htm*.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–92, 121 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration, with application to UCODE, a computer code for universal inverse modeling, and MODFLOWP, a computer code for inverse modeling with MODFLOW: U.S. Geological Survey Water-Resources Investigations Report 98–4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00–184, 209 p.

Hvorslev, M.J., 1951, Time lag and soil permeability in groundwater observations: Vicksburg, Miss., U.S. Army Corps of Engineers Waterways Experiment Station, Bulletin 36, p. 1–50.

Hyder, Zafar; Butler, J.J., Jr.; McElwee, C.D.,; and Liu, Wehzhi, 1994, Slug tests in partially penetrating wells: Water Resources Research, v. 30, p. 2,945–2,957.

Hydrosolve, Inc., 2002, AQTESOLV for Windows, user's guide: Reston, Va., 185 p.

Indiana Department of Natural Resources, 2002, Water well record database—Digital data, 2002: Division of Water, Water Rights and Use Section, accessed July 14, 2010, at *http://www.in.gov/dnr/water/3595.htm*.

Indiana Geological Survey, 2003, COAL_AML_FEATURES_IN: Abandoned Mine Lands, Miscellaneous Site Features in Indiana, 1:24,000, polygon shapefile, accessed July 2008 at *http://inmap.indiana.edu/dload_page/coal.html*.

Keys, W.S., 1990, Borehole geophysics applied to groundwater investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E2, 150 p.

Kearl, P.M., 1997, Observations of particle movement in a monitoring well using the colloidal borescope: Journal of Hydrology, v. 200, p. 323–344.

Kuniansky, E.L., Lowery, M.A., and Campbell, B.G., 2009, How processing digital elevation models can affect simulated water budgets: Ground Water, v. 47, no. 1, p. 97–107.

Melchiorre, Erik; Dale, Deborah; Mills, James, Jr.; and Chapman, Brandon, 2005, Geochemical and stable isotope evidence for precipitation and groundwater sourcing of recharge at the Green Valley site, Vigo County, Indiana: Mine Water and the Environment, v. 24, p. 88–100.

Melchiorre, Erik; Mills, James, Jr.; Dale, Deborah; and Chapman, Brandon, 2005, A new occurrence of xitieshanite [Fe3+(SO4)Cl.6H2O] crystals in acid-mine seepways, Green Valley, Vigo County, Indiana, U.S.A.: American Mineralogist, v. 90, p. 1,581–1,521.

Midwestern Regional Climatic Center, 2010a, Historical climate data, Temperature summary, Station 128723 TERRE HAUTE 8 S, IN, 1971–2000 NCDC normals: Accessed April 14, 2010, at *http://mcc.sws.uiuc.edu/climate_midwest/historical/temp/in/127370_tsum.html*.

Midwestern Regional Climatic Center, 2010b, Historical climate data, Precipitation summary, Station 128723 TERRE HAUTE 8 S, IN, 1971–2000 NCDC normals: Accessed April 14, 2010, at *http://mcc.sws.uiuc.edu/climate_midwest/historical/precip/in/127370_psum.html*.

Morris, D.A., and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948–60: U.S. Geological Survey Water-Supply Paper 1839–D, 42 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 2 v., 631 p.

Rutledge, A.T., 1998, Computer programs for describing the recession of groundwater discharge and for estimating mean groundwater recharge and discharge from streamflow records—Update: U.S. Geological Survey Water-Resources Investigations Report 98–4148, 43 p.

Sauer, V.B., and Meyer, R.W., 1992, Determination of error in individual discharge measurements: U.S. Geological Survey Open-File Report 92–144, 21 p.

Shaver, R.B., 1998, The determination of glacial till specific storage in North Dakota: Ground Water, v. 36, p. 552–557.

Schneider, A.F., 1966, Physiography, *in* Lindsey, A.A., ed., Natural features of Indiana: Indiana Academy of Science, p. 40–46.

Unger, D.L., Brake, S.S., Wolf, S.F., Mattox, J.M., and Hasiotis, S.T., 2003, Investigation of water chemistry and precipitate composition in an acid mine drainage system at the Green Valley coal mine site, Indiana *in* Geological Society of America 2003 annual meeting, Seattle, Wash., November 2–5, 2003: Geological Society of America Abstracts with Programs, v. 34, no. 7, p. 239.

U.S. Geological Survey, 2008, 1:100,000 Digital line graphs, accessed August 2008 at *http://edcsns17.cr.usgs.gov/EarthExplorer/*.

U.S. Geological Survey, 2010, National Water Information System, Web Interface—USGS 03346000 North Fork Embarras River near Oblong, IL: Accessed July 14, 2010, at *http://waterdata.usgs.gov/nwis/nwisman/?site_no=03346000*.

Wu, Y.-S., C.-H. Lee and J.-L Yu, 2008, Effects of hydraulic variables and well construction on horizontal borehole flowmeter measurements. Groundwater Monitoring and Remediation, v. 28, no. 1, Winter 2008, p, 65–74.

Appendixes 1–4

Appendix 1: Measured groundwater levels

Table A1. Groundwater levels measured at the Green Valley mine site, near Terre Haute, Indiana, 2008–9.

[mm/dd/yyyy, month/day/year;—, not measured or determined; groundwater levels reported as altitudes in feet above National Geodetic Vertical Datum of 1988]

Date measured (mm/dd/yyyy)	Local well identifier[1]										
	GV1	GV2	GV3	GV4	GV7A	GV7B	GV8A	GV8B	GV8C	GV9A	GV9B
05/22/2008	—	—	599.53	598.65	—	—	—	—	—	—	—
06/02/2008	—	607.00	—	—	—	—	—	—	—	—	—
06/05/2008	—	—	—	598.71	—	—	—	—	—	—	—
06/12/2008	—	—	—	599.23	—	—	—	—	—	—	—
06/19/2008	592.21	—	—	—	—	—	—	—	—	—	—
06/20/2008	—	—	—	—	608.76	—	—	—	—	—	—
06/25/2008	—	—	—	—	—	—	599.88	—	—	583.50	—
06/26/2009	—	—	—	—	—	—	—	—	—	—	—
06/27/2009	—	—	—	—	—	—	—	—	—	—	—
09/04/2008	590.86	602.39	597.83	598.92	607.90	—	599.70	—	597.71	585.40	—
10/09/2008	591.79	601.89	597.14	598.65	607.31	—	599.41	—	597.51	585.06	—
11/05/2008	591.52	601.91	597.19	598.47	607.13	—	599.25	—	597.27	584.89	—
12/16/2008	592.93	603.01	598.24	598.01	606.83	—	598.97	—	597.04	584.31	—
01/20/2009	—	606.81	598.24	597.70	607.18	607.37	598.80	—	596.88	584.09	584.13
03/03/2009	592.91	608.94	598.57	597.42	607.29	607.38	598.76	598.62	596.80	583.99	584.03
04/15/2009	593.04	609.43	599.64	597.50	607.63	607.7	598.82	598.65	597.03	584.27	584.32
06/04/2009	593.03	607.61	599.71	598.49	608.41	608.65	599.61	599.48	597.59	585.52	585.57
07/14/2009	592.62	—	599.41	598.64	608.27	608.58	599.61	599.48	597.66	585.51	585.54
08/25/2009	—	604.14	—	—	—	608.09	—	—	—	—	—
08/26/2009	591.85	—	—	—	607.73	—	599.53	599.41	597.31	—	—
08/27/2009	—	—	598.53	—	607.76	—	—	—	—	—	—
08/31/2009	—	—	—	—	—	—	599.51	—	—	585.30	585.34
09/01/2009	—	—	—	598.65	—	—	—	—	—	—	—
09/02/2009	—	—	—	—	—	—	—	—	—	—	—

Table A1. Groundwater levels measured at the Green Valley mine site, near Terre Haute, Indiana, 2008–9—Continued.

[mm/dd/yyyy, month/day/year; —, not measured or determined; groundwater levels reported as altitudes in feet above National Geodetic Vertical Datum of 1988

Date measured (mm/dd/yyyy)	Local well identifier[1]										
	GV1	GV2	GV3	GV4	GV7A	GV7B	GV8A	GV8B	GV8C	GV9A	GV9B
05/22/2008	—	—	—	—	—	—	—	—	—	—	—
06/02/2008	—	—	—	—	—	—	—	—	—	—	—
06/05/2008	—	—	—	—	—	—	—	—	—	—	—
06/12/2008	—	—	—	—	—	—	—	—	—	—	—
06/19/2008	—	—	—	—	—	—	—	—	—	—	—
06/20/2008	—	—	—	—	—	—	—	—	—	—	—
06/25/2008	—	—	—	—	—	—	—	—	—	—	—
06/26/2008	594.01	—	—	—	—	586.38	605.18	—	—	—	—
06/27/2008	603.40	—	—	599.05	—	—	—	—	—	—	—
09/04/2008	593.64	602.51	—	598.30	—	586.39	603.45	606.81	601.78	605.08	594.82
10/09/2008	593.54	602.10	—	597.74	—	586.33	602.63	606.29	601.06	604.22	594.73
11/05/2008	593.53	602.04	—	597.64	—	—	602.36	606.27	600.86	603.74	594.69
12/16/2008	593.78	601.60	—	597.40	—	586.28	602.20	607.66	600.49	603.22	593.98
01/20/2009	593.82	601.84	601.86	598.10	597.54	586.21	603.58	609.18	600.93	604.11	593.38
03/03/2009	593.79	601.96	601.99	598.30	598.08	586.28	604.35	609.47	601.32	604.58	593.23
04/15/2009	594.02	602.75	602.76	598.87	598.70	586.40	606.25	610.31	602.69	605.82	593.22
06/04/2009	594.08	603.37	603.33	599.67	599.42	586.80	606.82	609.69	603.29	607.59	594.09
07/14/2009	594.00	602.90	602.88	599.19	598.88	586.34	607.11	609.07	602.91	606.66	594.66
08/25/2009	—	—	—	—	—	—	—	—	—	—	—
08/26/2009	—	—	—	—	—	586.39	—	607.70	—	—	—
08/27/2009	—	—	—	—	—	—	604.52	—	602.25	605.52	—
08/31/2009	—	—	—	—	—	—	—	—	—	—	—
09/01/2009	—	603.10	602.36	598.54	598.46	—	—	—	—	—	594.83
09/02/2009	593.75	—	—	—	—	—	—	—	—	—	—

Table A1. Groundwater levels measured at the Green Valley mine site, near Terre Haute, Indiana, 2008–9.—Continued.

[mm/dd/yyyy, month/day/year;—, not measured or determined; groundwater levels reported as altitudes in feet above National Geodetic Vertical Datum of 1988]

Date measured (mm/dd/yyyy)	Local well identifier[1]			
	GV19	GV20	GV21	GV22
05/22/2008	—	—	—	—
06/02/2008	—	—	—	—
06/05/2008	—	—	—	—
06/12/2008	—	—	—	—
06/19/2008	—	—	—	—
06/20/2008	—	—	—	—
06/25/2008	—	—	—	—
06/26/2008	—	—	—	—
06/27/2008	—	—	—	—
09/04/2008	595.44	587.5	580.35	563.20
10/09/2008	595.43	586.87	580.01	562.85
11/05/2008	595.46	586.57	579.81	562.30
12/16/2008	595.43	586.94	579.64	562.84
01/20/2009	595.43	588.31	582.2	563.83
03/03/2009	595.43	588.75	580.54	564.07
04/15/2009	596.18	589.19	581.13	565.62
06/04/2009	595.21	—	581.58	565.90
07/14/2009	598.02	589.09	581.07	565.03
08/25/2009	—	588.01	—	—
08/26/2009	—	—	—	—
08/27/2009	—	—	—	—
08/31/2009	—	—	580.42	563.68
09/01/2009	—	—	—	—
09/02/2009	—	—	—	—

[1]Sites are shown on figure 4.

Appendix 2: Borehole geophysical logs of natural-gamma radiation

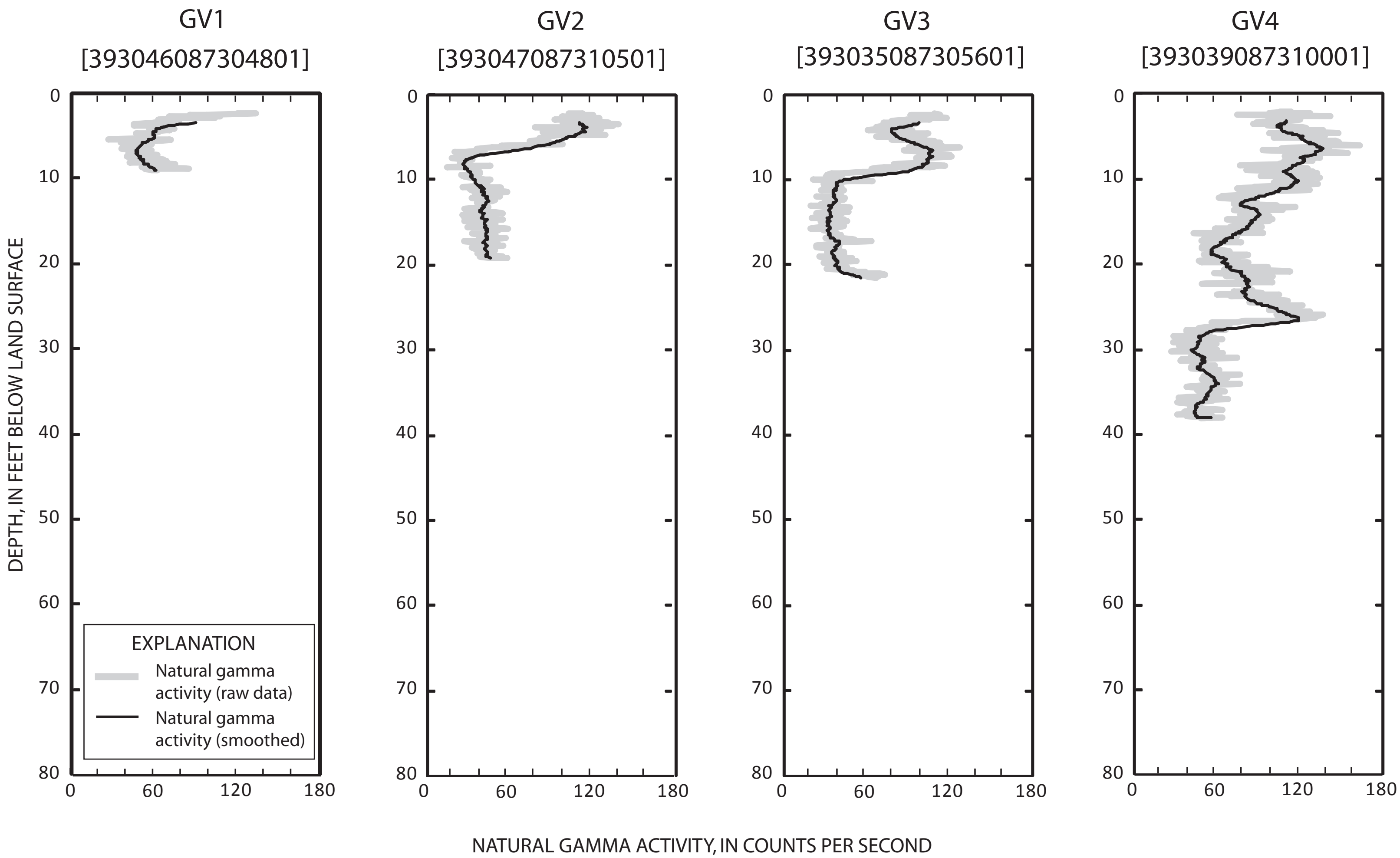


Figure A2–1. Borehole geophysical logs of natural-gamma radiation for wells GV1, GV2, GV3 and GV4. U.S. Geological Survey well identifier in brackets above each plot.

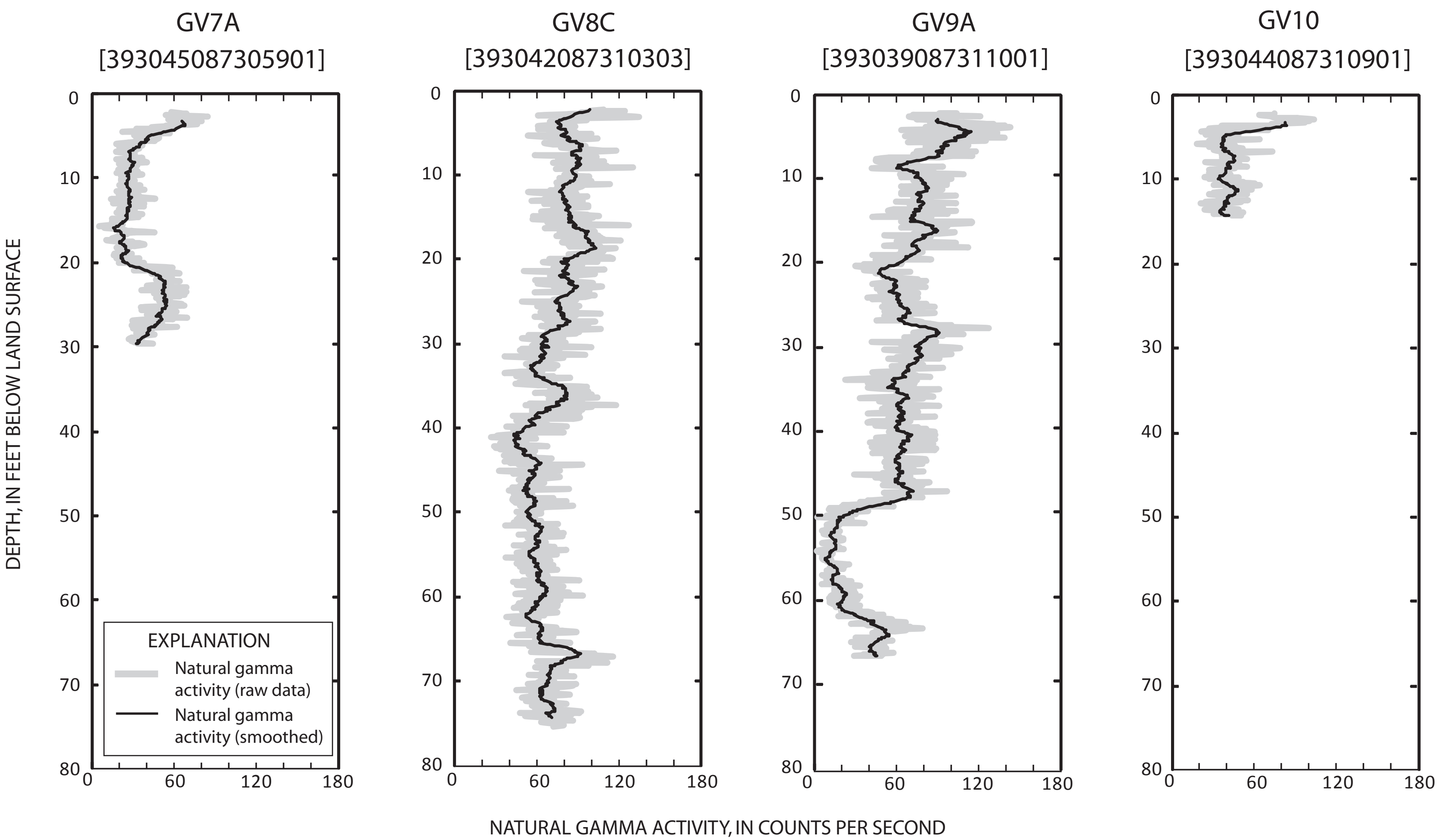


Figure A2–2. Borehole geophysical logs of natural-gamma radiation for wells GV7A, GV8C, GV9A, and GV10. U.S. Geological Survey well identifier in brackets above each plot.

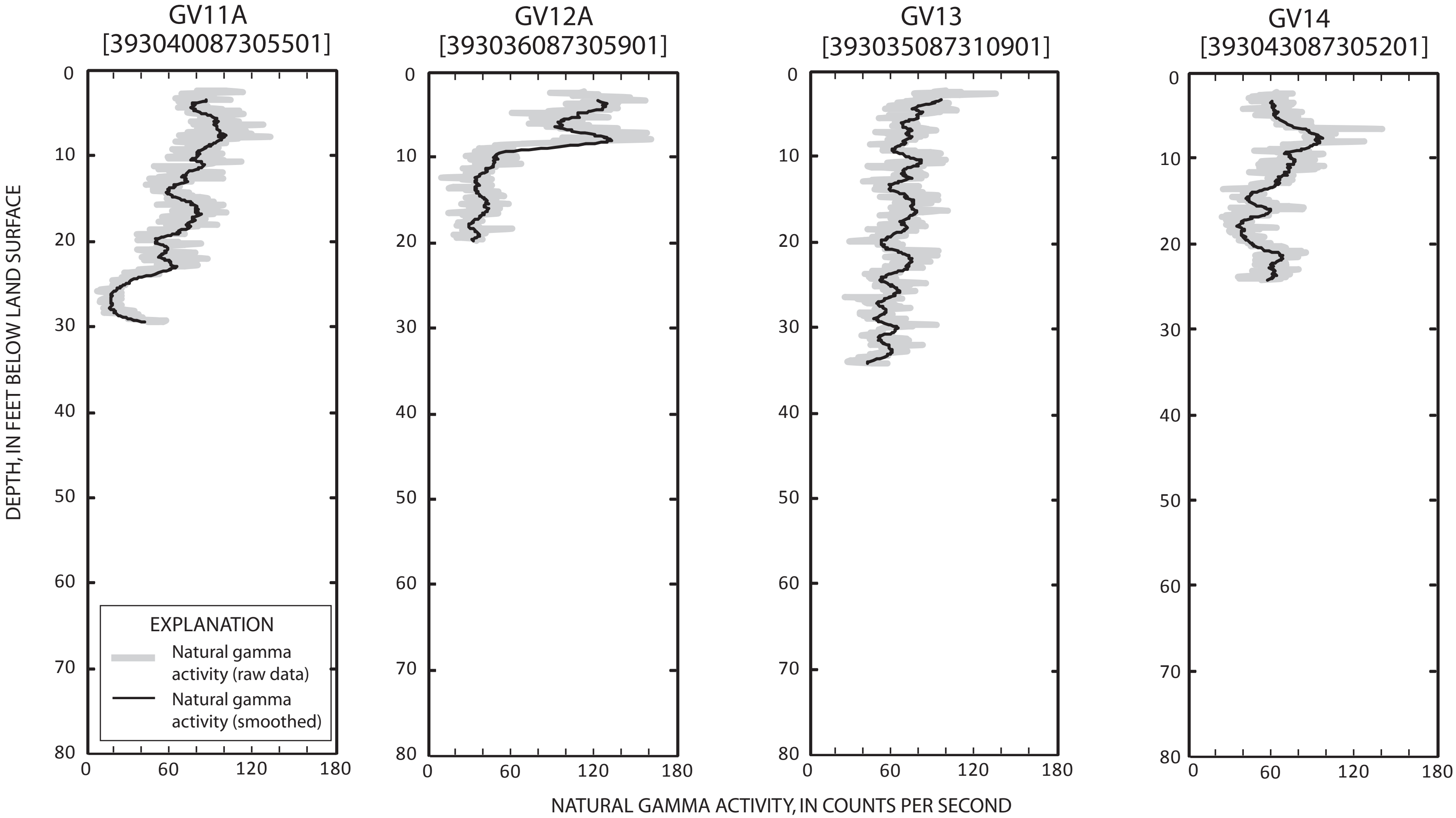


Figure A2–3. Borehole geophysical logs of natural-gamma radiation for wells GV11A, GV12A, GV13, and GV14. U.S. Geological Survey well identifier in brackets above each plot.

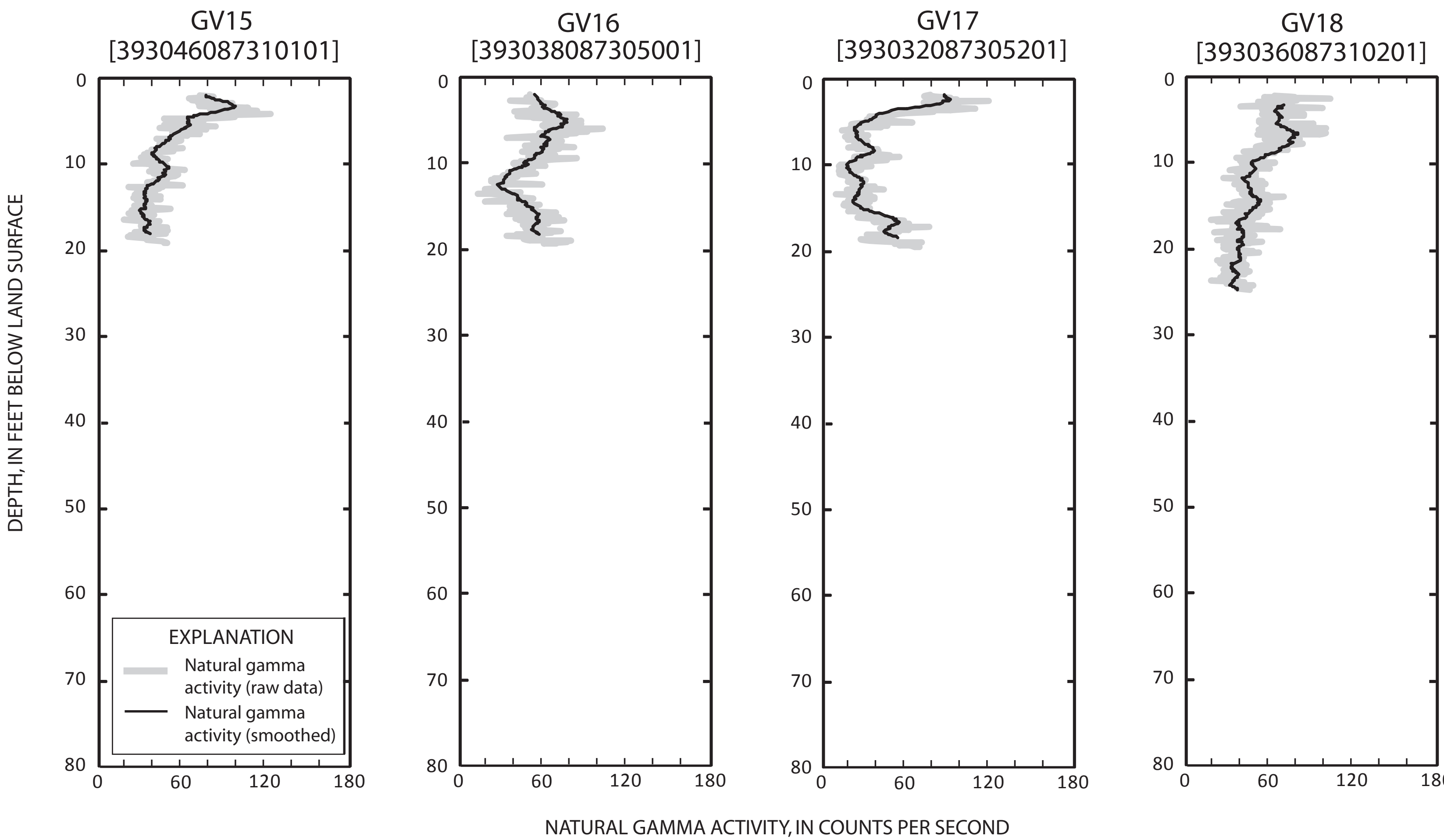


Figure A2–4. Borehole geophysical logs of natural-gamma radiation for wells GV15, GV16, GV17 and GV18. U.S. Geological Survey well identifier in brackets above each plot.

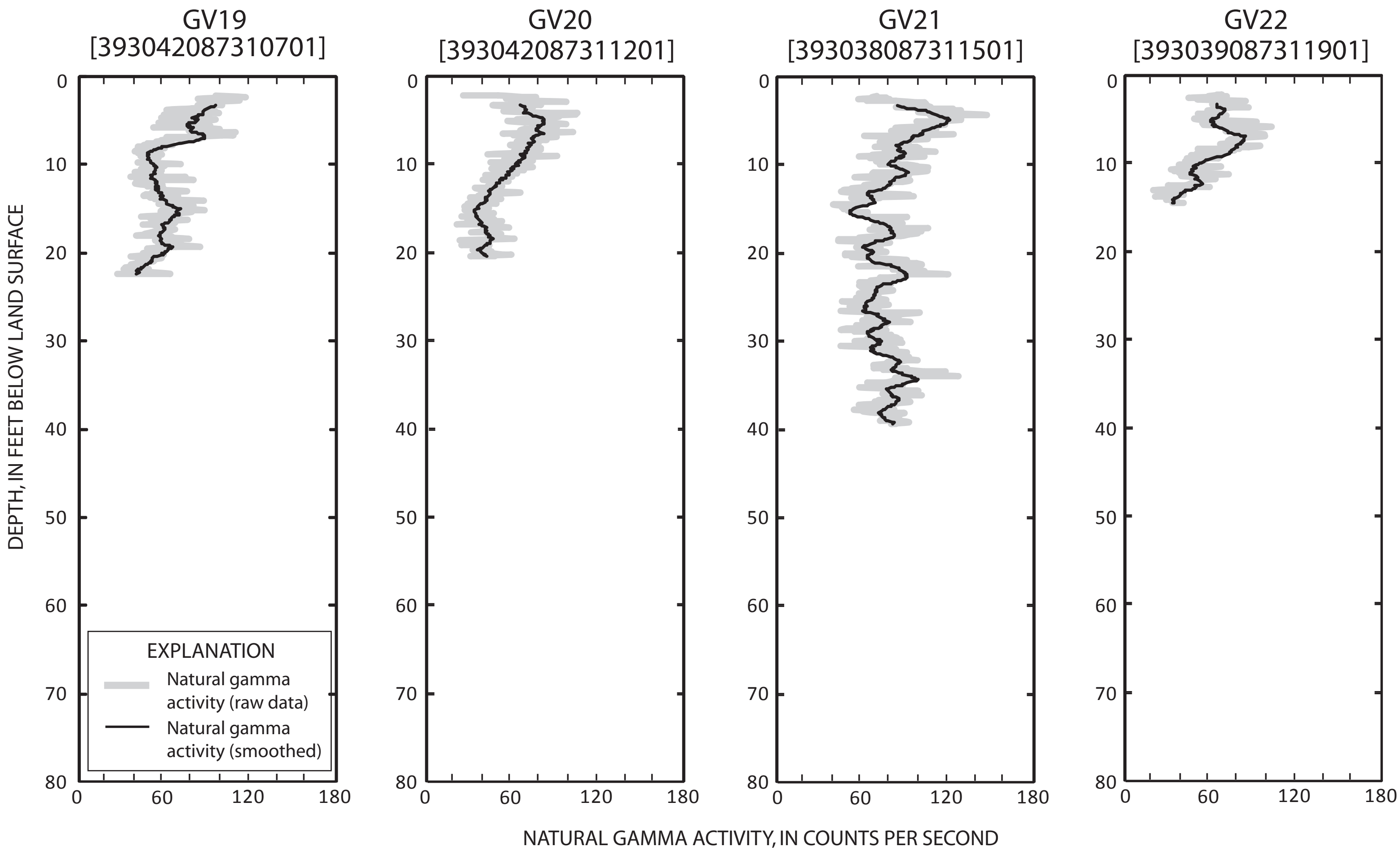


Figure A2–5. Borehole geophysical logs of natural-gamma radiation for wells GV19, GV20, GV21 and GV22. U.S. Geological Survey well identifier in brackets above each plot.

Appendix 3: Borehole geophysical logs of electromagnetic induction

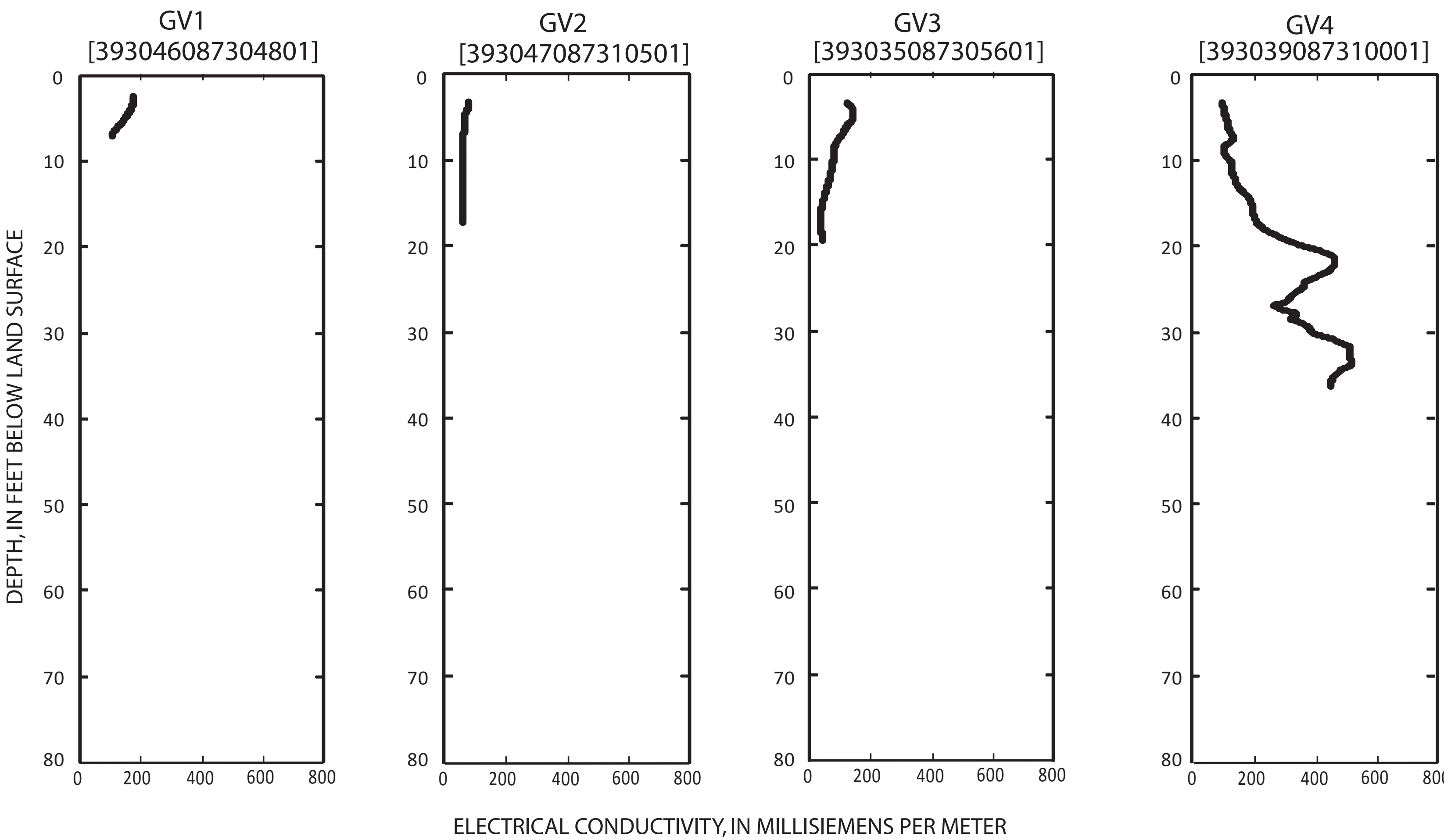


Figure A3–1. Borehole geophysical logs of electromagnetic induction for wells GV1, GV2, GV3 and GV4. U.S. Geological Survey well identifier in brackets above each plot.

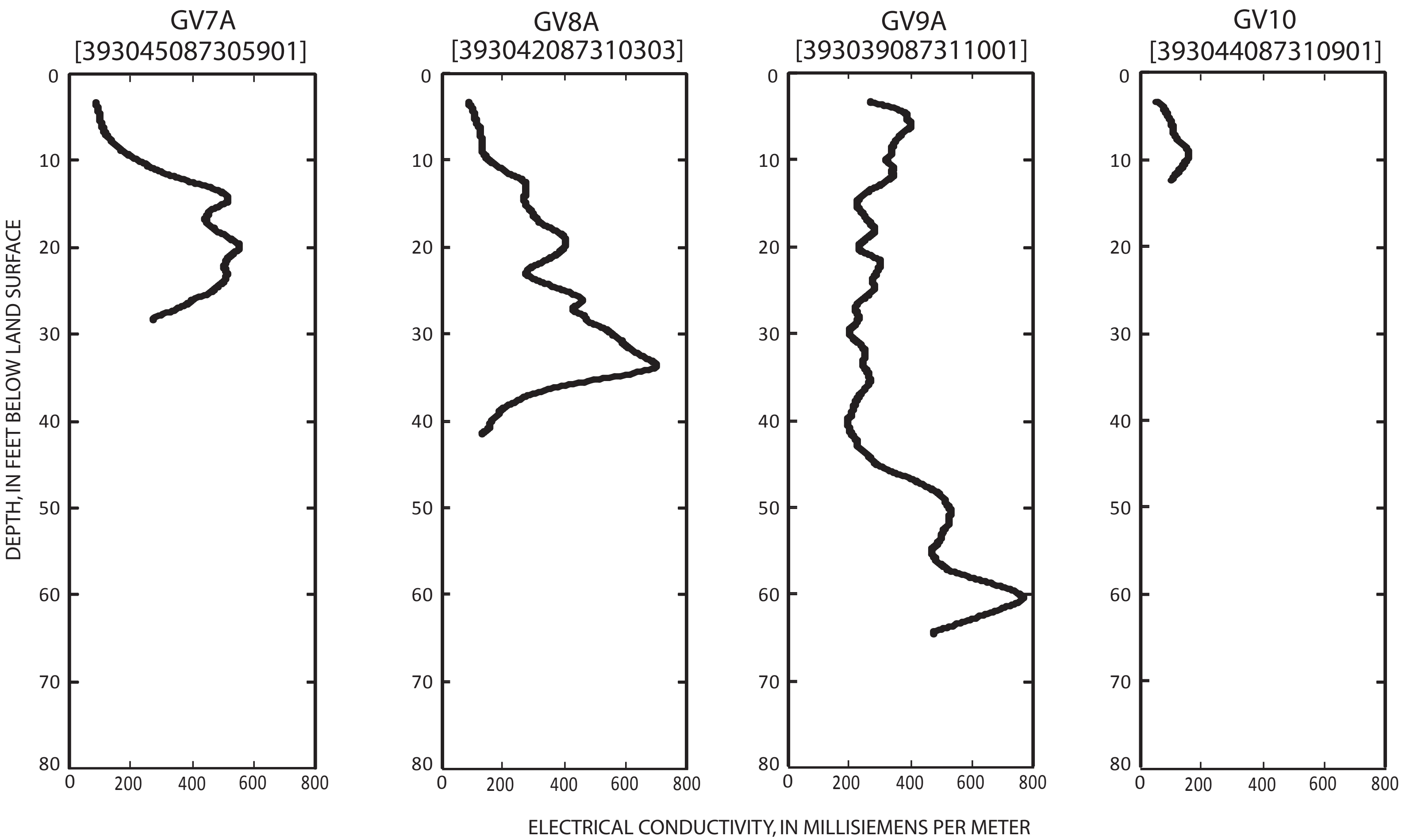


Figure A3–2. Borehole geophysical logs of electromagnetic induction for wells GV7A, GV8A, GV9A, and GV10. U.S. Geological Survey well identifier in brackets above each plot.

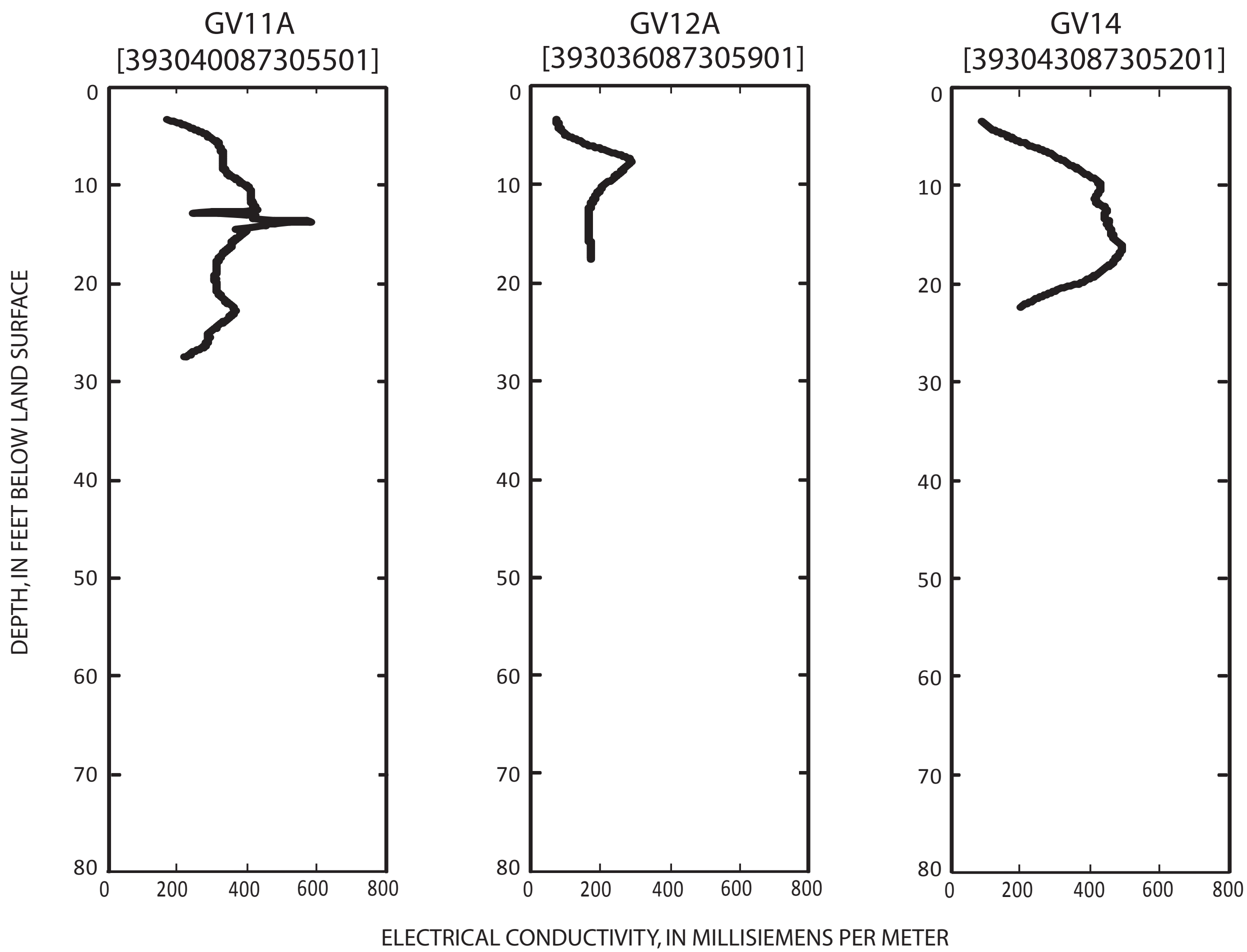


Figure A3–3. Borehole geophysical logs of electromagnetic induction for wells GV11A, GV12A, and GV14. U.S. Geological Survey well identifier in brackets above each plot.

Appendix 4: Plots of aquifer-test data with fitted analytical-solution lines

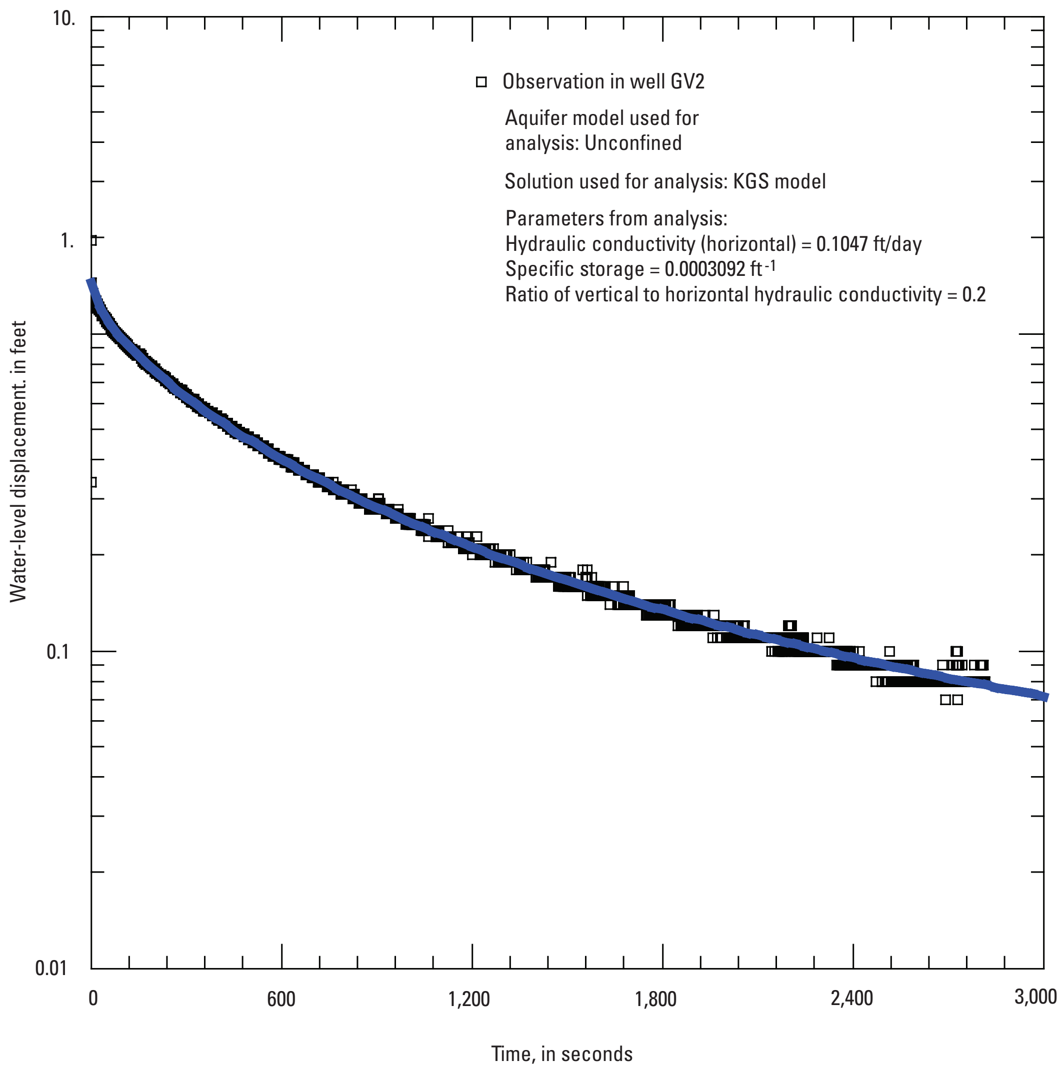


Figure A4–1. ime-displacement graph and the solution for the KGS method for well GV2 at the Green Valley site, near Terre Haute, Indiana (K = 0.10 feet per day). Well GV2 is screened in till.

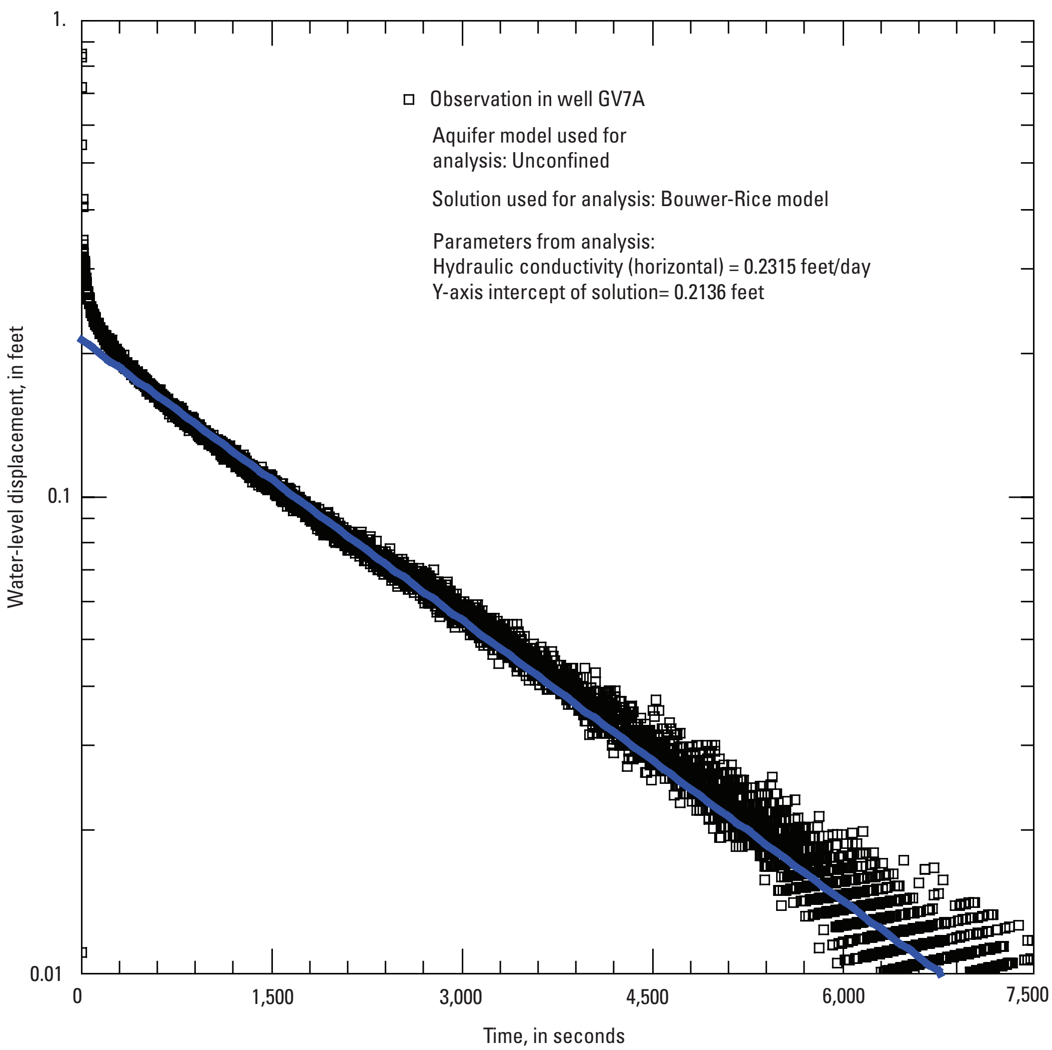


Figure A4–2. Time-displacement graph and the solution for the Bouwer and Rice method for well GV7A at the Green Valley site, near Terre Haute, Indiana (K = 0.23 feet per day). Well GV7A is predominantly screened in coal gob.

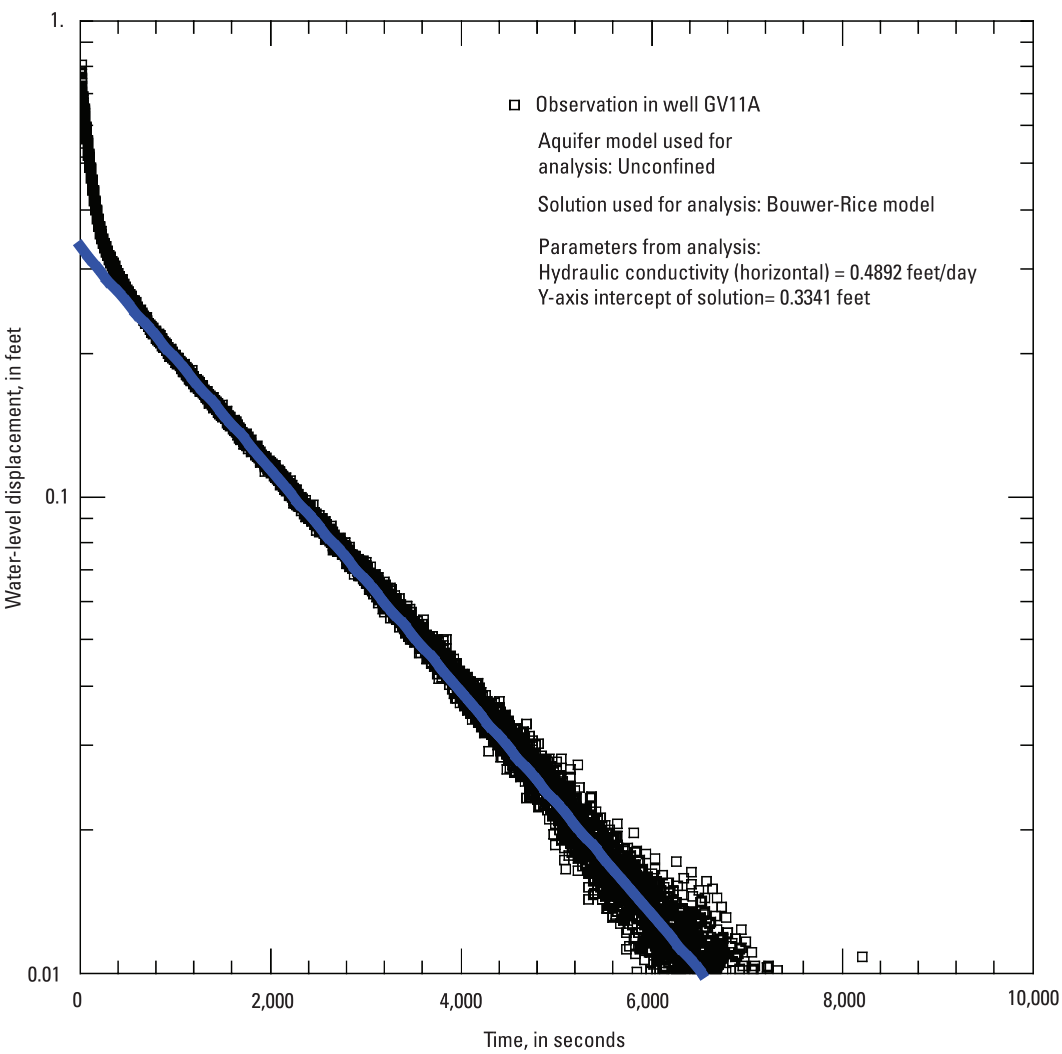


Figure A4–3. Time-displacement graph and the solution for the Bouwer and Rice method for well GV11A at the Green Valley site, near Terre Haute, Indiana (K = 0.49 feet per day).

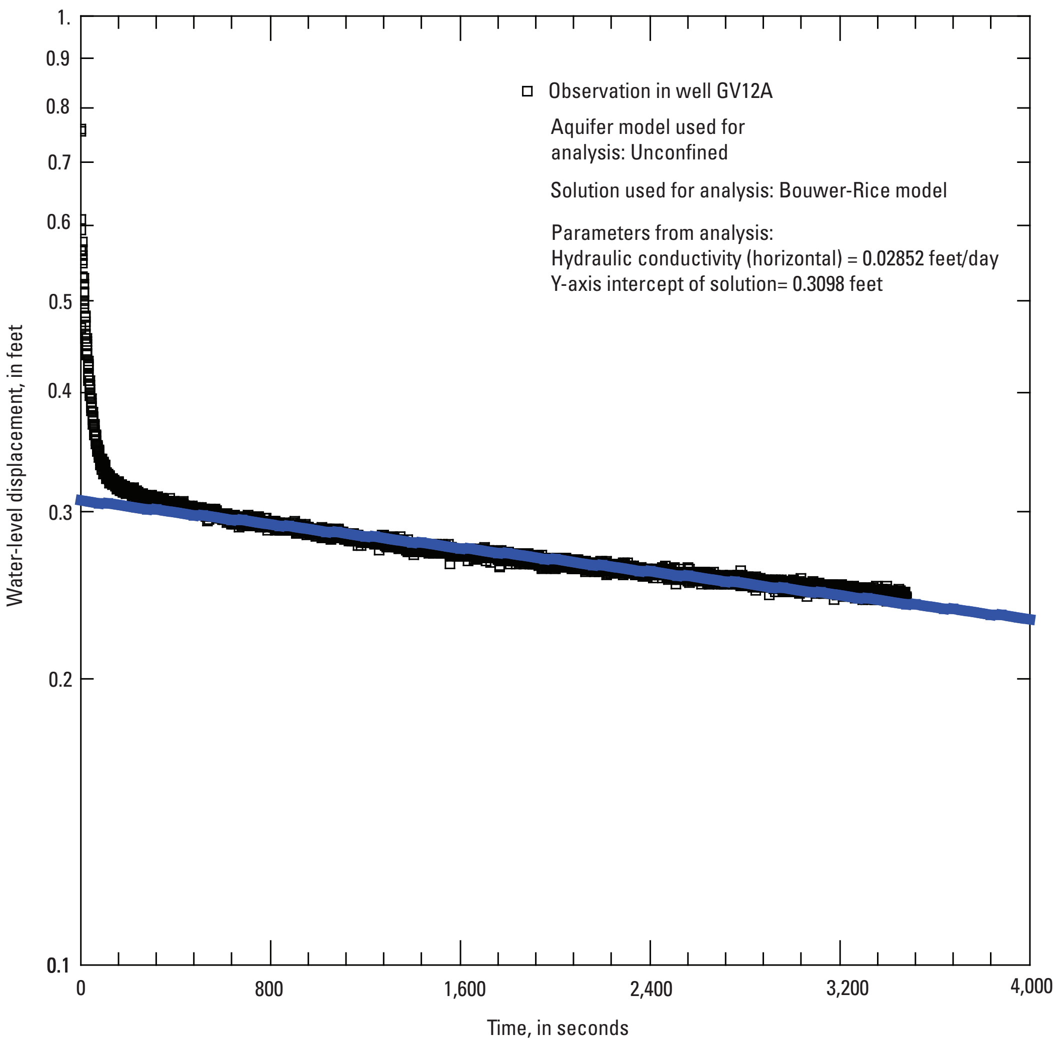


Figure A4–4. Time-displacement graph and the solution for the Bouwer and Rice method for well GV12A at the Green Valley site, near Terre Haute, Indiana (K = 0.03 feet per day). Well GV12A is predominantly screened in coal gob.

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