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Performance Evaluation Testing of Wells in the Gradient Control System at a Federally Operated Confined Disposal Facility Using Single Well Aquifer Tests, East Chicago, Indiana

Scientific Investigations Report 2016–5125

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

Cover. Photos showing equipment installed at the Confined Disposal Facility in East Chicago, Indiana, on September 4, 2014. Top left, the air slug testing apparatus installed on monitoring well MW–4B; bottom right, the aquifer testing equipment installed on extraction well EW–4B.

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By David C. Lampe and Michael D. Unthank

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
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	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl; petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	30.48	centimeter per day (cm/d)
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)
	Pressure	
feet of H_2O	2.99	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Specific capacity	
gallon per minute per foot ([gal/min]/ft)	0.2070	liter per second per meter ([L/s]/m)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Datum

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

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

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

Time is referenced to Eastern Standard Time.

Supplemental Information

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness ($[ft^3/d]/ft^2$)ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Abbreviations

CDF	Confined Disposal Facility
EPA	U.S. Environmental Protection Agency
ppm	parts per million
PSIG	pounds per square inch gage
RPM	revolutions per minute
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
S_w	wellbore skin factor

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By David C. Lampe and Michael D. Unthank

Abstract

The U.S. Geological Survey (USGS) performed tests to evaluate the hydrologic connection between the open interval of the well and the surrounding Calumet aquifer in response to fouling of extraction well pumps onsite. Two rounds of air slug testing were performed on seven monitoring wells and step drawdown and subsequent recovery tests on three extraction wells on a U.S. Army Corps of Engineers Confined Disposal Facility (CDF) in East Chicago, Indiana. The wells were tested in 2014 and again in 2015. The extraction and monitoring wells are part of the gradient control system that establishes an inward gradient around the perimeter of the facility. The testing established a set of protocols that site personnel can use to evaluate onsite well integrity and develop a maintenance procedure to evaluate future well performance.

The results of the slug test analysis data indicate that the hydraulic connection of the well screen to the surrounding aquifer material in monitoring wells on the CDF and the reliability of hydraulic conductivity estimates of the surrounding geologic media could be increased by implementing well development maintenance. Repeated air slug tests showed increasing hydraulic conductivity until, in the case of the monitoring wells located outside of the groundwater cutoff wall (MW–4B, MW–11B, MW–14B), the difference in hydraulic conductivity from test to test decreased, indicating the results were approaching the optimal hydraulic connection between the aquifer and the well screen. Hydraulic conductivity values derived from successive tests in monitoring well D40, approximately 0.25 mile south of the CDF, were substantially higher than those derived from wells on the CDF property. Also, values did not vary from test to test like those measured in monitoring wells located on the CDF property, which indicated that a process may be affecting the connectivity of the wells on the CDF property to the Calumet aquifer. Derived hydraulic conductivity values from the initial air slug test during the 2015 testing period for MW–11A and MW–14A are an order of magnitude less than those derived from the final test during the 2014 testing period indicating the development of a low conductivity skin between the final test of the 2014 testing period and the beginning of the 2015 testing period that created a decrease in the connection of the monitoring well screen to the surrounding aquifer material.

Repeated step drawdown and recovery testing of the extraction wells tested during this study provided results that indicate a slight increase in the development of a skin and a decrease in the connectivity of the extraction wells with the Calumet aquifer. Hydraulic conductivity values obtained from the test results were relatively similar in EW–4B and EW–14A but were substantially lower for EW–11C. This difference may be due to the presence of finer grained silt deposits in the area surrounding well nest 11. Skin factors calculated during the step drawdown and recovery analysis were lowest in EW–11C and relatively similar in EW–4B and EW–14A. Calculated skin factors increased slightly in the analysis of data collected in 2015 from that collected in 2014.

Comparisons of the specific-capacity values calculated from well development data collected following extraction well installation to those calculated during the single well aquifer tests at EW–4B, EW–14A and EW–11C indicate that the productivity of extraction wells on the CDF property has diminished since 2008. Values calculated for monitoring wells MW–4A, MW–11A, and MW–14A were used to evaluate the decrease in air slug derived hydraulic conductivity for monitoring wells within the groundwater cutoff wall between testing in 2014 and 2015.

Results from testing by this study indicate that implementation of an air slug testing regimen of the monitoring wells that control the gradient control system at the CDF throughout the course of a year may help sustain the connectivity between the monitoring wells and the surrounding aquifer and provide data to evaluate the need for different types of well development approaches to address chemical or biological fouling issues. Repeated step drawdown and recovery testing of the

extraction wells tested during this study provided results that indicate a slight increase in the development of a skin and a decrease in the connectivity of the extraction wells with the Calumet aquifer. Implementation of a specific capacity testing regimen can provide data to record and track well condition through time for individual extraction wells. Results from aquifer testing by this study indicate that specific capacity test results, when paired with recovery testing, provide useful data to measure the development of any low conductivity wellbore skin through the skin factors derived for the individual extraction wells. An initial annual schedule of specific capacity and recovery tests would provide sufficient data to identify substantial short-term changes in the operating condition of the extraction wells.

Introduction

The performance of water-withdrawal wells used to maintain an inward groundwater gradient at a site in East Chicago, Indiana, is a necessary operational concern for the site operator, the U.S. Army Corps of Engineers, Chicago District (USACE). The Confined Disposal Facility (CDF; fig. 1) uses extraction wells to confine possible migration of petroleum contaminated site groundwater and free-phase hydrocarbons as well as leachate from wet material recovered from the navigational dredging of the Indiana Harbor Canal. The CDF site was formerly the home of oil refining operations. Prior investigations documented subsurface hydrocarbon contamination, including free phase hydrocarbon at the water-table surface and periodic seepage of hydrocarbons to the south into the Lake George Branch, a segment of the Indiana Harbor Canal, both of which are connected to Lake Michigan. Water levels in the Indiana Harbor Canal vary continually because they are affected by water levels in Lake Michigan and upstream discharge from the Grand Calumet River (U.S. Fish and Wildlife Service, 2015).

Maintenance of inward horizontal hydraulic gradients on all sides of the CDF is a critical operating feature of the site that enables isolation and control of leachate from the dredged sediment. Twenty-two nests of 4 extraction wells each were initially installed in the aquifer inside a groundwater cutoff wall consisting of soil-bentonite slurry (figs. 2 and 3). An additional eight extraction wells were added to three well nests along the southern perimeter of the CDF in 2015. Withdrawal of groundwater by the extraction wells is designed to decrease groundwater levels inside the CDF relative to outside the wall (fig. 3). Extraction wells were about 30 feet (ft) deep with 5-ft screens at their base to limit the possibility for drawdown to reach the well screen and were designed to be screened below occasional residual petroleum contamination from prior site activities.

The hydraulic connection of extraction wells and monitoring wells at the CDF with aquifer materials outside their well screen is critical to the intended function of the gradient control system. A poor connection can increase drawdown in the extraction well and can delay water-level responses inside the well relative to changes in water levels outside the well. Beginning in 2012, some extraction wells on the CDF site began to experience fouling—a precipitate of unknown origin formed on the intake of the extraction well pump and caused the pump to overheat and become inoperable, which required site personnel to pull the equipment from affected wells and replace their pumps (fig. 4; Ben O'Neil, U.S. Army Corps of Engineers, oral commun., 2015). Of the affected extraction wells, some experience fouling more frequently than others.

Assessing changes in water-level recovery and water withdrawal characteristics of extraction and monitoring wells and the physical, chemical, and biological causes of those changes is a necessary part of well performance evaluation at the CDF. In 2014, the U.S. Geological Survey (USGS), in cooperation with the USACE, initiated an investigation to design and perform a trial of a well testing protocol that the USACE could use to evaluate the performance of the gradient control system at the CDF and to identify the source of the unknown precipitate causing the well fouling and subsurface conditions that may control the presence or absence of the precipitate on the CDF property. The first phase of the investigation involved planning and implementing a series of tests for extraction and monitoring wells at the CDF through the use of (1) single well aquifer tests of extraction wells to characterize water-level drawdown and recovery characteristics relative to the volume of water produced during a normal cycle of operation, and (2) single well air slug tests of monitoring wells to measure characteristics of the aquifer and monitoring well. The protocols were performed on three sets of extraction and monitoring wells at the CDF site to establish well characteristics present at the site during initial testing. Protocols were repeated 6 months later to measure any change over time to the characteristics of the wells that may be the result of subsurface conditions at the CDF. Slug tests were also performed on a USGS-operated monitoring well approximately 0.25 mile south of the CDF property to measure and compare aquifer conditions in similar deposits outside of the CDF property.

The information developed from this study addresses aspects of the USGS Water Science Goals and Objectives (Evenson and others, 2012) by increasing the understanding of hydrologic processes that affect groundwater availability and management and advancing the understanding of in-well and aquifer processes that affect well function and groundwater production at sites affected by contaminants. The USACE and its partners benefit by having reproducible metrics to demonstrate gradient control performance at the CDF to regulator and public stakeholders, thereby facilitating continued dredging operations and navigable conditions on the Indiana Harbor Canal.

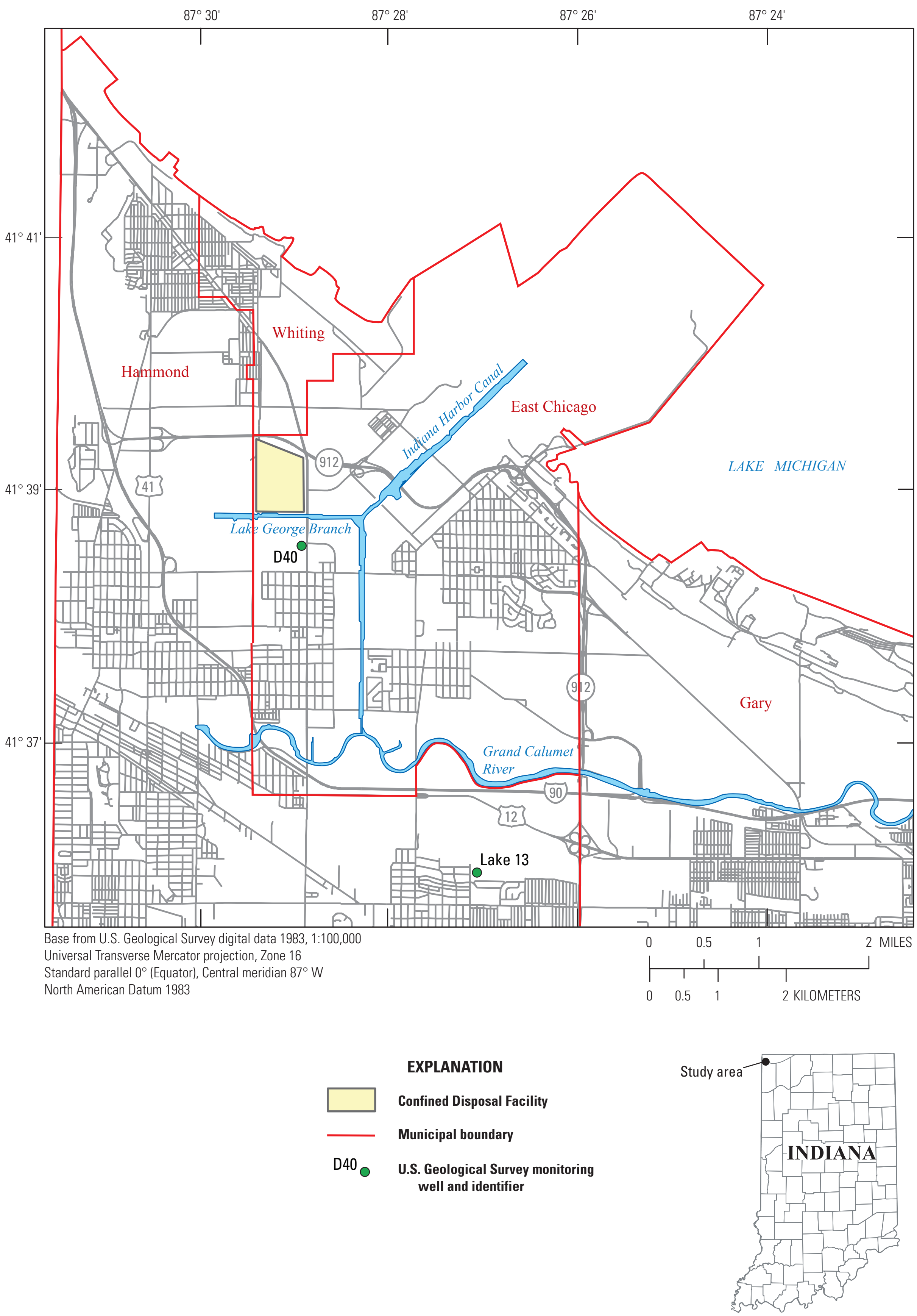
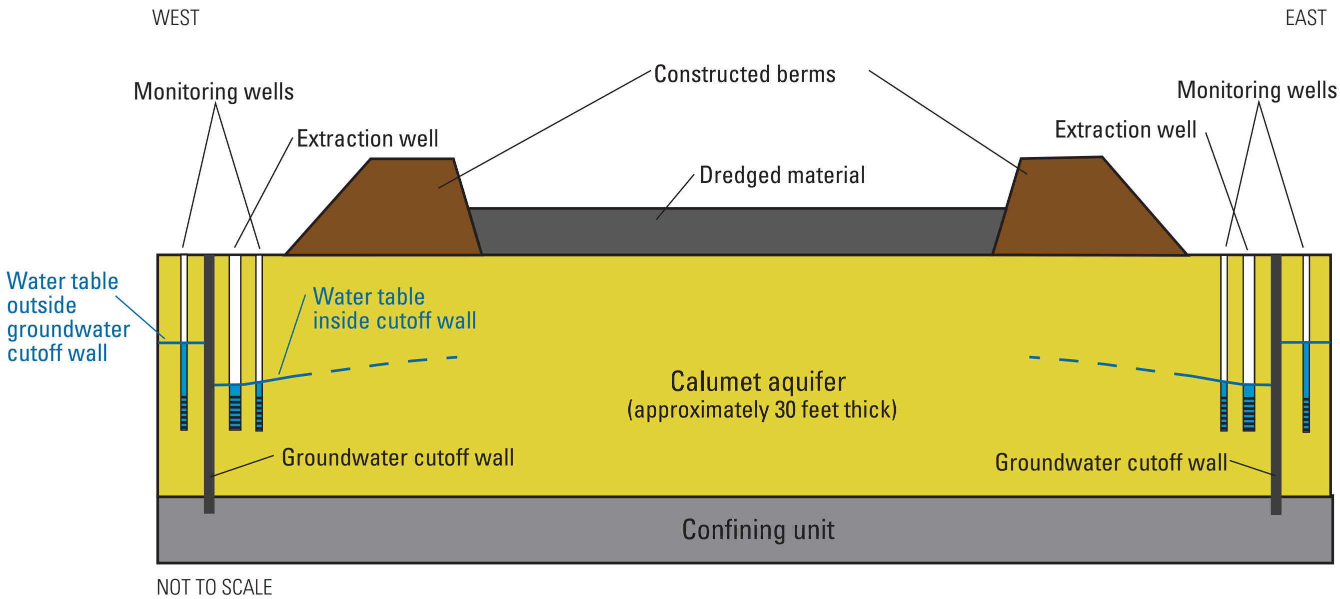


Figure 1. Location of the Confined Disposal Facility, East Chicago, Indiana.

Figure 2. Location of the Confined Disposal Facility, monitoring and extraction wells on the property, extraction wells with petroleum contamination identified from well boring logs, and wells for well nests 4, 11, and 14 that were included in this study. The groundwater cutoff wall is approximately 12 feet outside the location of each extraction well and in between the inner and outer monitoring well locations.



Monitoring wells inside of the Confined Disposal Facility are actually the same distance from the groundwater cutoff wall as the extraction wells, but for the purposes of this diagram, are shown next to the extraction well.

Figure 3. Conceptual cross-section diagram of the Confined Disposal Facility.

Figure 4. Precipitate of unknown origin adhered to the intake manifold of a pump installed in extraction well EW–4B, East Chicago, Indiana, May 8, 2014.

Purpose and Scope

The hydrologic investigation at the CDF in East Chicago, Ind., evaluated the performance of a subset of monitoring and extraction wells onsite and developed procedures that could be used to monitor well integrity to assess in the efficiency of the onsite gradient control system. A suite of single well tests (specific-capacity, step drawdown, recovery and air slug tests) were completed at three locations within the site representing three different levels of apparent well fouling (well nests 4, 11, and 14). Wells were tested once in August–September 2014 and again in March–May 2015 to estimate changes to the properties of the well and aquifer during the study period. Data collected during well installation and development and four rounds of water quality sampling were also used to estimate specific capacity. An analysis of the water quality sampling is not included in this report. The data and hydraulic interpretations made using the data from these tests are documented in this report.

Background

The USGS, in cooperation with Federal and State partners, has published numerous reports on the groundwater, surface-water, and water quality conditions in northwestern Indiana. Fenelon and Watson (1993) and Greeman (1995) analyzed the interaction of surface-water and groundwater levels in the vicinity of the Grand Calumet River and Indiana Harbor Canal. Kay and others (1996) analyzed the geohydrology, water levels, and directions of flow in the Calumet aquifer in northwestern Indiana and northeastern Illinois. As part of the study in Kay and others (1996), slug tests were performed in 26 wells to determine the horizontal hydraulic conductivity of the Calumet aquifer. Values of hydraulic conductivity ranged from 2.1 to 98 feet per day (ft/d) for wells completed in the coarse grained unconsolidated Calumet aquifer. Duwelius (1996) analyzed the distribution of hydraulic conductivity in the streambed sediments of the Grand Calumet River. Bayless and others (1998) analyzed the hydrology and geochemistry of slag-affected aquifers and groundwater in northwestern Indiana. Kay and others (2002) used isotopic analysis to identify sources of groundwater, groundwater flowpaths, and flow rates, and to assess aquifer vulnerability in the Calumet aquifer in northwest Indiana.

Description of Study Area

The CDF is in East Chicago, Ind., and is approximately 1.5 miles south of Lake Michigan and 2 miles east of the State line separating Indiana and Illinois (fig. 1). The CDF site is approximately 140 acres and is bounded by Indianapolis Boulevard to the east, Indiana State Route 912 (Cline Avenue) to the north, Norfolk Southern Railroad to the west, and the Lake George Branch, a segment of the Indiana Harbor Canal, to the south (fig. 2).

Beginning in 1918, the CDF property was the location of a petroleum refinery with peak productions of approximately 140,000 barrels of refinery products per day. Products included gasoline, fuel oil, kerosene, lubricating oils, grease, asphalt, propane, liquefied petroleum gas, phenols, paraffin wax, and, for a brief period of time during the 1940's, insecticides (U.S. Army Corps of Engineers, written commun., 2015). In 1981, the property owner filed for bankruptcy, and all aboveground materials and structures related to refinery operations were removed, and the site was covered with a layer of clean soil. Groundwater monitoring began in 1991 following the detection of hydrocarbon contamination, and a groundwater recovery system was installed in 1992 along the southern boundary of the CDF property on the north side of the Lake George Branch. Other groups of inorganic and organic compounds have been identified in soil and water samples collected prior to 1998 (fig. 5; U.S. Fish and Wildlife Service, 2015).

The USACE took possession of the property and began construction of the CDF in 2002 as the final repository of dredging wastes, including those from the Indiana Harbor and Indiana Harbor Canal. Railroad tracks that remained across the property were relocated and buried infrastructure was removed in preparation for the installation of an underground, groundwater cutoff wall, which now surrounds the CDF property on the north, west, and east sides to control groundwater flow. A steel sheet-pile groundwater cutoff wall and slurry-barrier groundwater cutoff wall seals the border with the Indiana Harbor Canal on the south side. The slurry-barrier and sheet-pile groundwater cutoff walls were installed at a depth of approximately 30 ft to connect with a lower confining unit, a silty clay to clay deposit (fig. 3). This groundwater cutoff wall system was intended to meet the permeability requirements of 2.83×10^{-4} ft/d for the CDF perimeter. Inside the groundwater cutoff wall and outside on the landward sides of the site, aquifer materials are capped with a soil layer and extend to the lower confining unit at a depth of about 30 ft or less.

Within the groundwater cutoff wall, a gradient control system was installed to maintain an inward groundwater gradient at the site. The gradient control system, at the time of the study, consisted of 22 nests, each nest composed of 4 extraction wells installed within the groundwater cutoff wall and a pair of monitoring wells, one inside and one outside of the wall (figs. 2 and 3). Eight additional extraction wells were added to three well nests along the southern perimeter of the CDF in 2015. Monitoring wells along the southern perimeter of the CDF use the water levels of the Lake George Branch as the exterior reference water elevation. An automated system uses continuous water-level data collected from the monitoring wells and the Lake George Branch to control the operation of the extraction wells within each nest. When the difference in water level between the inner and outer monitoring wells reaches a threshold, pumps in the extraction wells are activated to lower the water table. Lowering the water level in the extraction wells effectively increases the gradient inward toward the CDF across the groundwater cutoff wall. Groundwater from the extraction wells is pumped from the aquifer inside of the groundwater cutoff wall, moves through the water-collection system, and discharges into the unlined disposal cells in the center of the CDF prior to treatment by the onsite wastewater treatment plant and offsite discharge. Withdrawal of groundwater by the extraction wells is designed to decrease groundwater levels inside the groundwater cutoff wall relative to areas outside of the wall. The monitoring and extraction wells are approximately 30 ft deep with 5-ft screens at their base to limit the possibility for drawdown within the extraction wells to reach the well screen and to be screened below residual petroleum contamination. There are no pumps installed within the monitoring wells on the CDF property, and these wells were not routinely pumped or redeveloped. Locations of extraction wells with well boring logs indicating petroleum contamination are shown on figure 2.

Beginning in 2012, specific extraction wells on the CDF site began to experience fouling. A precipitate of unknown origin formed on the intake of some of the extraction well pumps causing them to overheat and become inoperable, ultimately requiring site personnel to pull the equipment from the well

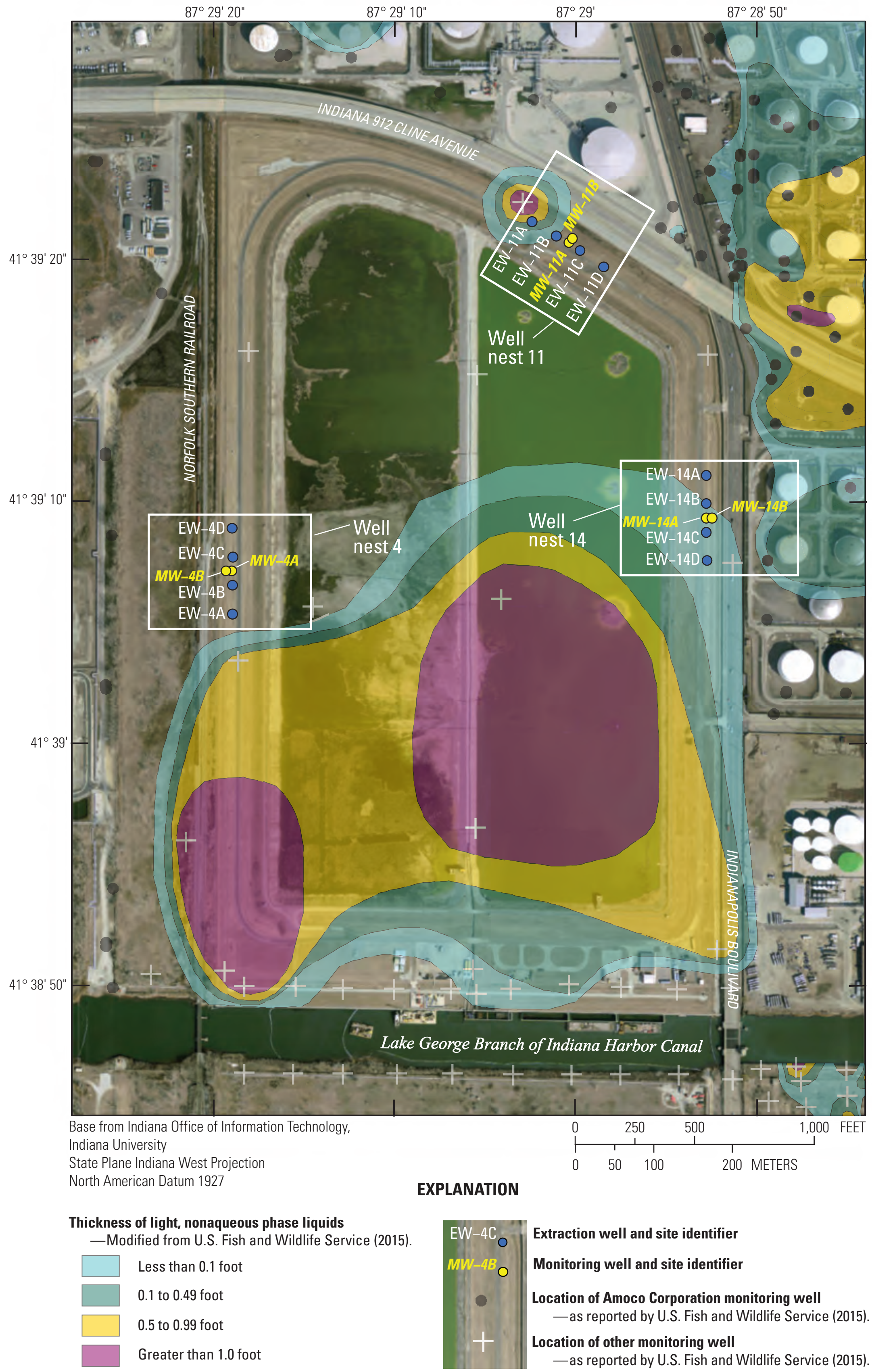


Figure 5. Thickness of light nonaqueous phase liquids on groundwater near the Confined Disposal Facility and Indiana Harbor Canal, East Chicago, Indiana (modified from U.S. Fish and Wildlife Service, 2015). Data represented on the figure were collected prior to 1998.

and replace each inoperable pump (fig. 4). Of the affected extraction wells, some experienced fouling more frequently than others.

Hydrogeologic Setting

The CDF is located in the Calumet area of Lake County in northwestern Indiana and is in the Calumet Lacustrine Plain physiographic province (Schneider, 1966). The province was made up of several distinct dune-beach complexes formed in the Pleistocene and Holocene Epochs when Lake Michigan was at higher levels than it is today (Leverett and Taylor, 1915; Bretz, 1951; Hansel and others, 1985). The dune, beach, and lacustrine silts, sands, and gravels that were deposited form a thin but laterally extensive surficial aquifer, referred to herein as the Calumet aquifer. In the area of the CDF, the Calumet aquifer extends approximately 35 ft below the land surface based on driller's well logs from the extraction wells installed onsite (U.S. Army Corps of Engineers, written commun., 2014). Glacial till and lacustrine clay immediately underlie the Calumet aquifer. The clay unit ranges in thickness from 50 to 140 ft in the area surrounding the CDF and forms a confining unit between the Calumet aquifer and the underlying carbonate bedrock aquifer (Fenelon and Watson, 1993).

Urban development in the late 1800's and early 1900's brought about notable changes in the area surrounding the CDF including the draining of marshes in low lying areas and the digging of the Indiana Harbor Canal to connect the Grand Calumet River to Lake Michigan, which caused a change in direction of flow in the river (Moore and Trusty, 1977). Slag, a byproduct of the steel making industry, was extensively used as fill material in depressions and marshy areas in the region, but it is not believed to have been used in the area of the CDF (Kay and others, 1996). Horizontal hydraulic conductivities reported by Kay and others (1996) and calculated from slug tests performed in wells anywhere from 5 to 30 ft deep in the Calumet aquifer range from 2.10 to 98 ft/d and have a median value of 12 ft/d.

Methods of Investigation

The gradient control system installed at the CDF consists of 22 nests of wells. At the start of the investigation, each nest consisted of four extraction wells inside of the groundwater cutoff wall and two monitoring wells, one inside of the groundwater cutoff wall and one outside (figs. 2 and 3). An additional 8 extraction wells were added to three well nests along the southern perimeter of the CDF in 2015. For this study, three nests of wells were identified by the USACE as being representative of different degrees of well fouling present at the CDF. Well nest 4 was identified as having experienced high levels of fouling, well nest 14 was experiencing well fouling to a lesser extent than well nest 4, and well nest 11 was experiencing little to no well fouling. The performance of the extraction and monitoring wells in these three well nests were evaluated by the use of single well tests to represent the other wells on the CDF property with varying degrees of fouling. Well information and water-level data given in this report were placed in the USGS National Water Information System, available at http://nwis.waterdata.usgs.gov/nwis.

Single Well Air Slug Tests

Results from successive slug tests were used to detect fouling conditions that affect the hydraulic connection of water levels in monitoring wells with water levels in the adjacent aquifer. Slug test results were used to indicate and quantify the presence of altered, lower conductivity conditions near the well (well skin) and whether the well has been appropriately developed or is in need of maintenance to remove material that may be affecting the connection to the surrounding aquifer material. A slug test consists of measuring the recovery of water level in a well after a near-instantaneous change in water level in the well due to introducing a solid object, an equivalent volume of water or pressurized air causing an abrupt increase, or decrease in water level (Butler, 1998). The measured change in water level through time can be used to estimate the hydraulic conductivity of the formation through theoretical models of test responses.

Air slug tests were completed in six monitoring wells on the CDF property, and one USGS monitoring well (D40) located approximately 0.25 mile south of the CDF property (figs. 1 and 2, table 1). Paired monitoring wells on either side of the groundwater cutoff wall at three locations on the CDF property were chosen as being representative of different degrees of well fouling present at the CDF. Monitoring well D40 was chosen as being representative of a background condition within the Calumet aquifer due to its proximity to the CDF, but the well is screened at a shallower depth than the wells on the CDF property. Multiple air slug tests were performed in each monitoring well using an air slug technique (Greene and Shapiro, 1995; fig. 6) during the August–September 2014 and March–May 2015 testing periods.

Air slug tests were conducted by pressurizing the air in the casing above the column of water in the well to depress the water level to a point below the static water level and then instantly releasing the applied air pressure to initiate recovery. The rising water level during the recovery part of the test was recorded and used to estimate hydraulic conductivity values for the aquifer (Greene and Shapiro, 1995). The air slug tests were conducted as follows:

1. Following the removal of any equipment installed in the monitoring well, a well head apparatus designed for pressurizing the well (fig. 6) was attached to the open well. An initial static water level was measured in the monitoring well using an electric water-level tape. An In-Situ Level TROLL® 700 30 PSI submersible pressure

Table 1. Well characteristics of the monitoring and extraction wells tested during the study.

[USGS, U.S. Geological Survey; —, not applicable]

USGS site identifier	Local identifier	Well nest	Borehole diameter, in inches	Casing inside diameter, in inches	Annulus thickness, in inches	Well depth, in feet	Screen length, in feet	Pump depth, in feet below top of casing	Assumed well skin thickness, in feet	Specific-capacity test performed	Slug tests performed	Step drawdown test performed
USGS 413908087291901	MW–4A	4	8	2	3	27.8	5	—	—	X	X	—
USGS 413908087291902	MW–4B	4	8	2	3	28	5	—	—	—	X	—
USGS 413907087291801	EW–4B	4	13	6	3.5	29.1	5	21.58	1	X	—	X
USGS 413921087290101	MW–11A	11	8	2	3	27.8	5	—	—	X	X	—
USGS 413921087290102	MW–11B	11	8	2	3	27.2	5	—	—	—	X	—
USGS 413920087285901	EW–11C	11	13	6	3.5	29.9	5	22.48	1	X	—	X
USGS 413909087285301	MW–14A	14	8	2	3	25	5	—	—	X	X	—
USGS 413909087285302	MW–14B	14	8	2	3	25	5	—	—	—	X	—
USGS 413911087285201	EW–14A	14	13	6	3.5	29.6	5	21.73	1	X	—	X
USGS 413835087245101	D40	—	—	2	—	7	3	—	—	—	X	—

transducer was deployed in the well at a depth such that it would remain submerged during the length of the test and set to make measurements at 0.25-second intervals.

2. The apparatus and well casing was pressurized using a small bicycle tire pump and pressure in the well casing was monitored by reading the pressure dial gage on the well head apparatus and the measurements made by the pressure transducer measurements. The maximum pressure in the well casing was recorded and the pressure was allowed to drop and stabilize.

3. Once stabilized, the remaining pressure was immediately released by opening the ball valve on the well head apparatus. The subsequent rising water was recorded and manual water-level check measurements were made through the well head apparatus during the water-level recovery period of the test. Pressure transducer recordings and manual measurements of the water level were continued until the initial static water level was achieved.

4. Following the recommendations of Butler and others (1996), a minimum of three slug tests were performed for each monitoring well tested during each testing period.

Figure 6. Air slug testing apparatus installed on monitoring well MW–4B, East Chicago, Indiana, September 4, 2014.

Before testing, well construction details were recorded, including the diameter of the well, the total depth of the well, the depth to the top of the well screen, and the length of the well screen (appendix 1). Periodic water-level tape down measurements were made before and during water-level recovery and following the slug tests to confirm the measurements being recorded by the pressure transducer.

Continuous data collected during the single well air slug testing were analyzed with the Bouwer and Rice (1976) method by using the AQTESOLV® software package (Hydrosolve, Inc., 2007). The Bouwer and Rice method is appropriate for use in analysis of slug test results from unconfined aquifer condition such as those in the tested monitoring wells. Solutions were fit using the raw data collected from the 0.20 to 0.30 range of normalized displacement following guidelines presented by Butler (1998). A set of simplifying assumptions was used in the analysis of slug tests. The vertical anisotropy used in the computations was assumed to be 1.0 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.

Single Well Aquifer Tests

Results from step drawdown tests were used to detect fouling conditions that potentially restrict the withdrawal of groundwater from extraction wells and the drawdown of groundwater levels in the adjacent aquifer inside the groundwater cutoff wall. A step drawdown test is a standard method for determining transmissivity and hydraulic conductivity of aquifer materials, evaluating well losses and wellbore skin factors, and calculating the efficiency of the well (Kruseman and deRidder, 1990). Tests are completed by pumping the well at a low constant-discharge rate while monitoring drawdown in the well. Once drawdown stabilizes, the pumping rate is increased to a higher constant-discharge rate until the drawdown stabilizes again. The process continues and is repeated through at least three steps. Aquifer and well properties are estimated by fitting collected drawdown and pumping rate data to mathematical solutions.

Step drawdown aquifer tests were completed in three extraction wells (fig. 2; table 1) at well nests 4, 11, and 14 that represented three different levels of apparent well fouling. The existing extraction well pump was replaced with a new test pump of the same model (Grundfos® Redi-Flo 3® Environmental Pump) in each tested well before testing to ensure that the condition of the pump screen was not a factor during the analysis of the test. The test pump was placed at the same approximate depth in the well as the existing extraction well pump. Control of the test pump was reconfigured to give the test operator full control of the pump revolutions per minute (RPM) rates so variable pumping rates could be used during the length of the test. Discharge from the test pump was set to bypass the existing collection system and travel above land surface so that flow rates could be measured (fig. 7). Flow rates were measured with a John C. Ernst, Inc. impeller type 4 0.5-inch stainless steel digital flow meter and totalizer. Discharge continued downstream from the flowmeter through a 1 1/4 inch diameter irrigation hose and ultimately discharged into the CDF's water-collection system through a surface access.

Figure 7. The aquifer testing equipment installed on extraction well EW–4B, East Chicago, Indiana, September 4, 2014.

The day before the step drawdown test, the tested extraction well (for example, EW–11C) and the two adjacent extraction wells (EW–11B and EW–11D) were taken offline and pumping of the wells was stopped to allow the aquifer to return to approach steady state. Extraction wells could not be taken offline for longer periods of time because of the mandatory inward hydrologic gradient on the CDF property. Water levels were measured at 1-hour intervals during the recovery phase before the test using pressure transducers installed in the wells for use in the CDF's gradient control system (fig. 8). The morning of the test, or the afternoon before the test (depending on the availability of the onsite workers and site conditions), the existing extraction well pump was replaced with the test pump. Water levels during the test were recorded in the test well using an InSitu® LevelTroll® 700 30 PSIG pressure

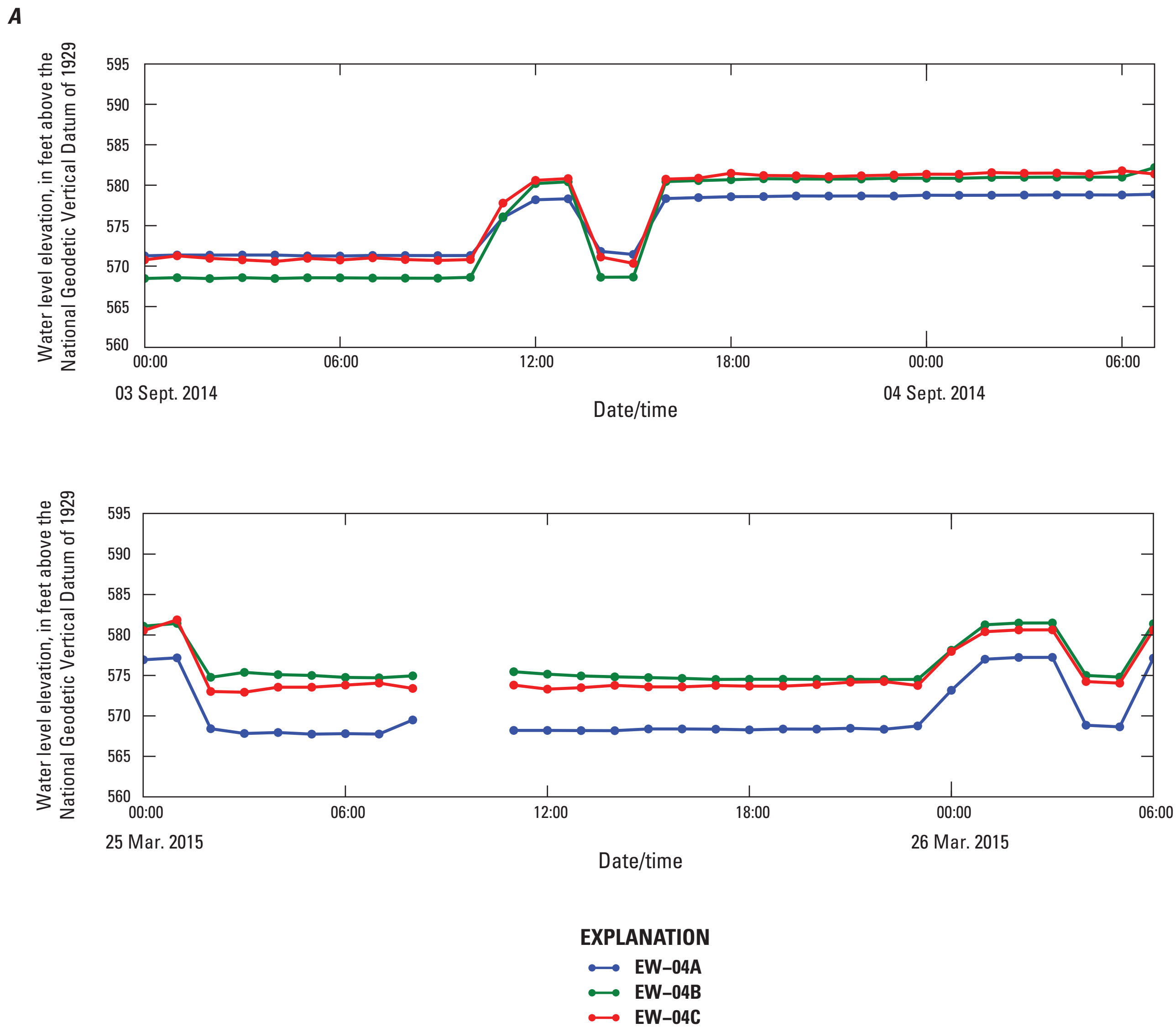


Figure 8. Water-level hydrographs for *A*, extraction well EW–4B and surrounding wells; *B*, extraction well EW–11C and surrounding wells; and *C*, extraction well EW–14A and surrounding wells for the period leading up to single well aquifer tests during the 2014 and 2015 testing periods. Plotted hourly data supplied from U.S. Army Corps of Engineers gradient control system (U.S. Army Corps of Engineers, written commun., 2015).

transducer with a factor reported accuracy of plus or minus 0.069 ft in 0.25-second intervals. Water levels were monitored in the nearest two extraction or monitoring wells using periodic measurements from electric water-level measuring tapes, but water levels in neighboring wells were not affected by any of the tests described in this report.

At the beginning of the test, the extraction well was pumped at a constant RPM designed to be a small percentage of the normal pumping rate for the well but high enough to discharge water through the flowmeter and ensure a pipe full flow condition. After 60 minutes, the RPM setting of the test pump was increased to a larger percentage of the maximum pumping rate for the well for at least 60 minutes, but no more than 120 minutes, then increased to a larger percentage of the maximum pumping rate for at least 60 minutes, but no more than 120 minutes. Pumping was then terminated and recovery measured until water levels returned to the pretest condition. Flow rates and drawdown recorded for each single well aquifer test are provided in figure 9.

B

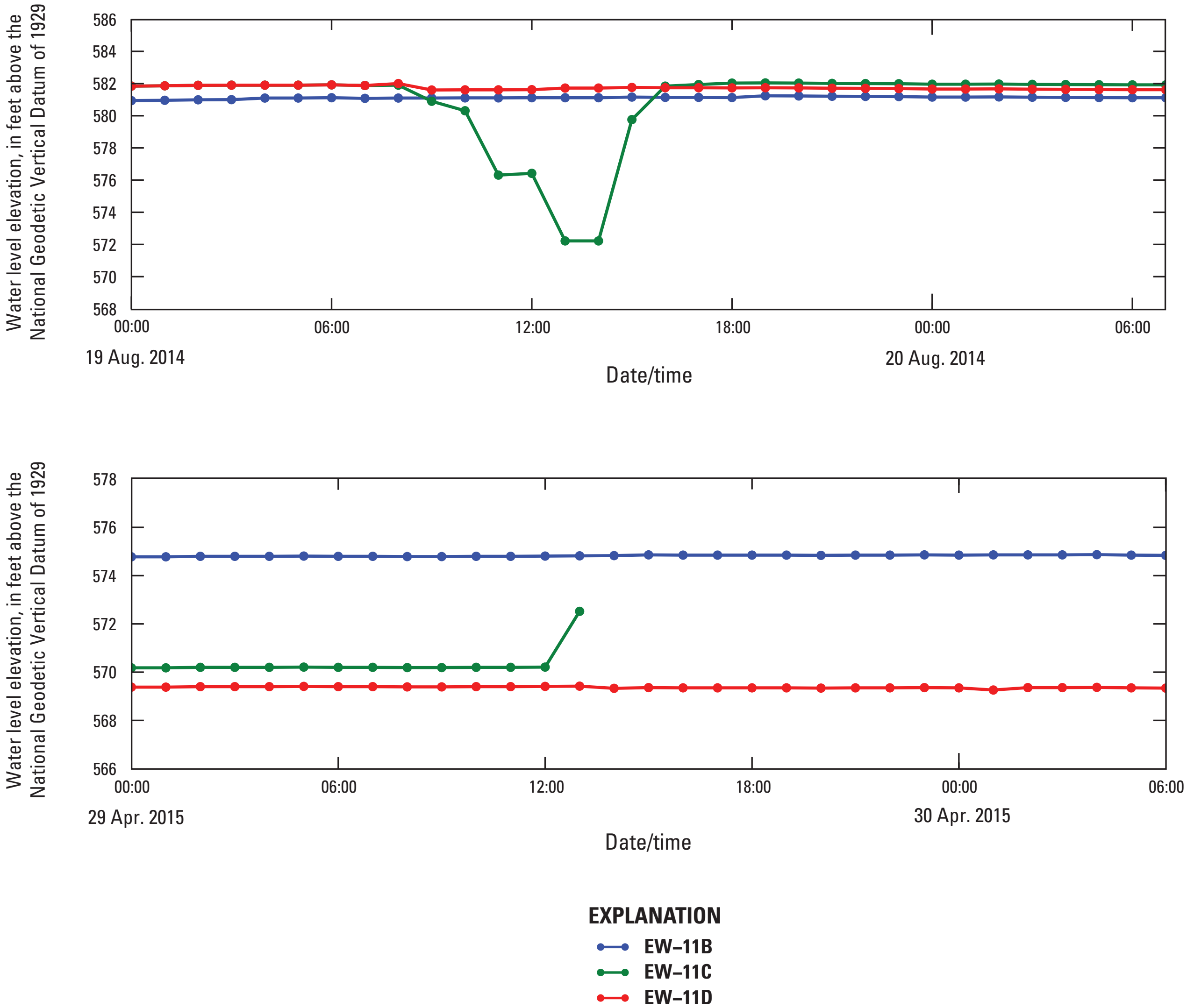


Figure 8. Water-level hydrographs for *A*, extraction well EW–4B and surrounding wells; *B*, extraction well EW–11C and surrounding wells; and *C*, extraction well EW–14A and surrounding wells for period leading up to single well aquifer tests during the 2014 and 2015 testing periods. Plotted hourly data supplied from U.S. Army Corps of Engineers gradient control system (U.S. Army Corps of Engineers, written commun., 2015).—Continued

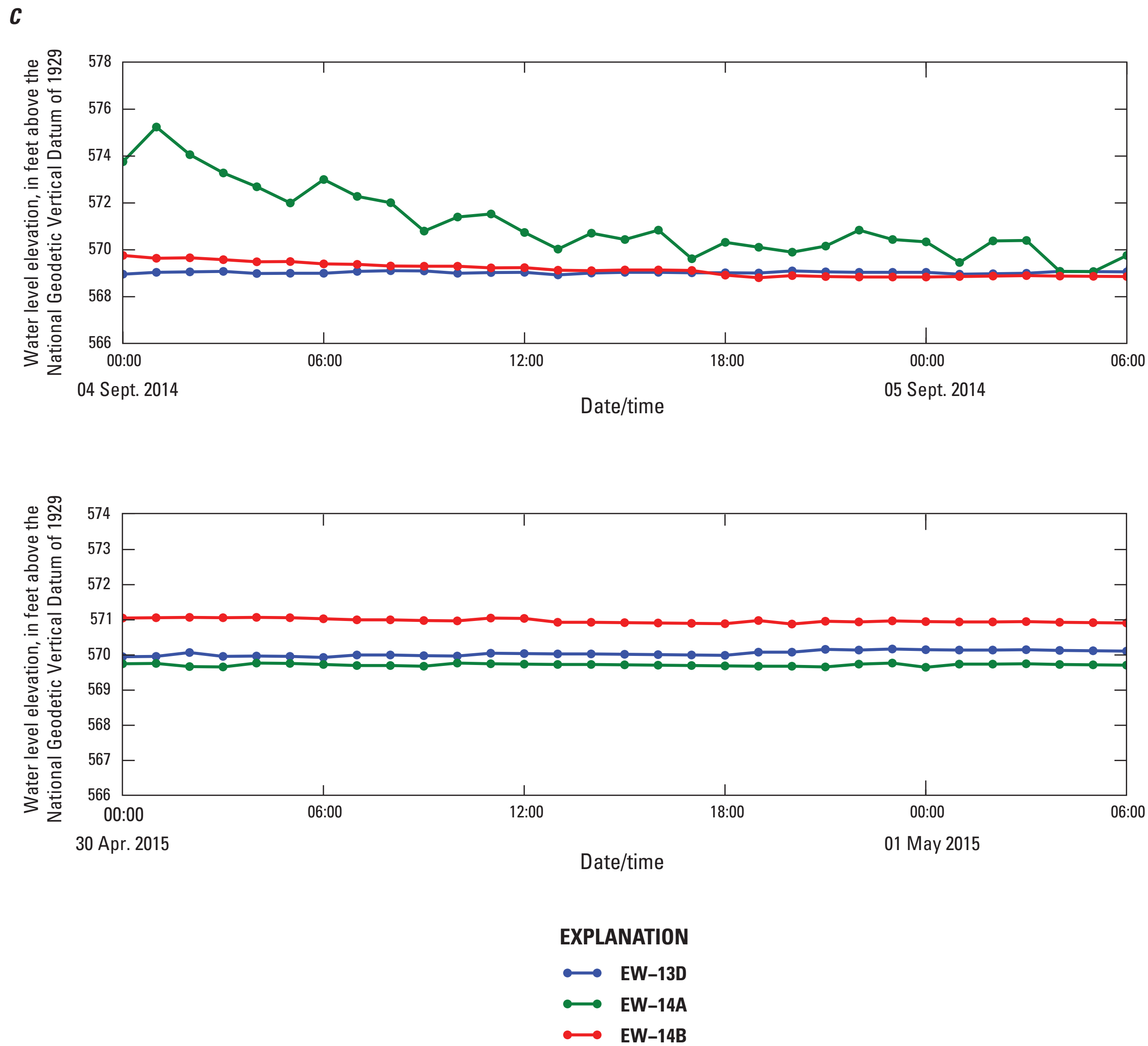
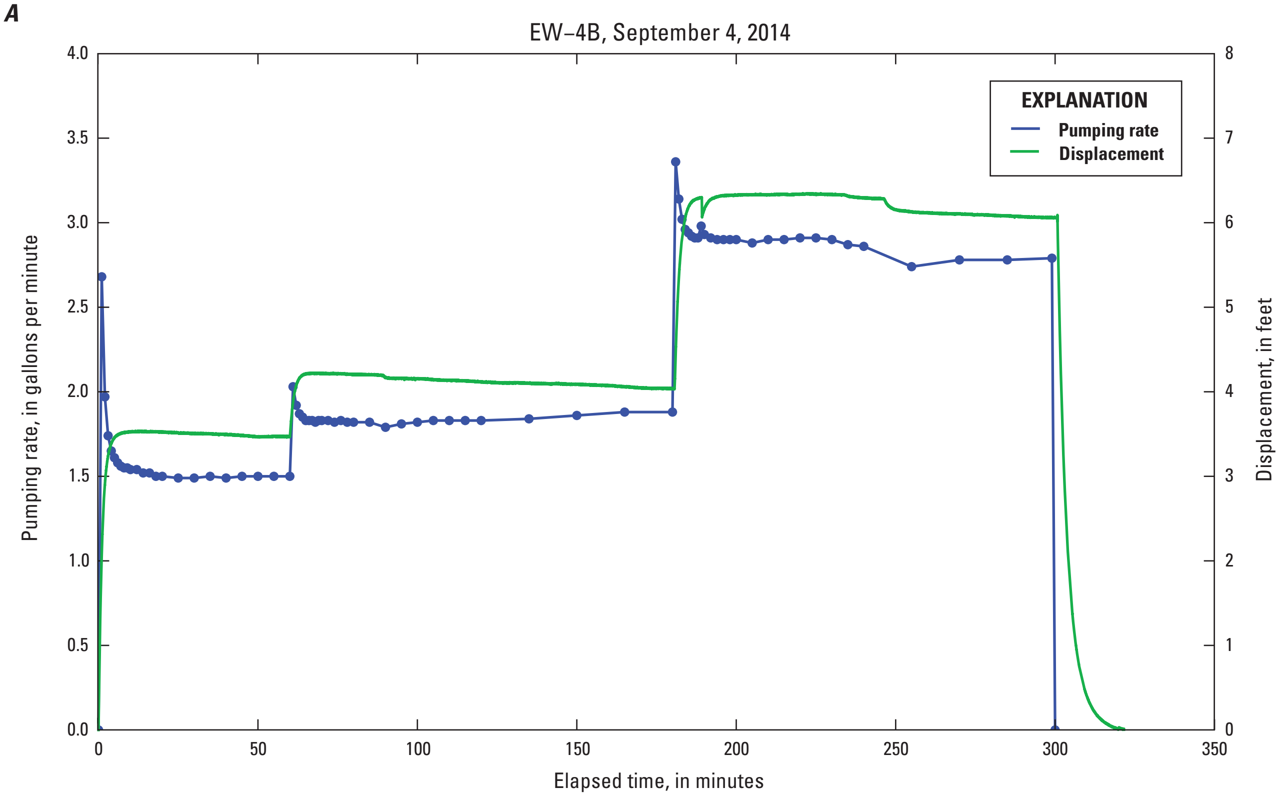


Figure 8. Water-level hydrographs for *A*, extraction well EW–4B and surrounding wells; *B*, extraction well EW–11C and surrounding wells; and *C*, extraction well EW–14A and surrounding wells for period leading up to single well aquifer tests during the 2014 and 2015 testing periods. Plotted hourly data supplied from U.S. Army Corps of Engineers gradient control system (U.S. Army Corps of Engineers, written commun., 2015).—Continued

A



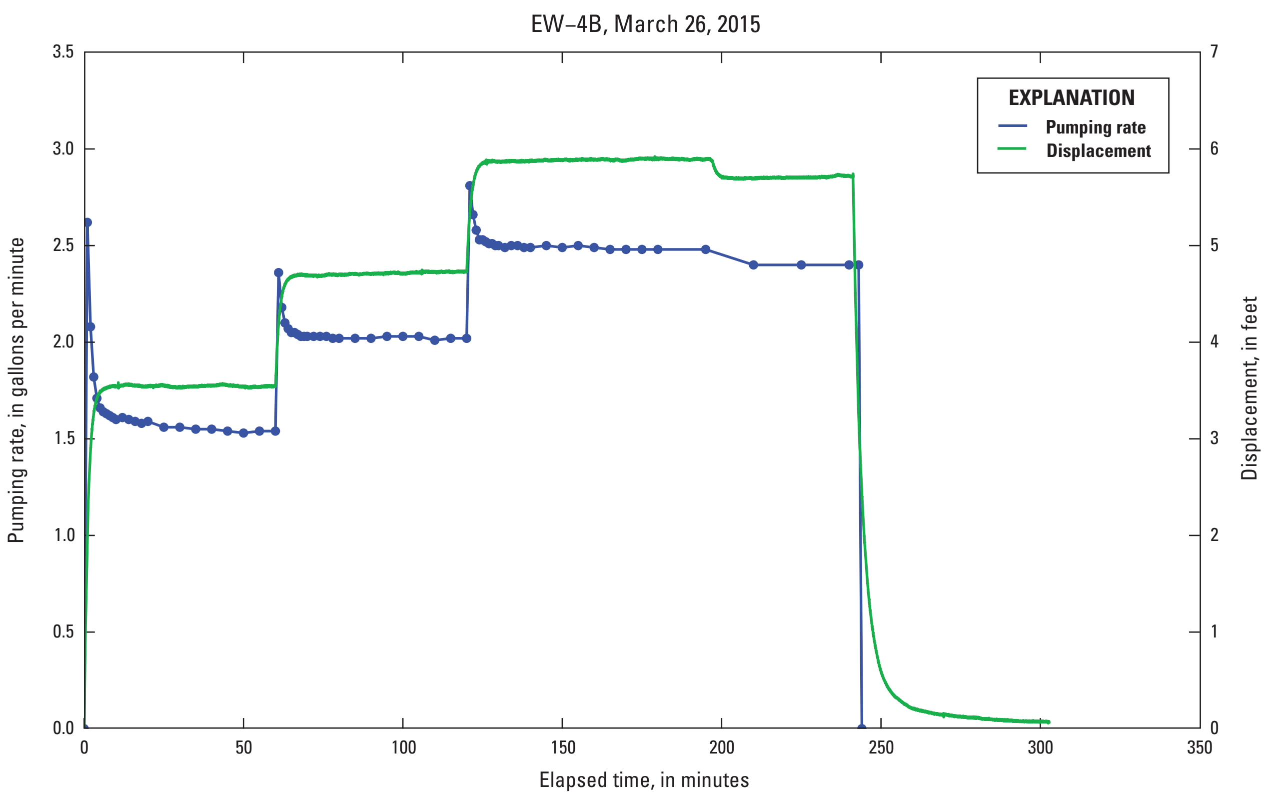
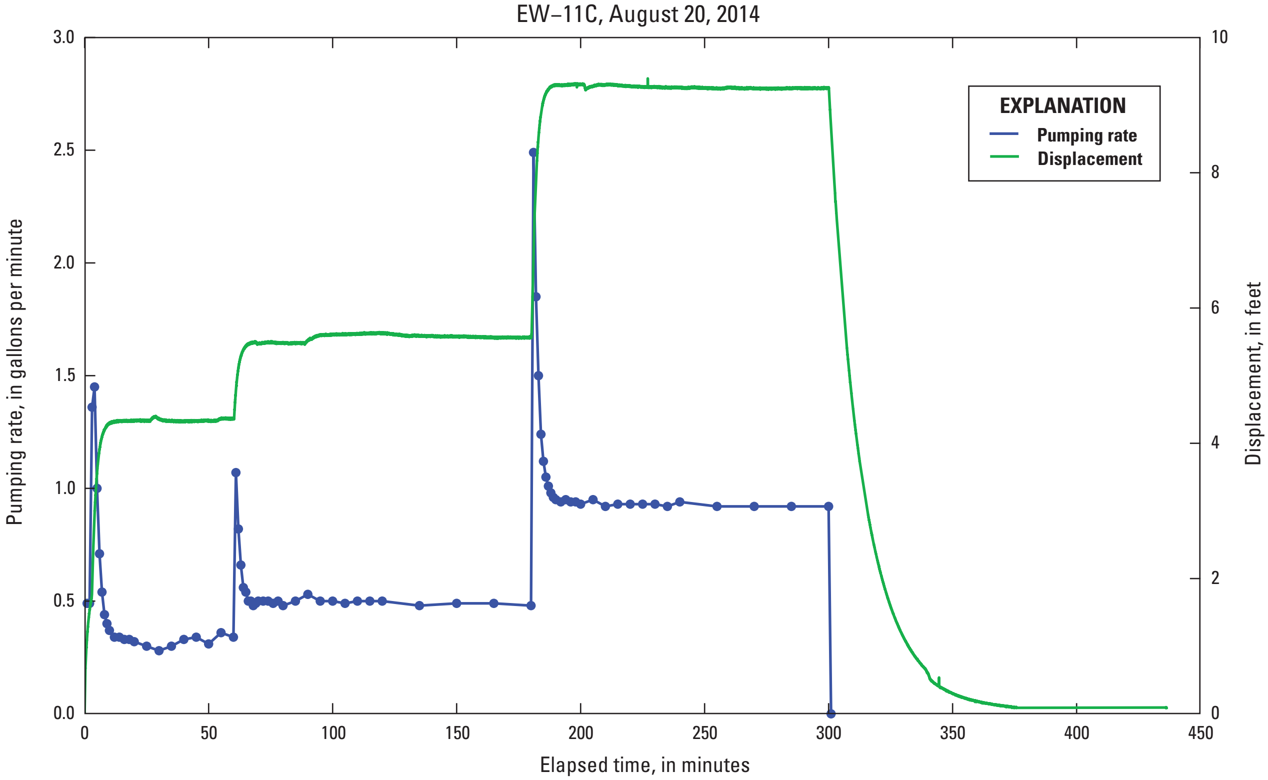


Figure 9. Pumping rate and drawdown recorded during the single well aquifer tests for *A*, extraction well EW–4B; *B*, extraction well EW–11C; and *C*, extraction well EW–14A during the 2014 and 2015 testing periods.

B



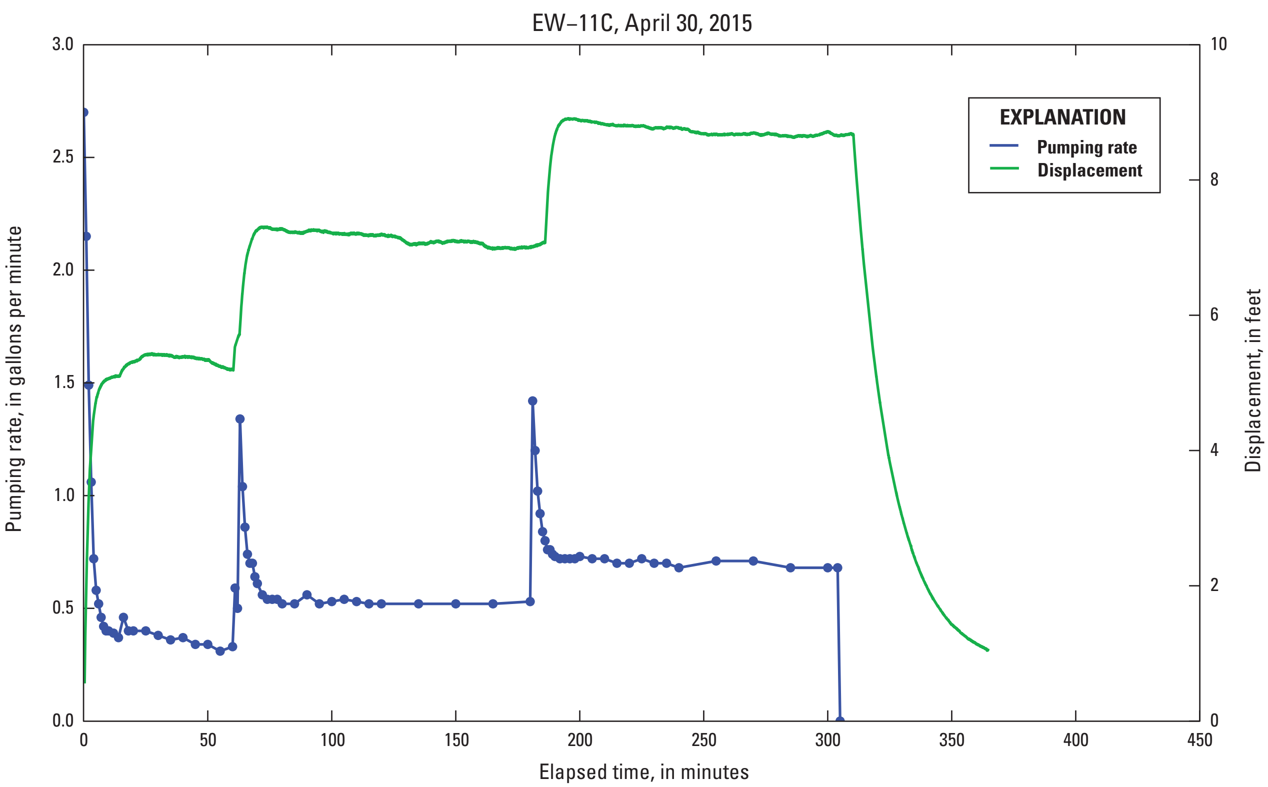


Figure 9. Pumping rate and drawdown recorded during the single well aquifer tests for *A*, extraction well EW–4B; *B*, extraction well EW–11C; and *C*, extraction well EW–14A during the 2014 and 2015 testing periods.—Continued

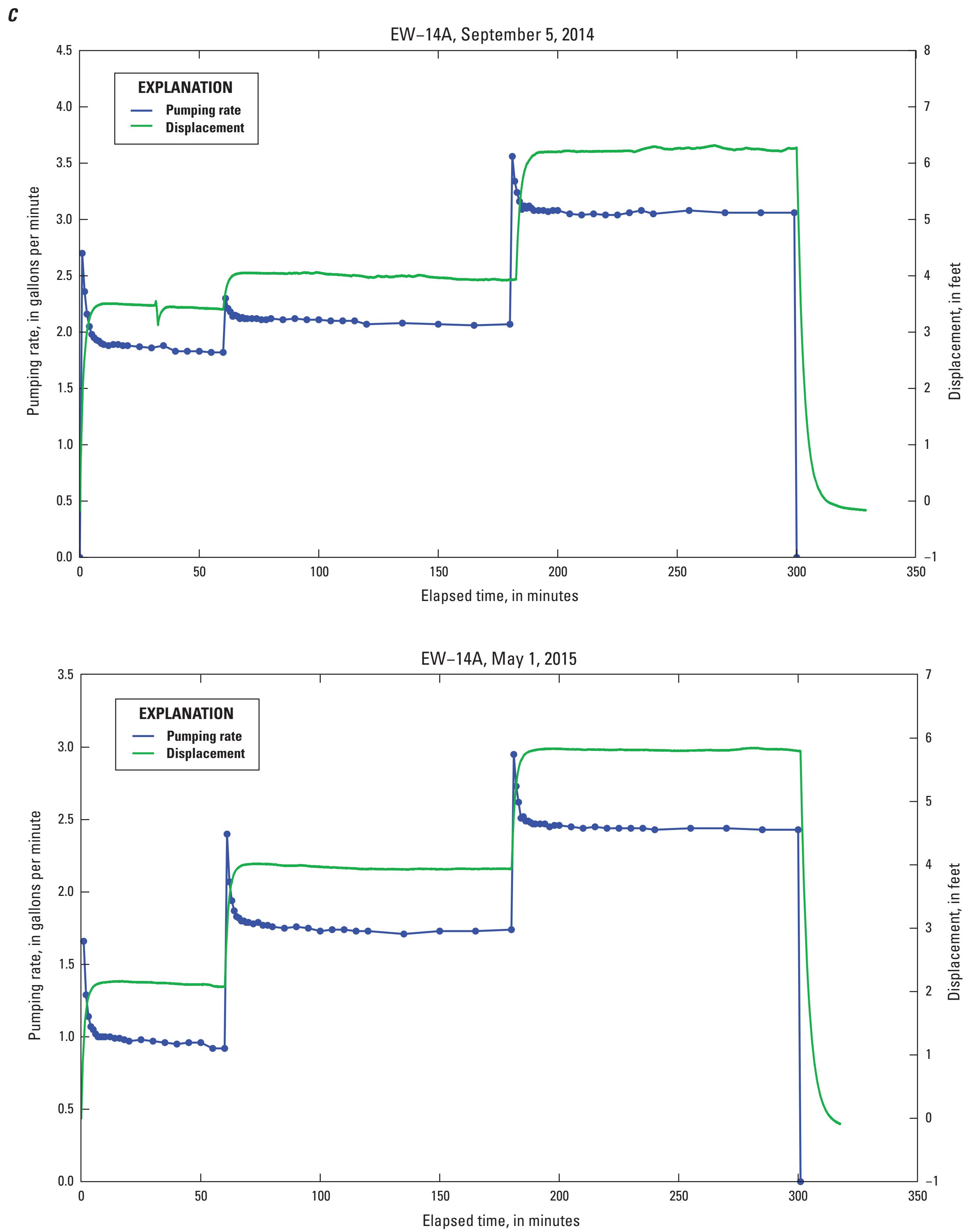


Figure 9. Pumping rate and drawdown recorded during the single well aquifer tests for *A*, extraction well EW–4B; *B*, extraction well EW–11C; and *C*, extraction well EW–14A during the 2014 and 2015 testing periods.—Continued

During the length of the test, climatic conditions were recorded with a weather station located on the CDF property (fig. 2). Barometric pressure and precipitation recorded during both testing periods are shown in figure 10. Background water levels were monitored in a monitoring well approximately 4 miles southeast of the CDF installed in the Calumet aquifer (fig. 11; Lake 13, USGS 413559087270301). Because there were no appreciable trends in pretest water levels, due to pumping recovery or barometric pressure, no corrections were applied to the single-well aquifer test data before analysis.

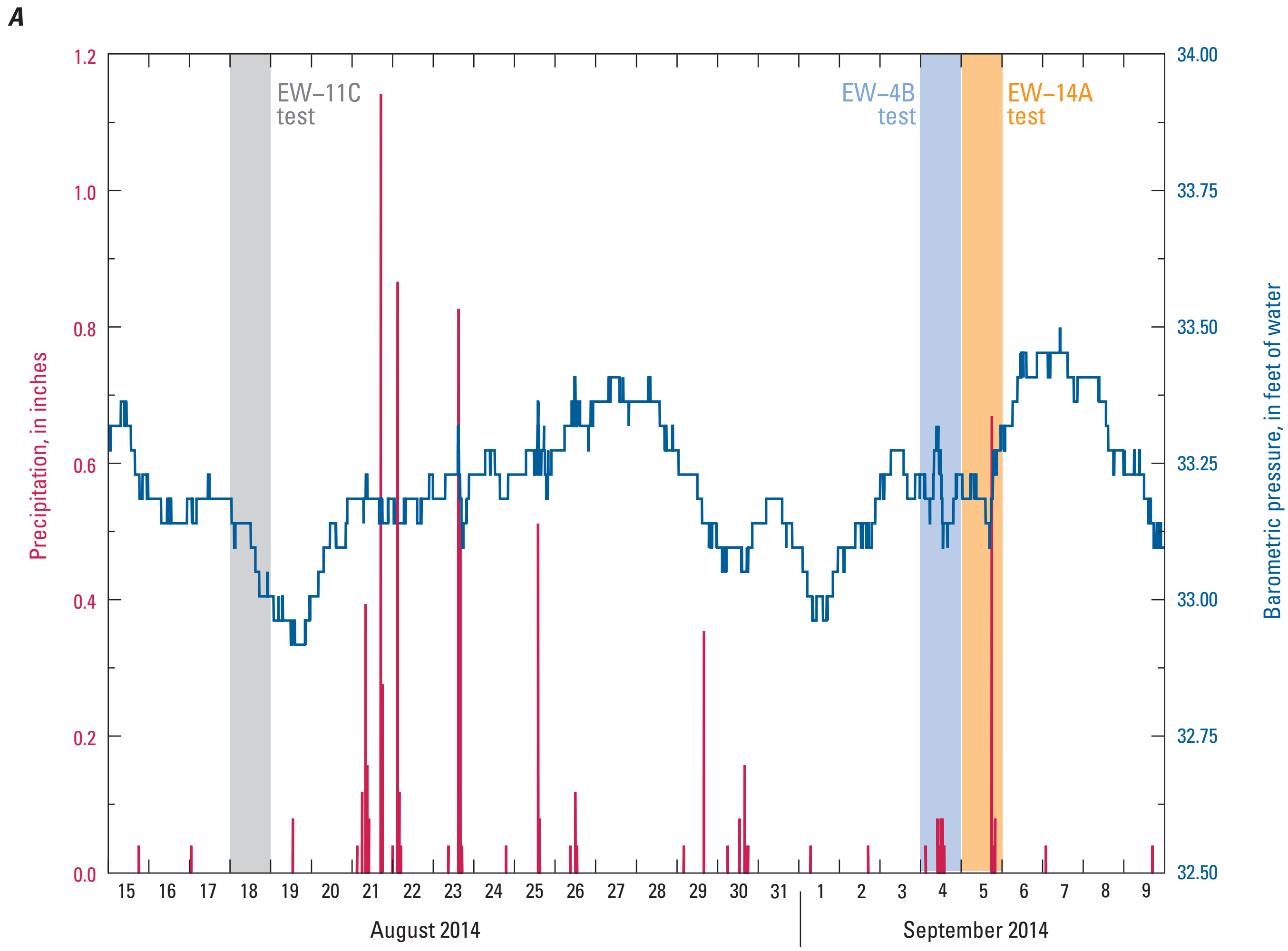


Figure 10. Barometric pressure and precipitation recorded from U.S. Geological Survey (USGS) weather station USGS 413853087290401 from *A*, August 15 to September 10, 2014 and *B*, March 15 to March 30, 2015, and April 20 to May 5, 2015. Location of weather station shown on figure 2.

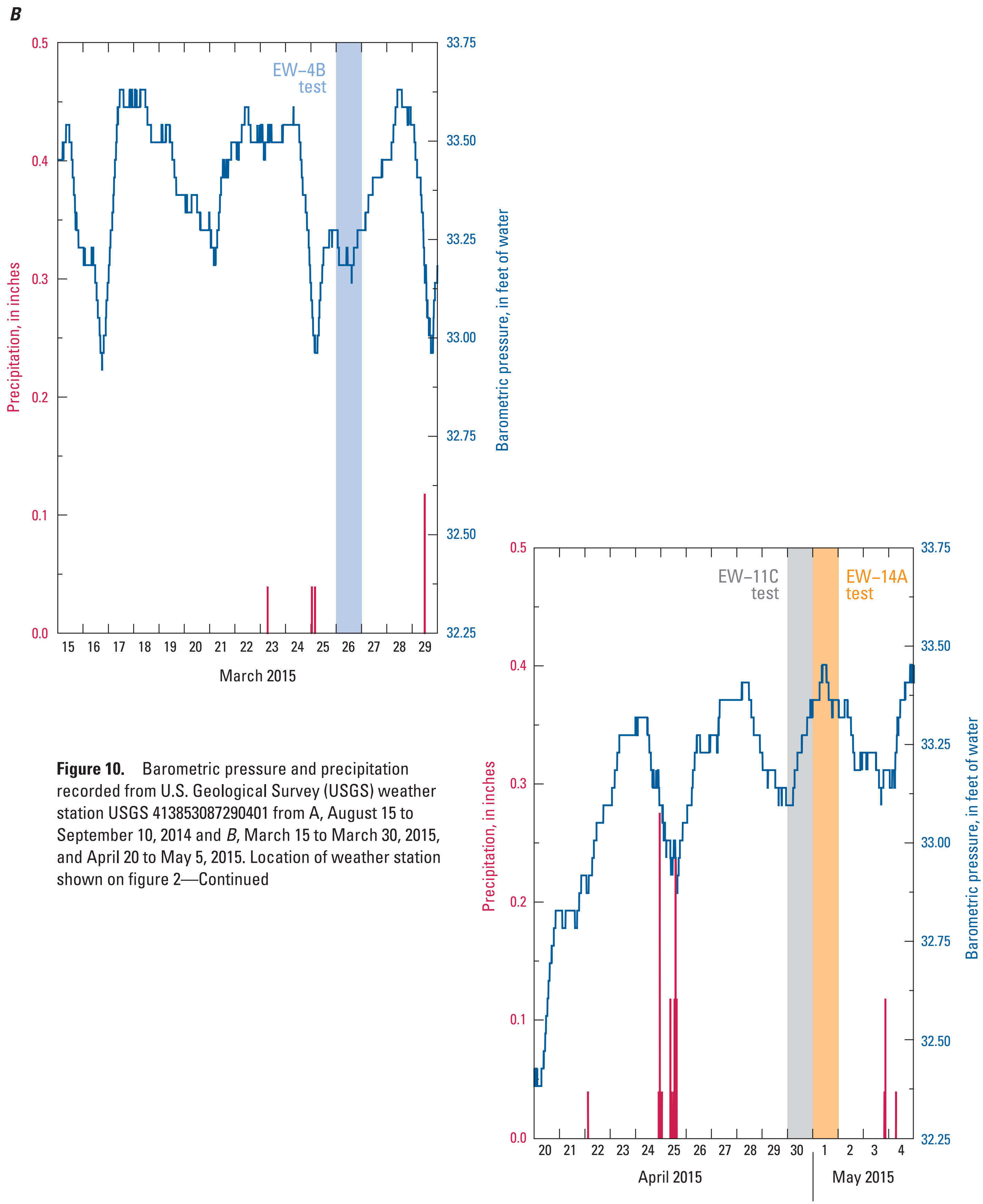


Figure 10. Barometric pressure and precipitation recorded from U.S. Geological Survey (USGS) weather station USGS 413853087290401 from A, August 15 to September 10, 2014 and *B*, March 15 to March 30, 2015, and April 20 to May 5, 2015. Location of weather station shown on figure 2—Continued

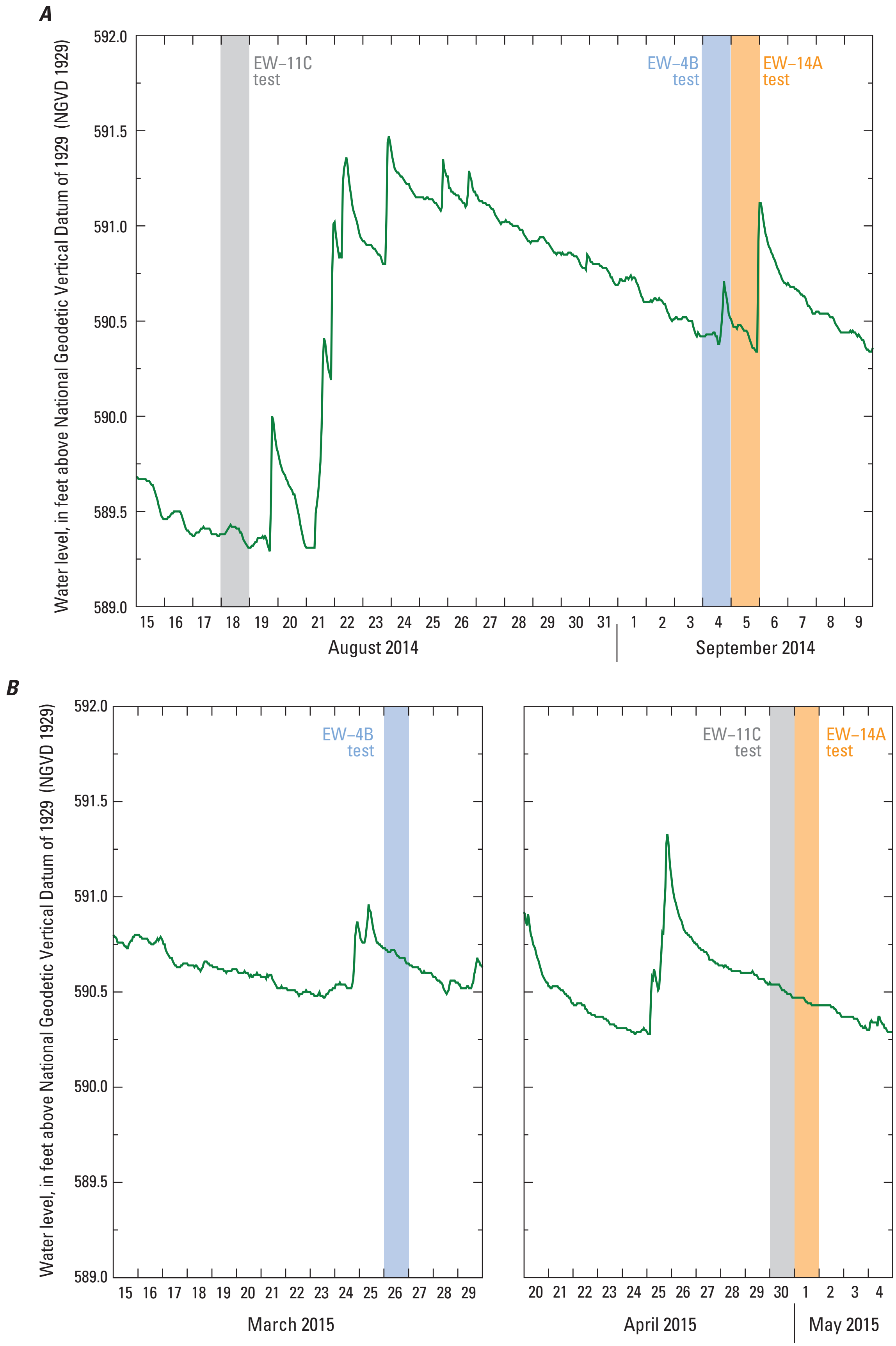


Figure 11. Water-level hydrographs for U.S. Geological Survey (USGS) Well Lake 13 (USGS 413559087270301) for the period of data collection during *A*, August–September 2014 and *B,* March–May 2015. Location of well shown on figure 1.

Step drawdown data collected during the single well aquifer testing completed in 2014 were analyzed with a modified version of the Dougherty and Babu (1984) method available for use in the AQTESOLV software package (Hydrosolve, Inc., 2007). Even though the Dougherty and Babu (1984) method was developed for use in estimating conditions in a confined aquifer setting, its use is generally accepted for unconfined conditions when drawdown during the test does not exceed approximately 30 percent of the saturated aquifer thickness (Sheets and others, 2015). The solution also accommodates the calculation of a wellbore skin factor (S_w), resulting from a zone of altered permeability near the wellbore, that can be used to account for the difference between measured and predicted responses in a pumping well (Hydrosolve, Inc., 2007). A positive skin factor indicates the interface between the aquifer and the wellbore is damaged, which may be a result of a zone of mud infiltration from drilling, bridging of screen opening, or occlusion from mineral precipitation or microbial growth.

Data collected in 2015 during each single well aquifer test were analyzed using the values of hydraulic conductivity derived during the analysis of the 2014 data. The hydraulic conductivity value derived from the 2014 period of data collection was multiplied by the saturated thickness of the surficial aquifer measured in 2015 to determine the transmissivity of the aquifer in 2015. The Dougherty and Babu (1984) solution was fit by varying the value of the skin factor parameter with the other parameter values including the calculated transmissivity held constant until a satisfactory fit was made. The percent change in skin factor from the analysis completed in 2014 to the analysis in 2015 was calculated.

The skin factor derived from the Dougherty and Babu (1984) method was used to calculate the hydraulic conductivity of the wellbore skin for each well by following the methods of Moench (1997) and using the following equation:

$$S_w = \frac{K_r * d_s}{K_s * r_w} \tag{1}$$

where

S_w is the skin factor,
K_r is the hydraulic conductivity of the aquifer in feet per day,
K_s is the hydraulic conductivity of the wellbore skin in feet per day,
d_s is the skin thickness in feet, and
r_w is the radius of the well in feet.
A 1-ft skin thickness was assumed for all wells.

Higher skin factor values represent conditions with a larger difference between the hydraulic conductivity of the aquifer and the wellbore skin. Lower skin factor values represent conditions with a smaller difference between the hydraulic conductivity of the aquifer and the wellbore skin.

Attempts were made to calculate well losses and efficiencies as outlined by Kruseman and deRidder (1990); however, it was determined that the Daugherty and Babu solution was insensitive to the parameters necessary to calculate them. Kawecki (1995) also suggests that comparison of well efficiency values between nearby wells of similar construction can be misleading due to minor changes in the aquifer materials surrounding each well. Efficiency, if available, can be used to compare the performance of one well at different times, but the same comparison can be made using multiple values of hydraulic properties like specific capacity for individual wells.

Data collected during the period of recovery following the cessation of pumping for each well was analyzed with the Moench (1997) method by using the AQTESOLV software package (Hydrosolve, Inc., 2007). The Moench (1997) solution also includes the calculation of a wellbore skin factor. The recovery data collected during the 2015 testing period was analyzed using a transmissivity calculated with the derived hydraulic conductivity from the 2014 recovery tests and the saturated thickness of the aquifer measured in 2015. The Moench (1997) solution was fit by varying the value of the skin factor parameter with the other parameter values, including the calculated transmissivity, which was held constant until a satisfactory fit was made. The Moench (1997) solution was used to acquire an independent estimate of both the transmissivity and skin effect following the guidance of Kawecki (1995), who observed that transmissivity values are less accurate when estimated from pumping datasets than those estimated from recovery datasets due to the ability to collect more accurate water-level data during periods of recovery.

Specific-Capacity Estimation

Specific-capacity values can be used to quantify the productivity of a well and compare its productivity through time (Freeze and Cherry, 1979; Kawecki, 1995). Specific capacity data were calculated for a subset of extraction wells from well discharge, duration of pumping, and water-level drawdown records from three different datasets: (1) data collected during well development following well installation in 2008 (U.S. Army Corps of Engineers, written commun., 2014); (2) data collected during water quality sampling in September–November, 2014; (3) and data collected during the first step of the step drawdown testing. Specific capacity was calculated using the following equation:

$$S_c = \frac{Q}{\left(h_o - h\right)} \tag{2}$$

where

S_c is the specific capacity in gallons per minute per foot of drawdown,
Q is the pumping rate in gallons per minute (calculated from the total volume discharged and the period of pumping), and
$h_o – h$ is the drawdown of the water level of the well during the period of pumping in feet.

Results of Performance Evaluation Testing of Wells in the Gradient Control System

Results of the performance evaluation testing of wells in the gradient control system at the CDF are presented as hydrologic parameters from single well slug tests and aquifer tests. Differences between successive test results at individual wells are used to infer whether well conditions and hydraulic connection with the aquifer varied between tests. Test results specifically include the following:

1. Hydraulic conductivity (K_r) estimates derived using data collected from single well air slug tests at monitoring wells MW–4A, MW–4B, MW–11A, MW–11B, MW–14A, MW–14B, and USGS Well D40 during two rounds of testing in August–September 2014, and March–May 2015;

2. Transmissivity (T), hydraulic conductivity of the Calumet Aquifer (K_r), skin factor (S_w), and hydraulic conductivity of the well skin (K_s) estimates derived by using the results of single well aquifer testing at extraction wells EW–4B, EW–11C, and EW–14A during two rounds of testing in August–September 2014, and March–May 2015; and

3. Specific capacity derived by using data from well development following extraction well installation in 2008 and data collected during the single well aquifer testing portion of this study in 2014 and 2015.

Single Well Air Slug Tests

Derived hydraulic conductivity values for each monitoring well with air slug tests performed in 2014 and 2015 are provided in table 2. The location of each monitoring well on the CDF property and its relative position to the groundwater cutoff wall can be determined from figures 2 and 3. Monitoring wells with names ending with the letter "A" are located within the groundwater cutoff wall (for example, MW–4A). Monitoring wells with names ending with the letter "B" are located outside of the groundwater cutoff wall (for example, MW–4B). The location of monitoring well D40 is provided on figure 1. Air slug test field log sheets and graphs showing model fit to collected data for all air slug tests are provided in appendix 1. Multiple air slug tests were performed on each well during two testing periods. A minimum of four tests were performed for each well during the first testing period in August–September 2014, and a minimum of three tests were performed for each monitoring well during the second testing period in March–May 2015.

Derived hydraulic conductivity values for monitoring wells D40, MW–4A, MW–4B, and MW–14B are approaching or within the range of values measured by Kay and others (1996) in monitoring wells completed in the Calumet aquifer in northwest Indiana and northeast Illinois. Hydraulic conductivity values for monitoring wells MW–11A, MW–11B, and MW–14A are less than those measured in previous investigations in the area.

The analysis of the slug test data indicate that, for monitoring wells on the CDF, the hydraulic connection of the well screen to the surrounding aquifer material and the reliability of hydraulic conductivity estimates of the surrounding geologic media could be increased by implementing well development maintenance similar to that provided by air slug testing. Plots of hydraulic conductivity values derived from successive air slug tests for each monitoring well are provided in figure 12. Slug test results for each well located on the CDF property indicate a low conductivity skin is present in each well (Butler, 1998) and that with each test in a given well the well became progressively more developed. The hydraulic connection between the well and the aquifer was apparently increased by the surging of water through the well screen during the pressurization and depressurization of the well casing. Results of repeated tests indicated increasing hydraulic conductivity until, in the case of the monitoring wells located outside of the groundwater cutoff wall (MW–4B, MW–11B, MW–14B), the difference in hydraulic conductivity from test to test decreases, indicating the results are approaching the optimal hydraulic connection between the aquifer and the well screen. The derived values of hydraulic conductivity from test to test in the monitoring wells within the groundwater cutoff wall continue to increase during each testing period. This result indicates improvement in the hydraulic connection of water levels in the monitoring wells with those in the aquifer between each test. These results indicate that the hydraulic connection of water levels in other monitoring wells at the CDF with those in the aquifer is also likely to benefit from well development similar to air slug testing. Well development that resulted from successive air slug tests appeared to diminish or remove low conductivity wellbore skins that affected the connection of the well screen to the surrounding aquifer material in the tested wells. One test for monitoring well MW–4B, two tests for MW–11B and one test for MW–14A were abandoned due to equipment issues during data collection.

Results from successive air slug tests of well D40 representing off-site aquifer conditions indicate that the well was not impacted by a low conductivity skin and that the derived values of hydraulic conductivity represent the lower bound on the hydraulic conductivity of the Calumet aquifer in the vicinity of the well. Hydraulic conductivity values derived from successive tests performed in monitoring well D40 were substantially higher than those derived for wells on the CDF property and similar to those reported by Kay and others (1996). Hydraulic conductivity values did not vary from test to test like those measured in monitoring wells located on the CDF property. Monitoring well D40 is installed in a shallower part of the Calumet aquifer than any of the extraction or observations wells on the CDF property.

Table 2. Horizontal hydraulic conductivity of the Calumet aquifer from multiple air slug tests at six monitoring wells on the Confined Disposal Facility and one U.S. Geological Survey monitoring well located 0.25 miles south of the Confined Disposal Facility in August–September 2014 and March–May 2015.

[All tests used water levels in the recovery phase (rising water levels) of the air slug test. USGS, U.S. Geological Survey; ft/d, foot per day; NA, not applicable]

USGS site identifier	Well name	Date	Time	Test number	Test	Solution	Pretest static water level, in feet below measuring point	Hydraulic conductivity of aquifer (K_r), in ft/d
USGS 413908087291901	MW–4A	09/03/2014	15:33	1	Air slug	Bouwer and Rice (1976)	14.45	1.11
		09/03/2014	15:58	2	Air slug	Bouwer and Rice (1976)	14.41	1.44
		09/03/2014	16:15	3	Air slug	Bouwer and Rice (1976)	14.15	1.53
		09/03/2014	16:30	4	Air slug	Bouwer and Rice (1976)	14.11	1.62
		09/03/2014	16:43	5	Air slug	Bouwer and Rice (1976)	14.08	1.86
		09/03/2014	16:59	6	Air slug	Bouwer and Rice (1976)	14.05	1.89
		03/24/2015	12:02	1	Air slug	Bouwer and Rice (1976)	15.06	1.67
		03/24/2015	12:24	2	Air slug	Bouwer and Rice (1976)	15.25	1.49
		03/24/2015	12:59	3	Air slug	Bouwer and Rice (1976)	15.35	1.75
		03/24/2015	13:28	4	Air slug	Bouwer and Rice (1976)	15.38	1.92
		03/24/2015	13:47	5	Air slug	Bouwer and Rice (1976)	15.39	1.96
		03/24/2015	14:50	6	Air slug	Bouwer and Rice (1976)	15.42	2.12
		03/24/2015	15:05	7	Air slug	Bouwer and Rice (1976)	15.43	2.24
		03/24/2015	15:20	8	Air slug	Bouwer and Rice (1976)	15.43	2.49
		03/24/2015	15:33	9	Air slug	Bouwer and Rice (1976)	15.43	2.53
		03/24/2015	15:46	10	Air slug	Bouwer and Rice (1976)	15.44	2.48
USGS 413908087291902	MW–4B	09/04/2014	09:07	1	Air slug	Bouwer and Rice (1976)	9.41	2.23
		09/04/2014	09:37	2	Air slug	Bouwer and Rice (1976)	9.41	2.52
		09/04/2014	09:58	3	Air slug	Bouwer and Rice (1976)	9.41	2.92
		09/04/2014	10:20	4	Air slug	Bouwer and Rice (1976)	9.42	3.49
		09/04/2014	10:42	5	Air slug	Bouwer and Rice (1976)	9.39	3.72
		09/04/2014	10:58	6	Air slug	Bouwer and Rice (1976)	9.37	3.94
		09/04/2014	11:16	7	Air slug	Bouwer and Rice (1976)	9.38	4.21
		09/04/2014	11:41	8	Air slug	Bouwer and Rice (1976)	9.39	4.55
		03/24/2015	14:22	1	Air slug	Bouwer and Rice (1976)	9.86	4.73
		03/24/2015	14:40	2	Air slug	Bouwer and Rice (1976)	9.85	4.46
		03/24/2015	14:56	3	Air slug	Bouwer and Rice (1976)	9.85	4.77
		03/24/2015	15:11	4	Air slug	Bouwer and Rice (1976)	9.84	4.80
		03/24/2015	15:26	5	Air slug	Bouwer and Rice (1976)	9.82	4.69
		03/24/2015	15:41	6	Air slug	Bouwer and Rice (1976)	9.81	4.79
		03/24/2015	15:53	7	Air slug	Bouwer and Rice (1976)	9.81	5.01
USGS 413921087290101	MW–11A	09/03/2014	12:02	1	Air slug	Bouwer and Rice (1976)	11.40	0.78
		09/03/2014	12:24	2	Air slug	Bouwer and Rice (1976)	14.39	1.08
		09/03/2014	12:42	3	Air slug	Bouwer and Rice (1976)	14.35	1.22
		09/03/2014	12:59	4	Air slug	Bouwer and Rice (1976)	14.33	1.30
		09/03/2014	13:15	5	Air slug	Bouwer and Rice (1976)	14.31	1.42
		09/03/2014	13:30	6	Air slug	Bouwer and Rice (1976)	14.30	1.47
		09/03/2014	13:46	7	Air slug	Bouwer and Rice (1976)	14.28	1.54

Table 2. Horizontal hydraulic conductivity of the Calumet aquifer from multiple air slug tests at six monitoring wells on the Confined Disposal Facility and one U.S. Geological Survey monitoring well located 0.25 miles south of the Confined Disposal Facility in August–September 2014 and March–May 2015.—Continued

[All tests used water levels in the recovery phase (rising water levels) of the air slug test. USGS, U.S. Geological Survey; ft/d, foot per day; NA, not applicable]

USGS site identifier	Well name	Date	Time	Test number	Test	Solution	Pretest static water level, in feet below measuring point	Hydraulic conductivity of aquifer (K_r), in ft/d
USGS 413921087290101 (continued)	MW–11A	03/26/2015	10:17	1	Air slug	Bouwer and Rice (1976)	14.35	0.025
		03/26/2015	12:01	2	Air slug	Bouwer and Rice (1976)	14.75	0.173
		03/26/2015	13:27	3	Air slug	Bouwer and Rice (1976)	14.75	0.261
USGS 413921087290102	MW–11B	08/20/2014	14:47	1	Air slug	Bouwer and Rice (1976)	9.56	0.25
		08/20/2014	15:31	2	Air slug	Bouwer and Rice (1976)	9.56	0.35
		09/04/2014	13:11	1	Air slug	Bouwer and Rice (1976)	9.29	0.41
		09/04/2014	14:03	2	Air slug	Bouwer and Rice (1976)	8.97	0.40
		09/04/2014	14:39	3	Air slug	Bouwer and Rice (1976)	8.98	0.49
		09/04/2014	15:05	4	Air slug	Bouwer and Rice (1976)	8.96	0.50
		09/04/2014	15:33	5	Air slug	Bouwer and Rice (1976)	8.95	0.53
		03/26/2015	10:25	1	NA	Test aborted	9.34	NA
		03/26/2015	10:34	2	NA	Test aborted	9.29	NA
		03/26/2015	11:00	3	Air slug	Bouwer and Rice (1976)	9.34	0.46
		03/26/2015	11:23	4	Air slug	Bouwer and Rice (1976)	9.27	0.56
		03/26/2015	11:54	5	Air slug	Bouwer and Rice (1976)	9.20	0.42
		03/26/2015	12:25	6	Air slug	Bouwer and Rice (1976)	9.20	0.49
		03/26/2015	12:59	7	Air slug	Bouwer and Rice (1976)	9.19	0.63
		03/26/2015	13:33	8	Air slug	Bouwer and Rice (1976)	9.18	0.64
		03/26/2015	14:01	9	Air slug	Bouwer and Rice (1976)	9.18	0.64
		03/26/2015	14:38	10	Air slug	Bouwer and Rice (1976)	9.18	0.66
		03/26/2015	15:08	11	Air slug	Bouwer and Rice (1976)	9.16	0.68
USGS 413909087285301	MW–14A	08/19/2014	11:33	1	Air slug	Bouwer and Rice (1976)	11.77	0.41
		08/19/2014	13:38	2	Air slug	Bouwer and Rice (1976)	11.70	0.49
		08/19/2014	15:07	3	Air slug	Bouwer and Rice (1976)	11.58	0.53
		08/20/2014	09:45	4	Air slug	Bouwer and Rice (1976)	11.52	0.63
		08/20/2014	10:45	5	Air slug	Bouwer and Rice (1976)	11.46	0.63
		03/25/2015	10:44	1	Air slug	Test aborted	11.92	NA
		03/25/2015	10:56	2	Air slug	Bouwer and Rice (1976)	13.01	0.07
		03/25/2015	12:00	3	Air slug	Bouwer and Rice (1976)	13.22	0.22
		03/25/2015	13:48	4	Air slug	Bouwer and Rice (1976)	13.11	0.19
USGS 413909087285302	MW–14B	08/20/2014	11:35	1	Air slug	Bouwer and Rice (1976)	9.73	1.77
		08/20/2014	12:09	2	Air slug	Bouwer and Rice (1976)	9.75	2.06
		08/20/2014	12:30	3	Air slug	Bouwer and Rice (1976)	9.75	2.32
		08/20/2014	12:47	4	Air slug	Bouwer and Rice (1976)	9.75	2.50
		08/20/2014	13:08	5	Air slug	Bouwer and Rice (1976)	9.74	2.83
		03/25/2015	10:28	1	Air slug	Bouwer and Rice (1976)	9.91	2.82
		03/25/2015	11:03	2	Air slug	Bouwer and Rice (1976)	10.07	3.81
		03/25/2015	11:17	3	Air slug	Bouwer and Rice (1976)	10.09	4.22
		03/25/2015	11:35	4	Air slug	Bouwer and Rice (1976)	10.08	4.22

Table 2. Horizontal hydraulic conductivity of the Calumet aquifer from multiple air slug tests at six monitoring wells on the Confined Disposal Facility and one U.S. Geological Survey monitoring well located 0.25 miles south of the Confined Disposal Facility in August–September 2014 and March–May 2015.—Continued

[All tests used water levels in the recovery phase (rising water levels) of the air slug test. USGS, U.S. Geological Survey; ft/d, foot per day; NA, not applicable]

USGS site identifier	Well name	Date	Time	Test number	Test	Solution	Pretest static water level, in feet below measuring point	Hydraulic conductivity of aquifer (K_r), in ft/d
USGS 413909087285302 (continued)	MW–14B	03/25/2015	12:02	5	Air slug	Bouwer and Rice (1976)	10.10	4.14
		03/25/2015	12:21	6	Air slug	Bouwer and Rice (1976)	10.11	4.10
		03/25/2015	12:49	7	Air slug	Bouwer and Rice (1976)	10.08	4.14
		03/25/2015	13:12	8	Air slug	Bouwer and Rice (1976)	10.09	4.20
		03/25/2015	13:30	9	Air slug	Bouwer and Rice (1976)	10.09	4.44
		03/25/2015	13:47	10	Air slug	Bouwer and Rice (1976)	10.09	4.61
USGS 413835087245101	D40	09/01/2014	16:44	1	Air slug	Bouwer and Rice (1976)	7.68	21.45
		09/01/2014	16:51	2	Air slug	Bouwer and Rice (1976)	7.68	20.81
		09/01/2014	16:59	3	Air slug	Bouwer and Rice (1976)	7.68	20.60
		09/01/2014	17:07	4	Air slug	Bouwer and Rice (1976)	7.68	21.37
		04/29/2015	15:11	1	Air slug	Bouwer and Rice (1976)	5.87	16.76
		04/29/2015	15:14	2	Air slug	Bouwer and Rice (1976)	5.87	16.57
		04/29/2015	15:17	3	Air slug	Bouwer and Rice (1976)	5.87	17.61
		04/29/2015	15:20	4	Air slug	Bouwer and Rice (1976)	5.87	17.32
		04/29/2015	15:24	5	Air slug	Bouwer and Rice (1976)	5.87	17.06
		04/29/2015	15:26	6	Air slug	Bouwer and Rice (1976)	5.87	17.79
		04/29/2015	15:29	7	Air slug	Bouwer and Rice (1976)	5.87	16.70
		04/29/2015	15:32	8	Air slug	Bouwer and Rice (1976)	5.87	17.10
		04/29/2015	15:35	9	Air slug	Bouwer and Rice (1976)	5.87	17.74
		04/29/2015	15:38	10	Air slug	Bouwer and Rice (1976)	5.87	17.46

Derived hydraulic conductivity values from the first air slug test of the 2015 testing period for MW–11A and MW–14A were an order of magnitude less than those derived from the final test from the 2014 testing period (figures 12*C* and 12*E*). These results indicate the development of a low conductivity skin between the well and aquifer after the final test of the 2014 testing period and before the beginning of the 2015 testing period. All three monitoring wells that were inside the groundwater cutoff wall were pumped and sampled during four rounds of water-quality sampling performed by USGS personnel for a different scope of this investigation that was after the 2014 air slug testing period and before the beginning of the 2015 testing period. Specific-capacity values calculated from the well purging notes taken during the four rounds of water quality sampling are similar during all four periods of sampling, indicating there was no gradual decrease in well performance during the rounds of water-quality sampling. The low conductivity skin created a condition that decreased the connection of the monitoring well screen to the surrounding aquifer material. The low conductivity skin could be due to well screen clogging or a clogging of the filter pack material that surrounds the well screen itself. The monitoring wells on the CDF property were otherwise used for water-level recording proposes only and no well development or periodic maintenance was performed on the wells between testing periods (Scott Peterson, O'Brien and Gere, oral commun., 2015).

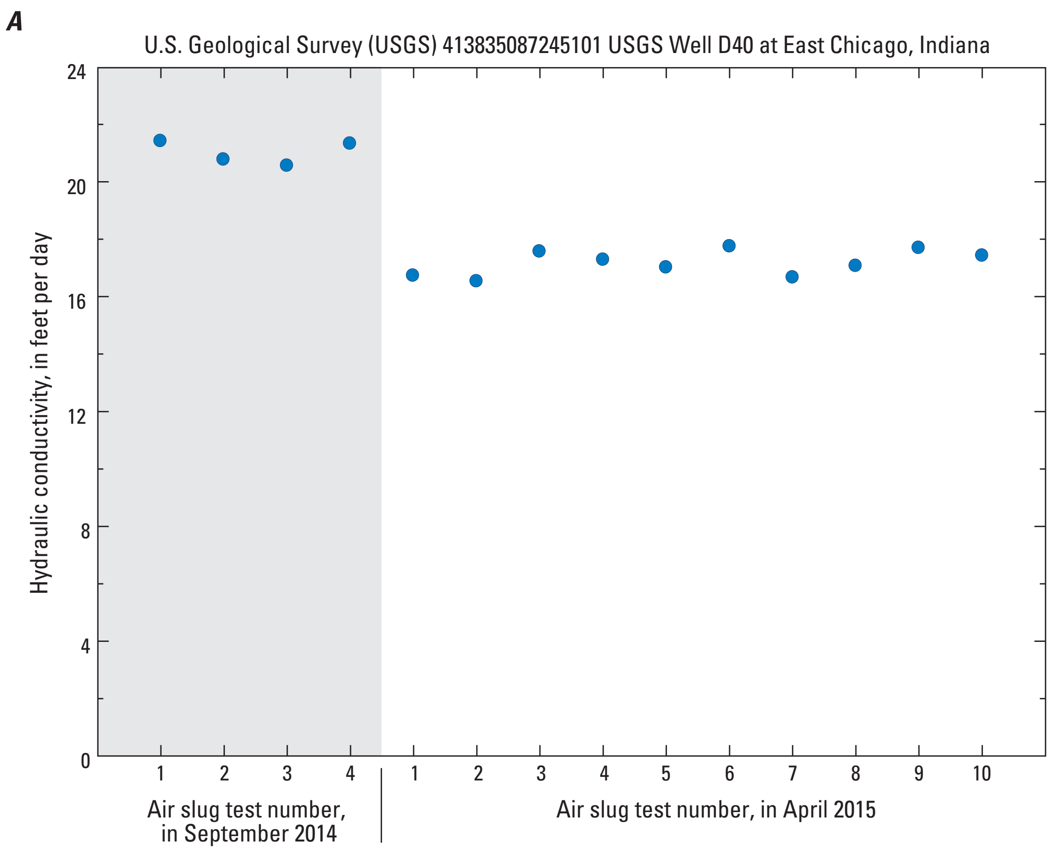
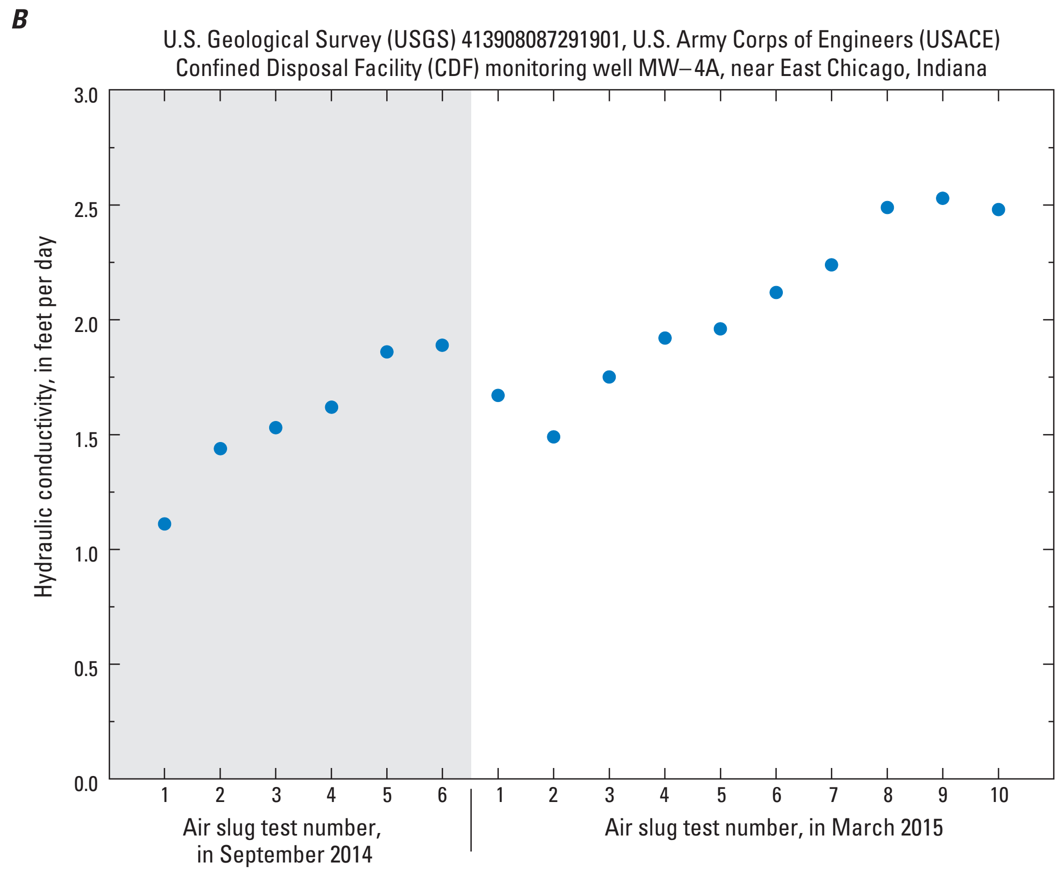


Figure 12. Hydraulic conductivity calculated from successive air slug testing for *A*, U.S. Geological Survey monitoring well D40 located approximately 0.25 mile south of the Confined Disposal Facility (CDF) property, and monitoring wells, *B*, MW–4A, *C*, MW–4B, *D*, MW–11A, *E*, MW–11B, *F*, MW–14A and *G*, MW–14B located on the property of the CDF in East Chicago, Indiana.



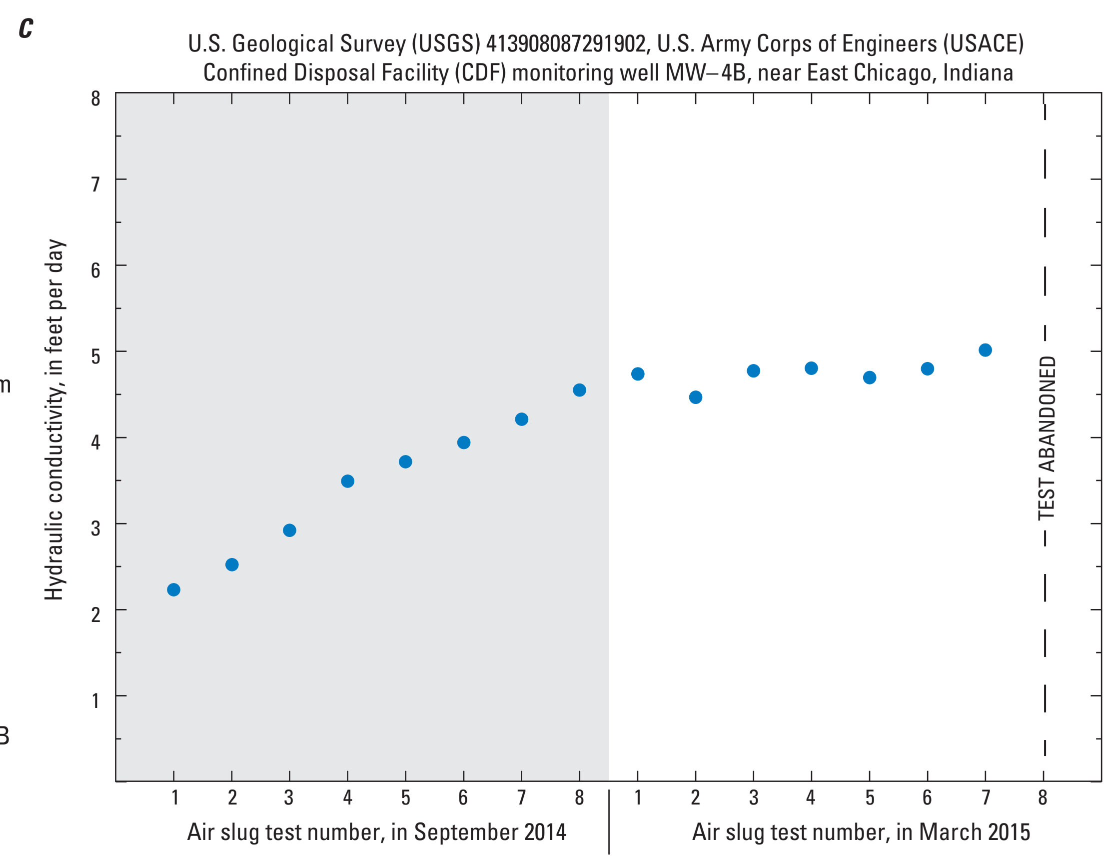
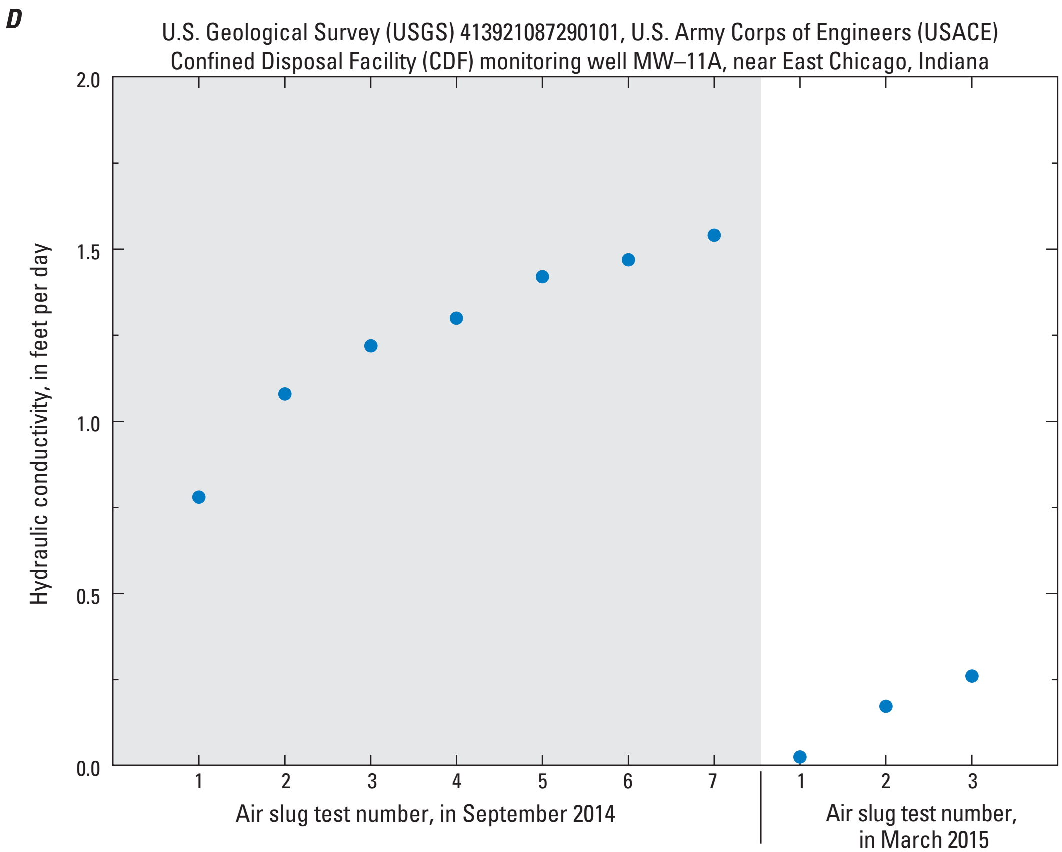


Figure 12. Hydraulic conductivity calculated from successive air slug testing for *A*, U.S. Geological Survey monitoring well D40 located approximately 0.25 mile south of the Confined Disposal Facility (CDF) property, and monitoring wells, *B*, MW–4A, *C*, MW–4B, *D*, MW–11A, *E*, MW–11B, *F*, MW–14A and *G*, MW–14B located on the property of the CDF in East Chicago, Indiana.—Continued



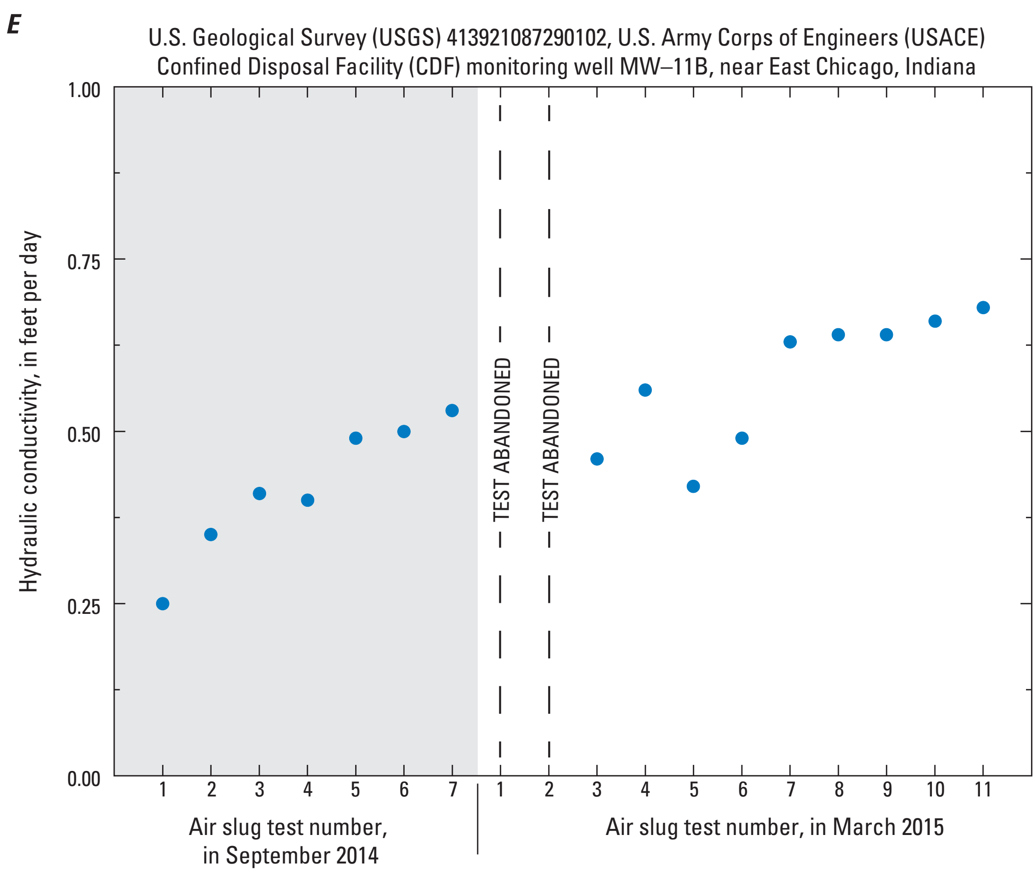


Figure 12. Hydraulic conductivity calculated from successive air slug testing for *A*, U.S. Geological Survey monitoring well D40 located approximately 0.25 mile south of the Confined Disposal Facility (CDF) property, and monitoring wells, *B*, MW–4A, *C*, MW–4B, *D*, MW–11A, *E*, MW–11B, *F*, MW–14A and *G*, MW–14B located on the property of the CDF in East Chicago, Indiana.—Continued

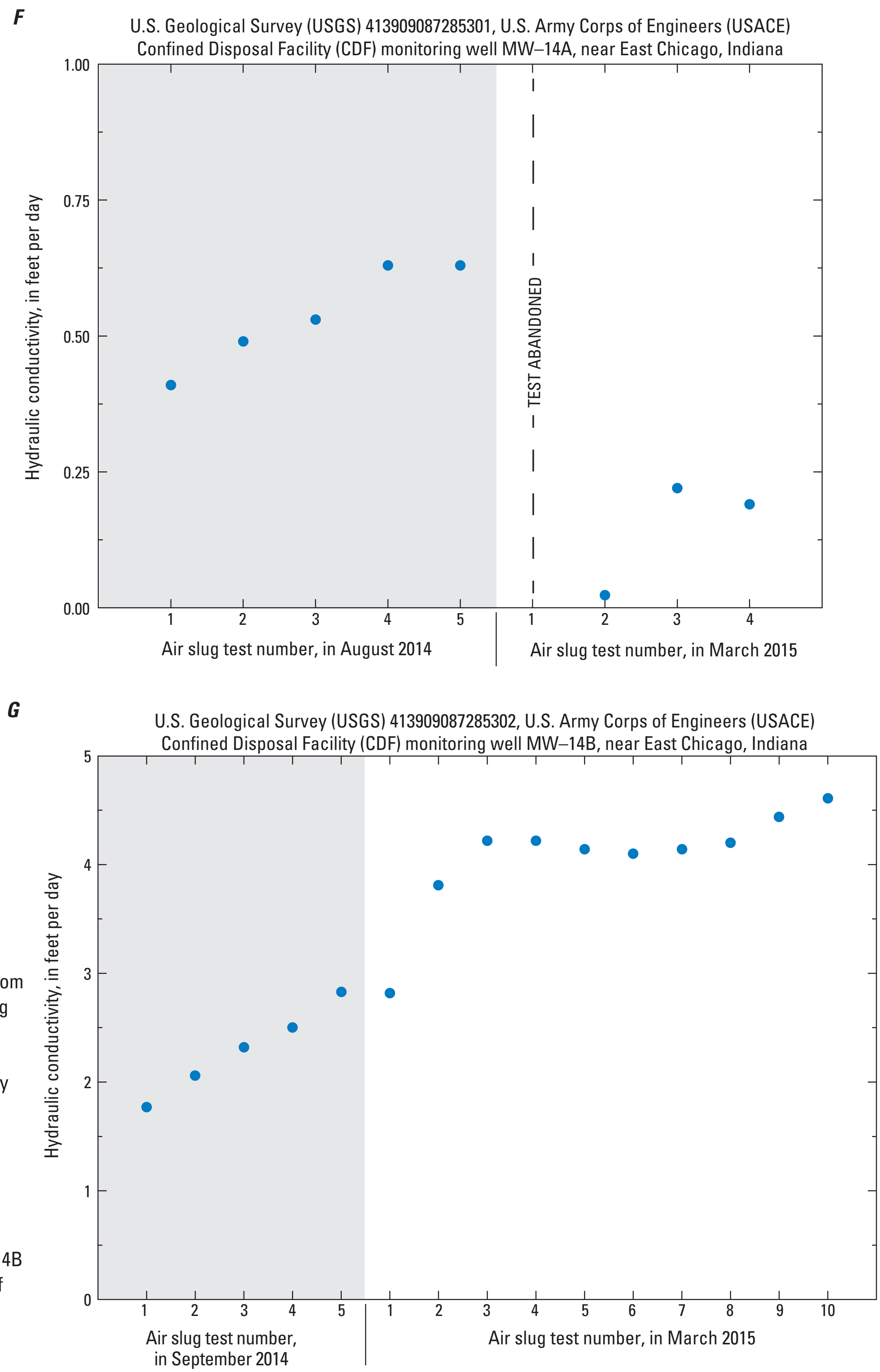


Figure 12. Hydraulic conductivity calculated from successive air slug testing for *A*, U.S. Geological Survey monitoring well D40 located approximately 0.25 mile south of the Confined Disposal Facility (CDF) property, and monitoring wells, *B*, MW–4A, *C*, MW–4B, *D*, MW–11A, *E*, MW–11B, *F*, MW–14A and *G*, MW–14B located on the property of the CDF in East Chicago, Indiana.—Continued

Single Well Aquifer Testing

Derived transmissivity and hydraulic conductivity values for the Calumet aquifer, the skin factor and hydraulic conductivity of the well skin for each well, and the parameter values used for each AQTESOLV calculation for data collected in 2014 and 2015 are provided in table 3. Aquifer test field log sheets and graphs showing model fit to collected data for all step drawdown and recovery tests are provided in appendix 2. Transmissivity, hydraulic conductivity, and skin factor values in table 3 have been rounded to two significant figures. Raw values calculated with the analytic solutions are provided on the plots in appendix 2.

Extraction Well EW–4B

The transmissivity value for extraction well EW–4B derived from data collected in September 2014 was 1,500 feet squared per day (ft^2/d) for the step drawdown and recovery tests (table 3). The hydraulic conductivity value was 62 ft/d. A skin factor of 20 was calculated for both the step drawdown and recovery tests and was used to estimate the hydraulic conductivity value of the skin as 12 ft/d (approximately 20 percent of the estimated aquifer hydraulic conductivity). The solution was insensitive to the value of the storage coefficient, so changes in its value did not change transmissivity estimates, and a value of 0.1 was used.

The step drawdown and recovery test results indicated a slight decrease in productivity of extraction well EW–4B between the 2014 and 2015 tests, slightly diminishing its capability to drawdown the water table inside the groundwater cutoff wall. The calculated skin factor increased slightly from the 2014 to the 2015 period of testing indicating that the hydraulic conductivity of the wellbore skin decreased by 1 ft/d (table 3). Skin factors were calculated for extraction well EW–4B using data collected during the 2015 period of testing and the hydraulic conductivity value estimated from the 2014 data. The calculated skin factor for extraction well EW–4B was 22 for the step drawdown and recovery tests, which was used to estimate the hydraulic conductivity value of the skin as 11 ft/d (approximately 20 percent of the estimated apparent aquifer hydraulic conductivity).

Extraction Well EW–11C

The procedure to calculate aquifer transmissivity and conductivity values was modified for extraction well EW–11C because the flow rates recorded during the first segment of the step drawdown test fell below the accepted rates for the impeller flow meter used during the 2014 and 2015 periods of testing. The data collected during the initial step of the step drawdown test were not analyzed. Data collected during the second and third steps of the tests were analyzed separately and results of both analyses as well as results from the recovery test are provided in table 3. Transmissivity calculated from the values for the middle step of the step drawdown tests in 2014 and 2015 were 110 ft^2/d. Transmissivity calculated from the last step of the step drawdown test and the recovery test in 2014 were higher values of 650 and 580 ft^2/d respectively in 2014 and 630 and 560 ft^2/d respectively in 2015. Similarly, hydraulic conductivity values were 5 ft/d for the middle step, and 27 and 24 ft/d from the last step of the step drawdown test and recovery test respectively. The solution was insensitive to the value of the storage coefficient, meaning changes in its value did not change transmissivity estimates, and a value of 0.1 was used.

The step drawdown and recovery test results indicated a slightly decreased but similar productivity of extraction well EW–11C between the 2014 and 2015 tests, indicating that its capability to drawdown the water table inside the groundwater cutoff wall was unchanged between the tests. Calculated skin factors increased slightly from the 2014 to the 2015 period of testing indicating that the hydraulic conductivity of the wellbore skin decreased slightly for all three tests (table 3). A calculated skin factor of 7 was used to estimate a hydraulic conductivity value of 3 ft/d for the wellbore skin for the middle step of the 2014 step drawdown test (approximately 60 percent of the estimated aquifer hydraulic conductivity). Calculated skin factors of 42 and 36 for the last step of the 2014 step drawdown test and the recovery test, respectively, were used to calculate wellbore skins of 3 ft/d (approximately 10 percent of the estimated aquifer hydraulic conductivity).

Skin factors were calculated for extraction well EW–11C using data collected during the 2015 period of testing and the hydraulic conductivity value estimated from the 2014 data. A skin factor of 8, calculated from data collected in 2015, was used to estimate a hydraulic conductivity value for the wellbore skin of 3 ft/d for the middle step of the step drawdown test (approximately 50 percent of the estimated aquifer hydraulic conductivity). The calculated skin factor of 49 and 43 for the last step of the 2015 step drawdown test and the recovery test was used to calculate wellbore skins of 2 ft/d (approximately 8 percent of the estimated aquifer hydraulic conductivity).

Extraction Well EW–14A

Two sets of transmissivity and hydraulic conductivity values were estimated using the data collected during the step drawdown and recovery test in 2014. Data collected during the first and second steps were used to calculate a transmissivity value of 1,300 ft^2/d. Values calculated from the data collected during the last step of the step drawdown test and recovery test were comparable (1,500 and 1,200 ft^2/d, respectively). Hydraulic conductivity values for the aquifer for all three solutions ranged from 49 ft/d for the recovery test to 63 ft/d for the last step of the step drawdown test. The solution was insensitive to the value of the storage coefficient, so changes in its value did not change transmissivity estimates, and a value of 0.1 was used.

Table 3. Parameters used and derived hydraulic properties of the Calumet aquifer and extraction wells from data collected in three extraction wells on the Confined Disposal Facility in August–September 2014 and March–May 2015.

[USGS, U.S. Geological Survey; ft/d, foot per day; ft^2/d, square foot per day; >, greater than; —, not applicable]

USGS site identifier	Well name	Test	Solution	Date of test	Period of data used	Pretest static water level, in feet below top of casing	Specific yield	Radius of well, in feet	Thickness of the skin (ds), in feet	Aquifer saturated thickness, in feet	Skin factor (S_w)	Transmissivity, in ft^2/d	Storativity	Hydraulic conductivity of aquifer (K_r), in ft/d	Hydraulic conductivity of skin (K_s), in ft/d
USGS 413907087291801	EW–4B														
		Step draw-down	Dougherty and Babu (1984)	09/04/2014	0–300 minutes	9.29	—	0.25	1	24.71	20	1,500	0.1	62	12
		Recovery	Moench (1997)	09/04/2014	> 300 minutes	9.29	1	0.25	1	24.71	20	1,500	0.1	62	12
		Step draw-down	Dougherty and Babu (1984)	03/26/2015	0–300 minutes	12.72	—	0.25	1	21.28	22	1,300	0.1	62	11
		Recovery	Moench (1997)	03/26/2015	> 300 minutes	12.72	1	0.25	1	21.28	22	1,300	0.1	62	11
USGS 413920087285901	EW–11C														
		Step draw-down	Dougherty and Babu (1984)	08/20/2014	60–180 minutes	9.52	—	0.25	1	24.06	7	110	0.1	5	3
		Step draw-down	Dougherty and Babu (1984)	08/20/2014	180–300 minutes	9.52	—	0.25	1	24.06	42	650	0.1	27	3
		Recovery	Moench (1997)	08/20/2014	> 300 minutes	9.52	1	0.25	1	24.06	36	580	0.1	24	3
		Step draw-down	Dougherty and Babu (1984)	04/30/2015	60–180 minutes	10.11	—	0.25	1	23.47	8	110	0.1	5	3
		Step draw-down	Dougherty and Babu (1984)	04/30/2015	180–300 minutes	10.11	—	0.25	1	23.47	49	630	0.1	27	2
		Recovery	Moench (1997)	04/30/2015	> 300 minutes	10.11	1	0.25	1	23.47	43	560	0.1	24	2
USGS 413911087285201	EW–14A														
		Step draw-down	Dougherty and Babu (1984)	09/05/2014	0–180 minutes	8.56	—	0.25	1	24.44	15	1,300	0.1	54	14
		Step draw-down	Dougherty and Babu (1984)	09/05/2014	180–300 minutes	8.56	—	0.25	1	24.44	18	1,500	0.1	63	14
		Recovery	Moench (1997)	09/05/2014	> 300 minutes	8.56	1	0.25	1	24.44	14	1,200	0.1	49	14
		Step draw-down	Dougherty and Babu (1984)	05/01/2015	0–180 minutes	9.48	—	0.25	1	23.52	18	1,300	0.1	54	12
		Step draw-down	Dougherty and Babu (1984)	05/01/2015	180–300 minutes	9.48	—	0.25	1	23.52	22	1,500	0.1	63	11
		Recovery	Moench (1997)	05/01/2015	> 300 minutes	9.48	1	0.25	1	23.52	16	1,200	0.1	49	12

The step drawdown and recovery test results indicated a slight decrease in productivity of extraction well EW–14A between the 2014 and 2015 tests, slightly diminishing its capability to drawdown the water table inside the groundwater cutoff wall. Calculated skin factors increased from the 2014 to the 2015 period of testing for all three analyses indicating that the hydraulic conductivity of the wellbore skin decreased by 2 to 3 feet per day (table 3). Calculated skin factors for all three tests in 2014 were similar and ranged from 14 for the recovery test to 18 for the last step of the step drawdown test. These values were used to calculate values for the hydraulic conductivity of the wellbore skin during the 2014 test of 14 ft/d (approximately 25 percent of the estimated aquifer hydraulic conductivity). Skin factors were calculated for extraction well EW–14A using data collected during the 2015 period of testing and the hydraulic conductivity value estimated from the 2014 data. Skin factors calculated from data collected in 2015 ranged from 16 for the recovery test to 22 for the last step of the step drawdown test. These values were used to calculate values for the hydraulic conductivity of the wellbore skin of 11 and 12 ft/d. These hydraulic conductivity values are approximately 18 to 25 percent of the estimated aquifer hydraulic conductivity.

Specific-Capacity Estimation

Specific-capacity values can be used to quantify the productivity of a well and compare its productivity through time (Freeze and Cherry, 1979; Kawecki, 1995). Specific capacity for a subset of extraction wells was calculated from well discharge, duration of pumping, and water-level drawdown records from three different datasets: (1) data collected for 77 wells during well development by a private consulting company following well installation in 2008 (table 4; fig. 13; U.S. Army Corps of Engineers, written commun., 2014), (2) data collected during USGS water quality sampling in September–November 2014 (table 5), and (3) data collected during the first step of the step drawdown testing (table 5). Values calculated from the extraction well development data in 2008 range from 0.37 (EW–11C) to 2.23 gallons per minute per foot (gal/min/ft) of drawdown (EW–16C) (table 4 and fig. 14). Values for the extraction wells in 2008 that were tested during this study were 0.37 (EW–11C), 1.04 (EW–4B), and 1.59 gal/min/ft of drawdown (EW–14A). The value calculated for EW–11C is the lowest of the total number of values on the CDF (fig. 14). The EW–4B value is between the 25th percentile and median value and the value for EW–14A is between the 75th and 90th percentiles of the total number of calculated specific-capacity values of extraction wells on the CDF.

All specific-capacity values calculated for the extraction wells tested during this study were substantially less than those computed using the initial specific capacity test data from 2008. Specific-capacity values for this study were computed using the data collected during the first step of the step drawdown testing completed in August–September 2014 and March–May 2015 (table 5). Specific capacity for EW–4B was 0.43 gal/min/ft of drawdown in September 2014 and 0.44 gal/min/ft of drawdown in March 2015; both were less than half the 2008 specific capacity test result of 1.04 gal/min/ft of drawdown. Values for EW–11C were estimated to be less than or equal to 0.09 gal/min/ft of drawdown in August 2014 and less than or equal to 0.07 gal/min/ft of drawdown in April 2015 due to the pumping rate falling below the accepted rates for the impeller used during the tests. Both specific capacity test values for EW–11C were substantially less than 2008 specific capacity test result of 0.37 gal/min/ft of drawdown. Specific capacity values for EW–14A were 0.54 gal/min/ft of drawdown in September 2014 and 0.45 gal/min/ft of drawdown in May 2015; both were less than one-third the 2008 specific capacity test result of 1.59 gal/min/ft of drawdown.

Specific-capacity values calculated for the three monitoring wells tested during this study located within the groundwater cutoff wall using well purging data collected during water quality sampling for another phase of this study are also presented in table 5. Specific-capacity values for these wells ranged from 0.12 to 0.26 gal/min/ft of drawdown for MW–4A, 0.08 to 0.43 for MW–11A, and 0.04 to 0.05 for MW–14A.

Table 4. Specific-capacity values calculated from extraction well development logs recorded following extraction well installation in 2008.

Extraction well name	Duration of pumping, in minutes	Pumping rate, in gallons per minute	Maximum displacement, in feet	Specific capacity, in gallons per minute per foot of drawdown
EW–1A	100	8.99	9.25	0.97
EW–2B	60	23.35	15.00	1.56
EW–2C	107	24.07	14.20	1.69
EW–2D	68	25.10	14.40	1.74
EW–3A	64	18.52	14.40	1.29
EW–3B	62	18.66	13.60	1.37
EW–3C	63	13.48	14.20	0.95
EW–3D	56	12.43	14.90	0.83
EW–4A	104	9.57	14.30	0.67
EW–4B	79	15.57	14.90	1.04
EW–4C	77	10.14	14.75	0.69
EW–4D	89	14.64	13.45	1.09
EW–5A	61	19.62	14.25	1.38
EW–5B	96	10.90	12.80	0.85
EW–5C	70	16.31	13.65	1.20
EW–5D	69	19.72	11.90	1.66
EW–6A	70	15.84	11.30	1.40
EW–6B	67	24.87	12.20	2.04
EW–6C	22	23.09	15.00	1.54
EW–6D	150	12.41	11.10	1.12
EW–7A	74	14.03	11.95	1.17
EW–7B	37	18.54	12.30	1.51
EW–7C	83	15.11	11.60	1.30
EW–7D	70	15.79	11.30	1.40
EW–8A	148	9.89	10.98	0.90
EW–8B	95	12.18	10.65	1.14
EW–8C	185	9.23	11.50	0.80
EW–8D	110	13.38	12.22	1.10
EW–9A	111	10.14	11.40	0.89
EW–9B	105	15.13	12.50	1.21
EW–9C	98	11.96	13.82	0.87
EW–9D	35	15.11	13.00	1.16
EW–10A	161	13.77	12.65	1.09
EW–10B	71	21.28	13.70	1.55
EW–10C	92	6.96	10.70	0.65
EW–11A	82	12.27	11.10	1.11
EW–11B	87	17.21	11.10	1.55
EW–11C	105	4.70	12.70	0.37
EW–11D	110	11.13	13.25	0.84

Table 4. Specific-capacity values calculated from extraction well development logs recorded following extraction well installation in 2008.—Continued

Extraction well name	Duration of pumping, in minutes	Pumping rate, in gallons per minute	Maximum displacement, in feet	Specific capacity, in gallons per minute per foot of drawdown
EW–12A	90	15.00	13.68	1.10
EW–12B	120	6.92	11.02	0.63
EW–12C	71	11.96	12.92	0.93
EW–12D	125	9.83	12.60	0.78
EW–13A	60	14.42	12.18	1.18
EW–13B	65	9.17	12.25	0.75
EW–13C	102	10.45	13.61	0.77
EW–13D	72	8.75	11.25	0.78
EW–14A	90	12.43	7.81	1.59
EW–14B	55	15.09	12.90	1.17
EW–14D	79	15.51	15.20	1.02
EW–15A	30	14.37	14.25	1.01
EW–15B	85	12.25	14.72	0.83
EW–15C	68	12.10	8.06	1.50
EW–15D	96	5.24	10.31	0.51
EW–16A	77	21.88	15.80	1.39
EW–16B	75	24.95	13.25	1.88
EW–16C	74	28.38	12.75	2.23
EW–16D	68	24.15	13.50	1.79
EW–17A	98	13.68	13.50	1.01
EW–17B	76	18.82	12.30	1.53
EW–17C	59	19.83	13.20	1.50
EW–17D	68	19.56	13.40	1.46
EW–18A	59	19.86	14.05	1.41
EW–18B	76	21.30	13.30	1.60
EW–18C	113	11.98	11.15	1.07
EW–18D	73	19.85	14.08	1.41
EW–19A	84	18.64	11.90	1.57
EW–19B	100	18.37	10.70	1.72
EW–19D	76	10.05	9.80	1.03
EW–20A	75	18.96	13.90	1.36
EW–20B	106	15.25	10.30	1.48
EW–20C	72	10.68	9.30	1.15
EW–20D	155	4.64	12.40	0.37
EW–21B	69	15.03	12.00	1.25
EW–21C	90	14.44	7.30	1.98
EW–21D	85	24.93	14.15	1.76
EW–22C	90	16.40	8.35	1.96

Figure 13. Specific-capacity values calculated from extraction well development logs recorded following extraction well installation in 2008.

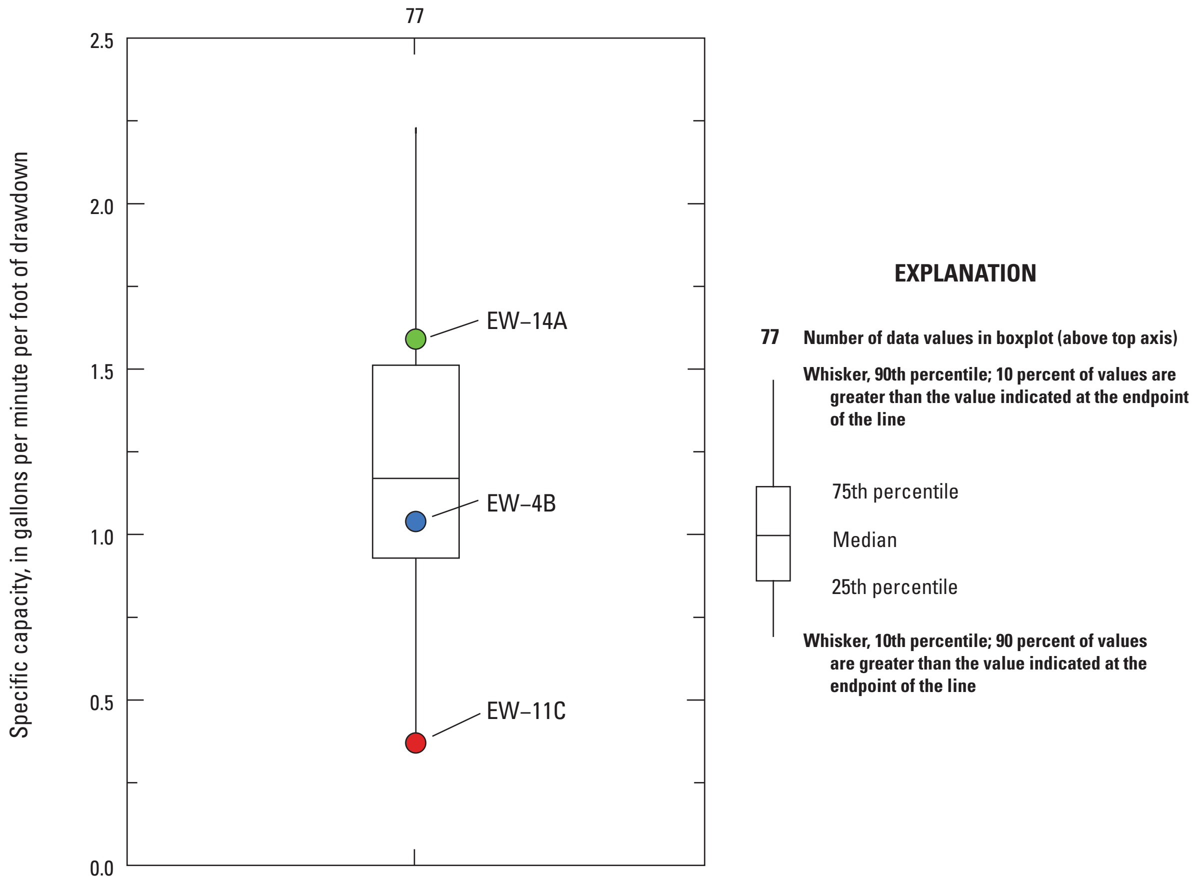


Figure 14. Specific-capacity values calculated from the initial well development records for 77 extraction wells on the Confined Disposal Facility.

Table 5. Specific-capacity values for extraction wells calculated from data collected during step drawdown testing in August–September 2014 and March–May 2015, and for monitoring wells calculated from data collected during water quality sampling in September–November 2014.

[USGS, U.S. Geological Survey; —, not applicable; ≤, less than or equal to]

USGS site identifier	Well name	Date of test	Type of test	Period of data used	Pumping rate, in gallons per minute	Drawdown, in feet	Specific capacity, in gallons per minute per foot of drawdown
USGS 413907087291801	EW–4B	09/04/2014	Step drawdown	0–60 minutes	1.50	3.51	0.43
		03/26/2015	Step drawdown	0–60 minutes	1.55	3.54	0.44
USGS 413920087285901	EW–11C	08/20/2014	Step drawdown	0–60 minutes	[1]0.40	4.33	≤ 0.09
		04/30/2015	Step drawdown	0–60 minutes	[1]0.34	4.70	≤ 0.07
USGS 413911087285201	EW–14A	09/05/2014	Step drawdown	0–60 minutes	1.83	3.42	0.54
		05/01/2015	Step drawdown	0–60 minutes	0.96	2.12	0.45
USGS 413908087291901	MW–4A	09/10/2014	Constant discharge rate test	—	0.25	1.10	0.23
		10/09/2014	Constant discharge rate test	—	0.25	—	—
		10/23/2014	Constant discharge rate test	—	0.24	2.12	0.12
		11/06/2014	Constant discharge rate test	—	0.20	0.76	0.26
USGS 413921087290101	MW–11A	09/09/2014	Constant discharge rate test	—	0.25	3.00	0.08
		10/07/2014	Constant discharge rate test	—	0.26	1.38	0.19
		10/20/2014	Constant discharge rate test	—	0.17	0.39	0.43
		11/03/2014	Constant discharge rate test	—	0.18	1.10	0.16
USGS 413909087285301	MW–14A	09/10/2014	Constant discharge rate test	—	—	—	—
		10/08/2014	Constant discharge rate test	—	0.25	4.95	0.05
		10/22/2014	Constant discharge rate test	—	0.11	2.22	0.05
		11/05/2014	Constant discharge rate test	—	0.13	3.10	0.04

[1] Values of specific capacity for indicated wells were estimated because the pumping rate fell below the accepted rates for the impeller flowmeter used during testing.

Indications of Appropriate Well Treatments from Aquifer Test Results

Comparisons of the specific-capacity values calculated from well development data collected following extraction well installation to those calculated during the single well aquifer tests indicate that the productivity of extraction wells on the CDF property has diminished since 2008 (fig. 15). Repeated slug testing within the monitoring wells on the CDF property, both inside and outside of the slurry wall, shows increasing values of hydraulic conductivity, which indicates that repeated air slug tests increased the connection of the monitoring well to the surrounding aquifer material and the ability of the well to record the water level in the surrounding aquifer. The decrease in the calculated hydraulic conductivity from air slug tests performed during August–September 2014 to March–May 2015 for MW–11A and MW–14A indicate the development of an altered, low conductivity wellbore skin that is affecting the connection of the well screen to the surrounding aquifer material. Additional air slug tests or other well development actions like surging the wells, applying compressed air, or extended periods of pumping could decrease the affect of the wellbore skin on the well screen connection with aquifer materials.

Hydraulic conductivity values of the wellbore skin and aquifer estimated from the step drawdown test for EW–11C are an order of magnitude lower than those estimated for EW–4B and EW–14A, and hydraulic conductivity values estimated from air slug tests for MW–11B are an order of magnitude lower than those estimated from similar tests in MW–4B and MW–14B. These differences may be due to the presence of finer grained silt deposits in the area surrounding well nest 11 as reported on geologic logs for EW–11A, EW–11B, EW–11C, and EW–11D.

Results from testing by this study indicate that implementation of an air slug testing regimen of the monitoring wells that control the gradient control system at the CDF throughout the course of a year may help maintain the connectivity between the monitoring wells and the surrounding aquifer and provide data to evaluate the need for different types of well development activities to address chemical or biological fouling issues. An initial round of air slug tests for the monitoring wells including those tested as part of this report following well development activities would be required to establish a baseline for those individual monitoring wells. An example air slug testing procedure is provided in Appendix 3 (modified from Cunningham and Schalk, 2011). Also, a simple well integrity test preformed before and after any well development

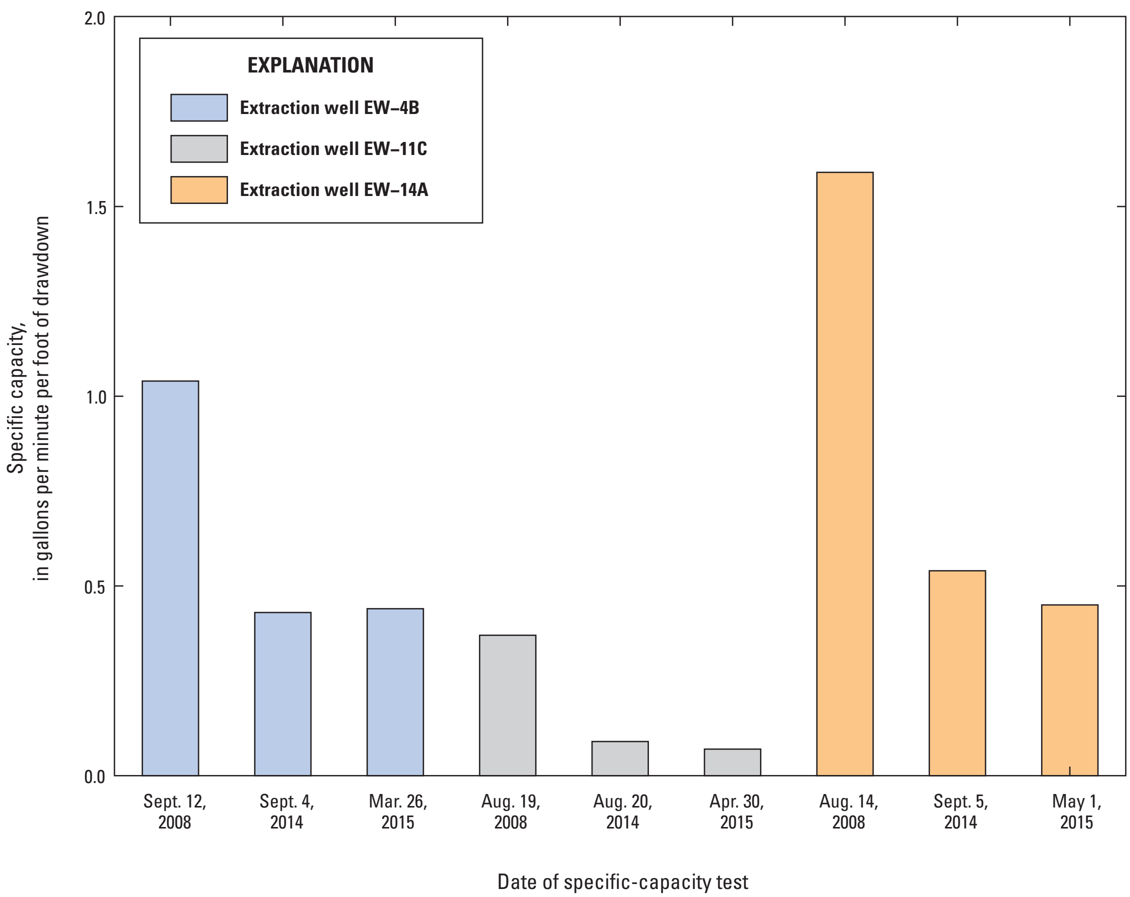


Figure 15. The decrease in specific capacity for extraction wells EW–4B, EW–11C, and EW–14A from 2008 to 2015.

activity, for example a fixed volume of water addition and timed water level recovery, would provide sufficient data to evaluate whether the development effort produced a change in the hydrologic condition of the monitoring well.

Repeated step drawdown and recovery testing of the extraction wells tested during this study provided results that indicate a slight increase in the development of a skin and a decrease in the connectivity of the extraction wells with the Calumet aquifer. An additional series of specific-capacity and recovery testing in the extraction wells before and immediately following well development activities, such as physical surging of water levels in the wells or applying compressed air at intervals could provide data to evaluate the effectiveness of development activities on the overall productivity of the well and the utility of ensuring the connectivity of the extraction wells with the Calumet aquifer.

Implementation of a specific capacity testing regimen can provide data to record and track well condition through time for individual extraction wells (Kawecki 1995). Initial baseline values can either be established from those presented in table 4 from initial well development data or recorded following a more recent set of well development activities. Because the CDF gradient control system is not equipped to measure water withdrawal rates from the individual extraction wells, a modified surrogate statistic using pump impeller rate, in revolutions per minute (RPM) could be used as a surrogate in place of pumping volume, however this statistic could only be used to compare the results from identical models of pumps after an initial baseline for each extraction well was established.

Results from aquifer testing by this study indicate that specific capacity test results, when paired with recovery testing, provide useful data to measure the development of any low conductivity wellbore skin through the skin factors derived for the individual extraction wells. The gradient control system pumps could be used to draw down water levels during the length of the test. Following the collection of data for use in specific capacity calculations, pumping could be terminated, recovery data collected until water levels return to pretest levels, and the dataset used in the recovery test analysis to compute skin factors. An example specific capacity and recovery testing procedure is provided in Appendix 4 (modified from Cunningham and Schalk, 2011).

The implementation of annual specific capacity and recovery tests for two to three years would provide sufficient data to identify substantial changes in the operating condition of the extraction wells. Extraction wells that have already experienced impairment could be tested on a more frequent schedule. Following the first two to three years, the test schedule could be modified to continue testing extraction wells with the most change on a more frequent basis than those that show less change in operating condition. Under this system, once the performance of an extraction well was affected by a given threshold (30 percent of baseline conditions, for example), well development activities could be implemented to return the extraction well as much as possible to baseline conditions. Similarly, air slug tests could be made initially at a less frequent interval than that of the extraction well testing because water is not actively pumped from the monitoring wells. Following the initial rounds of testing, each monitoring well could be evaluated and the schedule modified to test wells that show the most change in hydraulic characteristics more frequently than those that show less change. The process of testing each monitoring well and time interval between tests should be sufficiently comprehensive to provide data to assure that hydraulic connectivity with the aquifer is maintained. If the response of a monitoring well to repeated air slug tests deteriorates by some previously identified metric, such as the number of tests until a stable conductivity value is achieved as an example, well development activities could be implemented to return the extraction well to baseline conditions.

Summary and Conclusions

The Confined Disposal Facility (CDF) property was initially the location of a petroleum refinery and later produced insecticides. In 1981, the property owner filed for bankruptcy and all aboveground structures were removed from the site. Hydrocarbon contamination was detected in 1991 and a groundwater recovery system was installed. The U.S. Army Corps of Engineers took possession of the property, began construction of the CDF in 2002, and installed the groundwater cutoff wall and gradient control system that surrounds the property and maintains an inward groundwater gradient to control groundwater flow. In 2012, some extraction wells on the CDF site began to experience fouling—a precipitate of unknown origin formed on the intake of the extraction well pump causing the pump to overheat and become inoperable, and requiring site personnel to pull the equipment from the well and replace the pump.

A suite of single well tests (air slug, step drawdown, recovery, and specific-capacity tests) were completed to evaluate the performance of extraction wells in three of the 22 well nests that constitute the gradient control system surrounding the CDF, and to assist in the understanding of procedures that could be used to monitor well integrity to assist in the efficiency of the system. Tests were completed at well nests that were believed to represent three different levels of fouling. Testing was performed once in August–September 2014 and again in March–May 2015 to capture any changes that may occur to the properties of the well and aquifer during the period of investigation.

Air slug tests were completed in six monitoring wells on the CDF property, and one U.S. Geological Survey monitoring well, chosen as being representative of a background condition within the Calumet aquifer, located approximately 0.25 mile south of the CDF property. Continuous data collected during the single well slug testing were analyzed with the Bouwer and Rice method by using the AQTESOLV software package.

The results of the slug test analysis data indicate that the hydraulic connection of the well screen to the surrounding aquifer material in monitoring wells on the CDF and the reliability of hydraulic conductivity estimates of the surrounding geologic media could be increased by implementing well development maintenance. Derived hydraulic conductivity values from air slug tests for monitoring wells D40, MW–4A, MW–4B, and MW–14B were approaching or within the range of values measured in monitoring wells completed in the Calumet aquifer in northwest Indiana and northeast Illinois. Hydraulic conductivity values for monitoring wells MW–11A, MW–11B, and MW–14A were below those measured in previous investigations in the area. Plots of hydraulic conductivity values derived from successive air slug test for each monitoring well located on the CDF property indicated that, with each test in a given well, the well was being developed—the hydraulic connection between the well and the aquifer was being affected by the surging of water through the well screen during the pressurization and depressurization of the well casing. Results of repeated tests show increasing hydraulic conductivity until, in the case of the monitoring wells located outside of the groundwater cutoff wall (MW–4B, MW–11B, MW–14B), the difference in hydraulic conductivity from test to test decreases, indicating the results are approaching the optimal hydraulic connection between the aquifer and the well screen. The derived values of hydraulic conductivity from test to test in the monitoring wells located within the groundwater cutoff wall (MW–4A, MW–11A, MW–14A) continued to increase during each testing period indicating the wells are in need of development due to the presence of a low conductivity wellbore skin that is affecting the connection of the well screen to the surrounding aquifer material. Hydraulic conductivity values derived from successive tests performed in monitoring well D40 were substantially higher than those derived for wells on the CDF property and similar to those reported in previous investigations and values do not vary from test to test like those measured in monitoring wells located on the CDF property indicating that the well is not in need of development and that the derived value of hydraulic conductivity is representative of the lower bound on the hydraulic conductivity of the Calumet aquifer in the vicinity of the well.

Hydraulic conductivity values derived from air slug tests from the first test of the 2015 testing period for MW–11A and MW–14A were an order of magnitude less than those derived from the final test from the 2014 testing period indicating the development of a low conductivity skin between the final test of the 2014 testing period and the beginning of the 2015 testing period creating a decrease in the connection of the monitoring well screen to the surrounding aquifer material. The low conductivity skin could be due to well screen clogging or a clogging of the filter pack material that surrounds the well screen itself. Specific-capacity values calculated from the well purging notes taken during the four rounds of water quality sampling between the 2014 and 2015 testing periods were similar during all four periods of sampling, indicating there was no gradual decrease in well performance during the rounds of testing.

Step drawdown aquifer tests were completed in three extraction wells on the CDF property. Continuous data collected during the tests were analyzed with a modified version of the Dougherty and Babu method available for use in the AQTESOLV software package. Data collected during the period of recovery following the cessation of pumping for each well was analyzed with the Moench method by using the AQTESOLV software package. Both the Dougherty and Babu and Moench solutions include the calculation of a wellbore skin factor, resulting from a zone of altered permeability near the wellbore, that can be used to account for the difference between measured and predicted response in a pumping well. A positive skin factor indicates the interface between the aquifer and the wellbore is damaged, which may be a result of a zone of mud infiltration from drilling, bridging of screen opening, or mineral precipitation. Higher skin factor values are representative of conditions with a larger difference between the hydraulic conductivity of the aquifer and the wellbore skin. Lower skin factor values are representative of conditions with a smaller difference between the hydraulic conductivity of the aquifer and the wellbore skin. The skin factor derived from the analysis was used to calculate the hydraulic conductivity of the wellbore skin for each well. Data collected during the period of recovery following the cessation of pumping for each well was analyzed with the Moench method by using the AQTESOLV software package to acquire an independent estimate of both the transmissivity and skin effect.

The step drawdown and recovery test results indicated a slight decrease in productivity of extraction well EW–4B between the 2014 and 2015 tests, slightly diminishing its capability to drawdown the water table inside the groundwater cutoff wall. Transmissivity values for extraction well EW–4B derived from data collected in September 2014 were 1,500 feet squared per day (ft^2/d) for the step drawdown and recovery tests. Hydraulic conductivity values were 62 feet per day (ft/d). A skin factor of 20 was calculated for both the step drawdown and recovery tests and was used to estimate the hydraulic conductivity value of the skin as 12 ft/d (approximately 20 percent of the estimated aquifer hydraulic conductivity). A skin factor of 22 was calculated using step drawdown and recovery test data collected during testing completed in March 2015 and was used to estimate the hydraulic conductivity value of the skin as 11 ft/d (approximately 20 percent of the estimated aquifer hydraulic conductivity). The calculated skin factors increased by 10 percent from the 2014 to the 2015 period of testing indicating that the hydraulic conductivity of the wellbore skin decreased by 1 foot per day.

The step drawdown and recovery test results indicated a slightly decreased but similar productivity of extraction well EW–11C between the 2014 and 2015 tests, indicating that its capability to drawdown the water table inside the groundwater cutoff wall was unchanged between the tests. Transmissivity values for extraction well EW–11C derived from data collected in September 2014 during the middle step of the step drawdown test was 110 ft^2/d. Transmissivity calculated from the last step of the step drawdown test and the recovery test were higher values of 650 and 580 ft^2/d, respectively. Similarly, hydraulic conductivity values were 5 ft/d for the middle step of the step drawdown test, and 27 and 24 ft/d from the last step of the step drawdown test and recovery test, respectively. A calculated skin factor of 7 was used to estimate hydraulic conductivity value of 3 ft/d for the wellbore skin for the middle step of the step drawdown test (approximately 60 percent of the estimated aquifer hydraulic conductivity). Calculated skin factors of 42 and 36 for the last step of the step drawdown test and the recovery test, respectively, were used to calculate wellbore skins of 3 ft/d (approximately 10 percent of the estimated aquifer hydraulic conductivity). A skin factor of 8, calculated from data collected in 2015, was used to estimate a hydraulic conductivity value for the wellbore skin of 3 ft/d for the middle step of the step drawdown test (approximately 50 percent of the estimated aquifer hydraulic conductivity). The calculated skin factor of 49 and 44 for the last step of the step drawdown test and recovery test were used to calculate wellbore skins of 2 ft/d (approximately 8 percent of the estimated aquifer hydraulic conductivity). Calculated skin factors increased slightly from the 2014 to the 2015 period of testing indicating that the hydraulic conductivity of the wellbore skin decreased slightly for all three tests.

The step drawdown and recovery test results indicated a slight decrease in productivity of extraction well EW–14A between the 2014 and 2015 tests, slightly diminishing its capability to drawdown the water table inside the groundwater cutoff wall. Transmissivity values for extraction well EW–14A derived from data collected in September 2014 during the first two steps of the test were 1,300 ft^2/d. Values calculated from the data collected during the last step of the step drawdown test and recovery test were comparable (1,500 and 1,200 ft^2/d, respectively). Hydraulic conductivity values for the aquifer for all three solutions ranged from 49 ft/d for the recovery test to 63 ft/d for the last step of the step drawdown test. Calculated skin factors for all three tests were similar and ranged from 14 for the recovery test to 18 for the last step of the step drawdown test. These values were used to calculate values for the hydraulic conductivity of the wellbore skin of 14 ft/d (approximately 25 percent of the estimated aquifer hydraulic conductivity). Skin factors calculated from data collected in 2015 ranged from 16 for the recovery test to 22 for the last step of the step drawdown test. These values were used to calculate values for the hydraulic conductivity of the wellbore skin of 11 and 12 ft/d (approximately 18 to 25 percent of the estimated aquifer hydraulic conductivity). Calculated skin factors increased from the 2014 to the 2015 period of testing for all three analyses indicating that the hydraulic conductivity of the wellbore skin decreased by 2 to 3 feet per day.

Comparisons of the specific-capacity values calculated from well development data collected following extraction well installation to those calculated during the single well aquifer tests indicate that the productivity of extraction wells on the CDF property has diminished since 2008. Specific capacity for a subset of extraction wells was calculated from well discharge, duration of pumping, and water-level drawdown records from three different datasets: (1) data collected for 77 wells during well development by a private consulting company following well installation in 2008, (2) data collected during USGS water quality sampling in September–November 2014, and (3) data collected during the first step of the step drawdown testing. Specific-capacity values calculated from the initial extraction well development in 2008 were used to compare the initial performance of the extraction well tested during this investigation to that of the other 85 extraction wells on the CDF property, and as a comparison to values calculated from data collected in 2014 and 2015 for extraction wells EW–4B, EW–11C, and EW–14A. Values calculated for monitoring wells MW–4A, MW–11A, and MW–14A were used to evaluate the decrease in air slug derived hydraulic conductivity for monitoring wells within the groundwater cutoff wall between testing in 2014 and 2015.

Specific-capacity values calculated from the extraction well development data in 2008 range from 0.37 (EW–11C) to 2.26 gal/min/ft of drawdown (EW–16C). Values calculated from the 2008 data for the extraction wells tested in 2014 and 2015 during this study are 0.37 (EW–11C), 1.04 (EW–4B), and 1.59 gal/min/ft of drawdown (EW–14A). Values calculated from step drawdown test completed for this study for EW–4B ranged from 0.43 gal/min/ft of drawdown in September 2014 to 0.44 gal/min/ft of drawdown in March 2015. Values for EW–11C ranged from 0.09 gal/min/ft of drawdown in August 2014 to 0.07 gal/min/ft of drawdown in April 2015. Values for EW–14A ranged from 0.54 gal/min/ft of drawdown in September 2014 to 0.45 gal/min/ft of drawdown in May 2015.

Comparisons of the specific-capacity values calculated from well development data collected following extraction well installation to those calculated during the single well aquifer tests indicate that the productivity of the extraction wells on the CDF property have diminished since 2008. The decrease in the calculated hydraulic conductivity from air slug tests performed during August–September 2014 to March–May 2015 for MW–11A and MW–14A indicate the development of an altered, low conductivity wellbore skin that is affecting the connection of the well screen to the surrounding aquifer material. Additional air slug tests or other well development actions like surging the wells, applying compressed air, or extended periods of pumping could decrease the affect of the wellbore skin on the well screen connection with aquifer materials.

Results from testing by this study indicate that implementation of an air slug testing regimen of the monitoring wells that control the gradient control system at the CDF throughout the course of a year may help sustain the connectivity between the monitoring wells and the surrounding aquifer and provide data to evaluate the need for different types of well development approaches to address chemical or biological fouling issues. Repeated step drawdown and recovery testing of the extraction wells tested during this study provided results that indicate a slight increase in the development of a skin and a decrease in the connectivity of the extraction wells with the

Calumet aquifer. Implementation of a specific capacity testing regimen can provide data to record and track well condition through time for individual extraction wells. Results from aquifer testing by this study indicate that specific capacity test results, when paired with recovery testing, provide useful data to measure the development of any low conductivity wellbore skin through the skin factors derived for the individual extraction wells. An initial annual schedule of specific capacity and recovery tests would provide sufficient data to identify substantial short-term changes in the operating condition of the extraction wells.

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Appendixes 1–4

Appendix 1. Air Slug Test Field Log Sheets and Graphs of Air Slug Test Data with Fitted Analytical-Solution Lines

Available for download from https://doi.org/10.3133/sir20165125/Appendix1_SlugTests/

Modeled K and pretest water levels can be found in table 2.

Appendix 2. Aquifer Test Field Log Sheets and Graphs of Aquifer-Test Data with Fitted Analytical-Solution Lines

Available for download from https://doi.org/10.3133/sir20165125/Appendix 2_Aq test/

The data-collection form from slug testing at U.S. Geological Survey monitoring well D40 during 2014 was not completed during data collection and is therefore not included.

Appendix 3. Air Slug Testing Procedure for Evaluating Hydraulic Condition of Gradient Control System Monitoring Wells

Introduction

During an air slug test, the water level in a well is changed rapidly, and the rate of water-level response to that change is measured. From these data, an estimate of hydraulic conductivity can be calculated using appropriate analytical methods (for example, Bouwer and Rice, 1976).

A slug test requires a rapid ("instantaneous") water-level change and measurement of the water-level response at high frequency. During an air-slug test, a rapid change in water level is induced by slowly increasing air pressure in the well casing to displace water, and instantaneously releasing the pressure within the well casing. The water-level changes are measured with a submersible pressure transducer that is capable of making multiple measurements per second and has a range that is appropriate for the range of water levels expected in the monitoring well during the length of the test.

The following air slug testing procedure has been modified from a groundwater technical procedure released by the U.S. Geological Survey for general use by the public (Cunningham and Schalk, 2011). It was modified to include the air slug technique used for this study and details required when testing wells in the U.S. Army Corps of Engineers Confined Disposal Facility (CDF) in East Chicago, Indiana gradient control system were added.

Recommended Materials and Instruments

1. Field notebook or worksheet
2. Well-construction diagram that includes the elevation of the screen and total depth of the well in reference to the top of well casing.
3. Data logger and submersible pressure transducer. The submersible pressure transducer should be capable of making at least one measurement per 0.25 second and have a range that is appropriate for the range of water levels expected in the monitoring well during the length of the test.
4. A well head apparatus designed for pressurizing the well (fig. 6).
5. A small bicycle pump or air compressor.
6. Bungee cord or other device to secure the transducer cable.
7. Water level measuring device (steel or electric tape).
8. Appropriate decontamination equipment.
9. Field computer.

Instructions

1. If testing a monitoring well inside of the groundwater cutoff wall, ensure that the neighboring extraction wells on either side of the monitoring well have been switched off for an appropriate amount of time so that water levels in the monitoring well are not being affected by pumping.
2. Measure the depth to water in the monitoring well with the water level measuring device repeatedly to ensure the water level is not changing. Record final water level in field notebook or worksheet.
3. Remove any equipment including the gradient control system pressure transducer from the monitoring well.
4. Attach the well head apparatus designed for pressurizing the well. Record the water depth in the well below the well head apparatus measuring point. Attach the bicycle pump to the fitting on the well head apparatus.
5. Install the pressure transducer that will be recording data during the length of the air slug test through the appropriate opening in the well head apparatus. Secure the pressure transducer cable using the plug designed to create an air tight seal on well head apparatus. The transducer should be installed at a depth below the anticipated water level following pressurization of the well casing. Use the water level recorded in step 4 to determine depth.
6. Check all brackets to ensure an air tight connection between the well head apparatus and well casing. Ensure the pressure release valve is in the closed position.
7. Using the field computer, set the transducer to record zero drawdown initially. Start the logging of the water level using the pressure transducer. Set the logging interval to 0.25 second. Set the field computer to display a real time graph of water level data.

8. Using the bicycle pump, pressuring the well casing by quickly pumping the bicycle pump and allowing the pressure to peak at approximately 60 pounds per square inch (lb/in^2). Pressure should slowly decrease over time to a lower pressure. The real time graph of water level on the field computer should indicate water level has changed. If pressure does not hold or is quickly decreasing, check fittings on well head apparatus and repeat.

9. Release the pressure in the well casing by turning the lever on the pressure release valve when the gauge shows approximately 20 lb/in^2, or the water levels displayed on the real-time graph stabilize. A puff of air should escape from the pressure release valve. A rapid change in water level should be indicated on the real time water level display. Record the time pressure was released, the peak pressure and pressure indicated on gauge when released.

10. Allow water levels to stabilize. Measure water level beneath wellhead apparatus measuring point after water levels have stabilized. When the water level is equal to the initial water level, or when readings change less than 0.01 foot per 10 minutes, note the time and stop data recording.

11. Review the data for completeness and accuracy. This can be done on the data logger or on a field computer. Optionally, the test can be analyzed in the field on a field computer using aquifer test software.

12. Repeat test at least three times, or until stabilization time is approximately the same, or analyzed aquifer properties are within approximately 0.5 feet per day for three consecutive tests.

13. Remove and decontaminate test pressure transducer and well head apparatus. Replace gradient control system pressure transducer. Measure and record the depth to water in the monitoring well.

Data Analysis

Analyze the continuous data collected during the single well air slug testing using the Bouwer and Rice (1976) method and the guidelines presented by Butler (1998) and the procedures described within this report to determine the hydraulic conductivity of the formation surrounding the monitoring well screen. To establish a baseline condition, compare the initial set of values of hydraulic conductivity derived from the analysis. Consistent values of hydraulic conductivity indicate that the air slug tests are not modifying the connection of the monitoring well to the surrounding aquifer material and the derived value of hydraulic conductivity is representative of the aquifer materials surrounding the monitoring well screen (fig. 12*A*). Increasing values of hydraulic conductivity indicate that repeated air slug tests are increasing the connection of the monitoring well to the surrounding aquifer material and the ability of the well to record the water level in the surrounding aquifer and that each successive test is further developing the well (fig. 12*C*). Initially, repeat the testing procedure on a more frequent basis (for example, every three months for the first year). Following the first two to three rounds of testing, evaluate each monitoring well and modify the schedule to retest monitoring wells that show the most change more frequently than those that show less change. The process of testing each monitoring well should be sufficient to maintain connectivity with the aquifer. If the response of a monitoring well to repeated air slug tests deteriorates by some previously identified metric (number of tests until a stable conductivity value is achieved, for example), consider well development actions to return the monitoring well to baseline conditions.

Appendix 4. Specific Capacity and Recovery Testing Procedure for Evaluating Gradient Control System Extraction Wells

Introduction

Specific-capacity values can be used to quantify the productivity of a well and compare its productivity through time, and can be calculated from well discharge, duration of pumping, and water-level drawdown records collected during a aquifer test (Freeze and Cherry, 1979; Kawecki, 1995). Once analyzed, specific capacity values of individual wells can be used to compare the efficiency of those wells to each other, and the change in efficiency through time.

Recovery tests use data collected during the portion of an aquifer test following the cessation of pumping that initiated the drawdown of the water level in the well. The analysis of a recovery test provides aquifer transmissivity and wellbore skin factors that can be used to evaluate the efficiency and condition of the extraction well following the procedures provided in this report.

During the specific capacity and recovery test, the extraction well pump can be used to pump the well at a constant rate that induces a drawdown of the water level in the well to a constant level above that of the well screen. Water-level changes are measured with a submersible pressure transducer that is capable of making multiple measurements per second and has a range that is appropriate for the range of water levels expected in the monitoring well during the length of the test. The flow rate of the water discharging from the well during the length of the test is necessary to calculate specific capacity and can be either measured periodically, or, if a discharge measurement is not possible, a modified statistic using pump revolutions per minute (RPM) in place of pumped gallons per minute could be used, however it is recommended that this modified specific capacity statistic could only be used to compare the results from identical models of pumps and an initial baseline for each extraction well would need to be established.

The following specific capacity and recovery testing procedure has been modified from groundwater technical procedures released by the U.S. Geological Survey for general use by the public (Cunningham and Schalk, 2011). It was modified to include the specific capacity and recovery techniques used for this study and details required when testing wells in the U.S. Army Corps of Engineers Confined Disposal Facility (CDF) in East Chicago, Indiana gradient control system were added.

Recommended Materials and Instruments

1. Field notebook or worksheet
2. Well-construction diagram that includes the elevation of the screen and total depth of the well in reference to the top of well casing.
3. Data logger and submersible pressure transducer. The submersible pressure transducer should be capable of making at least one measurement per second and have a range that is appropriate for the range of water levels expected in the monitoring well during the length of the test.
4. Bungee cord or other device to secure the transducer cable.
5. Water level measuring device (steel or electric tape).
6. Appropriate decontamination equipment.
7. Field computer.

Instructions

1. Ensure that the neighboring extraction wells on either side of the extraction well being tested have been switched off for an appropriate amount of time that water levels in the well are not being affected by pumping.
2. Measure the depth to water in the extraction well with the water level measuring device repeatedly to ensure the water level is not changing. Record final water level in field notebook or worksheet.
3. Install the pressure transducer that will be recording data during the length of the test in the extraction well. Secure the pressure transducer cable using the bungee cord to a solid object near the top of the well casing to ensure the transducer does not move during the length of the test. The transducer should be installed at a depth below the anticipated water level following pumping of the well. Use the water level recorded in step 4 to determine depth.

4. Using the field computer, set the transducer to record zero drawdown initially. Start the logging of the water level using the pressure transducer. Set the logging interval to one second. Set the field computer to display a real time graph of water level data.

5. Begin the test by turning on the pump to an RPM setting that will draw down the water level in the well to a level at least 1 to 2 feet above both the transducer and the elevation of the extraction well screen. The RPM of the pump used during the test may need to be at a lower setting than one used during the normal operation of the gradient control system. The RPM setting can be determined by evaluating the regular RPM setting and recorded water level of the well during the regular operation of the gradient control system. Record the time the pump was started on the field sheet. Record the RPM of the pump.

6. Once a constant water level has been established within the extraction well and recorded on the real time water level display, measure the depth to water in the extraction well with the water level measuring device, record the measurement and time of measurement. If a discharge rate of the pump is available from an inline flowmeter or similar device, record the discharge rate. Continue recording data for at least 2 hours while periodically checking that the water level in the well is constant either by reviewing the real time water level display, or making measurements with the water level measuring device. Periodically record the measured discharge rate and time of measurement, if available.

7. Following the data collection period, measure the depth to water in the extraction well with the water level measuring device, record the measurement and time of measurement, and turn the pump off and allow the water level in the extraction well to recover. Record the time the pump was switched off. Continue recording water level data with the pressure transducer.

8. Allow water levels to stabilize. Measure water level beneath the measuring point after water levels have stabilized. When the water level is equal to the initial water level, or when readings change less than 0.01 foot per 10 minutes, note the time and stop data recording.

9. Review the data for completeness and accuracy. This can be done on the data logger or on a field computer. Optionally, the test can be analyzed in the field on a field computer using aquifer test software.

10. Remove and decontaminate the test pressure transducer. The extraction well tested and the neighboring extraction wells can be returned to normal operation.

Data Analysis

Determine the specific capacity of the extraction well by calculating the duration of pumping from the times recorded on the field sheet in minutes, the average amount of drawdown in feet recorded during the test from the continuous data recorded with the transducer, and either the pump RPM setting, or the average discharge in gallons per minute recorded during the test and using equation 2 from this report.

Analyze the continuous data collected during the recovery portion of the test using the Moench (1997) method and the procedures described within this report to determine the hydraulic conductivity of the formation surrounding the extraction well screen and the skin factor. The skin factor can be used to determine the hydraulic conductivity of any low conductivity wellbore skin present in the well.

To establish a baseline condition, ensure the well has been fully developed prior to the test and the extraction well pump is in good working order, and repeat the test annually to measure any significant changes in the condition of the extraction wells. Extraction wells that have already experienced impairment could be tested on a more frequent schedule. Following the first two to three years of testing, evaluate data collected for each well and modify the schedule to test extraction wells that show the most change in specific capacity value more frequently than those that show less modification. Consider well development actions as the condition of the well deteriorates over time. If the gradient control system pump requires replacement, retest the extraction well prior to (if possible) and following replacement of the pump to determine if well performance was affected by the condition of the pump.

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