Prepared in cooperation with the U.S. Environmental Protection Agency

Hydrogeologic Framework, Hydrology, and Refined Conceptual Model of Groundwater Flow for Coastal Plain Aquifers at the Standard Chlorine of Delaware, Inc. Superfund Site, New Castle County, Delaware, 2005–12

Scientific Investigations Report 2014–5224

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

Cover. Red Lion Creek tide control structure with reinforced dike and five outflow gates, looking from the Delaware River at low tide in 2010. Photograph by Todd Keyser, Delaware Department of Natural Resources and Environmental Control.

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047.0	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Multiply	By	To obtain
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
	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)

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

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). The local datum conversion from NGVD 29 to the North American Vertical Datum of 1988 (NAVD 88) is -0.78 ft.

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.

*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.

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Hydrogeologic Framework, Hydrology, and Refined Conceptual Model of Groundwater Flow for Coastal Plain Aquifers at the Standard Chlorine of Delaware, Inc. Superfund Site, New Castle County, Delaware, 2005–12

By Michael J. Brayton, Roberto M. Cruz, Luke Myers, James R. Degnan, and Jeff P. Raffensperger

Abstract

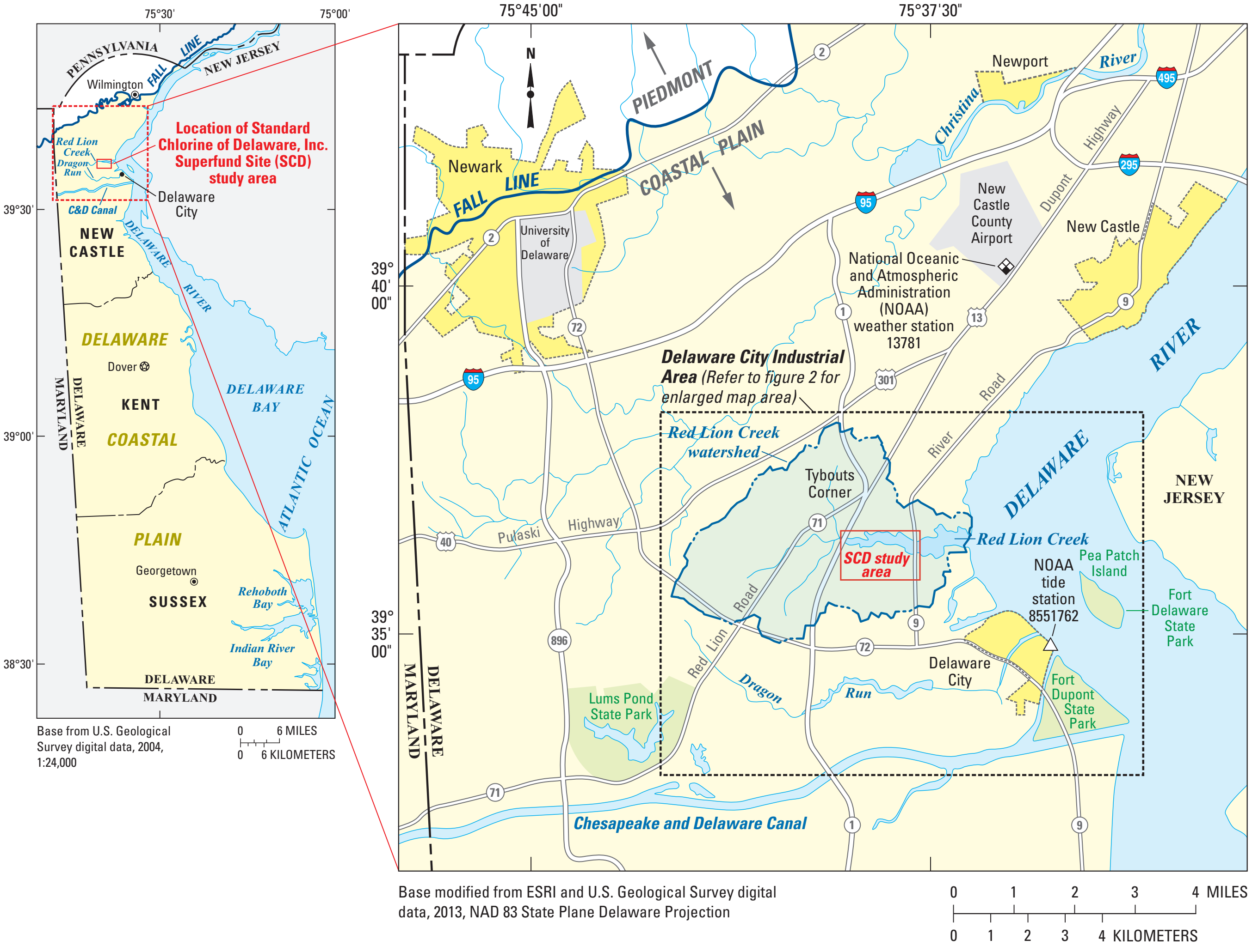
From 1966 to 2002, activities at the Standard Chlorine of Delaware chemical facility in New Castle County, Delaware resulted in the contamination of groundwater, soils, and wetland sediment. In 2005, the U.S. Geological Survey (USGS), in partnership with the U.S. Environmental Protection Agency, Region 3, and the Delaware Department of Natural Resources and Environmental Control began a multi-year investigation of the hydrogeologic framework and hydrology of the confined aquifer system. The goals of the ongoing study at the site (the Potomac Aquifer Study) are to determine the hydraulic connection between the Columbia and Potomac aquifers, determine the direction of groundwater flow in the Potomac aquifer, and identify factors affecting the fate of contaminated groundwater. This report describes progress made towards these goals based on available data collected through September 2012.

The regional hydrogeologic framework indicates that the site is underlain by Coastal Plain sediments of the Columbia, Merchantville, and Potomac Formations. Two primary aquifers underlying the site, the Columbia and the upper Potomac, are separated by the Merchantville Formation confining unit. Local groundwater flow in the surficial (Columbia) aquifer is controlled by topography and generally flows northward and discharges to nearby surface water. Regional flow within the Potomac aquifer is towards the southeast, and is strongly influenced by major water withdrawals locally. Previous investigations at the site indicated that contaminants, primarily benzene and chlorinated benzene compounds, were present in the Columbia aquifer in most locations; however, there were only limited detections in the upper Potomac aquifer as of 2004. From 2005 through 2012, the USGS designed a monitoring network, assisted with exploratory drilling, collected data at monitoring wells, conducted geophysical surveys, evaluated water-level responses in wells during pumping of a production well, and evaluated major aquifer withdrawals. Data collected through these efforts were used to refine the local conceptual flow system. The refined conceptual flow system for the site includes: (a) identification of gaps in confining units in the study area, (b) identification and correlation of multiple water-bearing sand intervals within the upper Potomac Formation, (c) connections between groundwater and surface water, (d) connections between shallow and deeper groundwater, (e) new water-level (or potentiometric surface) maps and inferred flow directions, and (f) identification of major local pumping well influences. The implications of the revised conceptual flow system on the occurrence and movement of site contaminants are that the resulting detection of contaminants in the upper Potomac aquifer at specific well locations can be attributed primarily to either advective lateral transport, direct vertical contaminant transport, or a combination of vertical and lateral movement resulting from changes in water withdrawal rates over time.

Introduction

The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency, Region 3 (EPA), is involved in an ongoing study to characterize the flow system and define the hydrogeologic framework of the Columbia and Potomac aquifers in the vicinity of the former Standard Chlorine of Delaware, Inc. (SCD) Superfund Site near Delaware City, New Castle County, Delaware (fig. 1). The presence of site-related contaminants from the former chemical manufacturing facility, including benzene and chlorinated benzene compounds, in both the Columbia and underlying Potomac aquifers may pose a threat to public water-supply wells screened within the Potomac Formation and located approximately 3 miles southeast and downgradient from the site.

This investigation (the Potomac Aquifer Study) was designed to determine the extent of the hydraulic connection between the Columbia and underlying Potomac aquifers, to



Base from U.S. Geological Survey digital data, 2004, 1:24,000

Base modified from ESRI and U.S. Geological Survey digital data, 2013, NAD 83 State Plane Delaware Projection

Figure 1. Location of Standard Chlorine of Delaware, Inc. Superfund Site study area and Delaware City industrial area in northern New Castle County, Delaware.

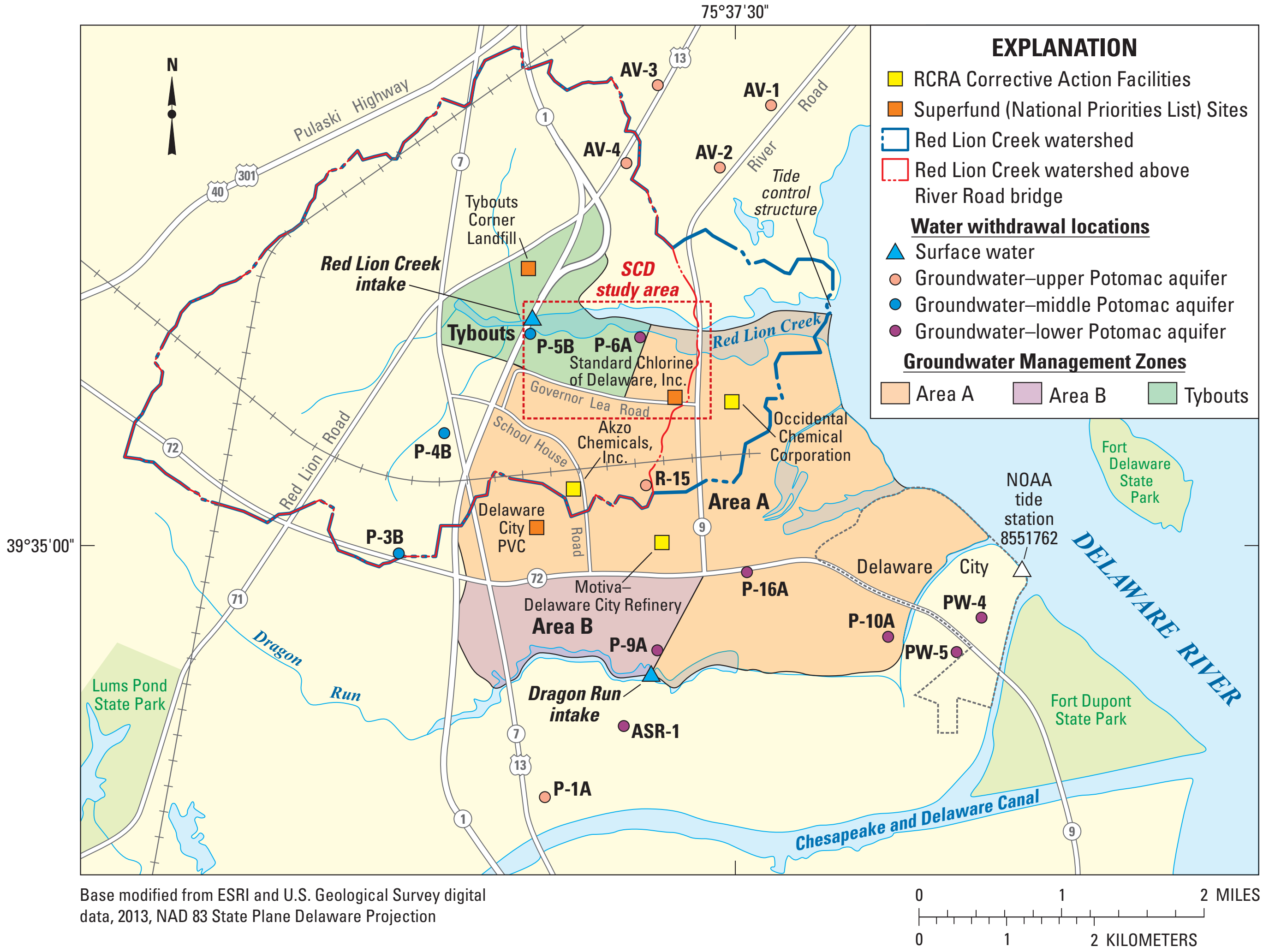
determine the direction of groundwater flow in the Potomac aquifer, and to identify factors affecting the fate of contaminated groundwater. The EPA will use the results of this study to help design a final remedy for groundwater at the site with a goal of protecting human health and the environment (U.S. Environmental Protection Agency, 2011).

Purpose and Scope

This report describes recent local refinements to the hydrogeologic framework and hydrology of the Coastal Plain sediments underlying the SCD site. The refinements were used to improve the local conceptual model of groundwater flow, which serves as the basis for determining the hydrogeologic and hydrologic factors that influence contaminant movement in groundwater at the site. Refinements were made possible using new data collected during 2005–12 from activities that included exploratory drilling, geophysical surveys, expansion of an observation-well network, and observations from production well pumping. Analysis of these new data are described in this report to provide detail on the hydrogeologic framework, the direction of groundwater flow, the connections between aquifers, and the effects of pumping and other hydraulic stresses at a local (study area) scale.

Description of Study Area

The SCD Superfund Site is located within the Delaware City Industrial Area (DCIA), which contains a large oil refinery built in the early 1950s, and several chemical-producing facilities built in subsequent decades (fig. 2). The study area described in this report includes Standard Chlorine of

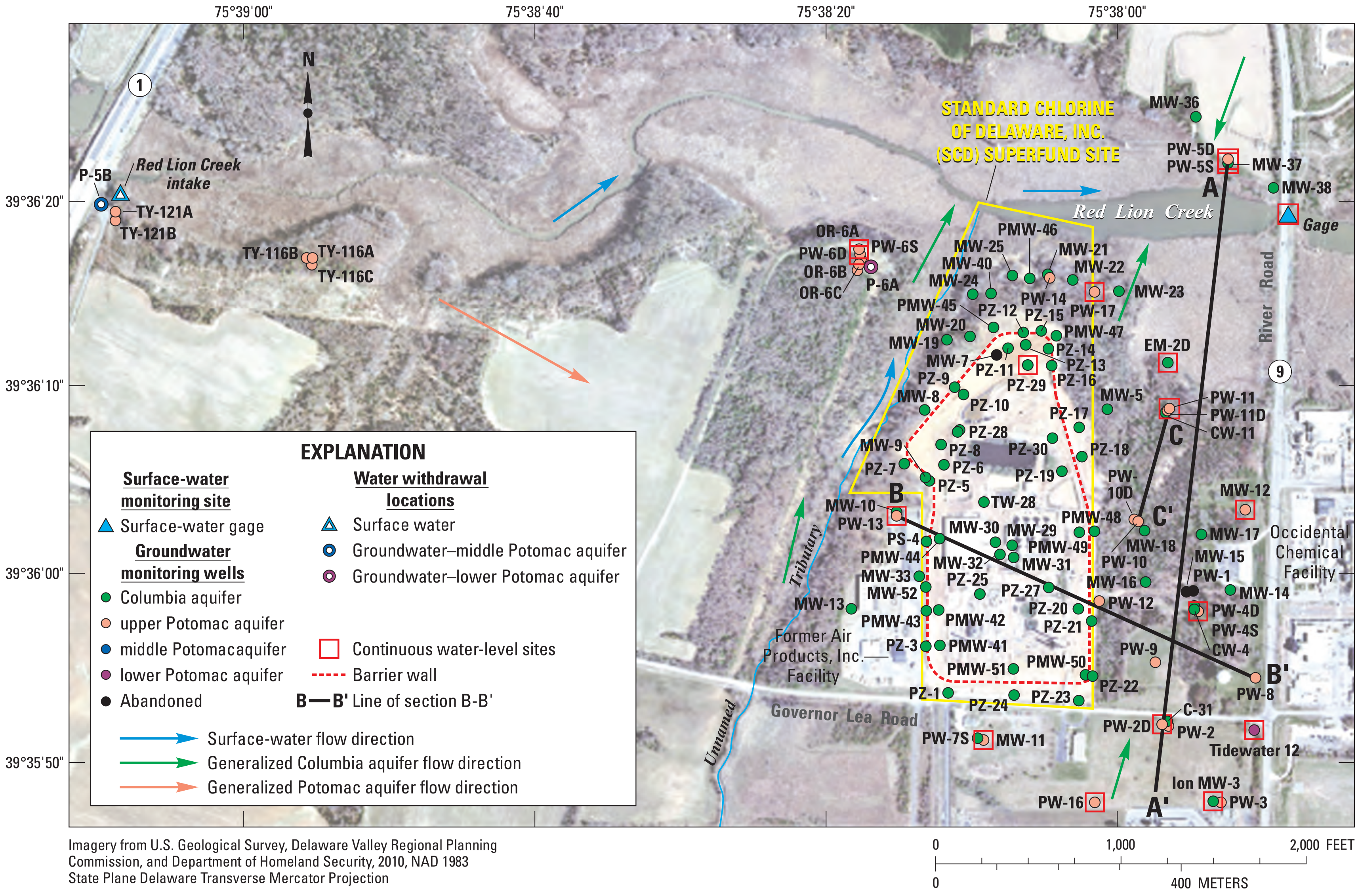


Base modified from ESRI and U.S. Geological Survey digital data, 2013, NAD 83 State Plane Delaware Projection

Figure 2. Location of Delaware City Industrial Area, Red Lion Creek watershed, water withdrawal intakes, and groundwater management zones related to sites designated as U.S. Environmental Protection Agency Superfund National Priorities List (NPL) Sites or Resource Conservation and Recovery Act (RCRA) Corrective Action Facilities (U.S. Environmental Protection Agency, 2012.).

Delaware, Inc., a 65-acre former chemical manufacturing facility, and areas extending approximately one-half mile beyond the site property (tax map) boundary. The SCD site is bounded to the north by Red Lion Creek, to the east by Occidental Chemical Corporation (Oxychem) Facility and Delaware Route 9 (River Road), to the west by the former Air Products, Inc. Facility and an un-named tributary of Red Lion Creek, and to the south by Governor Lea Road (fig. 3). The Chesapeake and Delaware Canal is located 3 miles to the south, and the Delaware River is located 1 mile to the east (fig. 2). A site-related monitoring-well network that includes wells on adjacent properties has enabled the hydrogeologic characterization of a broader area surrounding the site (fig. 3).

In addition to SCD, other nearby industrial sites, including some that are no longer in operation, are also listed as EPA Superfund National Priorities List (NPL) sites including Delaware City PVC and Tybouts Corner Landfill, or listed as Resource Conservation and Recovery Act (RCRA) corrective action sites including Motiva Delaware City Refinery (currently Delaware City Refining Company or DCRC), Occidental Chemical Corporation (Oxychem), and Akzo Chemicals, Inc. Several of these sites are located within all or part of the 10.15-square-mile (mi^2) Red Lion Creek watershed (fig. 2). Considering the known and potential contamination of groundwater resources within the existing industrial footprint, a Groundwater Management Zone (GMZ) with three sub-zones: A, B, and Tybouts was established by the State of Delaware, Department of Natural Resources and Environmental Control (Delaware Department of Natural Resources and Environmental Control, 2011). In this report, the geographic boundary of the GMZ and the DCIA are considered identical and described as bounded by the Delaware



Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983
State Plane Delaware Transverse Mercator Projection

Figure 3. Location of study area including Standard Chlorine of Delaware, Inc. (SCD) Superfund Site, New Castle County, Delaware, monitoring well network, and lines of section A-A′, B-B′, and C-C′.

River to the east, Delaware Route 13 (approximately) to the west, Red Lion Creek (approximately) to the north and Dragon Run to the south (fig. 2). Land use is primarily industrial; however, many open fields owned by the oil refinery are leased for agriculture. There are no residential areas within the DCIA-GMZ as currently defined (U.S. Environmental Protection Agency, 2012), except for a part of the town of Delaware City located approximately 1.5 miles (mi) southeast of the Delaware City Refinery.

Environmental Setting

Land in the area has been settled for more than three centuries, when ancestral Coastal Plain forests were cleared for farming, and settlements were built near waterways for shipping and commerce. In the areas near the Delaware River, water sources are abundant and the availability of surface water and groundwater has led to a long history of resource development and water-based commerce. Easy access to water for transportation and resource use eventually led to industrial development of the Delaware City area, which is also served by major roads and highways (fig. 2).

Physiography and Cultural Features

The SCD site is in New Castle County, Delaware, which contains 60 percent of the State's population and has a population density of 1,263 persons per square mile (U.S. Census Bureau, 2013). Although the county is densely populated, there are no residences within 1 mile of the SCD site. New Castle County has experienced continued growth in recent years and current plans recommend that the SCD site should eventually be re-zoned for light industry or open space. Land cover at the site is partly wooded (approximately 20 percent), partly industrial (approximately 20 percent), containing concrete pads after infrastructure removal, and the remaining land cover (approximately 60 percent) is either marsh or open grassy field. There are other open grassy fields nearby, including agricultural fields to the west, where soybeans currently are grown (U.S. Environmental Protection Agency, 2011). Most industrial facilities in the area were built on land that had been previously cleared for farming, which was the primary land use for several hundred years until around 1950. The site is located on unconsolidated sediments of the North Atlantic Coastal Plain, approximately 8.5 mi from the Fall Line, where bedrock that forms the uplands of the Appalachian Piedmont is found in outcrops (fig. 1). Topography ranges from gentle slopes to steep scarps, with elevation ranging from sea level at Red Lion Creek to 70 feet (ft) above sea level south of the site. Soils present at the site are part of the Matapeake-Sassafras and Tidal Marsh associations (Black & Veatch, 2007). Soils generally are several feet thick and well-drained in upland areas. Thicker soils are present in marsh areas and overlie wetland sediments fringing Red Lion Creek.

Climate

The climate of northern Delaware is considered humid temperate, and is influenced by the proximity to the Delaware Bay and the Atlantic Ocean. Weather and climate data collected at the New Castle County airport (National Oceanic and Atmospheric Administration [NOAA] weather station 13781, "Wilmington New Castle Airport," Delaware, COOP ID 079595), located 5.2 mi from the SCD site (fig. 1), are considered representative of site conditions. The mean annual temperature is 54.4 degrees Fahrenheit (°F), with a mean daily maximum of 63.5 °F and a mean daily minimum of 45.1 °F. Mean annual precipitation is 42.8 inches (in.) and is fairly evenly distributed throughout the year, with each month receiving generally between 3 to 4 in. Snowfall averages 19 in., occurring generally from mid-December to mid-March. Storm events have historically produced daily rainfall in excess of 2 in. in every month of the year. Large storm events from June through October are often associated with tropical storms, hurricanes, or their remnants, and have produced daily rainfall totals ranging from 4 to 8 in. Storm systems throughout the year are capable of causing coastal flooding (Office of Delaware State Climatologist, 2013; Brinson, 2013).

Site History

A chronology of events is provided for the SCD facility (table 1), which was constructed on farmland in 1965 and began producing chlorobenzene compounds in 1966. A variety of chlorobenzene compounds (chlorobenzene, paradichlorobenzene, orthodichlorobenzene, and lesser amounts of metadichlorobenzene and trichlorobenzene) were produced from 1966 to May 2002 by combining (through reaction and distillation) chlorine and benzene from adjacent industrial facilities. Marketable products and wastes were stored in above ground tanks, some of which were heated. Leakage from pipes and tanks was collected in catch basins and sumps for processing; however, a crack in Catch Basin #1 of the wastewater treatment plant was detected and repaired in 1976 after leaking unknown quantities into the subsurface. A release of approximately 5,000 gallons (gal) of monochlorobenzene occurred in September 1981, while a railroad car located on the southwest part of the property was being filled. Efforts were made to contain and recover surface runoff, and contaminated soils were excavated and removed. After determining the extent of shallow groundwater contamination, a limited groundwater recovery and treatment system was installed in 1982 to address these releases (Black & Veatch, 2007).

A second major release occurred in January 1986, when a single large tank failed, damaging other nearby tanks and leading to the release of approximately 400,000 gal of paradichlorobenzene, and approximately 169,000 gal of trichlorobenzene. Other intermediary compounds were likely part of this mixture but the exact quantities are unknown, complicating the understanding of subsequent contaminant degradation during the years since the tank failure occurred. This major

Table 1. Chronology of events at the Standard Chlorine of Delaware, Inc. Superfund Site, New Castle County, Delaware.

[USGS, U.S. Geological Survey; EPA, U.S. Environmental Protection Agency; OU, operable unit, an EPA number identifying a part of a site with which remedial actions are associated; DNREC, Delaware Department of Natural Resources and Environmental Control; SCD, Standard Chlorine of Delaware, Inc.]

Event	Date
Standard Chlorine of Delaware, Inc. (aka Metachem) facility in operation	1966 to May 2002
Major releases leading to Site's National Priorities List (NPL) listing	1981 and 1986
Final Listing on the EPA NPL	07/22/1987
Remedial Investigation of shallow groundwater (OU-1), and soils and sediment (OU-2) completed	1992
Feasibility Study completed for OU-1 and OU-2	1995
Record of Decision selecting remedy for OU-1 and OU-2 signed	03/09/1995
Metachem files bankruptcy petition	05/10/2002
EPA and DNREC officially assume control of SCD site	5/14/2003
Amendment to 1995 Record of Decision	09/27/2004
USGS begins investigation of aquifer interaction and establishes long-term monitoring network in support of final remedy for groundwater (OU-4)	August 2005
Remedial action on-site construction started	07/17/2006
Completion of subsurface barrier wall within Columbia aquifer (OU-1)	May 2007
Final Remedial Investigation Report	August 2007
SCD shallow (Columbia aquifer) groundwater pump and treat system active inside the barrier wall	June 2008
Delaware City Refinery production well R-15 shut down	11/11/2009
Record of Decision selecting remedy for former plant area cap (OU-3) signed	09/29/2010
Red Lion Creek tide gate malfunction began during Hurricane Irene and caused a rise in creek stage, inundating parts of the wetland at the site	8/29/2011
Delaware City Refinery production well R-15 resumes pumping at steady 350 gallons per minute	10/26/2011
Estimated date for bringing contaminated groundwater migration under control (OU-4)*	December 2017

* U.S. Environmental Protection Agency (2011).

spill covered land surface within the immediate plant area, and also spread to the northwest entering an unnamed tributary of Red Lion Creek, eventually flowing to the confluence with Red Lion Creek. A high and ebbing tide at the time of the spill caused further dispersal along the shoreline of the creek both upstream and downstream. Booms, dikes, and a filter fence were used to minimize further discharge to the creek. A sedimentation basin was constructed on site to store contaminated sediments, in addition to several waste piles. Following the initial cleanup response, the facility was stabilized and the production of chlorobenzenes resumed (U.S. Environmental Protection Agency, 1995).

As a result of the 1986 release, the SCD site was listed on the EPA NPL (Superfund) registry on July 22, 1987 and has been the subject of continuing subsurface investigations and site remediation. Extensive groundwater contamination was identified in the surficial (unconfined) Columbia aquifer, and has persisted (Roy F. Weston, Inc., 1992; Black & Veatch Special Project Corporation, written commun. to Hilary Thornton [EPA], 2005). Site contaminants have also more recently been detected at monitoring wells screened in the sands of the upper Potomac Formation to the north, west, and east of the site (U.S. Environmental Protection Agency, 2011), although the extent of contamination in the confined aquifer has not been fully characterized. Chemicals of concern that have been detected at SCD are listed in Appendix 1 (U.S. Environmental Protection Agency, 2010, 2011), and many of these have been detected as Dense Non-Aqueous Phase Liquids (DNAPLs) in the dissolved phase. Non-Arachlor polychlorinated biphenyls (PCBs) have also been detected in soils, sediment, and groundwater (U.S. Environmental Protection Agency, 2011). In addition, elevated chloride levels at the site have been partially attributed to spills of hydrochloric acid (HCl) associated with the 1986 tank failures (Black & Veatch, 2007).

Major remedial activities at the SCD site have included the removal of contaminants and industrial equipment and the installation of a subsurface barrier "wall" or subsurface curtain consisting of clay and bentonite slurry installed so that the bottom of the wall is in contact with existing low-permeability clay layers. A pump and treat system was installed within the barrier wall to remove contaminants from groundwater, and to help prevent the spread of contamination by reversing groundwater gradients. A final remedy for deep groundwater (EPA Operable Unit-4) will be developed from results of current USGS site investigations.

Hydrogeologic Setting and Conceptual Flow System

The study area is located in the Atlantic Coastal Plain Physiographic Province in central New Castle County, Delaware (fig. 1), near the Delaware River and approximately 8.5 mi southeast of the Fall Line, which marks the eastern extent of the bedrock uplands of the Piedmont. The Atlantic Coastal Plain sediments consist of sequences of unconsolidated gravels, sands, silts, and clays that form a southeast-dipping wedge that rests on older metamorphic, igneous, and consolidated sedimentary basement rocks (Cushing and others, 1973; Trapp and Meisler, 1992). Sediments range from Cretaceous to Holocene in age and were deposited in fluvial, deltaic, and marine environments. Later reworking by modern and ancestral streams and rivers has resulted in the downcutting of Cretaceous age sediments and the deposition of new channel and terrace deposits that constitute part of the surficial aquifer and control local topography. Surface-water features and associated ancestral river channels are also important in shaping the flow system due to the abundant low-lying areas where groundwater intersects surface water.

Hydrogeology

Three major formations exist in the vicinity of SCD: coarse to medium sands and gravels of the Quaternary Columbia Formation; a confining unit of marine deposits consisting of fine silt and clay of the Upper Cretaceous Merchantville Formation; and alternating layers of clay, silt, and fine to medium sand of the Cretaceous Potomac Formation. Due to its fluvial origin, the sediments of the Potomac Formation can be quite heterogeneous and stratigraphically complex (McKenna and others, 2004). Sands present within the various fluvial depositional environments of the formation are discontinuous and variable in thickness and extent, which limits stratigraphic correlation; however, the Potomac Formation can be stratigraphically partitioned into three major sub-formations (upper, middle, and lower), each approximately 250 ft thick near the SCD study area. Sand layers found within each of these sub-formations vary in thickness and are interbedded with silts and clays, however, their bulk transmissivity provides suitable public and industrial water supplies. Thus, the water-bearing sands found within these geologic formations are regionally designated as the upper, middle, and lower Potomac aquifers, corresponding to the sub-formation name. Some previous studies refer to these aquifers as the upper hydraulic zone, middle hydraulic zone, and lower hydraulic zone (Black & Veatch, 2007), but this report will use the aforementioned nomenclature. The base of the upper Potomac aquifer has been evaluated using pollen data indicating that it represents the Upper/Lower Cretaceous boundary (table 2) (McKenna and others, 2004). The upper Potomac aquifer has been further divided into distinct hydrogeologic units within the SCD study area and is discussed later in this report, along with further discussion of the Columbia and Merchantville Formations as they relate directly to the SCD study area (see **Hydrogeologic Framework**, *this report*).

Table 2. Stratigraphic correlation chart of geologic and hydrogeologic units in the vicinity of the Standard Chlorine of Delaware, Inc. Superfund Site[1].

System	Series	Geologic formation and unit	Hydrogeologic unit
Quaternary	Holocene	undifferentiated (Qm)	Silt, clay, and peat
	Upper Pleistocene	Scotts Corners (Qsc)	Surficial aquifer (Columbia aquifer)
		Lynch Heights (Qlh)	
	Middle Pleistocene	Columbia (Qcl)	
Cretaceous	Upper Cretaceous	Merchantville (Kmv)	Merchantville confining bed
		upper Potomac (Kpt)	top sand aquifer (discontinuous)
			confining bed
			upper Potomac A-sand aquifer
			confining bed
			upper Potomac B-sand aquifer
			confining bed
			upper Potomac C-sand aquifer
	Lower Cretaceous	middle Potomac (Kpt)	middle Potomac aquifer
		lower Potomac (Kpt)	lower Potomac aquifer
Lower Paleozoic to Precambrian			Consolidated basement rocks

[1] Modified from Benson and McLaughlin, 2006; Martin and Denver, 1982.

The upper part of the middle Potomac aquifer contains an approximately 150-ft-thick sequence of fine-grained silt and clay, followed by alternating layers of sand and silt capable of producing sustained water. An approximately 50-ft-thick confining layer at the base of the middle Potomac aquifer distinguishes it from the lower Potomac aquifer, which is relatively more abundant in aquifer quality sands. Several industrial and water-supply wells are screened in the lower part of the Potomac Formation, particularly in the southeast part of the DCIA (fig. 2).

Pleistocene erosion due to the lowering of sea level during the last glacial period resulted in rivers downcutting into the Merchantville and Potomac Formations in dendritic patterns that correspond with several present day surface-water features. In some locations, these channels were refilled with undifferentiated sediments (sand, gravel, and clay) of the Columbia Formation (Phillips, 1987), or other Quaternary age sediments. Other more linear erosional features exist such as the Reybold paleochannel, which runs parallel to the present day Delaware River and likely formed during Pleistocene deglaciation from the release of floodwaters (Jengo and others, 2013). Holocene sediments overlying the Columbia Formation are also present as marsh deposits and consist of black to dark gray organic rich silty clay with beds of peat ranging in thickness from 1 to 40 ft (Ramsey, 2005).

Flow System

Conceptualization of the flow system provides a context for investigations described in this report. Understanding the groundwater-flow system is particularly important for defining and delineating controls on the movement of water and contaminants, and is critical for the development of remediation strategies. Water in the Atlantic Coastal Plain enters the aquifer system as rainfall and snowmelt that moves through the soil and subsoil to the water table. Most of the water that reaches the water table in the surficial aquifer discharges to local streams (Cushing and others, 1973). Some of the groundwater discharges to larger streams and rivers and in coastal zones, may discharge to wetlands, tidal rivers, or estuaries. A relatively small part of groundwater recharge becomes part of a deeper flow system that includes confined aquifers that extend downdip toward the Atlantic Ocean (Shedlock and others, 2007).

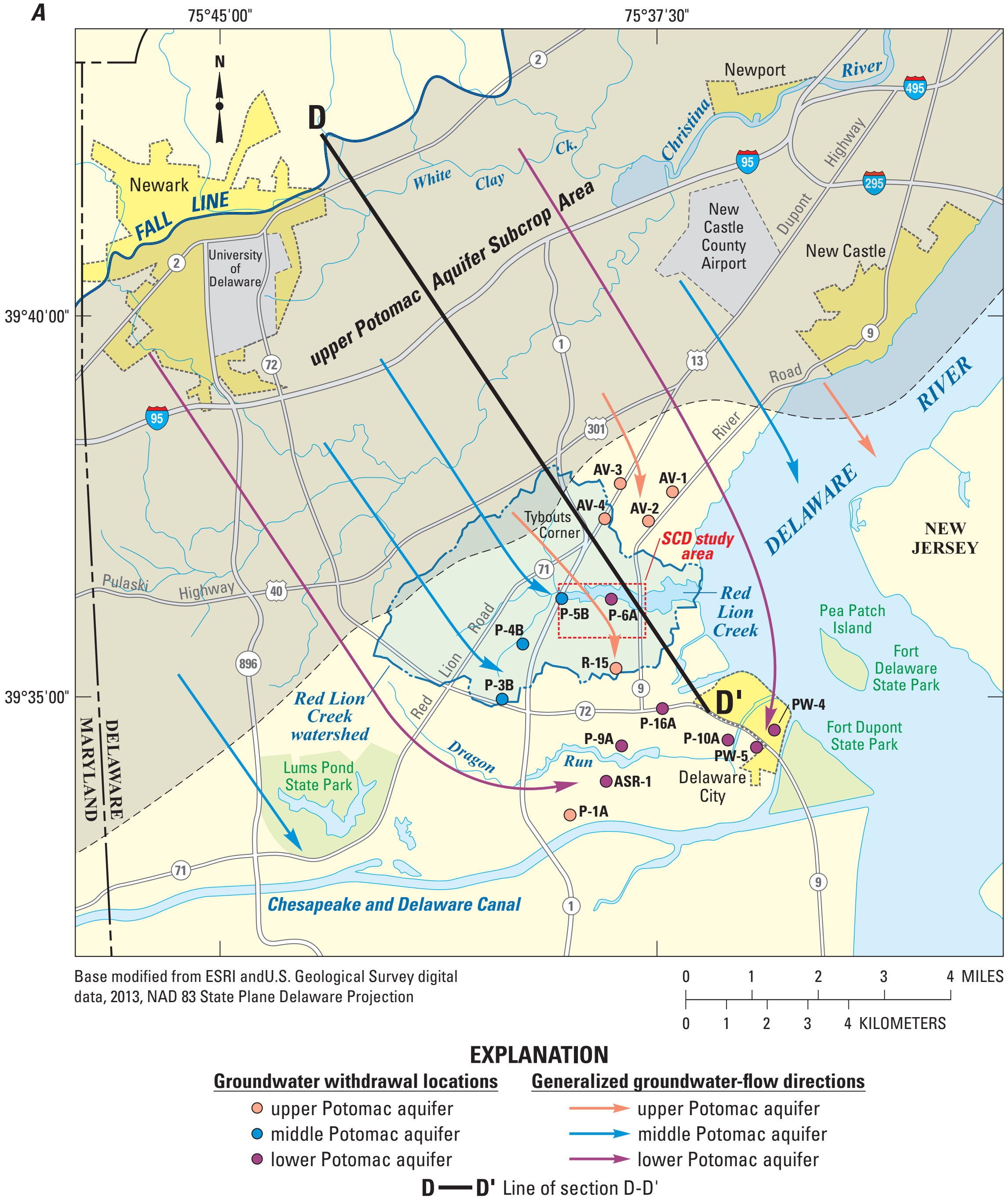
The regional flow system within the confined aquifers of the Potomac Formation is characterized by relatively slow downdip (southeast) flow, controlled mainly by hydrostratigraphy (figs. 4a, b). Most of the regional recharge occurs to the northwest of the site where the upper Potomac aquifer subcrops under Quaternary surficial sediments, primarily of the Columbia Formation. The middle and lower Potomac aquifers tend to contact basement rocks in an onlapping unconformable pattern (Benson and McLaughlin, 2006; McKenna and others, 2004), and are likely recharged by leakage through confining layers (fig. 4b). Models of groundwater flow in the Maryland and Delaware parts of the Atlantic Coastal Plain estimate average regional flow rates of approximately 0.1–0.2 feet per day (ft/d) in the aquifers (Fleck and Vroblesky, 1996). These rates are affected by pumping wells, which also affect groundwater-flow directions (fig. 4a). Historical long-term water use has led to documented regional and local cones of depression in the potentiometric surface of the Potomac aquifer associated with production well fields (Martin, 1984). Water levels within Potomac aquifer layers vary depending on production well demands from wells screened in each particular aquifer. Groundwater salinity in some locations has increased from pumping-induced recharge of Delaware River water to the aquifer system (Phillips, 1987). Vertical flow in the region is consistently downward from the surficial aquifer to the Potomac aquifer, and downward between sand layers (aquifers) within the Potomac Formation. Limited cross-formational flow is possible, especially where confining units are thin or absent (fig. 4b); this may provide recharge to the middle and lower Potomac aquifers without extensive outcrop/subcrop areas.

Local flow conditions in the study area are similar to regional flow patterns. The saturated part of the Columbia Formation forms a surficial aquifer (herein the Columbia aquifer), and the flow system within this aquifer is unconfined and conceptualized as being controlled mainly by topography and the location of surface-water features. Groundwater in the surficial aquifer is recharged by direct infiltration of precipitation. Previous studies (Black & Veatch, 2007) have shown the depth to water ranges from 20 ft below land surface in the uplands to near land surface in wetland (lowland) areas, where elevation approaches mean sea level. Flow is generally from higher to lower land-surface elevations, resulting in groundwater discharge to small streams and creeks. In the vicinity of the SCD site, groundwater flow in the Columbia aquifer is generally northward toward Red Lion Creek and away from the local topographic high just southeast of the barrier wall (fig. 3).

Locally, recharge from the Columbia aquifer to the underlying Potomac aquifer occurs where confining units are thin or absent. Water level, or head, in the Potomac aquifer is generally considered confined although spatially distinct areas exist where no confining unit is present between the base of the surficial (Columbia) aquifer and the top of the confined (Potomac) aquifer. In the vicinity of SCD, groundwater flow in various layers of the Potomac aquifer is generally downdip from northwest to southeast, however flow directions are influenced by local pumping of the confined aquifers (figs. 4a, b) and are the subject of detailed discussion in this report.

Surface-Water Features

The most prominent nearby surface-water feature is the Delaware River, which conceptually serves as an eastern flow boundary for both surface-water and groundwater discharge. The Delaware River experiences semi-diurnal tides; the tide cycles through a high and low twice each day, with one of the two high tides being higher than the other, and one of the two low tides being lower than the other. In and around the DCIA



Base modified from ESRI andU.S. Geological Survey digital data, 2013, NAD 83 State Plane Delaware Projection

Figure 4. Regional flow system *(A)* map showing surface-water features, subcrop areas of the Potomac aquifer system, major groundwater intakes near the Standard Chlorine of Delaware, Inc. Superfund Site (SCD) study area, and generalized flow lines for the regional groundwater system, and *(B)* generalized cross section showing recharge areas and the confined aquifer flow system.

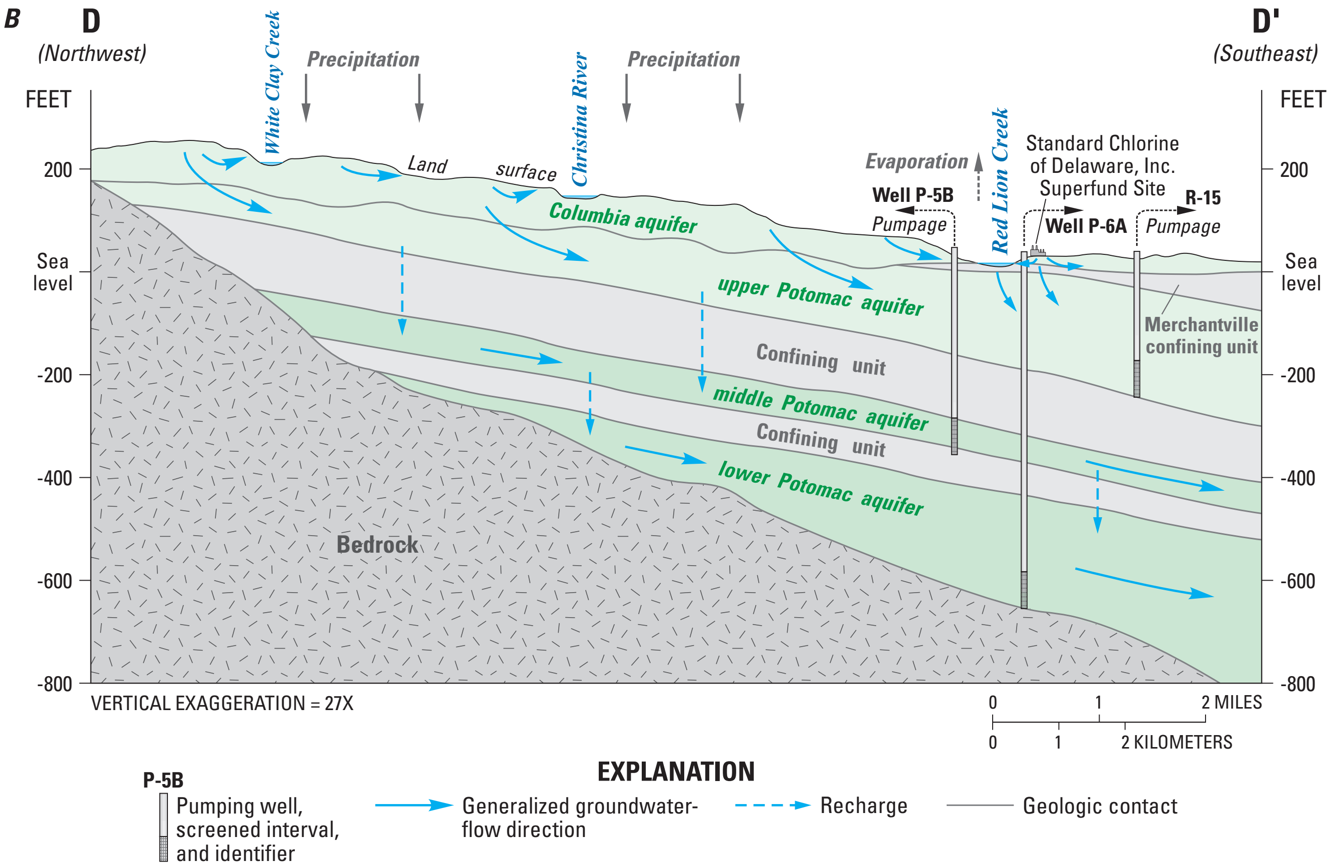


Figure 4. Regional flow system *(A)* map showing surface-water features, subcrop areas of the Potomac aquifer system, major groundwater intakes near the Standard Chlorine of Delaware, Inc. Superfund Site (SCD) study area, and generalized flow lines for the regional groundwater system, and *(B)* generalized cross section showing recharge areas and the confined aquifer flow system.—Continued

on the western shore of the Delaware River, small streams drain into creeks (approximately 10-mi^2 watersheds), which then drain eastward directly to the Delaware River. Dragon Run, located to the south, and Red Lion Creek, located to the north, are the primary drainages in the DCIA (fig. 2). Dragon Run and Red Lion Creek are occasionally used to provide industrial supply water to the Delaware City refinery (Delaware City Refining Company).

Surface water at and near the SCD site is present in Red Lion Creek, its tributaries, and the nearby marsh system connected to the creek. Surface-water runoff at the SCD site generally moves north into Red Lion Creek, or into small streams that drain north into the creek. The average depth of Red Lion Creek is 0.3 to 3.3 ft (Roy F. Weston, Inc., 1992). Shallow groundwater discharges to the creek and to wetland areas surrounding the creek. Water from Red Lion Creek drains during low tide through a tide control structure located approximately one-half mile downstream from Delaware State Route 9 (fig. 2). The Creek is not normally subject to tidal influence because gates on the tide control structure close during high tide to prevent water from entering from the Delaware River (fig. 5). Tide control structures are common on the Delaware coastline and were installed for protection from storm surge and flooding, and to lower water levels along creeks to protect farm land and promote better drainage (Mickowski, 1986).

Study Approach and Data-Collection Methods

A variety of approaches and data-collection methods were used to create and refine a conceptual model of the local hydrogeologic framework, including exploratory drilling into the Potomac Formation, geophysical surveys, groundwater and surface-water-level monitoring, pumping a local production well, and examination of local pumping influences on groundwater. USGS involvement at the SCD site began in 2005 with a site assessment of the existing water-level monitoring network, including the evaluation of seven wells screened in the Potomac aquifer at that time. From 2007 through 2010, surface and borehole geophysical tools, in combination with exploratory drilling, were used to locate sand layers within the Potomac aquifer and to determine the presence, absence, lateral extent, and thickness of the confining clay and silt layers (see **Hydrogeologic Framework**, *this report*). New wells were installed in stages, expanding the Potomac Aquifer Study monitoring network to include wells screened in multiple (deeper) sand layers within the upper Potomac aquifer. Time-series water-level data were used to evaluate long-term (multi-year) changes in groundwater levels in response to water withdrawals and variable recharge from infiltration of precipitation, tidal fluctuations, and surface-water leakage (see **Hydrology**, *this report*). Production well pumping was conducted to evaluate the cross-aquifer connection locally between the water table and confined flow system (see **Hydrology**, *this report*). Finally, the effects of water withdrawals on local and regional flow systems also were examined (see **Water Withdrawal Influences on the Local Flow System**, *this report*).

Exploratory Drilling

A new site drilling program was developed in 2007 in response to the detection of site-related contaminants in upper Potomac aquifer well PW-1 in 2003, and in response to the need for a better understanding of the distribution of confining clays in the upper Potomac aquifer underlying the site. The USGS provided technical assistance to EPA and DNREC in developing a drilling approach first by investigating approximately one-quarter mile beyond the SCD site boundary, and then drilling adjacent to (east, north, west, and south) the site. Twenty-one additional monitoring wells (table 3) were installed as part of the Potomac Aquifer Study from 2007–10. Each well was completed with a 5-ft stainless steel screen, targeting specific aquifer intervals for water-quality sampling and long-term compliance monitoring. There has been no drilling into the upper Potomac aquifer in the former plant area (southern half of the area inside the barrier wall) due to the risk of carrying contaminants downward from the Columbia aquifer during the drilling process, and therefore, the distribution of confining clay layers in the upper Potomac Formation beneath

Figure 5. Red Lion Creek tide control structure with reinforced dike and five outflow gates, looking from the Delaware River at low tide in 2010. [Photograph by Todd Keyser, Delaware Department of Natural Resources and Environmental Control.]

the site is inferred from the drilling logs of wells completed immediately adjacent to the former plant area (fig. 3).

Rotosonic drilling was used to achieve nearly continuous core recovery to a targeted depth of 200 to 250 ft below land surface at five locations where deep wells also were completed (PW-2D, PW-8, PW-10D, PW-11D, and PW-16 (table 3; fig. 6) The drilling bit and core barrel were advanced in 10-ft increments from land surface downward, and descriptions of lithology from recovered cores were recorded by an on-site professional geologist. A vertical water-quality profiling approach was also used, whereby a temporary screen was installed into the borehole at each depth having water-bearing sands with at least a 10-ft separation from the previous sand interval. Water-quality samples were collected for each sand interval after it was pumped long enough to purge any drilling water introduced into the formation. Boreholes at each drilling location were logged by USGS using a natural gamma tool, and results were compared with descriptions of lithology to determine screen placement before final well construction was completed. Multiple nested wells were installed at six locations, and include wells screened in the Columbia aquifer and (or) in successive sands of the upper Potomac aquifer (table 3). In this study, new wells completed in the Columbia Formation were named “CW” (Columbia well). Multiple new wells completed in the upper Potomac Formation were named “PW” (Potomac well), and are further designated as “S,” shallow, or “D,” deep (table 3).

The potential for cross-formation contamination resulted in several design considerations for the drilling program, including the use of secondary (double) casings at all wells, and drilling depth restrictions where contaminants were encountered. Double casings were installed at all drilling locations using mud rotary techniques prior to beginning rotosonic profiling. As required by DNREC, double casings were installed at each new well location, with the bottom of the casing typically set at least 2 ft into the existing confining

Table 3. Characteristics for wells installed during Potomac Aquifer Study exploratory drilling, 2007–10.

[DNREC, Delaware Department of Natural Resources and Environmental Control; DGS, Delaware Geological Survey; bls, below land surface; color coding reflects aquifer depth: green = Columbia and upper Potomac-top, pink = upper Potomac-A, orange = upper Potomac-B, yellow = upper Potomac-C; NGVD 29, National Geodetic Vertical Datum of 1929]

Local site name	DNREC permit number	DGS well identfier	Depth of boring (feet bls)	Screened aquifer	Altitude of screened interval, NGVD 29 (feet)	Date well installed
CW-11	228525	Dc42-50	40	Columbia	-12 to -17	6/28/09
CW-4	219241	Dc53-83	69	Columbia	-9 to -14	5/11/07
PW-4S	218938	Dc53-84	80	upper Potomac-top sand	-21 to -26	5/7/07
PW-7S	218549	Dc52-79	85	upper Potomac-top sand	-26 to -31	3/31/07
PW-5D	218552	Dc43-30	110	upper Potomac-A	-89 to -94	3/25/07
PW-5S	218550	Dc43-29	71	upper Potomac-A	-59 to -64	3/27/07
PW-6D	218554	Dc42-44	180	upper Potomac-A	-128 to -133	4/19/07
PW-6S	218553	Dc42-43	107	upper Potomac-A	-58 to -63	4/20/07
PW-8	219238	Dc53-86	162	upper Potomac-A	-101 to -106	5/15/07
PW-10D	228519	Dc43-37	250	upper Potomac-A	-142 to -147	8/4/09
PW-11	228522	Dc42-51	135	upper Potomac-A	-115 to -120	8/21/09
PW-10	228524	Dc43-36	107	upper Potomac-A	-72 to -77	8/22/09
PW-2D	231209	Dc53-187	250	upper Potomac-B	-175 to -180	6/6/10
PW-16	231210	Dc52-173	240	upper Potomac-B	-172 to -177	6/17/10
PW-11D	228520	Dc42-52	255	upper Potomac-C	-215 to -220	7/21/09
Locations where site-related contaminants have been detected						
PW-4D	218725	Dc53-85	150	upper Potomac-A	-83 to -88	4/26/07
PW-9	228523	Dc53-133	148	upper Potomac-A	-83 to -88	7/9/09
PW-12	228521	Dc52-127	132	upper Potomac-A	-79 to -84	8/8/09
PW-14	231211	Dc42-57	69	upper Potomac-A	-57 to -62	5/18/10
PW-17	231212	Dc42-58	105	upper Potomac-A	-83 to -88	6/2/10
PW-13	231310	Dc42-56	170	upper Potomac-A	-115 to -120	6/3/10

Figure 6. Photographs showing *(A)* rotosonic drilling, *(B)* recovered core, *(C)* core from Merchantville confining unit, and *(D)* core from upper Potomac confining unit. [Photographs by U.S. Geological Survey.]

units (Merchantville or upper Potomac) to limit cross-formation contamination from the Columbia into the upper Potomac Formation. Depth of drilling in the upper Potomac was limited at some locations because benzene and chlorobenzene compounds were detected during drilling (table 3) using a photo ionization detector (PID) for volatile gases. Concern for cross-formation contamination had previously led to the abandonment of well PW-1 in 2007 due to questions regarding well integrity. For monitoring purposes, well PW-1 was replaced with well PW-4D, located approximately 100 ft to the south.

Geophysical Surveys

The results of surface-geophysical surveys and borehole-geophysical logging from this study were used together with previously collected geophysical logs to better define site scale subsurface features and how they relate to drilling logs and hydrogeology. The locations of geophysical surveys were determined with a global positioning system (GPS) for geospatial referencing in a geographic information system (GIS). Natural gamma logs were collected for selected wells in 2006, prior to barrier wall installation and for each new boring location during 2007–10. Electrical and seismic surface-geophysical methods were used at the site beginning in 2008 (Degnan and Brayton, 2010), with additional data collection and interpretation currently ongoing (2014). Natural gamma radiation borehole geophysical logs were collected at selected wells to differentiate fine-grained from coarse-grained sediment. Selected gamma log results (gamma responses) are presented in figure 7. Descriptions of standard borehole-geophysical logging methods and interpretation can be found in Keys (1990). Direct current (DC) resistivity measurements taken from core that was collected and preserved during drilling has assisted in the interpretation of data from surface DC resistivity surveys, enabling features to be verified at specific depths (Degnan and Brayton, 2010). An analysis of boring logs from drilling, in combination with DC resistivity data, has furthered the understanding of how the flow system varies laterally and with depth.

Water-Level Monitoring Network

A water-level monitoring network was established for the collection of discrete and continuous water-level data in order to provide a better understanding of the local flow system (fig. 3). Data collection was focused on monitoring water levels in wells screened in the upper Potomac aquifer; however, shallow water-table reference wells were measured to help understand aquifer recharge and a stage recorder on Red Lion Creek was measured to help understand the response of creek stage to precipitation events. Sites were established and water-level data were collected following standard USGS procedures (Cunningham and Schalk, 2011). Delaware Geological Survey (DGS) names were obtained for each well and well characteristics were added to the USGS Groundwater Site Inventory (GWSI) database. The vertical datum for all sites is the National Geodetic Vertical Datum of 1929 (NGVD 29); local datum conversion from NGVD 29 to the North American Vertical Datum of 1988 (NAVD 88) is -0.78 ft as computed in datum reference tables for NOAA tide station 8551762 located near Delaware City (fig. 1). Other site characteristics for wells and a stage recorder at Red Lion Creek are listed in Appendix 2. Professional surveys were conducted at the site in 2006, 2008, and 2010 using differential GPS. Location and elevation data from these surveys were compared with existing data in the USGS database for consistency, and updated when necessary.

USGS data collection began in August 2005 with a set of discrete water-level measurements at existing Potomac aquifer wells and expanded over time to include continuous water-level measurements at approximately 16 sites and discrete monthly water-level measurements at approximately 45 sites. Continuous water-level measurements were made every 15 minutes using vented pressure transducers. Instrumented sites included 2 wells screened in the Columbia aquifer (Ion-MW3 and CW-11), 13 wells screened in the upper Potomac aquifer (MW-11, MW-12, PW-2D, PW-3, PW-4D, PW-5S, PW-6S, PW-7S, PW-11, PW-11D, PW-13, PW-16, and PW-17), 1 well screened in the lower Potomac aquifer (Tidewater-12), and Red Lion Creek at the Delaware Route 9 (River Road) bridge. Red Lion Creek was instrumented for collection of stage (surface-water level or height) data in June 2007, and is still an active data-collection site. The watershed area upstream of the stage recorder is 8.90 mi^2 (fig. 2). Some minor data gaps exist for creek stage because Red Lion Creek is subject to freezing from mid-December through the end of February, and typically freezes for up to 1 week at a time. A summary of the period of record for sites that had continuous data collection is listed in Appendix 2.

Monthly discrete water-level measurements were collected at approximately 45 sites, including sites instrumented with pressure transducers; site conditions or access issues decreased the total number of measurements during some months. Measurement dates were coordinated with EPA's site consultant, HydroGeoLogic, Inc., which measured water levels in a separate network of shallow Columbia aquifer wells associated with the remedial pump and treat system. All water-level data collected by the USGS are stored in the National Water Information System (NWIS) database, and are publically available at http://waterdata.usgs.gov/nwis.

Production-Well Pumping to Evaluate Aquifer Interconnections

A 3-day constant rate pumping test was conducted by the USGS from August 28–31, 2010 on well OR-6A (fig. 3) to evaluate the interconnection of the upper Potomac aquifer and overlying surficial Columbia aquifer, and the interconnection of different sand layers within the upper Potomac aquifer. The study area for this evaluation included monitoring locations inside and outside the SCD barrier wall and wells located on surrounding properties. The pumping period was preceded by a period of limited rainfall, mitigating potential recharge to the surficial aquifer and confined aquifer system. Only 0.30 in. of precipitation was recorded in the 14 days preceding the pumping period, and no precipitation occurred during the pumping period.

Design and Equipment

An evaluation of water-level responses in wells during pumping of well OR-6A was designed using: (a) results published during a previous pumping test conducted at well OR-6A (fig. 3) from October 1–3, 1990 by Roy F. Weston, Inc. (Roy F. Weston, Inc., 1992), (b) data collected from the existing monitoring well network, and (c) lithologic observations from exploratory drilling. Well OR-6A was selected for pumping because of its construction characteristics, the length and depth of screen, the absence of site-related contamination, and a discharge location near Red Lion Creek. Well OR-6A is an 8-in.-diameter, single-cased steel well screened 102–176 ft below land surface and located approximately 1,800 ft northwest of the site. The sampling history for this well shows only trace detections of volatile organic compounds (VOCs). During pumping, PID readings were collected approximately every hour for the initial 24 hours and intermittently thereafter; no detections were noted. Water levels at the pumping well (OR-6A) were collected from a 1-in. PVC observation tube within the well using an electric water-level meter. Access and permission to pump well OR-6A was granted by the Delaware City Refining Company (Aaron Vahid, Delaware City Refining Company, oral commun., 2010).

Prior to the 72-hour pumping period, a step-drawdown test was conducted on August 27, 2010 to evaluate the pumping efficiency of the well using four discharge rates ranging from 350–485 gallons per minute (gal/min) in step durations of 1 hour at each rate. A 2-stage Goulds submersible pump with a 30 horsepower Franklin Electric motor was installed to a depth of 105 ft below land surface and 2.5 feet below the top of the well screen. After completion of the step test, a 450 gal/min pumping rate was selected and approved in consultation with DNREC and EPA.

The pumping of well OR-6A was scheduled following the complete recovery of the upper Potomac aquifer after the November 2009 temporary idling of refinery production well R-15, located approximately one-half mile south of SCD (fig. 2). Water levels at monitoring wells PW-3 and MW-11, located to the south of the SCD site, reached full recovery from the pumping effects of well R-15 in June 2010 at a distance of approximately 2,900 ft northeast of well R-15. Pumping well OR-6A and observation well PW-11 screened in the upper Potomac aquifer and located west and east of SCD, respectively, reached full recovery in April 2010.

The pumping of well OR-6A began August 28, 2010 at 13:40 EST, and a constant discharge rate of 450 gal/min was achieved within 2 percent (± 9 gal/min) for the duration of pumping. The discharge rate was measured using a Layne and Bowier Circular Orifice Table for a 6-in. pipe and 5-in. orifice (Cunningham and Schalk, 2011). The pump was powered by diesel generator for the duration of the 72-hour period without interruption or power loss. Pumped water was discharged northeastward towards the wetland area and Red Lion Creek by agreement between the USGS, EPA, and DNREC. Data collected by USGS personnel at the pumping well (OR-6A) included discrete water levels, water quality, VOCs in the headspace using a PID, and pump discharge and performance parameters throughout the duration of active pumping.

Water-Level Measurements

Water-level measurements during the pumping period were collected from the USGS Potomac Aquifer Study well network and from the Columbia aquifer well network maintained by EPA site contractor HydroGeoLogic, Inc. Wells in the USGS Potomac Aquifer Study network, well characteristics and integrity, procedural methods, and instrument maintenance followed technical guidance provided in Groundwater Technical Procedures of the USGS (Cunningham and Schalk, 2011). During the evaluation of water-level responses in wells during pumping of well OR-6A, HydroGeoLogic, Inc. measured discrete water levels in the majority of the Columbia aquifer well network. These wells are not inventoried in the USGS NWIS database because of incomplete drilling records, however, known characteristics for these wells are provided in Appendix 3 (wells are identified by local site name and DGS identification number if available).

Discrete and continuous water-level measurements were collected in 81 wells from August 26 through September 1, 2010. Of these measured wells, 52 were completed in the Columbia Formation, 24 in upper Potomac A-sand, 2 in the upper Potomac B-sand, 2 in the upper Potomac C-sand, and 1 well (Tidewater-12) in the lower Potomac aquifer (Appendix 3). Continuously monitored wells were instrumented with In-Situ Level Troll vented pressure transducers using an observation interval of 15 minutes and were checked approximately every 6 hours using electric water-level meters. Monitoring well PW-6S was instrumented prior to the start of pumping to a 5-minute measurement frequency during the pumping of well OR-6A. Continuous measurements were calibrated using discrete monthly observations and verified during the pumping period using additional discrete measurements.

Measuring the Effects of Water Withdrawals

The influence of water withdrawals on local and regional flow systems was examined because of the potential to influence flow direction and contaminant movement. Groundwater and surface-water withdrawal locations within approximately 3 mi of SCD were considered for this part of the study (fig. 2; table 4). Groundwater is used for both industrial and public water supply and surface water is used only for industrial water supply. Water use information for drinking water and industrial water withdrawal locations using at least 10,000 gallons per day (gal/d) was compiled from annual reports submitted to DNREC, summarized by month and year. These reported withdrawals were compared to water levels in monitoring wells at SCD to look for obvious relations between local withdrawals, and water levels and groundwater flow. Four supply wells (AV-1, AV-2, AV-3, and AV-4), are located to the north of Red Lion Creek and upgradient of SCD (fig. 2), and the remaining wells are located south of Red Lion Creek. Annually averaged daily use was calculated in million gallons per day (Mgal/d) and tabulated for comparison (table 4). Withdrawal locations having a daily water use less than 10,000 gal (0.01 Mgal/d), which includes most domestic and small business users, were not considered in this evaluation because of their limited impact on aquifers relative to other large users locally.

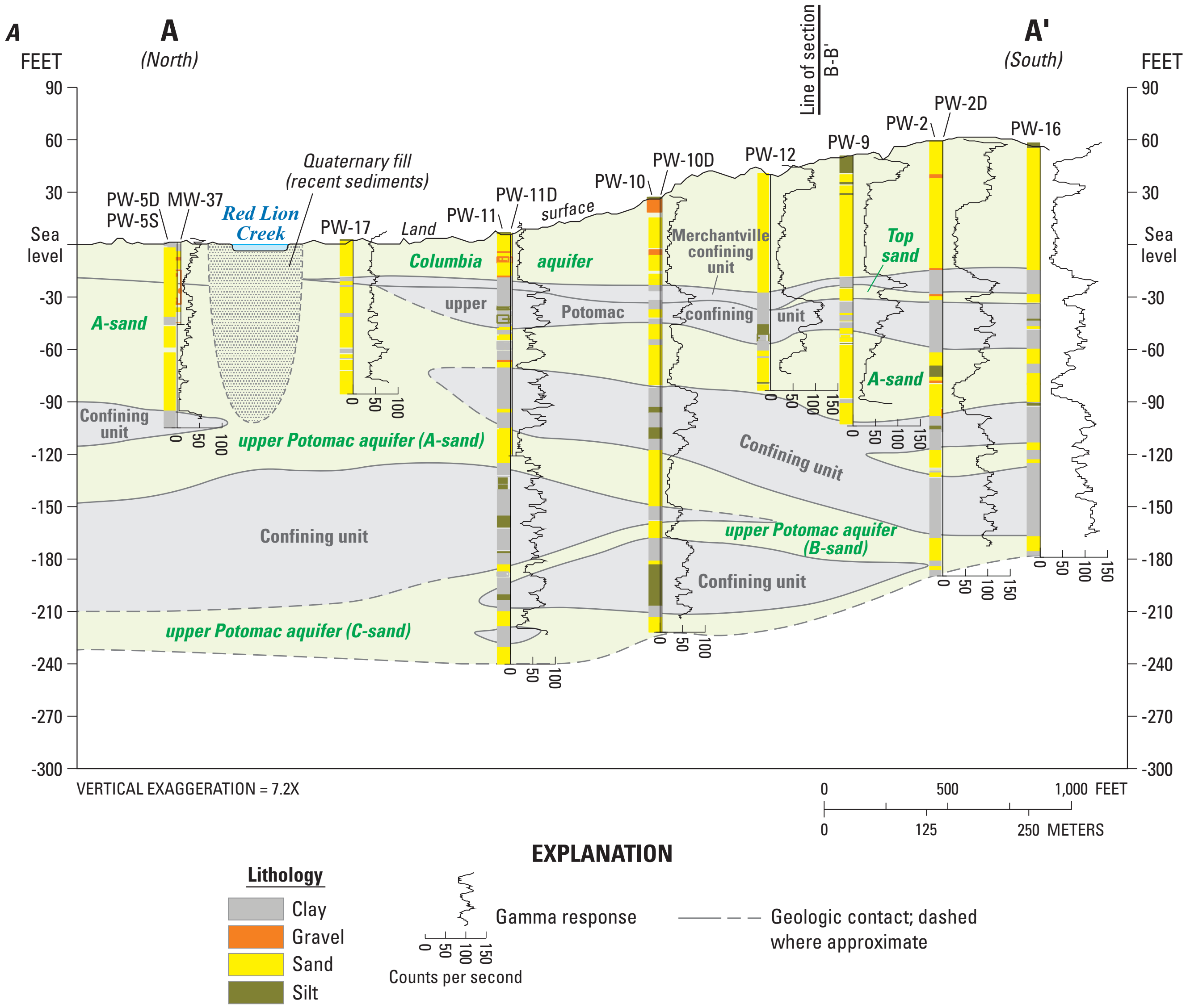


Figure 7. Wells, lithologic descriptions, and gamma responses for *(A)* cross section A-A′ from north to south, and *(B)* cross section B-B′ from northwest to southeast.

Hydrogeologic Framework

The hydrogeologic framework of the Columbia and Potomac Formations underlying the SCD site is complex and the heterogeneity of hydraulic properties of aquifers contained within these formations is enhanced by channel geometry and discontinuous confining layers. Defining the extent, altitude and thickness of confining silt and clay beds is important because they may limit contaminant transport and distribution. However, paleochannel and flood-plain deposits from braided, anastomosed, and meandering fluvial system environments are also found within the formations, further complicating interpretation of the connections between aquifer sand layers (McKenna and others, 2004).

Interpretations of the hydrogeologic framework of the SCD site are based on exploratory drilling and geophysical survey data collected at the site for this study in the context of the regional framework interpreted by the DGS (McKenna and others, 2004). Data from other studies at the site were also used; however, previous studies were largely focused on the Columbia Formation due to the extent of contamination discovered in the Columbia aquifer. As part of those previous drilling explorations, permanent Columbia aquifer observation wells were installed throughout the 1980s and early 1990s, and many are still in use. Prior to the installation of the contaminant barrier wall, extensive geologic characterization of the Columbia Formation on site was completed using cone penetrometer technology as part of the barrier wall engineering

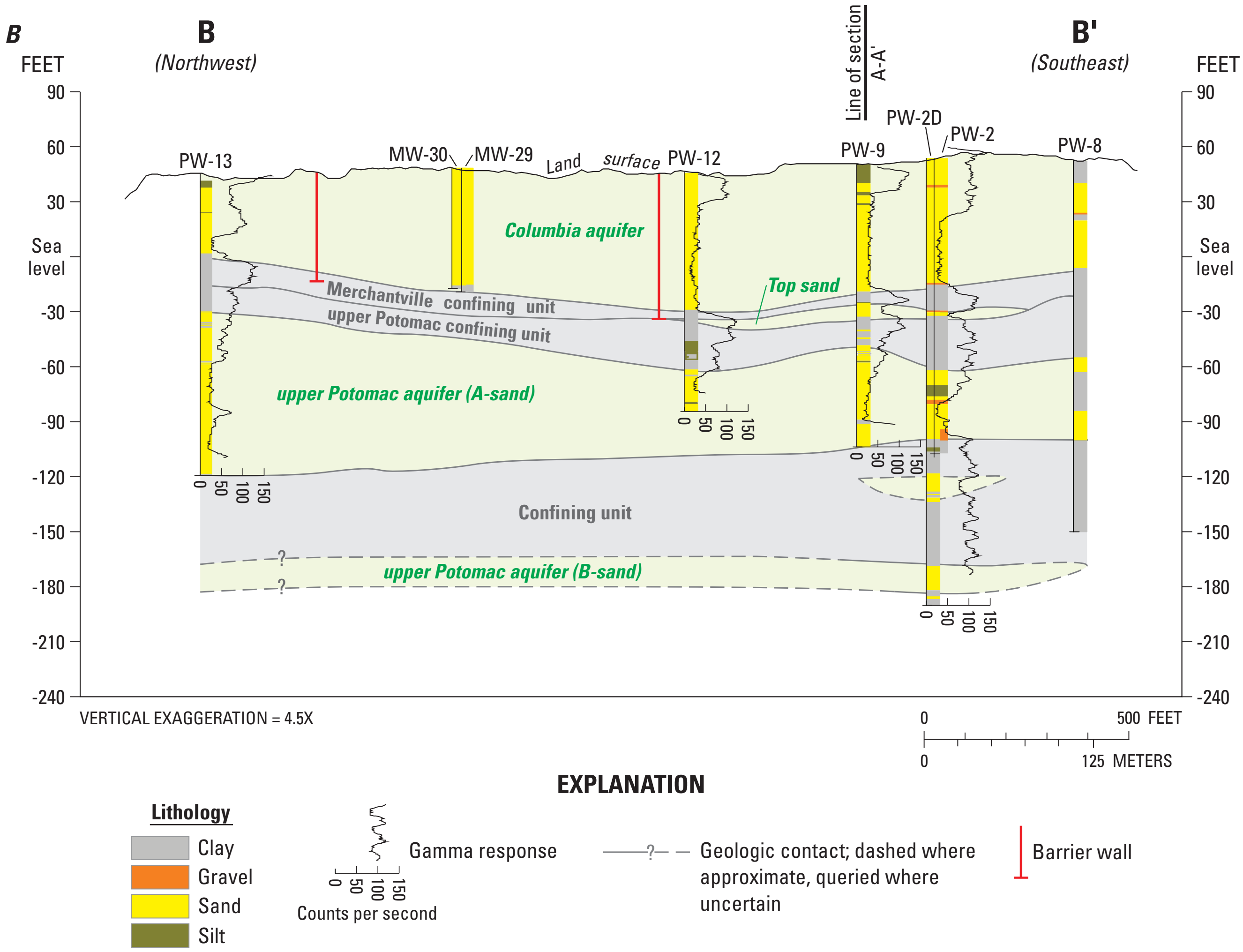


Figure 7. Wells, lithologic descriptions, and gamma responses for *(A)* cross section A-A′ from north to south, and *(B)* cross section B-B′ from northwest to southeast.—Continued

process (Black & Veatch, 2007). These data provided additional boring locations where the bottom of the Columbia and (or) the top of the Merchantville Formations were identified.

More recent efforts (such as this study) have focused on the upper Potomac Formation, and have used an iterative process over several years alternating between periods of drilling and subsurface exploration using geophysical resistivity surveys. Additional insight was gained by reviewing information from the adjacent Oxychem site to the east (lithology, interpretive cross sections, and borehole geophysical logs). To the west of SCD, lithologic information for the upper Potomac is limited. Drilling conducted during this study from 2007–10 (table 3; fig. 6) has provided information on contaminant distribution, information on the distribution of sand and clay layers to a depth of 250 ft in some locations, and enabled the identification of three locally distinct and continuous sand units (aquifers) within the upper Potomac aquifer (table 2), and a Cretaceous age discontinuous sand layer at the top of the upper Potomac Formation. An understanding of the complex hydraulic connections between these sands, which also helps to distinguish them, has been developed through the analysis of water-level monitoring data and from observations during the pumping of well OR-6A (see **Hydrology**, *this report*).

Columbia Formation, Columbia Aquifer, and Other Quaternary Age Sediments

Unconfined saturated sands within the Pleistocene age Columbia Formation (Qcl) form the uppermost unconfined (surficial) aquifer at the SCD site, referred to as the Columbia aquifer (fig. 7). Locally, the Columbia Formation is 8 to 84 ft thick (Black & Veatch, 2007), averaging 56 ft thick and is composed of orange to yellow to reddish-brown sand with some coarse sand, gravel, and scattered beds/stringers

Table 4. Annually averaged daily water withdrawal at major withdrawal locations near the Standard Chlorine of Delaware, Inc. Superfund Site, New Castle County, Delaware.

[DGS, Delaware Geological Survey; DNREC, Delaware Department of Natural Resources and Environmental Control; SCD, Standard Chlorine of Delaware, Inc. Superfund Site; bls, below land surface; Mgal/d, millon gallons per day; wells are color coded based on Potomac aquifer hydrologic zone: pink = upper, blue = middle, purple = lower; names in parentheses indicate previous well name used; --, no data]

Name of location	DNREC permit number	DGS well identifier	Distance from SCD (miles)	Direction from SCD	Date constructed	Diameter of screened interval (inches)	Altitude of land surface (feet)	Depth of screened interval (feet bls)	Altitude of screened interval (feet)	Potomac aquifer hydrologic zone	Hole depth (feet)	Annually averaged daily water withdrawal (Mgal/d)				
												2001	2005	2007	2010	2012
Groundwater withdrawal locations north of Red Lion Creek																
AV-1	43962	Dc33-07	2.09	North	9/17/79	12	19	155–215	-136 to -196	upper	215	1.39	1.44	1.45	1.44	0.90
AV-2	43963	Dc33-08	1.56	North	3/10/79	12	28	125–225	-97 to -197	upper	225	0.29	0.29	0.25	0.15	0.31
AV-3	104641	Dc32-22	2.08	North	7/28/95	12	60	131–180	-72 to -115	upper	180	0.76	0.83	0.79	0.78	0.65
AV-4	177379	Dc32-35	1.56	North	4/11/01	10	55	117–142	-62 to -87	upper	142	0.11	0.09	0.10	0.20	0.14
Groundwater withdrawal locations south of Red Lion Creek																
R-15 (P-15)	10066	Dc52-24	0.72	South	4/2/56	12	70	302–333	-232 to -263	upper	364	0.52	0.49	0.44	0.01	0.49
P-1A	53065	Ec22-17	3.03	South	9/9/83	12	9	237–280	-228 to -271	upper	280	0.19	0.40	0.42	0.12	0.47
P-3B (P-3A)	216291	Eb15-17	2.19	Southwest	10/26/07	14	78	518–548	-440 to -470	middle	560	0.15	0.1	0.19	0.11	0.15
P-4B (P-4A)	216292	Dc51-43	1.55	West	9/11/07	14	37	375–483	-338 to -446	middle	500	0.17	0.13	0.02	0.10	0.11
P-5B	72826	Dc41-57	0.98	West	2/22/88	10	12	343–515	-331 to -503	middle	525	0.33	0.25	0.06	0.04	0.13
P-6A	10057	Dc42-06	0.35	Northwest	11/10/55	8	34	668–698	-634 to -664	lower	713	0.18	0.33	0.23	0.02	0.23
P-9A	163874	Ec12-25	1.89	South	9/16/99	14	45	545–570	-500 to -525	lower	590	1.00	0.56	1.07	0.08	0.89
P-10A	53066	Ec14-08	2.40	Southeast	10/24/83	14	14	630–714	-616 to -700	lower	714	1.19	1.31	1.05	0.69	0.94
P-16A	91371	Ec13-21	1.47	South	6/25/92	12	35	513–564	-478 to -529	lower	593	0.30	0.22	0.49	0.23	0.41
PW-4	036504	Ec15-27	3.08	Southeast	11/5/76	8	13	692–722	-679 to -709	lower	722	0.04	0.06	0.03	0.04	0.05
PW-5	037981	Ec15-28	2.83	Southeast	5/4/77	8	11	707–737	-696 to -726	lower	780	0.14	0.07	0.10	0.08	0.06
ASR-1	216229	Ec22-18	2.43	South	11/1/06	12	50	545–665	-495 to -615	lower	665	--	--	--	--	--
Surface-water withdrawal locations (intakes)																
Red Lion Creek	8013	--	0.98	West	--	--	--	--	--	--	--	0.00	0.00	0.00	0.01	0.23
Dragon Run	8014	--	2.05	South	--	--	--	--	--	--	--	--	--	1.29	0.20	1.34

of silt and clay. The Columbia Formation consists of glacial outwash deposited by braided rivers; sands are primarily medium-grained, typically cross-bedded with gravel found at the base (Ramsey, 2005). This basal sand and gravel layer was encountered at many locations drilled near the site from 2007 through 2010. In general, the Columbia Formation is underlain by either the Merchantville or Potomac Formations. Previous investigations indicated that there may be a sink or depression at the base of the Columbia Formation along the east side of the site near well PW-12 (Black & Veatch, 2007) that would allow accumulation of contaminants on top of confining layers. The recent drilling program could not verify this feature because of the on-site risk of enabling movement of contaminants into the deeper aquifer(s) during drilling.

The recent (2007–10) drilling confirmed previous conclusions about the extent and thickness of the Columbia Formation. Deep drilling was not practical in marsh areas; therefore, additional information was obtained through hand coring and drive point (piezometer) installation as part of the USGS wetland investigation (Lorah and others, 2014). As surface elevation decreases towards Red Lion Creek, the thickness of the Columbia Formation also decreases. Columbia Formation sands extend into the marsh towards the creek and are typically overlain by recent Holocene sediments, although in some places the Columbia Formation appears to be absent (Lorah and others, 2014), particularly adjacent to and beneath the creek. This implies a discontinuity of Columbia sand beneath the creek, which may limit the flow of shallow groundwater in the Columbia aquifer from the south to north side of the creek (fig. 7a). Site-related contaminants were not detected on the north side of the creek when drilling at site PW-5D, but trace amounts were detected in marsh drive points between PW-5D and the creek (Lorah and others, 2014).

On the north side of Red Lion Creek, data indicate that some of the fine to medium sand encountered during drilling may be from the Lynch Heights and (or) Scotts Corners Formations (Tom McKenna, Delaware Geological Survey, oral commun., 2007). These geologic units underlie terraces that are parallel to the present day Delaware River and eroded material from them may have been reworked and deposited during the last sea-level decline and rise, similar to other Pleistocene age sediments in the vicinity of paleo-drainage channels like Red Lion Creek. The lithology of core material from the PW-5D location indicates a mix of Quaternary sediments with a similar description, primarily yellowish brown, fine to coarse sands, with some gravel, and discontinuous beds of clayey silt. This sand sequence on the north side was approximately 25 ft thick and no confining layers were encountered.

All other drilling locations that are part of the Potomac Aquifer Study were located south of the creek and the surficial material that was encountered was from the Columbia Formation. The thickness of the Columbia aquifer sand, and in many locations, the depth to the Merchantville confining unit, was consistent with previous investigations. No significant contamination was detected (concentrations were less than instrument detection limits) within the Columbia Formation at the following drilling locations, identified by the Potomac Formation well installed at the same location: PW-4D, PW-6D, PW-7S, PW-8, PW-9, PW-10, PW-12, or PW-13 (fig. 3). The Potomac Formation well PW-11 showed trace detections of site-related contaminants (concentrations were equal to or less than lower instrument detection limits, in micrograms per liter) and a well screened in the Columbia aquifer at the same location (CW-11) has shown very low-level detections (concentrations were only several micrograms per liter).

Recent Holocene sediments, typically dark gray, organic, relatively uncompacted silts, are prevalent in the marsh areas on the fringe of the SCD site. Quaternary wetland sediments at the site are commonly described as Marsh Deposits (Qm) that are structureless to finely laminated, black to dark gray, organic-rich silty clay with some peat beds. They range in thickness from less than 1 ft to 40 ft thick near and under Red Lion Creek (fig. 7a), with an average thickness in the marsh area of approximately 6 ft (Lorah and others, 2014). The presence of site-related contaminants in marsh sediments is widespread, with some wetland areas to the northwest of the site having concentrations that approach solubility limits in water for various chlorobenzenes.

Merchantville Formation Confining Unit

The Cretaceous Merchantville Formation (Kmv) underlies the Columbia Formation and is a discontinuous layer of marine silty/sandy clay forming a leaky confining unit (Woodruff, 1986). Primary composition is light- to dark-gray, micaceous, glauconitic, silty fine-grained sand, with silty sand and clay (fig. 6). Roy F. Weston, Inc. (1992) found several locations where the Merchantville Formation is thin or non-existent, predominantly in the central part of the site. Black & Veatch (2007) also found other areas to the north of the site closer to Red Lion Creek where the Merchantville was missing. On site, the average thickness of the Merchantville Formation is 10 ft, and ranges from 0 to 22 ft. The thickest part of the unit is near the barrier wall in the southwest part of the study area. Drilling in the Columbia Formation for previous studies often used the top of the Merchantville as a terminus for drilling to limit downward migration of contaminants.

In previous investigations, the Merchantville was interpreted to be a low hydraulic conductivity layer continuous throughout the study area and sufficiently thick to prevent vertical contaminant migration. Whereas the physical properties of this unit may impede groundwater flow when sufficiently thick, flow through this unit is possible where it is thin due to its silty (rather than clayey) composition. Deposited in a marine environment, the original top of the formation was likely planar, however, it was extensively eroded prior to and during deposition of the Columbia Formation. Previous studies at nearby sites (Oxychem and Tybouts) indicated the presence of areas where the Merchantville was completely eroded by tributaries to the ancestral Delaware River, which formed incised valleys cutting through the Merchantville (Black & Veatch, 2007). These incised valleys were typically refilled with sands of the Columbia Formation to form paleochannels (see **Paleochannels and Erosional Features**, *this report*). One such feature was identified during test drilling (Black & Veatch, 2007) in the northeast part of the SCD site oriented in a line from well PZ-29 towards MW-22 (fig. 3). In these areas where the Merchantville was eroded, the Columbia Formation may directly overlie clay or sand of the Potomac Formation.

Potomac Formation and Related Aquifers

The Cretaceous Potomac Formation (Kpt) underlies the Merchantville Formation and is composed of fluvial sediments including very fine- to medium-grained sands in a matrix of silt and clay that are generally present deeper than 41 ft below land surface and continue down to the crystalline bedrock surface, approximately 700 ft below land surface at the SCD site. Thick (tens of feet) layers of silty clay to clayey silt ranging in color from dark-red, purple, gray, pink, and white are common, with beds of gray clayey silt often containing pieces of charcoal and lignite (fig. 6) (Ramsey, 2005). The predominantly clay layers form both isolated and continuous confining layers, which create an aquifer anisotropy that inhibits vertical groundwater movement. Although they are separated by an unconformity, clays of the Potomac and silty clays of the Merchantville Formations act together to form a confining layer of varying thickness (Woodruff, 1988), which has been observed at the SCD site (figs. 7a, b). The Potomac Formation clay is thicker and more extensive than the Merchantville silt/clay at the site and thus serves as the more effective confining unit in most locations, particularly to the south and east of the site where the upper Potomac confining unit thickens (figs. 7a, b).

Depositional Environments

Within a large anastomosed and meandering river system, such as that which formed the Potomac Formation, coarser material found in bed, bar, and levee deposits may result in preferential groundwater flow paths, and fine flood-plain material will form barriers to flow. The bulk of sediments in the Potomac Formation are fine-grained silts and clays. Sugarman and others (2005) suggested that silt and clay layers in the Potomac Formation originated from four paleo-environmental settings: (1) oxidized flood-plain soils, (2) intra-channel swamps, (3) oxbow and lake lacustrine sediments, and (4) active flood plain. These sediments form confining layers that were typically underlain and cut by Potomac channel sands. Understanding the depositional environment and distribution of these channel sands is the key to discriminating site-specific flow patterns. The DGS has subdivided the Potomac Formation into five facies (depositional environments), of which the first two facies (amalgamated channel sands and isolated channel sands) have good permeability and are laterally continuous. Crevasse splay and proximal levee sands are relatively thin and more variable in permeability and less continuous than the first two facies. Distal levee/ flood-plain deposits contain sand, but are thin, more silty, and are poor yielding compared with previously described facies. The final facies is weathered flood-plain deposits which contain mottled clays and silts and form large extensive confining units. Facies vary based on the flow channel locations and all potentially have some permeable sand and (or) the potential to provide aquifer leakage with limited connections (McKenna and others, 2004). Benson and McLaughlin (2006) described the lateral variations of the different facies within the Potomac Formation that make it a heterogeneous and complex hydrogeologic system.

Site-Specific Findings

Results from drilling and DC resistivity helped to identify areas where confining units were missing or conversely were thick. Confining units (Merchantville or Potomac) were not encountered north of Red Lion Creek (well PW-5), and were very thin adjacent to the creek to the south (well PW-17). In these locations, the Columbia aquifer is mostly in direct contact with sands of the upper Potomac aquifer, although some marsh sediments may be present. Locations to the north of the site where the confining units are absent correspond to areas where contaminant concentrations in marsh sediments are elevated. In areas to the east, south, and west of the SCD site, channel sands of the Columbia Formation are underlain by a varying thickness of marine silt and clay of the Merchantville Formation. The exact thickness of Merchantville confining beds was determined at borehole locations. DC resistivity surveys (Degnan and Brayton, 2010) were used to interpolate between boreholes and identify geologic contacts, although in many cases, a thin Merchantville unit was broadly interpreted as lumped together with silts and clay of the upper Potomac Formation because of the similar electrical conductivity response (fig. 8). In areas to the east of the site, an extensive thickness of confining silt and clay beds (well PW-8, fig. 7b) may limit contaminant transport and distribution to the east.

Site-Related Aquifer Distinctions

Three distinct continuous aquifers (A-, B-, and C-sand layers) were identified in the upper Potomac Formation at the SCD site based on interpretations of boring logs in cross sections (fig. 7a). Additional evidence for defining these sand layers is based on water-level response to pumping (see **Production Well R-15**, *this report*). An additional thin (less than 10 ft) discontinuous Cretaceous age sand layer was identified beneath the Merchantville confining unit at several locations near the site and is referred to in this report as the upper Potomac top sand (table 2). Two wells (PW-4S and PW-7S) were screened in this sand layer, which is part of the upper Potomac Formation. Water levels measured in these wells reflect water-table conditions and indicate a direct hydraulic connection to the overlying Columbia aquifer; therefore these

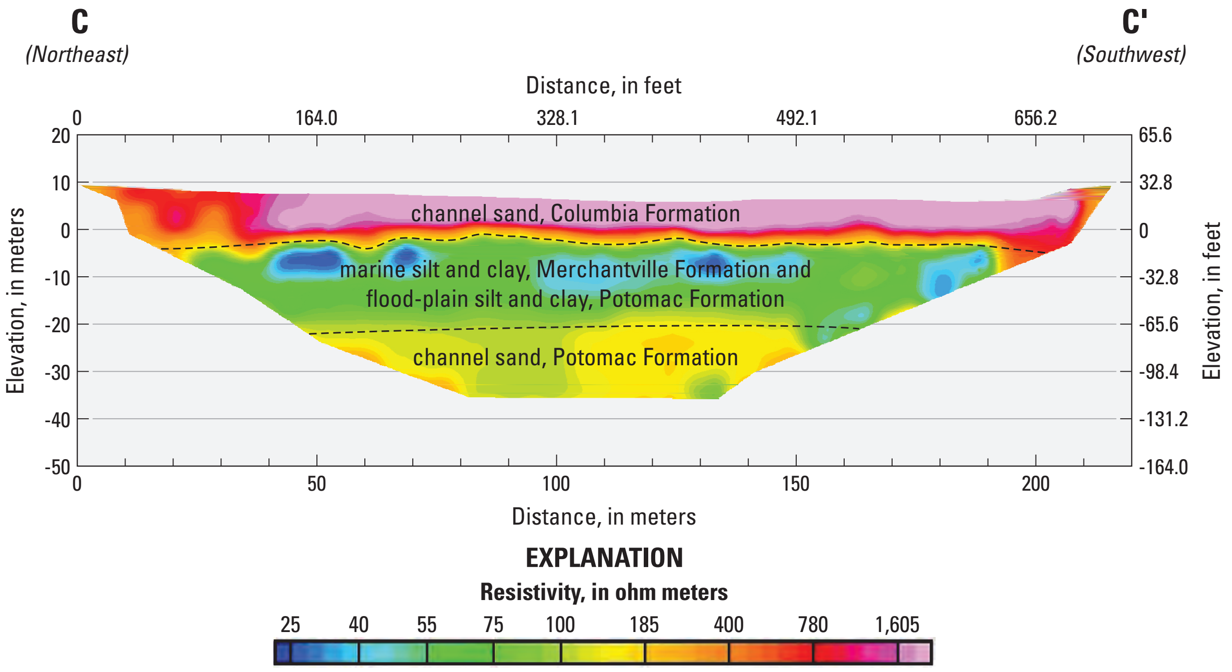


Figure 8. Cross section C-C′ showing direct-current resistivity results and interpretation of stratigraphy at the Standard Chlorine of Delaware, Inc. Superfund Site.

wells are represented on site maps as Columbia aquifer wells. This sand layer may represent “thin sands” crevasse splay/proximal levee sands (McKenna and others, 2004) considering the limited spatial distribution and thickness (less than 10 ft). The upper Potomac top sand aquifer was encountered during drilling at other well locations immediately to the east and south of the site (PW-9, PW-2, and MW-11). Approximately 20–30 ft of the upper Potomac confining unit (mostly clay) separate the top sand from the next Potomac sand layer (A-sand), which tends to thicken from north to south (fig. 7a), and from west to east (fig. 7b), although lateral variation is likely from the fluvial depositional environment. In other areas, the Merchantville confining unit is followed directly by Potomac clay layers, for example wells PW-6, PW-8, PW-10, PW-11, PW-12, and PW-13, because the top sand has either pinched out or become more silty in composition and functions as part of the confining unit.

The upper Potomac A-sand layer was encountered in all Potomac Formation borings at and near the SCD site and ranges in thickness from approximately 30 to 70 ft, but can be as thin as 10 ft (well PW-11). In most locations, it is present beneath the upper Potomac confining unit (figs. 7 a, b), but in some locations, such as near Red Lion Creek, an upper Potomac confining unit was not present (wells PW-17 and PW-5). The A-sand layer likely represents an “amalgamated channel sand” or “thick sand” (McKenna and others, 2004), which is laterally extensive as seen at the SCD site. This type of sand can contain more than one sand layer separated by silt or clay, as interpreted at drilling locations PW-10 and PW-11. Further distinction (or grouping) of these layers is based on measured hydraulic responses (see **Hydrology**, *this report*). Most upper Potomac Formation wells were screened in the A-sand layer because of the need to determine the distribution of contaminants detected within this sand interval. At several of the well locations (PW-4D, PW-9, PW-12, and PW-13), contaminants were detected above and within a fine-grained sand and silt presumed to be at the base of the A-sand layer. Confirming the presence of a confining clay layer below the contaminated interval was not possible at these locations because drilling was halted; however, evidence from other nearby drilling locations indicates that an extensive finer-grained (clay) confining layer exists beneath the A-sand at wells PW-4D, PW-9, and PW-12, which is supported by the lack of contaminant detections within the B-sand layer to the south. Additional information is needed in the area of well PW-13.

The B- and C-sand layers were typically thinner than the A-sand layer and were encountered beneath additional upper Potomac Formation confining clay layers of varying thickness. The B-sand was present beneath a secondary upper Potomac confining unit, which ranged in thickness from 40 to 60 ft (figs. 7a, b).The B-sand layer was encountered only at drilling locations PW-16 and PW-2D and ranged in thickness from approximately 10 ft at well PW-16 to 15 ft at well PW-2D. At drilling location PW-10, a secondary sand layer was identified and screened (well PW-10D) beneath the primary A-sand layer (well PW-10). Initial interpretation considered this as a B-sand layer, however, hydraulic responses (see **Water-Level Responses and Aquifer Interconnections During Production-Well Pumping**, *this report*) indicate that it represents a secondary (transitional) A-sand layer that likely connects to the B-sand layer, as shown in figure 7a. The C-sand layer was encountered at drilling locations PW-10 and PW-11, and was less than 10 ft thick, although it may consist of multiple thin layers as shown in the log for well PW-11 D (fig. 7a) Only one well was completed in the C-sand layer (PW-11D).

Paleochannels and Erosional Features

A variety of erosional features in terms of depth, width, and origin exist in the study area, with the most prominent site-related feature being Paleo-Red Lion Creek. Another prominent feature, the Reybold channel, is located east of the site, but has no effect on site-related groundwater flow. Less prominent paleochannel features also formed in the fluvial depositional environments of the Columbia and Potomac Formations. Interpretations of stratigraphy between well logs indicate that there are several areas where the Merchantville and sometimes the Potomac Formation confining layers are missing. The Columbia Formation is often thicker where it has filled paleochannels that were cut into the Merchantville and (or) Potomac Formations. These paleochannels result in preferential flow paths or areas of increased groundwater flow having higher than average yields (Woodruff, 1986). The absence of the Merchantville Formation in some locations resulted from fluvial erosion due to steeper gradients from the lowering of sea level during glacial periods in Pleistocene time (Phillips, 1987), which was followed by fluvial and braided deposition of the Columbia Formation during interglacial periods. Evidence from well logs and geophysical surveys indicates that the Pleistocene drop in sea level during one or more glacial periods provided a surface-water gradient that allowed the Paleo-Red Lion Creek (much larger drainage area) to cut through Merchantville and Potomac Formation confining clay layers before a confluence with the Paleo-Delaware River (Degnan and others, 2011). The creek was subsequently refilled as sea level rose. The in-filled Quaternary deposits include up to 60 ft of silt that may be underlain by as much as 40 ft of Columbia Formation or other Quaternary aged sands (fig. 7a). The Delaware River was cut as low as 130 ft below sea level during the Pleistocene near the location of the confluence with Red Lion Creek (Phillips, 1987) and this depth represents the potential limit of downcutting by Paleo-Red Lion Creek. The Paleo-Red Lion Creek erosional channel is twice as deep as the Reybold paleochannel at its northern point located approximately one-half mi to the east of the site. Having a different origin, the north to south oriented Reybold channel was formed by fluvial gradients likely derived from a glacial lake dam burst upstream along the Delaware River (Jengo and others, 2013). The presence of a similar north to south oriented erosional feature (if it exists) in the vicinity of SCD would complicate the interpretation of flow patterns.

Determining the presence of smaller erosional channels within the former chemical plant area has been limited by the depth of drilling, which has typically halted at the Merchantville confining unit approximately 65 ft below land surface in most locations. Terminating drilling at the Merchantville, or at an altitude close to present day sea level when the Merchantville was not encountered, was a precautionary standard to limit cross-contamination during the drilling process. At drilling locations adjacent to the site boundary to the east (wells PW-12, PW-9, and PW-4D) and to the west (well PW-13), Merchantville and Potomac confining units were present and the core logging did not indicate any erosional channels. If such channels exist on site, they are narrow and less extensive than either the Paleo-Red Lion Creek or the Reybold paleochannel.

Hydrology

Seven years of water-level data collection have enabled a robust characterization of the local flow system, with a focus on the interaction between the Columbia and upper Potomac aquifers at SCD. Developing a better understanding of groundwater flow within and between sand layers in the upper Potomac aquifer is driven by a need to characterize contaminant transport laterally within the A-sand and potentially downward to the B- and C-sands. Recharge occurs locally to the Columbia aquifer and continuously collected groundwater-level data from this study indicate that limited recharge to the upper Potomac aquifer also occurs locally where the aquifer subcrops and the confining unit is leaky. The altitude of groundwater was used to determine the groundwater-flow direction in the upper Potomac, which varied over time in response to both long- and short-term hydraulic stresses. Continuous water-level data were valuable for identifying stresses on the upper Potomac aquifer flow system and include precipitation, tidal fluctuation, creek stage change effects, and pumping effects (fig. 9). Patterns of long-term change in water levels were similar for most A-sand wells, indicating a nearly uniform response to various hydraulic stresses, which are examined in more detail in the sections that follow.

Water levels in well nests have consistently shown that vertical gradients at the site are downward from the Columbia to the Potomac aquifer and downward within the Potomac aquifer system, with changes in magnitude primarily controlled by water withdrawals from the upper Potomac aquifer. A direct connection between upper Potomac aquifers was identified by comparing creek stage and groundwater levels, whereby Red Lion Creek may promote recharge of the Potomac aquifer system at elevated creek stages. Aquifer connections were further demonstrated (and delineated) during pumping of a local production well (see **Water-Level Responses and Aquifer Interconnections during Production-Well Pumping** , *this report*) that induced water-level decline in Columbia aquifer wells in the northeast part of

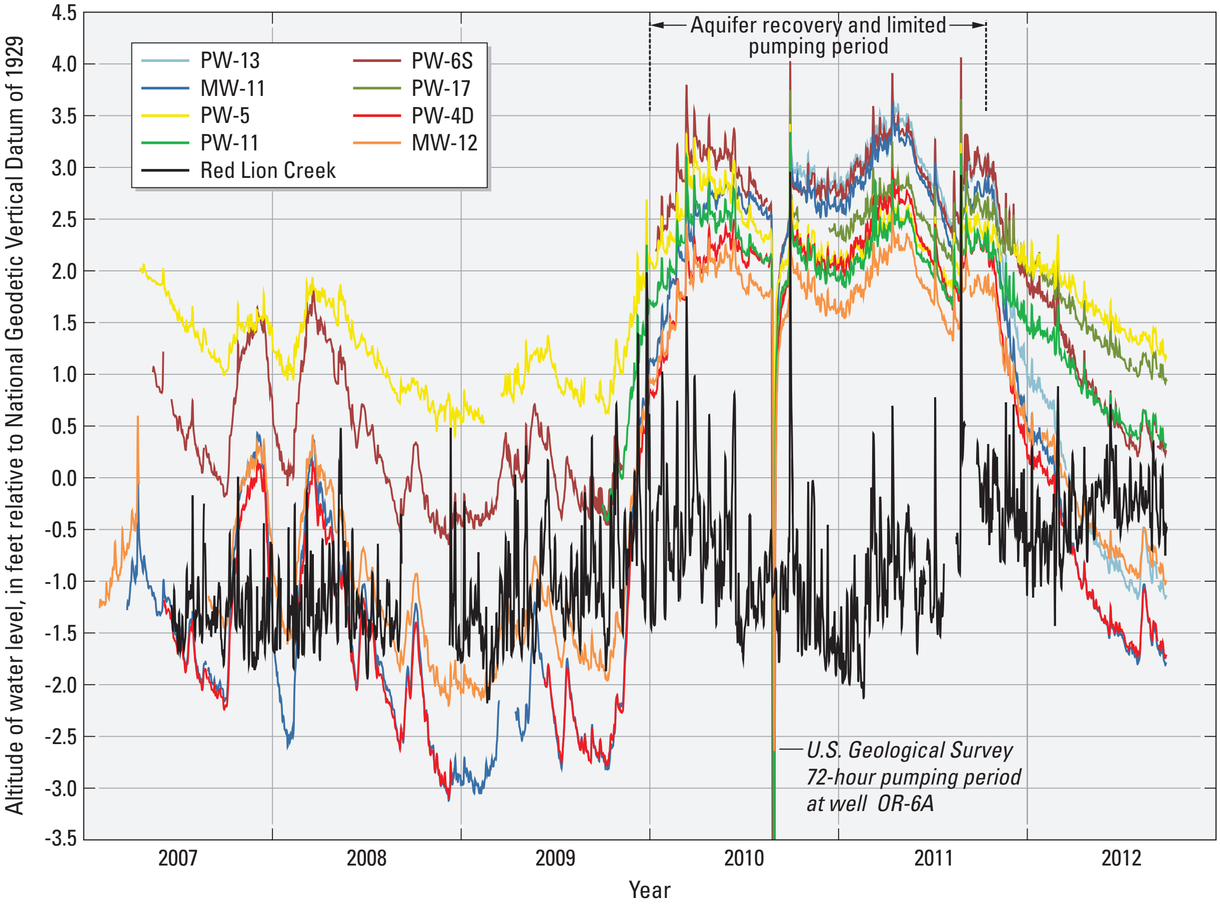


Figure 9. Daily average altitude of water levels for selected upper Potomac A-sand aquifer wells and Red Lion Creek near the Standard Chlorine of Delaware, Inc. Superfund Site, 2007–12.

the site near the creek and all upper Potomac wells. Pumping influences from local industrial production wells were shown to be a predominant stress on the upper Potomac aquifer system and caused much of the water-level variation that was observed.

Recharge and Discharge Patterns

Climate, evapotranspiration, and precipitation have a direct effect on available recharge to the surficial and underlying aquifers. Review of precipitation data over a multi-year period showed that large storm events as well as prolonged periods of above normal precipitation led to elevated water levels that imply direct recharge to both the Columbia and upper Potomac aquifers. Rainfall associated with Hurricane Irene (August 27–28, 2011; 6.94 in.) and the remnants of Tropical Storm Lee (September 5–8, 2011; 3.00 in.) made 2011 one of the wettest years on record. A plot of monthly precipitation from NOAA station 13781 shows variation due to large storm events and also shows prolonged periods of seasonally above or below normal precipitation such as the “wet” period associated with above average snowfall in the winter of 2010 (figs. 10a, b) and the “dry” period that began in January 2012 and continued for several months .

Overall precipitation from 2006 through 2012 was above normal (wet) during 3 of the years, normal during 4 of the years, and below normal (dry) during 1 year of the study (table 5). Non-normal is defined as deviation from the 30-year (1971–2000) mean annual precipitation of 42.81 in. by more or less than 14.7 percent (mean/ mean + 2 x variance). Recharge can also be affected by variations in evapotranspiration. During the study period, mean annual temperatures were equal to or greater than the long-term mean annual temperature, potentially resulting in higher evapotranspiration; however, these effects were not quantified.

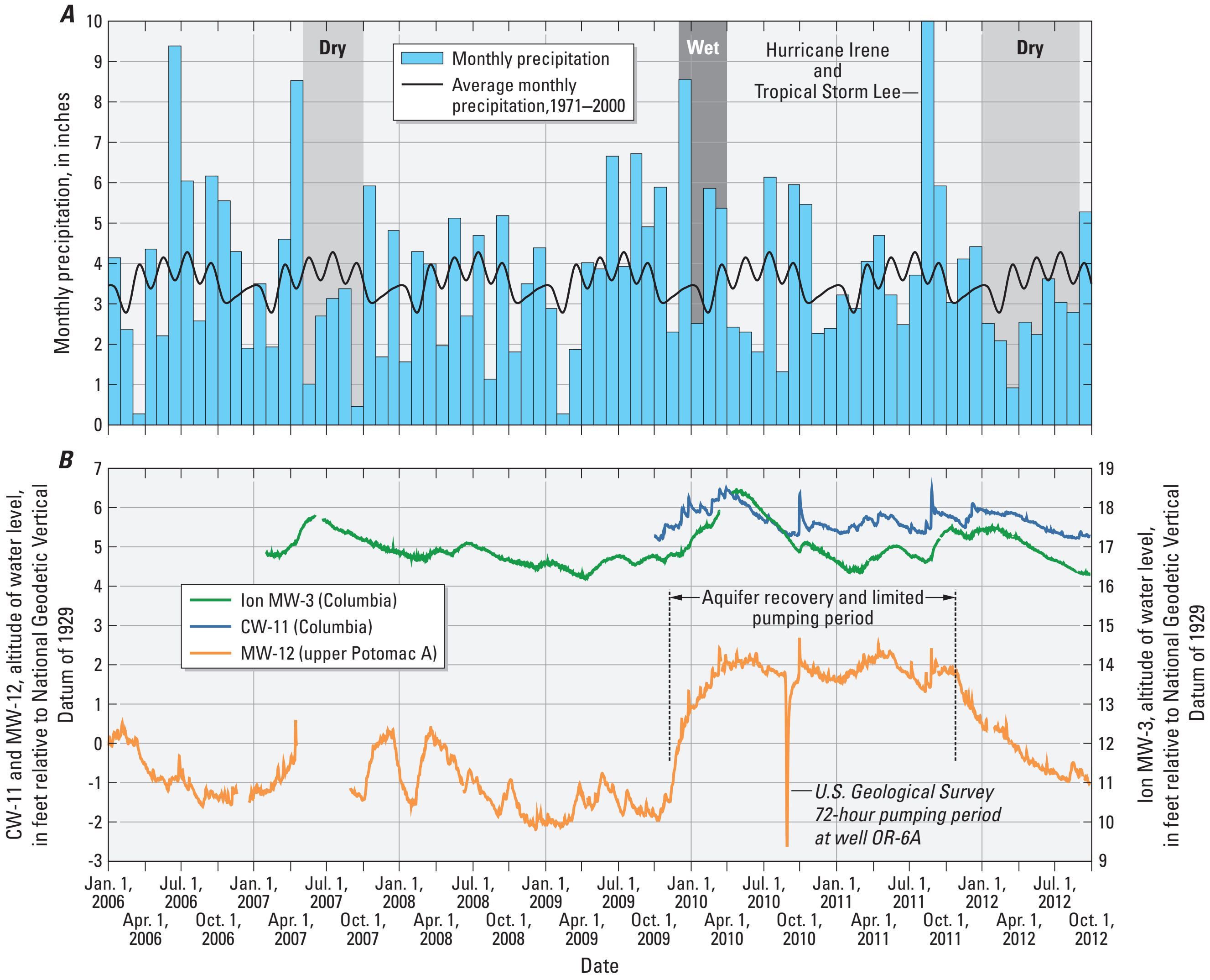


Figure 10. *(A)* Comparison of monthly precipitation and long-term average monthly precipitation in the Delaware City area, 2006–12 (precipitation data from National Oceanic and Atmospheric Administration station 13781), and *(B)* hydrograph showing water-level variation for water-table (Columbia aquifer) and confined aquifer (upper Potomac A-sand) wells compared with monthly precipitation. (Explanation shows screened aquifer in parentheses.)

Columbia Aquifer Recharge

The effects of direct aquifer recharge from precipitation can be seen by examining changes in water levels within the Columbia aquifer, which ranged from approximately 2 ft (well Ion MW-3) in the uplands to only 1 ft in the lowlands closer to the creek (well CW-11) (fig. 10). Some seasonal variability occurs, with peak annual water-table levels typically from March to May, resulting from winter and early spring seasonal recharge. Rainfall distribution was normal in 2007 and 2008 except for a prolonged (more than 3 months) dry period from May–September 2007, the effects of which can be seen in a decline in the Ion-MW-3 water level. The lowest water-table elevation was observed at the beginning of April 2009, following several months of minimal precipitation. Prolonged wet periods in recent years, notably from June 2009 to March 2010, and from August 2011 through December 2011 led to a sustained higher water table, peaking in early May 2010. In contrast, most of 2012 was dry, with a corresponding drop in the water-table elevation.

Dynamic recharge response to large storm events occurring over 1 to several days can be seen as spikes in the hydrograph on September 30, 2010 and August 27, 2011 for well CW-11 in the lowlands, and as moderate rises for upland well Ion MW-3 (fig. 10). Aquifer responses to storm events are discussed in detail (see **Response to Large Storm Events**, *this report*). Overall, the responsiveness of water levels in the Columbia aquifer to precipitation patterns indicates that direct aquifer recharge is a predominant source of water to the Columbia.

Potomac Aquifer Recharge

Recharge to the upper Potomac aquifer occurs more slowly and is more limited than the direct recharge to the Columbia aquifer. Differences in the long-term hydrographs for Columbia and Potomac aquifer wells help to distinguish recharge influences from pumping effects in the Potomac aquifer. Overall, during the study period, water levels for upper Potomac A-sand wells showed much greater variation (up to 6 ft) than Columbia wells (1 to 2 ft). Spanning both pumping and non-pumping periods, the annual range in water levels for upper Potomac A-sand wells was from 3 ft at well PW-5 near Red Lion Creek to approximately 6 ft at well MW-11 at the south end of the site (fig. 9). However, most of this variation can be explained by pumping effects (see **Production Well R-15**, *this report*). Recharge in the upper Potomac aquifer that is related to precipitation cannot easily be distinguished in the long-term hydrograph during periods of pumping influence, but during an approximately 2-year period (November 2009 through October 2011) pumping was minimized and the long-term pattern of recharge that was observed is similar for both the Columbia and upper Potomac A-sand (fig. 10), indicating the presence of a coupled recharge system between aquifers. During this period, the annual range in water levels for the upper Potomac was only 1 ft, which is a muted reflection of changes observed in the Columbia at well Ion MW-3, which had a 2-ft range.

During active pumping and aquifer recovery periods, changes in water levels in the upper Potomac did not mimic changes observed in the water table in the Columbia aquifer. For example, the water-table minimum in April 2009 at well Ion MW-3 did not have a corresponding minimum in upper Potomac well MW-12 (fig. 10). A reduction in pumping of the upper Potomac aquifer in November 2009 led to an immediate increase in water levels by 2 feet by January 1, whereas the increase in Columbia aquifer wells was less than 0.5 ft (fig. 10). Larger increases in Columbia aquifer water levels did not occur until after January 1, which is likely the result of above average snowfall during the winter of 2010. It is difficult to distinguish how the upper Potomac aquifer responded to this winter recharge because the hydrograph is masked by recovery from pumping.

During the period of limited pumping, more natural variation in water levels could be seen in the upper Potomac aquifer in response to recharge from the Columbia. Dry periods showed a similar pattern of decline in water levels for both the upper Potomac and Columbia aquifers. This pattern diverged at the end of October 2011 once pumping resumed in the upper Potomac. The upper Potomac water levels showed a steep decline, whereas Columbia water levels were maintained for at least 4 months, until persistent dry conditions during most of 2012 led to a continued water-level decline.

Groundwater Discharge

The majority of water recharging to the Columbia aquifer discharges to surface water and a minor amount recharges the upper Potomac aquifer. In order to assess the potential significance of groundwater discharge to tidal Red Lion Creek, Lorah and others (2014) compared estimates of vertical groundwater fluxes integrated over the area of the tidal creek (based on measured heads and hydraulic properties) with an estimate of total discharge from the watershed draining to tidal Red Lion Creek (based on historical streamflow data from a nearby streamgage). These estimates, with some limitations,

Table 5. Comparison of annual and long-term mean climate conditions in the Delaware City area, 2005–12.

[°F, degrees Fahrenheit; --, no data; temperature and precipitation data from National Oceanic and Atmospheric Administration, weather station 13781]

	Mean temperature	Mean maximum temperature (°F)	Mean minimum temperature (°F)	Precipitation (inches)	Precipitation percent difference compared with 30-year mean	Annual wetness condition
(1971–2000)[1]	54.4	63.5	45.1	42.81	--	--
2005	54.6	63.8	45.4	40.25	-5.98	normal
2006	56.2	65.6	46.9	49.41	15.42	wet
2007	55.7	65.0	46.3	41.81	-2.34	normal
2008	55.6	65.1	46.0	40.44	-5.54	normal
2009	54.4	63.0	45.8	52.06	21.61	wet
2010	56.0	65.3	46.8	43.96	2.69	normal
2011	56.3	65.5	47.0	56.58	32.17	wet
2012	57.4	66.9	48.0	36.30	-15.21	dry

[1] National Oceanic and Atmospheric Administration, 2004.

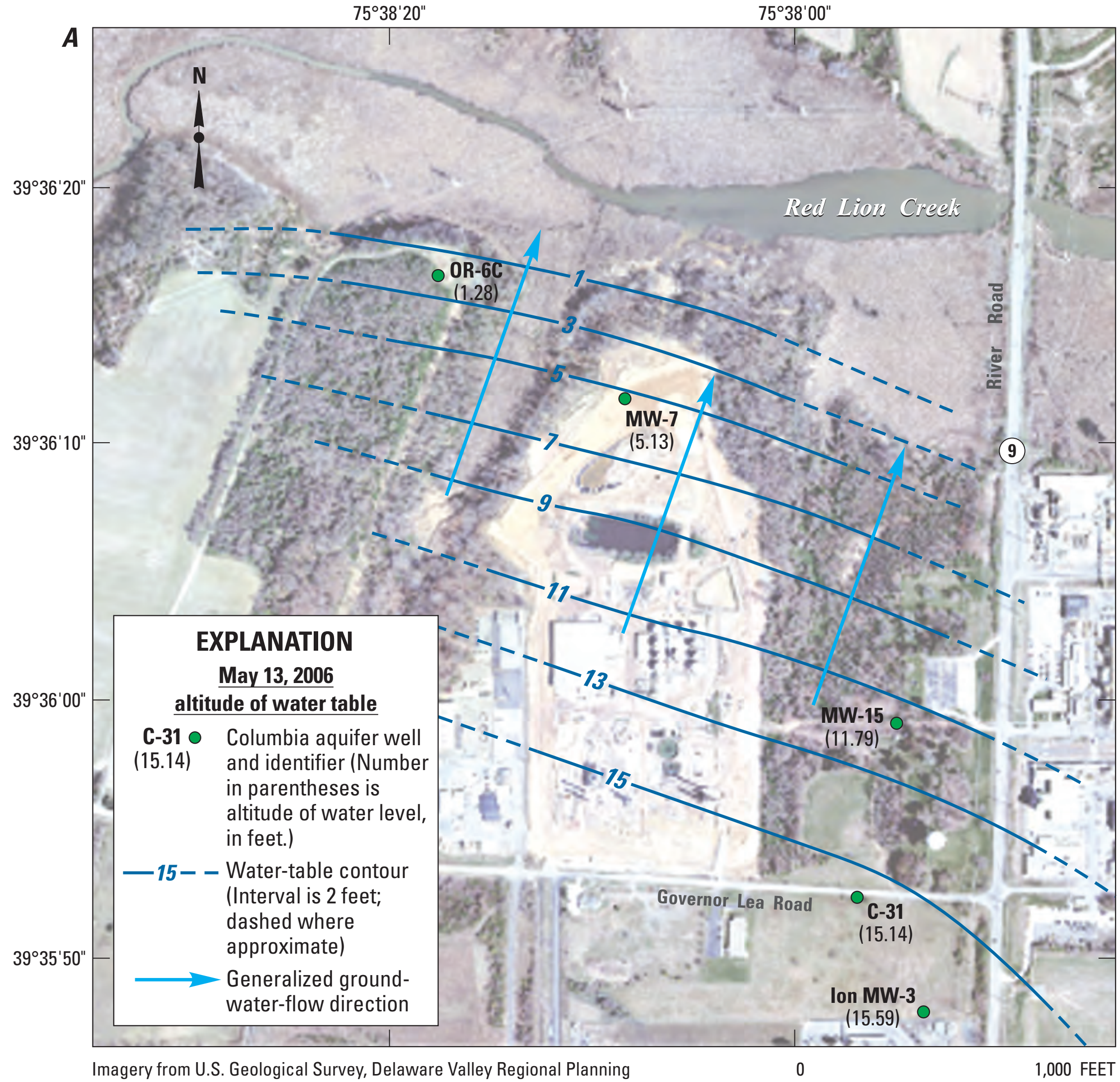
indicate that much, if not most, of the net recharge to the surficial aquifer in the sub-watershed of tidal Red Lion Creek discharges from groundwater to the tidal creek and wetland.

Localized groundwater discharge to the creek and marsh from the upper Potomac aquifer likely occurred during the limited pumping period (November 2009 through October 2011) when water levels in all monitored upper Potomac wells were higher than the creek stage and similar to Columbia aquifer water levels near the marsh (fig. 9). Thus, vertical gradients decreased during the limited pumping period (see **Vertical Gradients**, *this report*). Conversely, recharge of the A-sand aquifer from Red Lion Creek is possible when water levels drop below the level of the creek during pumping periods. It is unclear to what extent this occurs, because A-sand aquifer water levels dropped below creek stage in wells located south of the site, but not in wells adjacent to the creek.

Water-Table Contours, Potentiometric Surfaces, and Flow Directions

Monthly synoptic measurements of altitudes of water levels in wells were used to determine flow direction within the Columbia and upper Potomac aquifers for a range of dates throughout the period of study. Water-level data from specific dates were used to create water-table contour maps for the Columbia aquifer to illustrate the effect of the barrier wall on flow patterns. Water-level data from specific dates were used to create potentiometric surface maps for the upper Potomac A-sand aquifer to show pumping and limited pumping conditions, and their effect on groundwater-flow direction.

Groundwater flow in the Columbia aquifer is topographically driven and flow direction is consistent from year to year, and is generally south to north (fig. 11), as shown by previous



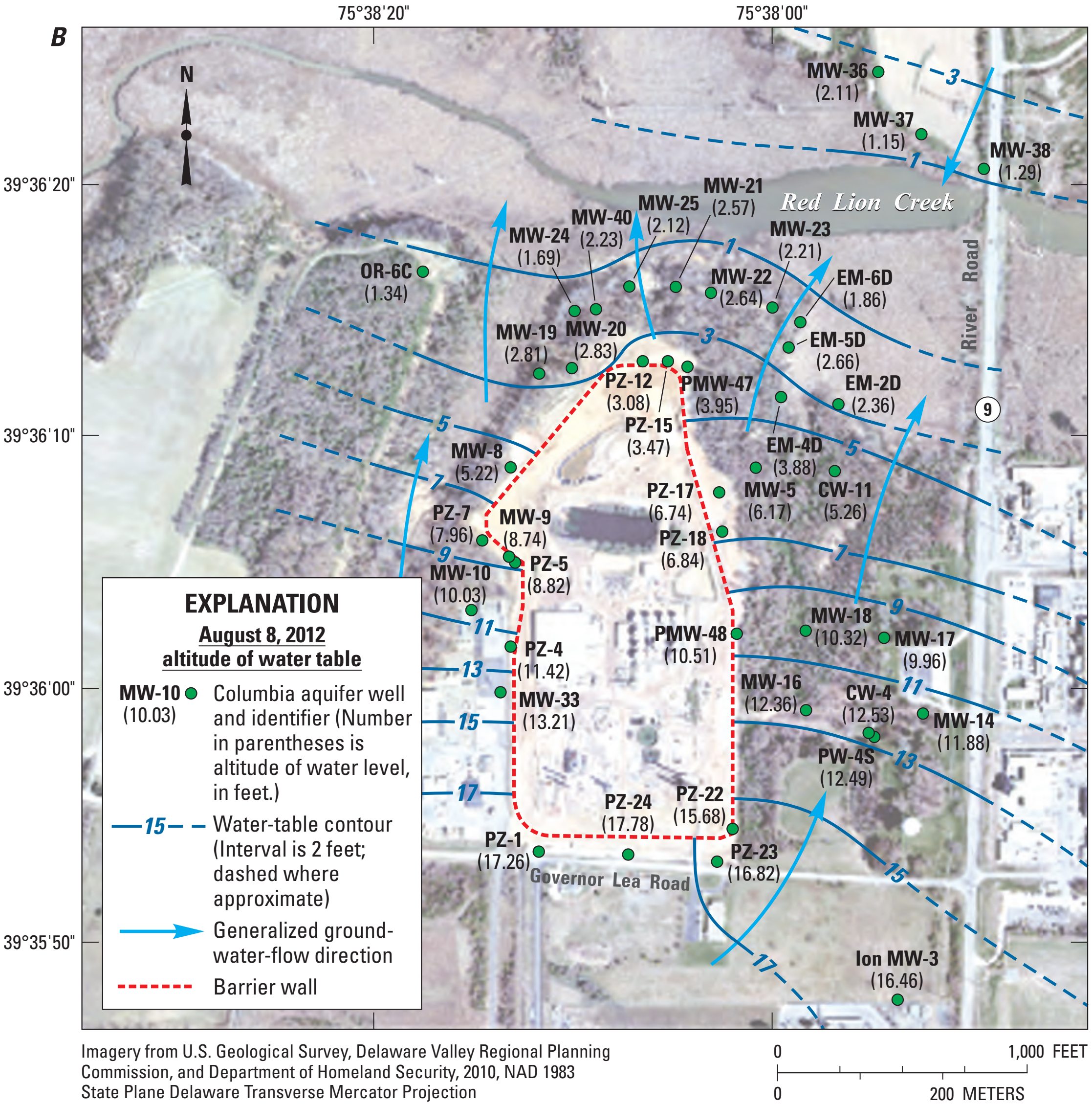
Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983 State Plane Delaware Transverse Mercator Projection

Figure 11. Water-table contours for the Columbia aquifer *(A)* May 13, 2006 prior to completion of the barrier wall, and *(B)* August 8, 2012 after completion of the barrier wall.

studies at the site (Roy F. Weston, Inc., 1992; Black & Veatch, 2007) The altitude of the water table near the site ranges from approximately 17 ft at the south end, to consistently just above sea level (0 to 1 ft) at the north end of the site near Red Lion Creek. Completion of the barrier wall in 2007 caused a divergence in flow direction near the south end of the wall so that groundwater is diverted to the west and east locally around the wall; however, the overall flow pattern outside the wall has remained consistently towards Red Lion Creek (fig. 11).

Groundwater inside the barrier wall is isolated from the natural local flow system and is pumped as part of remedial operations. Water-level measurements inside the barrier wall, collected by EPA site consultant HydroGeoLogic Inc., are used to optimize the operation of the remedial pump and treat system. The typical aggregate pumping rate for extraction wells located inside the barrier wall was 50 gal/min during the study period (Chris Wolfe, HydroGeoLogic, Inc., written commun., 2012). Groundwater pumped from inside the barrier wall is treated and discharged as overland runoff outside the barrier wall to the east (U.S. Environmental Protection Agency, 2011), and has little effect on the altitude of the water table outside the barrier wall.

As previously described in this report, the prevailing groundwater-flow direction for aquifers in the Potomac Formation is from northwest to southeast, following the regional bedrock dip direction. Flow direction was determined for the A-sand of the upper Potomac aquifer at SCD using water levels from wells having an altitude of screened interval from approximately -80 to -120 feet. The altitude of water level and flow direction are influenced by groundwater withdrawal wells in the study area. Two dates were selected to compare conditions between limited pumping

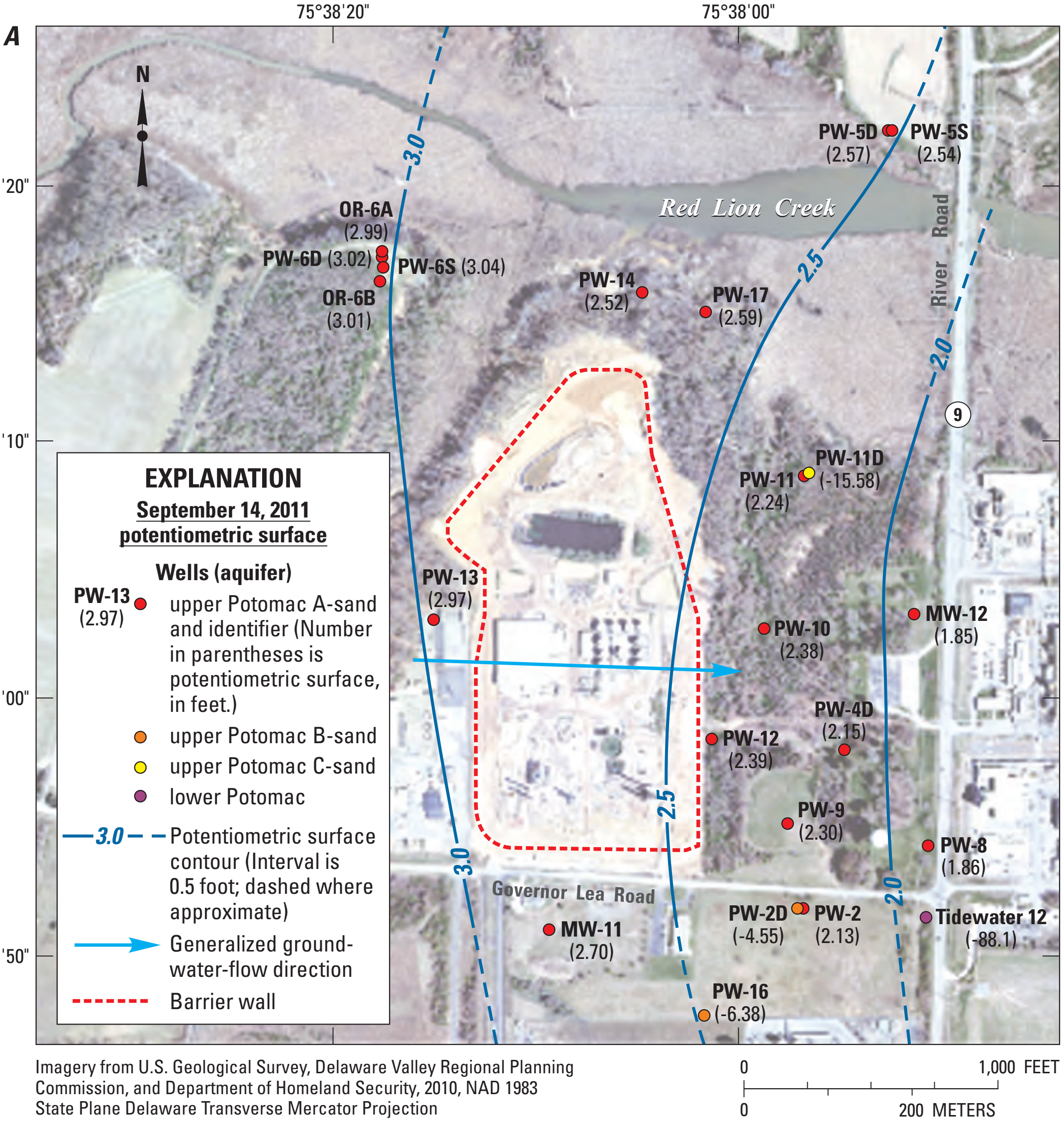


Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983 State Plane Delaware Transverse Mercator Projection

Figure 11. Water-table contours for the Columbia aquifer *(A)* May 13, 2006 prior to completion of the barrier wall, and *(B)* August 8, 2012 after completion of the barrier wall.—Continued

(September 14, 2011) and pumping (August 8, 2012) periods. Water levels during limited pumping conditions were up to 5 ft higher at the south end of the site, and up to 2 ft higher near Red Lion Creek (fig. 9). Flow direction in the upper Potomac A-sand was to the east towards the Delaware River during limited pumping (fig. 12a), and to the south when influenced by pumping (fig. 12b). Prior to November 2009, flow direction was consistently to the south during typical pumping conditions. Comparison of hydrographs from wells screened in the upper Potomac A-sand showed that well PW-3 is likely screened in a "perched" or disconnected sand interval, and water levels for this well were not used in the creation of the potentiometric surface maps.

Flow direction within B- and C-sands cannot be accurately determined due to an insufficient number of wells screened at the appropriate depths. Additional wells screened within these sand intervals, at altitudes of approximately -180 and -220 ft, would greatly assist in determining flow direction and would improve the understanding of the spatial extent of interconnections between the A-, B-, and C-sand layers in the upper Potomac aquifer.



Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983
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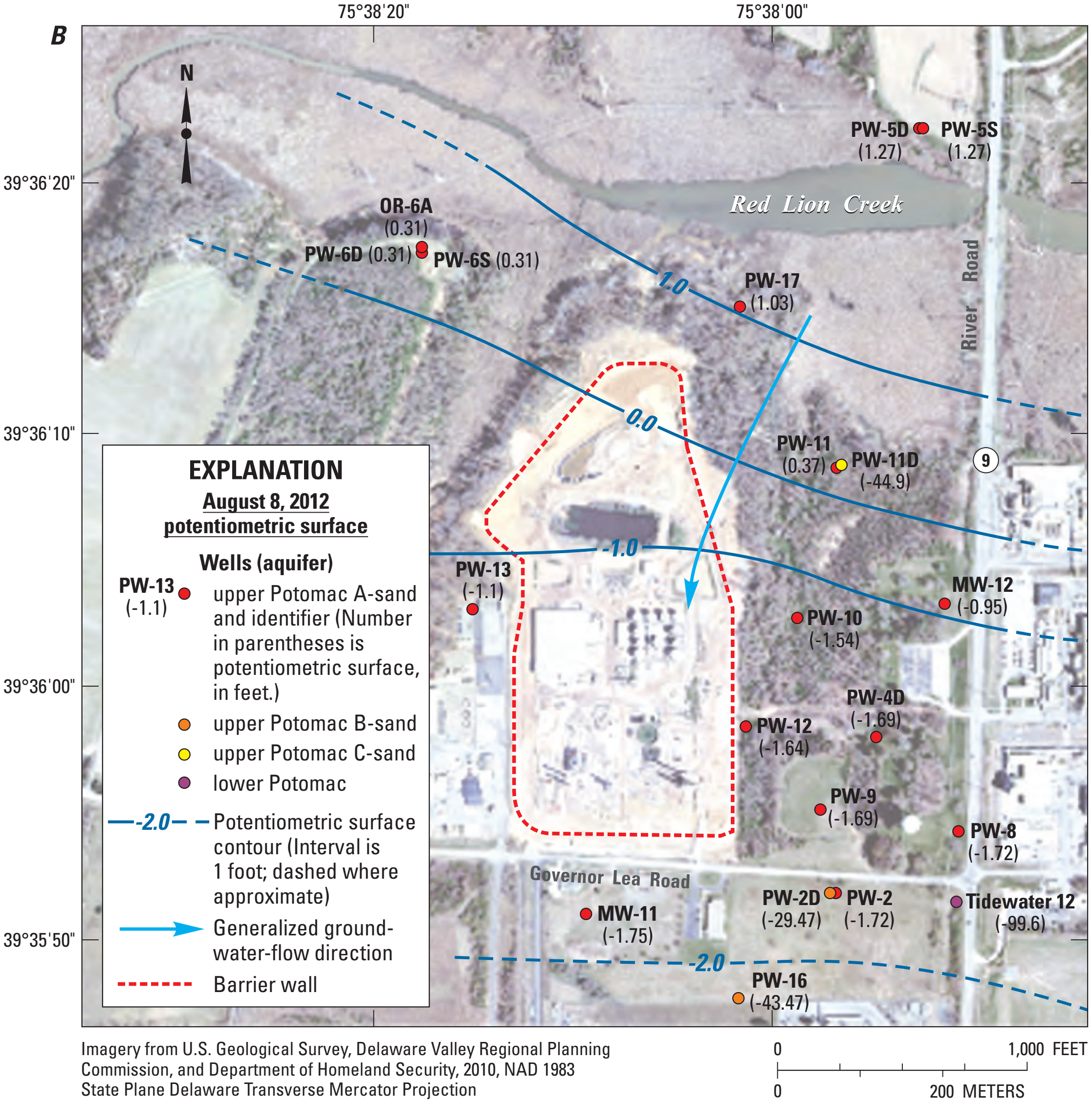
Figure 12. Potentiometric surface of the upper Potomac A-sand aquifer during *(A)* limited pumping conditions (September 14, 2011), and *(B)* typical pumping conditions (August 8, 2012), and heads for selected wells in deeper aquifer units.

Surface-Water Influences on Groundwater

Changes in the surface-water level near the SCD site caused by tides and precipitation have various influences on the groundwater system. Tidal fluctuations within the Delaware River minimally affect water levels in the Potomac aquifer system, and because of a tide control structure at the mouth of Red Lion Creek (figs. 2 and 5), creek stage is also minimally affected by tides in the Delaware River. Malfunction of the tide control structure provided insight into how tidally influenced changes in creek stage affect groundwater levels (see **Tidal Influences**, *this report*). Although Red Lion Creek and connected wetlands adjacent to the SCD site are a receiving source for overland runoff and shallow groundwater discharge, elevated creek stage within these areas can raise groundwater levels and contribute to aquifer recharge. Large increases in creek stage from precipitation associated with storm events results in a short-term increase in groundwater levels, particularly in wells adjacent to the creek. The potential to induce recharge from these storm events was examined.



Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983 State Plane Delaware Transverse Mercator Projection

Figure 12. Potentiometric surface of the upper Potomac A-sand aquifer during *(A)* limited pumping conditions (September 14, 2011), and *(B)* typical pumping conditions (August 8, 2012), and heads for selected wells in deeper aquifer units.—Continued

Tidal Influences

Water levels in wells screened in the upper Potomac aquifer show some tidal influences from both the Delaware River and Red Lion Creek. A 6-ft tidal range in the Delaware River produces very limited pressure loading and unloading on confined parts of the upper Potomac aquifer, affecting A-, B-, and C-sands uniformly across a broad area. Although it is isolated from direct tidal effects from the Delaware River because of the tide control structure, the creek does experience stage changes resulting from backwater effects related to discharge through the tide control structure (for example, the stage does not continue to fall, and may increase when the gates are closed during high tide in the Delaware River). Stage changes in the creek are much smaller in magnitude than changes in the Delaware River but more directly affect ambient groundwater levels in the upper Potomac aquifer near the SCD site. Malfunction of at least one tide gate is known to have occurred during Hurricane Irene, August 27–28, 2011, which resulted in tidal cycling within the creek and in the marsh adjacent to the SCD site. The center gate (out of five) remained stuck open after attempts to remove debris and repair it, which resulted in a gradual increase in base stage in Red Lion Creek (fig. 9) since water could not effectively be drained from the creek. Flow reversals due to tidal inflow have been observed at the Route 9 bridge and were measured most recently on December 19, 2012.

Variation in surface-water levels at different time scales was evaluated in this study. The typical monthly stage fluctuation in Red Lion Creek before the tide gate malfunction ranged from 1.8 ft below sea level to 0.0 ft above sea level, and after the malfunction ranged from 1.0 ft below sea level to 0.5 ft above sea level (Lorah and others, 2014). Daily stage fluctuation (range) before the malfunction was typically 0.18 ft, whereas after the malfunction, it was approximately 0.75 ft. Water levels in unconfined wells generally are not affected by tidal fluctuation in the Delaware River or the creek, however small episodic variations in water levels in shallow drive points (piezometers) in the fringing marshes have been observed, but are commonly less than 0.5 ft (Lorah and others, 2014). Tidal effects have not been observed in water-table wells upgradient of the fringing marsh.

Water levels in wells screened in upper Potomac aquifer sands (A, B, and C) are minimally affected by stage changes caused by tidal fluctuation, but did show a greater daily water-level range after the tide gate malfunction (fig. 13). The range of average daily water-level variation was examined for selected wells during time periods with minimal antecedent precipitation. Dates were selected at a similar point in time for each year from 2009 to 2012, during which less than 0.10 in. of precipitation had fallen for 7 days prior to water-level measurement. Tidal effects from the Delaware River, measured at NOAA tide station 8551762, accounted for minor (less than 0.04 ft) daily variations in water levels for the upper Potomac A- and B-sands prior to the tide gate malfunction. The C-sand (well PW-11D) is more confined and has a greater response to pressure loading and therefore shows a greater daily range (0.10 ft), although part of this variation may be attributed to deeper aquifer pumping influences from the cycling of production well pumps (see **Production Well R-15**, *this report*).

After the tide gate malfunction, wells located closer to the creek had an approximately fourfold increase in water-level variation (up to 0.16 ft) whereas wells located farther away from the creek to the south showed little change in water levels (fig. 13). The range of daily water levels in well PW-2D (upper Potomac B-sand) increased from 0.03 to 0.06 ft after the tide gate malfunction, indicating a limited hydraulic connection to the upper Potomac A-sand. There is no apparent effect from the tide gate malfunction on the daily water-level range for well PW-11D (upper Potomac C-sand), which is reasonable considering its depth and likely poor hydraulic connection to the creek.

Semi-diurnal water-level variations in the upper Potomac A-sand wells were not apparent before the tide gate malfunction but were easily distinguished after the tide gate malfunction. This evidence also reinforces the concept that the Delaware River itself has little effect on water-level variations for wells in the upper Potomac aquifer system. A comparison of water-level response over similar 3-day periods with no precipitation showed that responses in the upper Potomac A-Sand were greatest closest to the creek (fig. 14), but were evident as far as 1,700 ft away from the creek (well PW-13), indicating a good connection between the creek and the upper Potomac A-sand. This connection resulted from the erosion of confining layers near the creek and marsh. Tidal response variations in the upper Potomac B- and C-sands were apparent but muted, accounting for less than 0.05 ft of daily variation.

Red Lion Creek Stage Change Effects

The extent of interconnection between Red Lion Creek and the upper Potomac aquifer was further explored by examining water-level response in wells with evidence of correlation between water levels and precipitation-runoff-driven changes in creek stage. Red Lion Creek is very responsive to rainfall and will typically begin to show stage increases with as little as 0.50 in. of rainfall. Corresponding changes in groundwater levels have been observed and are typically 20–40 percent of maximum stage change for wells located close to the creek, and 10–20 percent of maximum stage change for wells father from the creek (fig. 15). Increased water levels due to elevated stage likely represent a combination of pressure loading from Red Lion Creek and some recharge from the creek to the aquifer.

Stage changes caused by precipitation are commonly larger than those that result from tidal effects. Precipitation events were selected from 2010–12 to examine stream stage and groundwater-level response. Discrete events were chosen when precipitation occurred over no more than a 2-day period, and was preceded by at least 4 days with no precipitation. The results showed that creek stage and water-level response in wells due to large storms (described in the next section) are

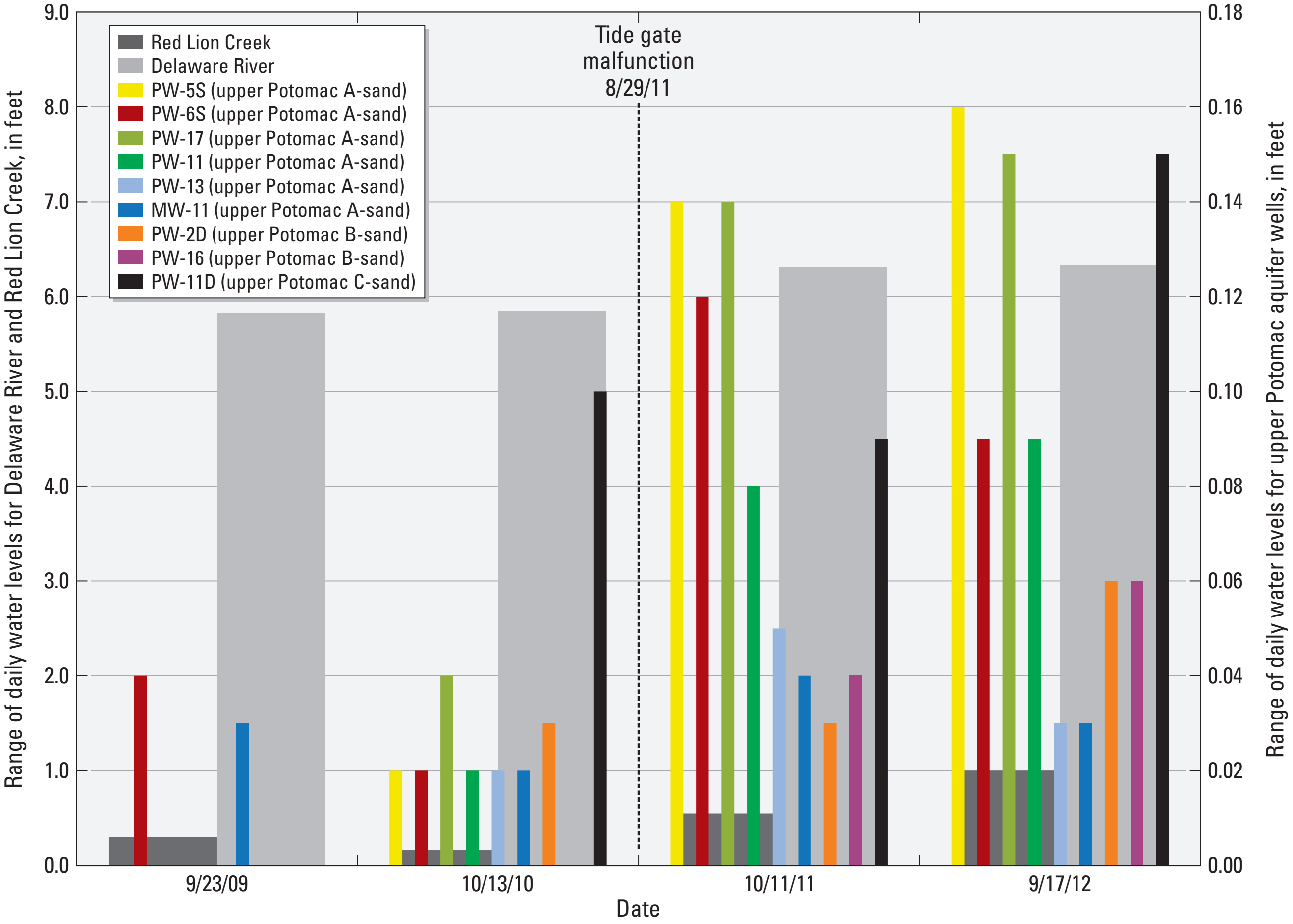


Figure 13. Daily water-level range in feet for the Delaware River, Red Lion Creek, and upper Potomac aquifer wells for selected dates following a 7-day period of minimal precipitation. (Explanation shows screened aquifer in parentheses.)

generally proportional to the total amount of precipitation for a specific event (fig. 15).

One in. of precipitation causes a 1-ft rise in creek stage and can be approximated using a linear empirical formula derived from 14 precipitation events (2010–12):

$$\text{Stage} = 0.62 * p + 0.48 \qquad (1)$$

where

p = precipitation, and the constant 0.48 is the average tidal stage fluctuation before and after the tide gate malfunction.

This stage-rainfall relation was calculated using daily rainfall data from ten dates (fig. 15) and data from the following additional dates (10/14/10, 8/14/11, 5/14/12, and 9/18/12). The formula can be extended for daily rainfall amounts greater than 7.58 in.; however, some variability in peak stage is possible due to the timing and spatial distribution of precipitation. Most precipitation events cause a relatively quick rise and fall in creek stage, although larger events can lead to a multiple day stage recession following peak stage.

Response to Large Storm Events

The response to storm events was more easily observed during minimal aquifer pumping periods, from November 2009 through October 2011. Hurricane Irene in August 2011 provided a good example of aquifer response for multiple aquifer sand intervals. Water levels for several sites were normalized to pre-event water levels (by setting the minimum to zero) and plotted together to analyze storm response to 6.94 in. of rainfall from Hurricane Irene (fig. 16). Following this storm event, higher water levels were sustained at many sites (from precipitation recharge), which differs from the response to stage change effects (from pressure loading) that typically last 1 to 2 days, are cyclical (show tidal fluctuation), and are not sustained as creek stage is lowered. Water-level responses to large storms differed depending on the location and depth of the screened interval for wells screened in the Columbia aquifer, and the upper Potomac A-, B-, and C-sands (fig. 16).

The Columbia aquifer response to Hurricane Irene showed that recharge in the uplands was minimal (well Ion MW-3), whereas recharge that occurred closer to the creek at well CW-11 resulted in a water-level increase of 1.0 ft that

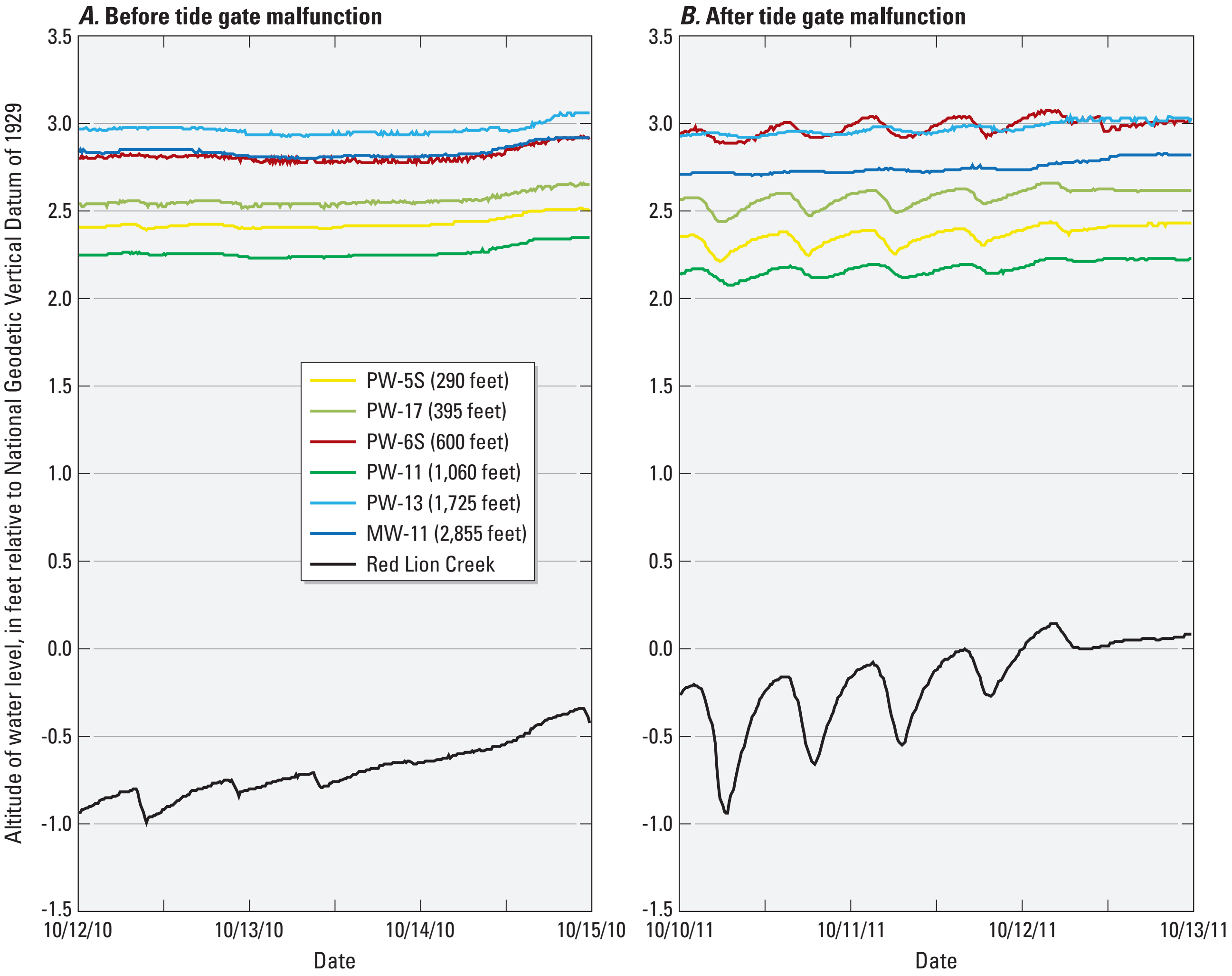


Figure 14. Water-level response in upper Potomac A-sand aquifer wells to tidal cycling in Red Lion Creek with no antecedent precipitation *(A)* before tide gate malfunction, and *(B)* after tide gate malfunction. (Explanation shows distance from Red Lion Creek in parentheses.)

was sustained for several days (fig. 16). Recharge of confined aquifer layers, as shown by water-level increases that are sustained in response to storms, occurs through leakage between aquifer layers. This indicates partial connectivity to the surficial system. Storm response increases in water levels within the upper Potomac B-sand (wells PW-16 and PW-2D) and the upper Potomac C-sand (well PW-11D) were not sustained over a several day period, although water levels at well PW-2D (closer to the creek) were higher than at well PW-16. Although trending downward, water levels remained 0.6 ft above prestorm levels in the upper Potomac A-sand nearly 2 days after precipitation ended, indicating that large storm events can effectively recharge the upper Potomac aquifer.

Connection Between Aquifers

The extent of connectivity between aquifers is directly related to the presence and relative thickness of confining units; where confining units are absent, direct recharge from overlying aquifers is possible. To help quantify potential water exchange, vertical gradients were calculated from water levels directly measured at several locations having nested pairs of wells. The changes in vertical gradients between aquifers over time also have led to a better understanding of the effects of a variety of short- and long-term hydraulic stresses, in particular, the effects of long-term industrial water withdrawals. The responses to recharge that were previously described have shown that aquifer layers are connected. Observed water-level

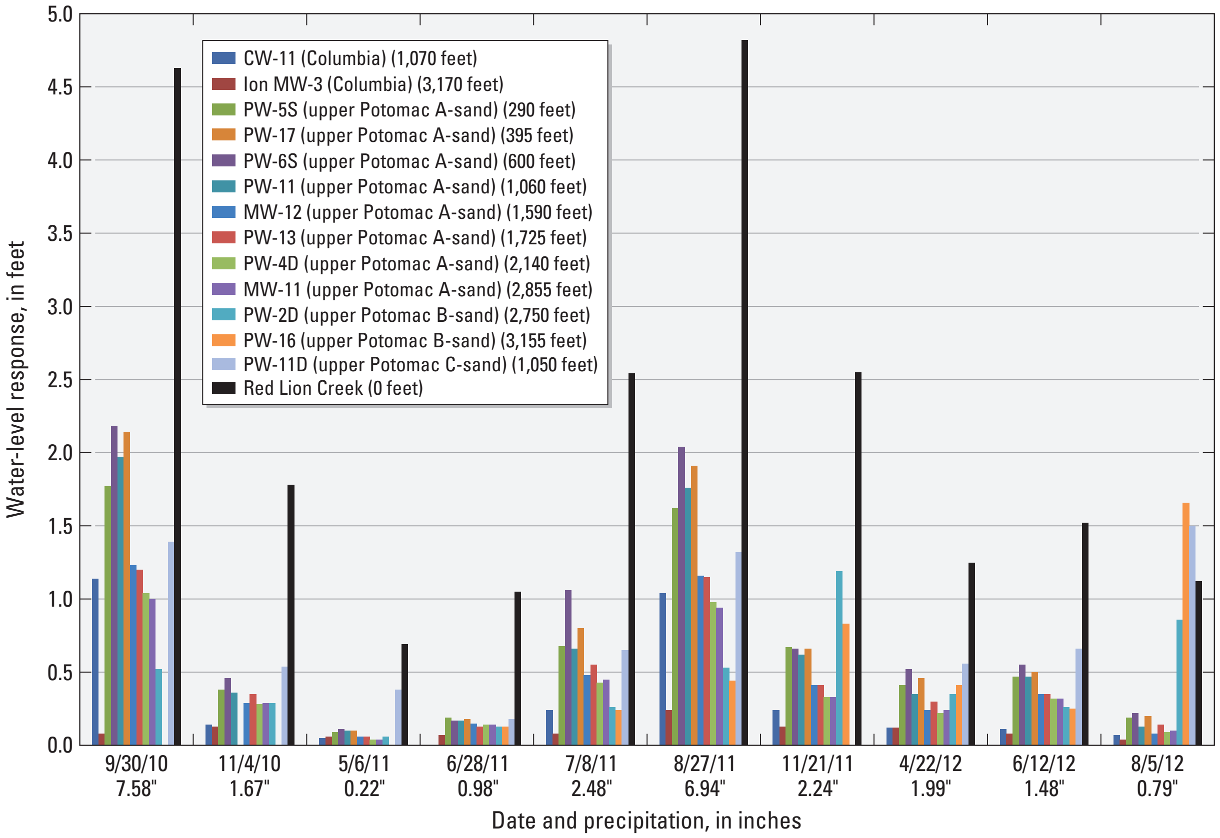


Figure 15. Maximum water-level response, in feet, measured at Red Lion Creek and selected Columbia and upper Potomac aquifer wells for selected discrete precipitation events, 2010–12. (Explanation shows screened aquifer and distance from Red Lion Creek in parentheses.)

responses during the pumping of well OR-6A allowed the identification of more specific areas of the site that have a good connection between aquifers.

Vertical Gradients

Vertical hydraulic gradients provide insight on the three-dimensional nature of the flow system and help to distinguish the relative importance of vertical flow compared to lateral flow. Vertical gradients measured in nested well pairs were consistently downward from the Columbia to the Potomac aquifers and downward within upper layers of the Potomac aquifer, except for well pairs located adjacent to Red Lion Creek (fig. 17). The magnitude of vertical gradients was affected by nearby industrial withdrawals. Hydraulic gradients were calculated using water levels measured in September of each year from 2007 through 2012 (except August 2012). The vertical gradients from the Columbia to the Potomac A-sand are typically downward and ranged from 0.3 (ft/ft or dimensionless) downward south of the site to slightly upward near the creek (at wells PW-6S and PW-5S) in September 2011, when upper Potomac A-sand water levels reached their peak when production wells were idled during the refinery shutdown. Along the north end of the site, gradients are slightly but consistently downward at well PW-17. Generally, during the limited pumping period from November 2009 through October 2011, the magnitude of vertically downward gradients decreased. At well pair MW-37/ PW-5S north of the creek, gradients were slightly upward to no gradient (0.02 to 0.00). Two pairs of wells (PW-5S/ PW-5D and PW-6S/ PW-6D) that are screened in nearly continuous upper Potomac A-sand showed no measurable gradients and are not shown as well pairs in figure 17. Gradients between another well pair (PW-10 and PW-10D) screened in the upper Potomac A-sand, but separated by a confining unit, showed slightly downward gradients during the study period, even during the limited pumping period. Gradients from the upper Potomac A-sand to the upper Potomac C-sand (PW-11 and PW-11D) were

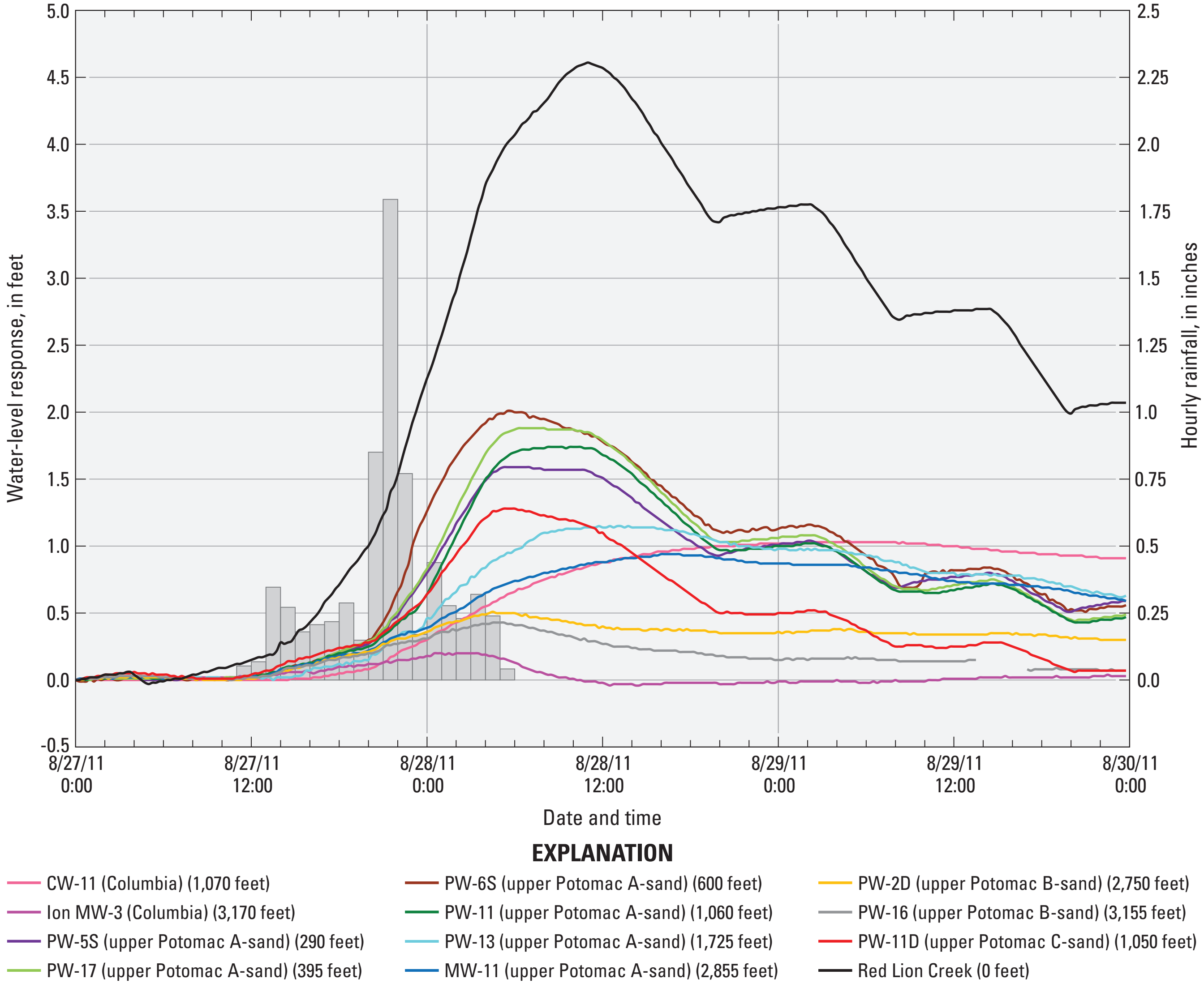


Figure 16. Hourly rainfall and normalized hydrograph showing recharge response in wells screened in the Columbia and upper Potomac aquifers during and after Hurricane Irene, August 27–30, 2011. (Explanation shows screened aquifer and distance from Red Lion Creek in parentheses; precipitation data from National Oceanic and Atmospheric Administration station 13781.)

downward during limited pumping periods (0.14 and 0.17), and strongly downward during pumping periods (0.54 and 0.65).

The fluvial depositional environment within the upper Potomac aquifer system at SCD creates multiple pathways for groundwater flow and contaminant movement. The interconnection of sands is complex, and changes in the magnitude of vertical gradients alter which pathways are favored over others. For example, a strongly downward component of flow at the north end of the site near well PW-17 resulted in contaminant migration downward through sand and silt layers. Subsequent decreases in the magnitude of vertical gradients may then favor lateral migration (spreading) of contaminants away from areas of known higher concentration.

Water-Level Responses and Aquifer Interconnections During Production-Well Pumping

Pumping for a 72-hour continuous period was conducted by USGS at well OR-6A and resulted in water-level data available for USGS network wells (Appendix 3) and non-USGS network wells (Appendix 4). Data for USGS network wells are also available at the USGS NWIS database (http://waterdata.usgs.gov/nwis), accessible using the site identifiers that appear in Appendix 2. Results of the step-drawdown test used to determine the pumping rate for the 72-hour pumping period are on file in the USGS Maryland-Delaware-D.C. Water Science Center office in Baltimore, Maryland.

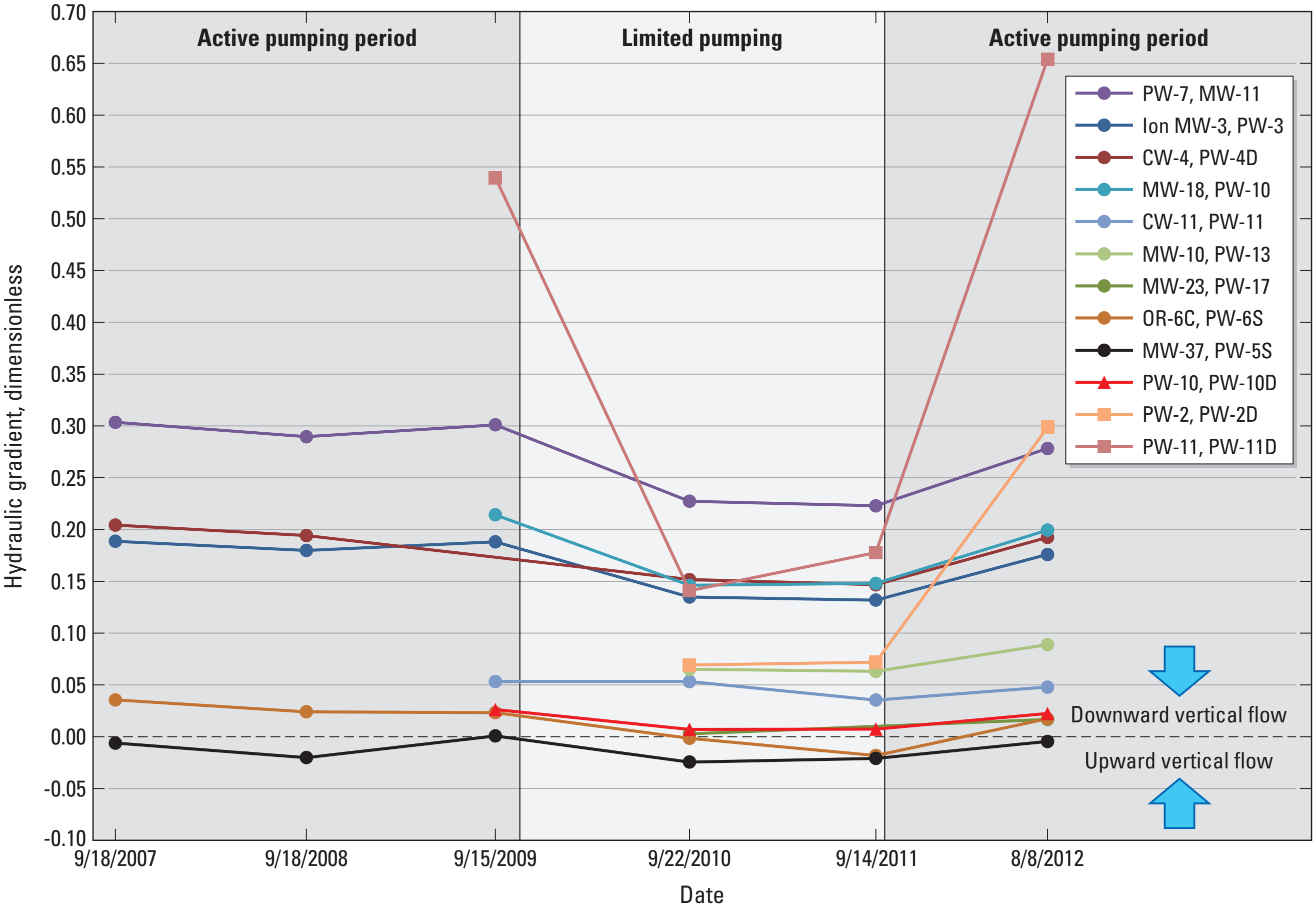
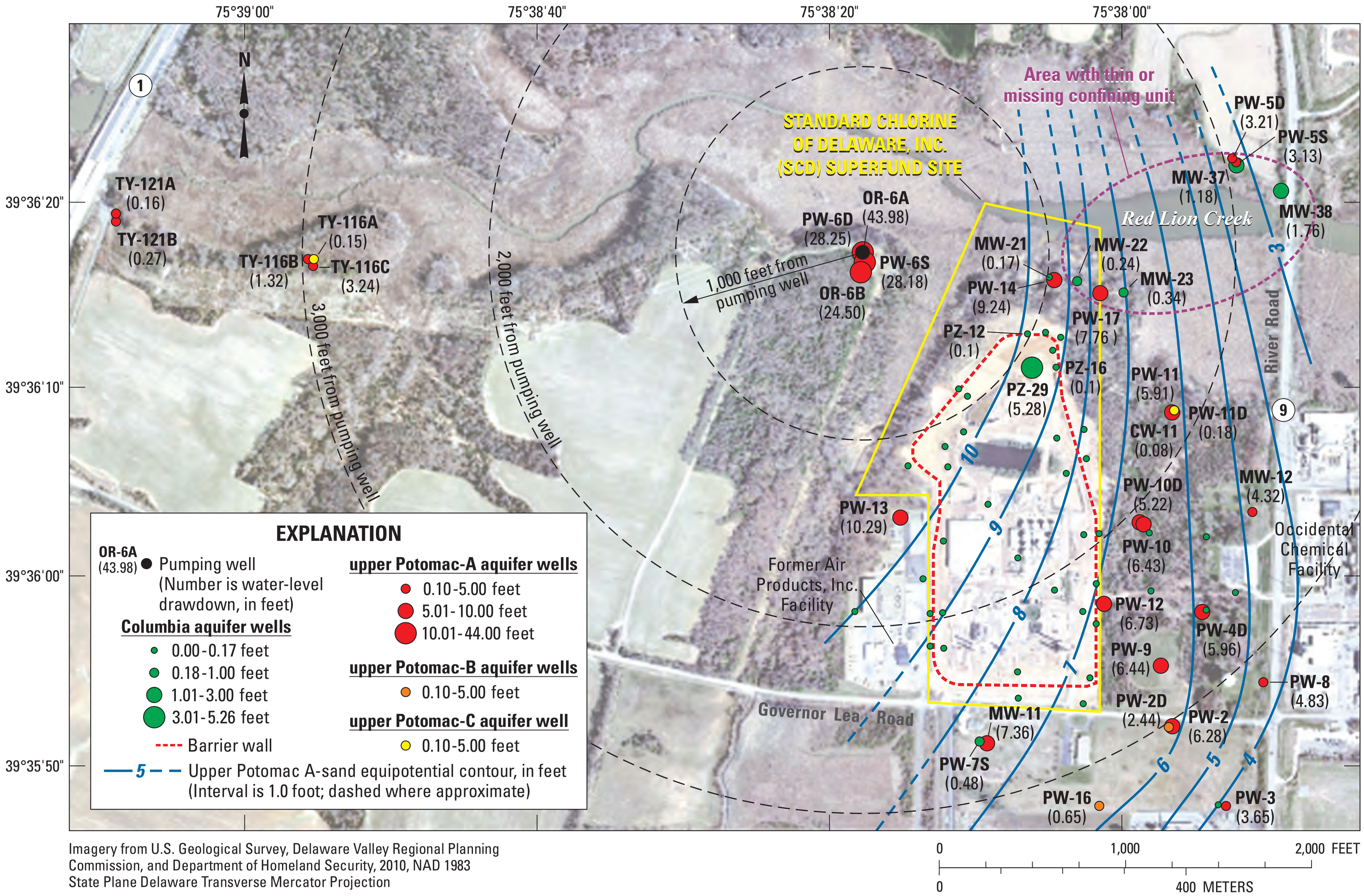


Figure 17. Time-series comparison of calculated vertical gradients for selected nested well pairs at the Standard Chlorine of Delaware, Inc. Superfund Site, 2007–12.

Water-Level Drawdown

Water-level drawdown was observed in some Columbia aquifer wells and in all upper Potomac aquifer wells and revealed anisotropy in the confined aquifer flow system. Pumping-induced drawdown was observed in 12 Columbia aquifer wells and in all 28 wells screened within the upper Potomac aquifer demonstrating hydraulic connectivity between the upper Potomac aquifer A-, B-, and C-sands underlying the site (fig. 18). Pumping at well OR-6A did not affect water levels within the lower Potomac aquifer, as measured at the Tidewater-12 well (shown in figure 3). Drawdown response in the upper Potomac aquifer was similar to that observed during the 1990 aquifer test, however, there were 24 more observation wells screened within the upper Potomac aquifer system in 2010 in addition to the 4 wells (OR-6A, OR-6B, MW-11, and MW-12) monitored during both pumping periods (Appendix 3).

The majority of Columbia wells showed no response to the 72-hour pumping of OR-6A; however, drawdown was induced in the surficial (Columbia) aquifer at the northeast end of the site near the wetlands and north of Red Lion Creek, confirming the absence of effective confining layers in the northeast area of the site near the creek (fig. 18). Observed drawdown greater than 0.07 ft was attributed to pumping; otherwise, changes less than 0.07 ft were attributed to a slow decline in unconfined water levels resulting from a lack of recent recharge, with only 0.30 in. of precipitation recorded during 14 days prior to the pumping period. Over 1 ft of drawdown was measured north of the creek, whereas closer to the site, drawdown measured less than 0.34 ft even though this area was closer to the pumped well (Appendixes 3 and 4). This supports interpretation from drilling logs that the Merchantville confining unit outside the barrier wall thins to the northeast and is completely eroded near Red Lion Creek and areas to the north of the creek where the greatest drawdown was observed (fig. 18). During the pumping period,



Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983
State Plane Delaware Transverse Mercator Projection

Figure 18. Maximum observed water-level drawdown for wells screened in the Columbia aquifer and upper Potomac aquifer, contours of maximum head change in the upper Potomac A-sand aquifer, and general area where the confining unit is thin or absent.

water levels in the Columbia aquifer did not drop below the level of the creek, which supports the conclusion that the creek and marsh serve as a discharge area for topographically driven flow within the water-table aquifer. In one Columbia aquifer well, OR-6C, located 74 ft from pumping well OR-6A, the water level increased during the pumping because of water being discharged at land surface from well OR-6A.

The absence of a confining layer near the creek also indicates that the creek itself may be a source of recharge to underlying aquifers, primarily the upper Potomac A-sand and by extension implies that a hydraulic connection therefore exists between the Columbia aquifer, Red Lion Creek, and the upper Potomac A-sand. Drilling logs from wells PW-5D and PW-17 further support this conclusion because Merchantville and Potomac Formation clays were not present. During the pumping of OR-6A, vertically downward flow gradients from the Columbia aquifer to the upper Potomac aquifer were enhanced at all locations. Red Lion Creek did not show any water-level changes in response to pumping at well OR-6A; however, water from the pumped well was discharged to the marsh and creek, so a decline was not expected. The tide control structure was functioning properly during the 72-hour period of pumping and fluctuations in creek stage during the pumping were less than 0.22 ft.

Surficial aquifer wells within the barrier wall did not show responses to the pumping of well OR-6A, except for well PZ-29, which is located in an area where the Merchantville Formation confining unit is very thin. This confining unit was likely penetrated during well installation, resulting in cross-screening into the upper Potomac aquifer. This well has since been properly abandoned by grouting so that it is not a pathway for vertically downward contaminant transport. The lack of drawdown in other Columbia aquifer wells within the barrier wall demonstrates a poor vertical hydraulic connection from the Columbia to the underlying upper Potomac aquifer. This is an important finding and implies that the barrier wall has been an effective tool for containing and limiting contaminated groundwater flow laterally towards the wetland and areas where confining units are absent.

Outside the barrier wall, there was some evidence of limited hydraulic connection between the Columbia and upper Potomac aquifers. Two wells (PW-4S and PW-7S) are screened in the upper Potomac top sand aquifer and long-term water-level data show correlation to water-table conditions observed in nearby Columbia aquifer wells. During the pumping of well OR-6A, drawdown was not observed at well PW-4S, however, drawdown of 0.48 ft was measured at well PW-7S, indicating that this sand layer may be connected to the upper Potomac A-sand southwest of the SCD site. The extent of this connection is unknown but may be better understood if additional hydrogeologic and water-level monitoring data were to become available from new wells to the west of well PW-7S.

In general, the maximum drawdown response in the upper Potomac A-sand was proportional to the distance from the pumped well; however, maximum drawdown was greater in a southward rather than eastward direction from the pumping well, indicating anisotropy, differences in permeability and (or) transmissivity, and a better hydraulic connection to sand layers to the south of the pumped well. The initial drawdown response to pumping supports this conclusion because well MW-11 located to the south began to show a response sooner than wells PW-4D and MW-12, which are located to the southeast at a similar distance (fig. 19). Maximum observed drawdown was greater in well PW-10 (6.43 ft) than in well PW-10D (5.22 ft), which is screened 70 feet lower than well PW-10 within a secondary sand layer. The magnitude of drawdown within this secondary sand layer indicates it is part of the upper Potomac A-sand aquifer, and not part of the upper Potomac B-sand aquifer, which was less responsive to pumping at well OR-6A. Towards the end of the 72-hour pumping period, drawdown began to decrease (the curve flattened) for wells PW-5S, PW-17, and PW-11, which indicates a boundary condition, interpreted as recharge from Red Lion Creek limiting the magnitude of drawdown. Water levels during the pumping dropped below creek stage for all wells located south of the creek, but did not drop below creek stage at well PW-5S, which is north of the creek. For continuously monitored wells, the time of maximum drawdown generally occurred between 1 hour prior to and 3 hours after the pumping finished, indicating a good hydraulic connection to the pumped well. The exception was well PW-3, where maximum drawdown occurred 9 hours after the pumping finished, indicating a poor hydraulic connection. A weaker drawdown response for wells located near Route 9 (MW-12, PW-8, and PW-3) also indicates a poor connection to other A-sand wells located to the west (fig. 19; Appendix 3.). This may be explained by a greater clay/silt fraction described in the lithologic logs for wells closer to Route 9. Wells located to the west of well OR-6A near the Tybouts Landfill showed drawdown response in four wells screened in upper Potomac A-sand (TY-116B, TY-116C, TY-121A, and TY-121B), but no response was greater than 3.24 ft, due to their greater distance from the pumped well (Appendix 3).

Pumping effects were observed in the upper Potomac B- and C-sand layers beneath the pumped interval (A-sand), confirming a measurable although limited hydraulic connection. Wells screened in the B-sand responded to pumping at well OR-6A, resulting in a drawdown of 2.44 ft at well PW-2D, and 0.65 ft at well PW-16. The stronger drawdown response at PW-2D indicates a stronger hydraulic connection to the A-sand at well PW-2D than at well PW-16. Two wells screened in the C-sand were minimally affected by pumping at well OR-6A, which resulted in a maximum drawdown of 0.18 ft at well PW-11D, and 0.15 ft of drawdown at well TY-116A. The extent of the connection between the upper Potomac A-sand and B- and C-sands is spatially variable and difficult to determine due to the limited number of wells screened lower in the B- and C-sands. The installation of additional wells would aid in understanding the response to pumping stresses within these aquifers.

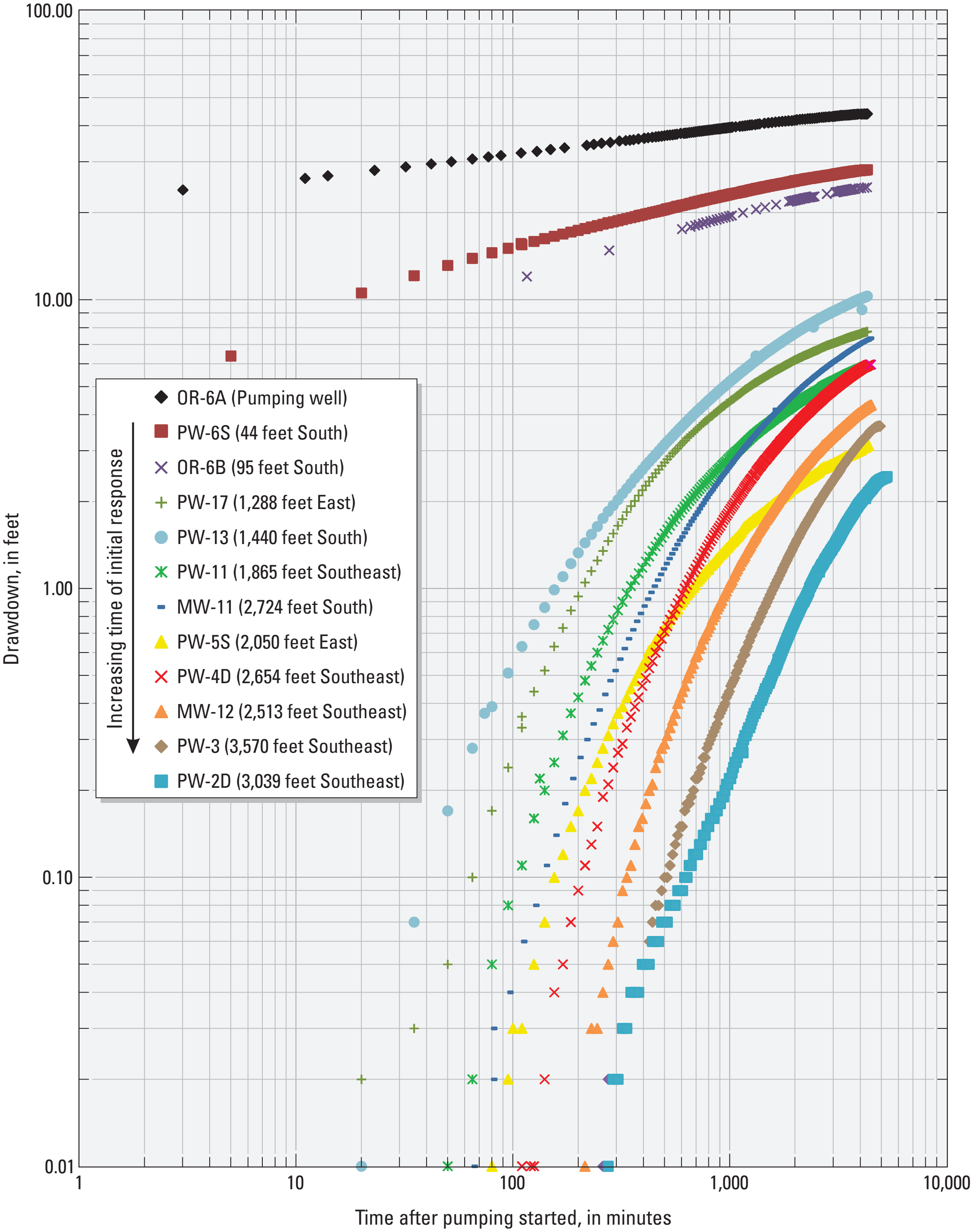


Figure 19. Log/log plot of time drawdown data for selected wells instrumented with continuous water-level recorders during 72 hours of pumping by the U.S. Geological Survey at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 28–31, 2010 (Explanation shows distance and direction from pumping well in parentheses.)

Water-Level Recovery

Water-level recovery to 50 percent of pre-pumping levels occurred in less than 24 hours for affected Columbia aquifer wells. The exact time for full recovery was not documented because the affected Columbia wells were not instrumented for continuous data collection. The recovery pattern in the A-sand was similar in magnitude and time delay to the observed drawdown pattern. Water-level recovery of 90 percent was achieved in upper Potomac A-sand wells within 12 days, for wells having continuous measurements (fig. 20). Recovery at other A-sand wells was similar, but periodic measurements were not frequent enough to permit direct comparison. Wells screened in the B-sand and C-sand showed a slow recovery time, indicating a weak connection to the A-sand, which is consistent with the small magnitude of observed drawdown in response to pumping.

Water-level recovery time generally increased farther away from the pumped well, although some differences were also noted for wells located a similar distance from well OR-6A (fig. 21). Recovery was quicker at well PW-17 than at well PW-13, which is likely due to a thin or missing confining unit and the proximity to Red Lion Creek as a source of aquifer recharge. A relatively quick recovery was expected at well PW-5S; however, water levels did not drop below creek stage during pumping at well OR-6A. Rather than being recharged from the creek, recovery in this well was likely due to upgradient recharge from a northwest direction, which would occur more slowly. Recovery time at well MW-11 was quicker than at well MW-12 even though they are similar distances from well OR-6A, indicating a good hydraulic connection to the south of the site. A relatively fast recovery time at well PW-13 indicates that more transmissive sands are located in the

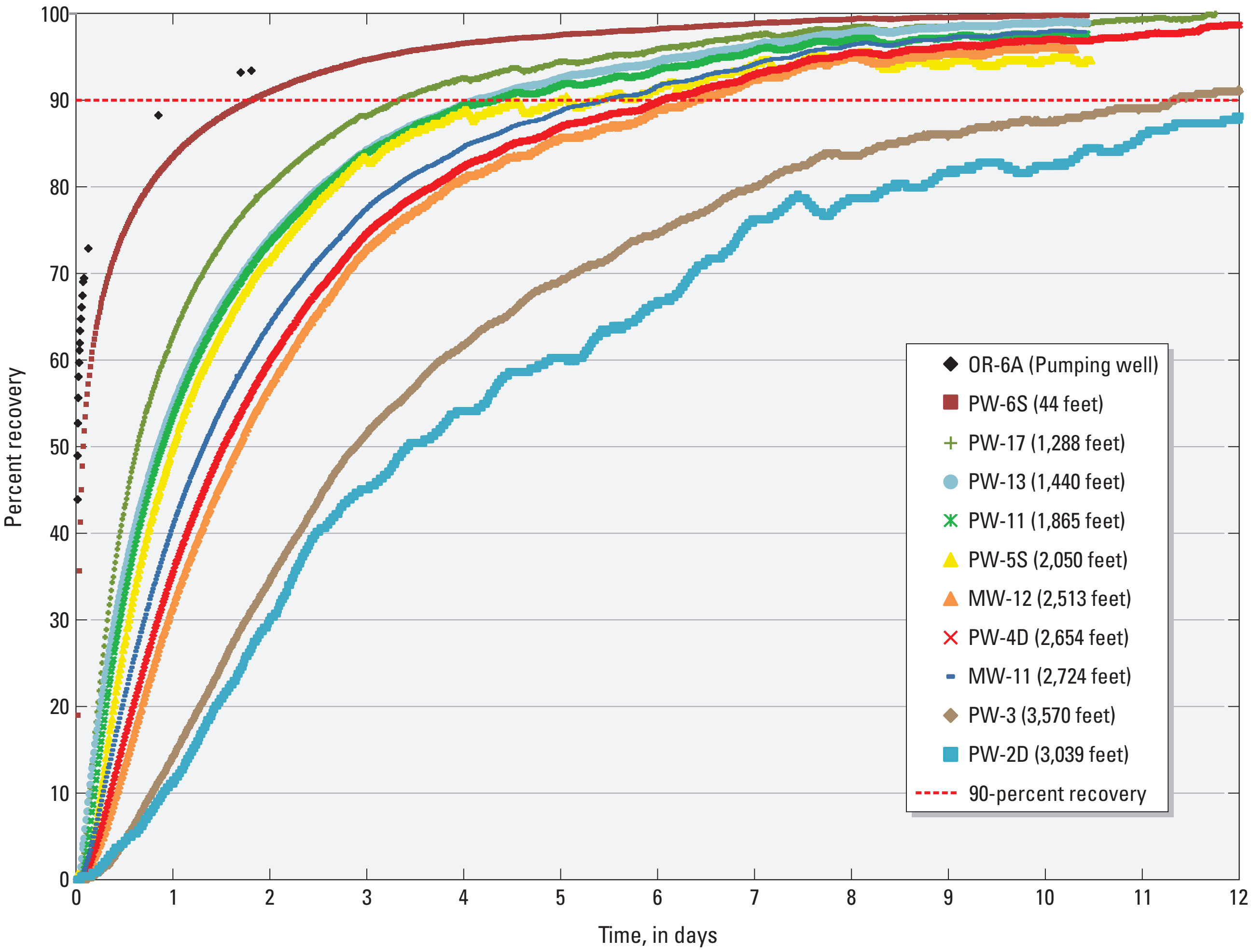
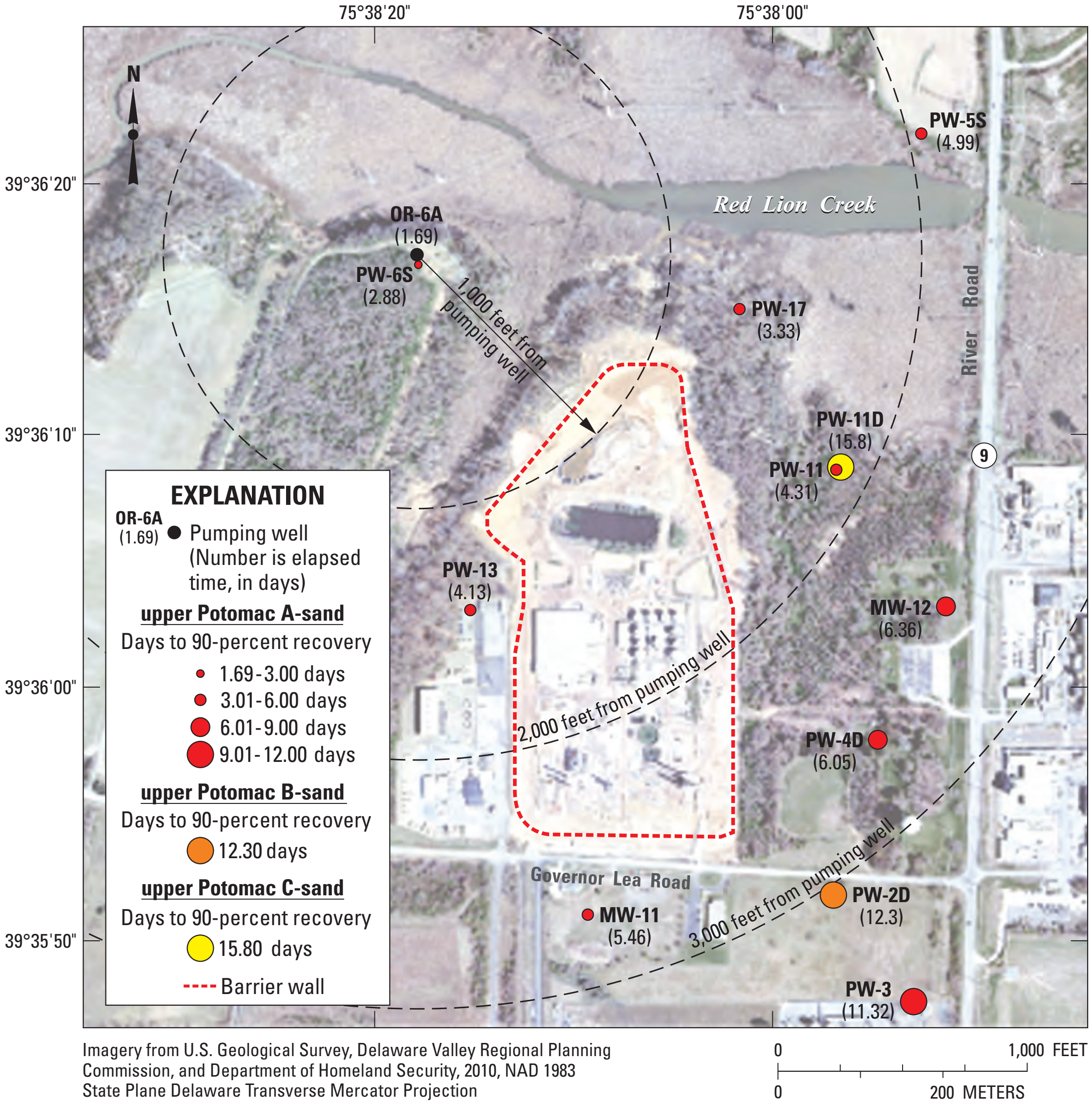


Figure 20. Percent recovery of water levels over elapsed time for selected continuously monitored upper Potomac aquifer wells after conclusion of 72 hours of pumping by the U.S. Geological Survey at well OR-6A, August 31, 2010. (Distance from pumping well shown in parentheses.)



Imagery from U.S. Geological Survey, Delaware Valley Regional Planning Commission, and Department of Homeland Security, 2010, NAD 1983 State Plane Delaware Transverse Mercator Projection

Figure 21. Elapsed time in days to reach 90-percent water-level recovery for selected continuously monitored wells screened in the upper Potomac aquifer, in response to conclusion of 72 hours of pumping by the U.S. Geological Survey at well OR-6A, August 31, 2010.

southwest area of the site, where lithology at depth is not as well characterized as other areas of the site that have multiple nested monitoring wells (fig. 3; table 3). The slow recovery time at well PW-3 supports the conclusion that this well is poorly connected to the upper Potomac A-sand and is likely perched.

During the 72-hour period, pumping in the upper Potomac A-sand caused vertically downward gradients to increase from the Columbia aquifer to the upper Potomac A-sand aquifer, as shown for several well pairs by comparing the increase from typical gradients to those that occurred during the pumping of well OR-6A: MW-23/PW-17 (from 0.02 to 0.11), CW-11/PW-11 (from 0.05 to 0.09), MW-10/PW-13 (from 0.09 to 0.15), CW-4/PW-4D (from 0.19 to 0.24), and PW-7/MW-11 (from 0.27 to 0.39). After the pumping of well OR-6A was complete, vertically downward gradients decreased to nearly the same magnitude calculated prior to beginning the pumping. A large recharge event approximately 1 month after completion of the pumping of well OR-6A raised A-sand water levels higher than pre-pumping levels, which can be seen in the long-term hydrograph (fig. 9).

Water Withdrawal Influences on the Local Flow System

The influence of groundwater withdrawals on the confined aquifer flow system is well documented and primarily attributed to pumping by industrial production wells. Head declines on the order of tens of feet have been measured in a cone of depression that extends radially from the DCIA. Changes in vertical and lateral flow gradients induced by aggregate pumping in the confined aquifer strongly control the flow system near SCD and may influence the potential movement of site-related contaminants. Pumping of water-table wells is limited, and related mostly to pump and treat extraction systems that have site-specific localized effects on the water table and little to no effect on the confined aquifer system.

Water Withdrawal Rates

The surficial aquifer in the Columbia Formation (Columbia aquifer) is infrequently used for small domestic water supplies and has historically been pumped at times for contaminant recovery. Five shallow recovery wells at the SCD site were pumped from 1992 through 2001 as part of mitigation efforts related to the 1986 spill. There are approximately five domestic wells located 1.5 mi to the north and northwest of the SCD site (Black & Veatch, 2007), with typical usage of less than 10,000 gal/d. These wells do not affect the shallow groundwater-flow system at SCD. In contrast, the current SCD shallow groundwater pump and treat system typically extracts 50,000 gal/d, causing drawdown of the water table within the barrier wall. No pumping effects have been observed in water-table wells outside the barrier wall, except during the USGS 72-hour pumping of well OR-6A in 2010.

Groundwater in the confined aquifers is primarily used for industrial purposes in the DCIA, with some withdrawal for public drinking-water supply. A series of exploratory wells were drilled to bedrock basement as part of a water supply study commissioned by the Tide Water Associated Oil Company (Leggette & Brashears, 1955) for estimating potential industrial use. Water levels for all Potomac aquifer layers in the area prior to 1955 were typically close to sea level, even within the deeper sands of the lower Potomac aquifer as measured at the Tidewater-12 well (Dc53-07). Industrial withdrawals began in 1955, sharply increased to approximately 3.5 Mgal/d in 1957, and reached 4.0 Mgal/d by 1980 (Martin and Denver, 1982). The typical total annual withdrawal from groundwater wells within 3 mi of SCD is approximately 6.7 Mgal/d. The largest user, DCRC, operates a network of withdrawal wells having a combined permitted usage of 5.5 Mgal/d. Production has ranged from 4 to 5 Mgal/d over the past 30 years, with annual production over the last 10 years averaging approximately 4 Mgal/d, except during the 2010 refinery shutdown, when it was 1.5 Mgal/d (Delaware City Refining Company, 2005–2012). Local drinking-water withdrawals from groundwater collectively amount to approximately 2.7 Mgal/d.

Surface water is also used for industrial processes by DCRC, but withdrawals have negligible effects on groundwater resources. The use of surface water is less desirable because it requires more treatment due to a higher mineral content than local groundwater. Sources of surface-water supply in decreasing order of average daily use during 2012 included: the Delaware River (358 Mgal/d), Dragon Run (1.34 Mgal/d), and Red Lion Creek (0.23 Mgal/d). The Red Lion Creek intake is located one-half mile upstream from SCD, and is the only surface intake that may potentially affect surface and groundwater interaction at the site. Given that the average daily total surface-water discharge near SCD is approximately 6.60 Mgal/d, flow in Red Lion Creek is only reduced on average by 3.5 percent when the intake is operational. Prior to July 2009, the Red Lion Creek intake was idle for a period of 9 years (Delaware City Refining Company, 2005–2012). The intake was used from July–December 2009, but then idled again until August 2011. The relative effect of upstream withdrawals on creek stage is minimal compared to the effects from tidal fluctuation due to the broken tide control structure.

Water-Level Changes Caused by Withdrawals

The relative effects of pumping wells screened in various Potomac aquifer layers on groundwater flow at the site were evaluated based on corresponding changes in water levels in monitoring network wells. The depth of the screened interval and changes in the withdrawal rate are more important than pumping well location relative to the site for understanding the effects on groundwater flow (table 3; fig. 2). Refinery production wells are periodically serviced to maintain yield, which requires temporary idling, removal of the pump, and re-development of the screened interval. Monitoring well responses during these multi-week-long service periods provided additional insight on how the local flow system operates. Pumping effects were identified in late 2007 and early 2008 (fig. 9), when observed recovery-drawdown curves for upper Potomac aquifer wells coincided with a servicing period for production well R-15 (discussed in the next section).

Water-level declines up to 200 ft below sea level in parts of the Potomac aquifer in New Castle County, Delaware have been documented since withdrawals began in the 1950s (Martin, 1984). Most of the decline near SCD is due to long-term sustained use by the DCRC. Lower head values in the Potomac aquifer relative to the water-table aquifer have enhanced a vertically downward flow gradient. A fairly constant aggregate groundwater use by the refinery over time has led to a steady state “pumping” condition for measured water levels within the upper, middle, and lower Potomac aquifers. This status was interrupted when most refinery production wells were idled during an ownership transition period from May 2010 to January 2011. During this time, selected wells were occasionally pumped to ensure that the pumps remained in good working condition, with only very limited withdrawals to support industrial plant maintenance (Rebecca Gudgeon, Delawere City Refining Company, oral commun., 2011). The ownership transition period occurred within the “aquifer recovery and limited pumping period” from November 2009 to October 2011. A widespread water-level recovery was observed during this period in local monitoring wells near the SCD site and in Potomac aquifer monitoring wells that are part of the regional DGS monitoring network (Tom McKenna, Delaware Geological Survey, oral commun., 2012).

The altitude of water levels in the lower Potomac aquifer near the site (Tidewater-12 monitoring well [Dc53-07]), typically range from -50 to -120 ft below sea level and show the aggregate long-term withdrawal effects from multiple deep withdrawal wells in the lower Potomac aquifer (P-6A, P-9A, P-10A, P-16A, and to a much lesser extent, PW-4, PW-5, and ASR-1 due to their relatively low pumping rates) (fig. 2). Short-term changes in water levels at well Tidewater-12 often correlate to rate changes at production well P-6A, located nearby (fig. 3). Production wells P-6A (lower Potomac) and P-5B (middle Potomac) are located close to the SCD site but an analysis of hydrographs showed that changes in withdrawal rate have little to no effect on water levels at monitoring wells at SCD, which are screened in the upper Potomac aquifer (fig. 22). Withdrawal rates at production well R-15 (upper Potomac), however, do affect water levels in the upper Potomac aquifer at the site and are discussed further in the next section.

Industrial groundwater withdrawal wells located closest to SCD (R-15, P-5B, and P-6A) (fig. 2) typically pump a combined 1 Mgal/d during normal operation. These wells were operated in very limited capacity (pumping less than 100,000 gal/d) from December 2009 to May 2010, and pumping was negligible while the refinery was idled from May 2010 to January 2011. A groundwater recovery was observed during this period, with a corresponding reduction in the magnitude of the vertically downward gradients, as previously described.

Analysis of hydrographs and pumping rates shows that other nearby production wells had little to no effect on water levels in the upper Potomac A-sand at the site. Production wells P-3B and P-4B are located west of the SCD site (fig. 2) and have little if any effect on water levels in the upper Potomac at SCD due to their relatively low combined pumping rates (less than 0.25 Mgal/d), and the depth of the screened interval (middle Potomac). Wells PW-4 and PW-5 (fig. 2) are screened in the lower Potomac aquifer and have a combined withdrawal of 0.13 Mgal/d that is consistent over the study period. These wells likely do not affect water levels in the

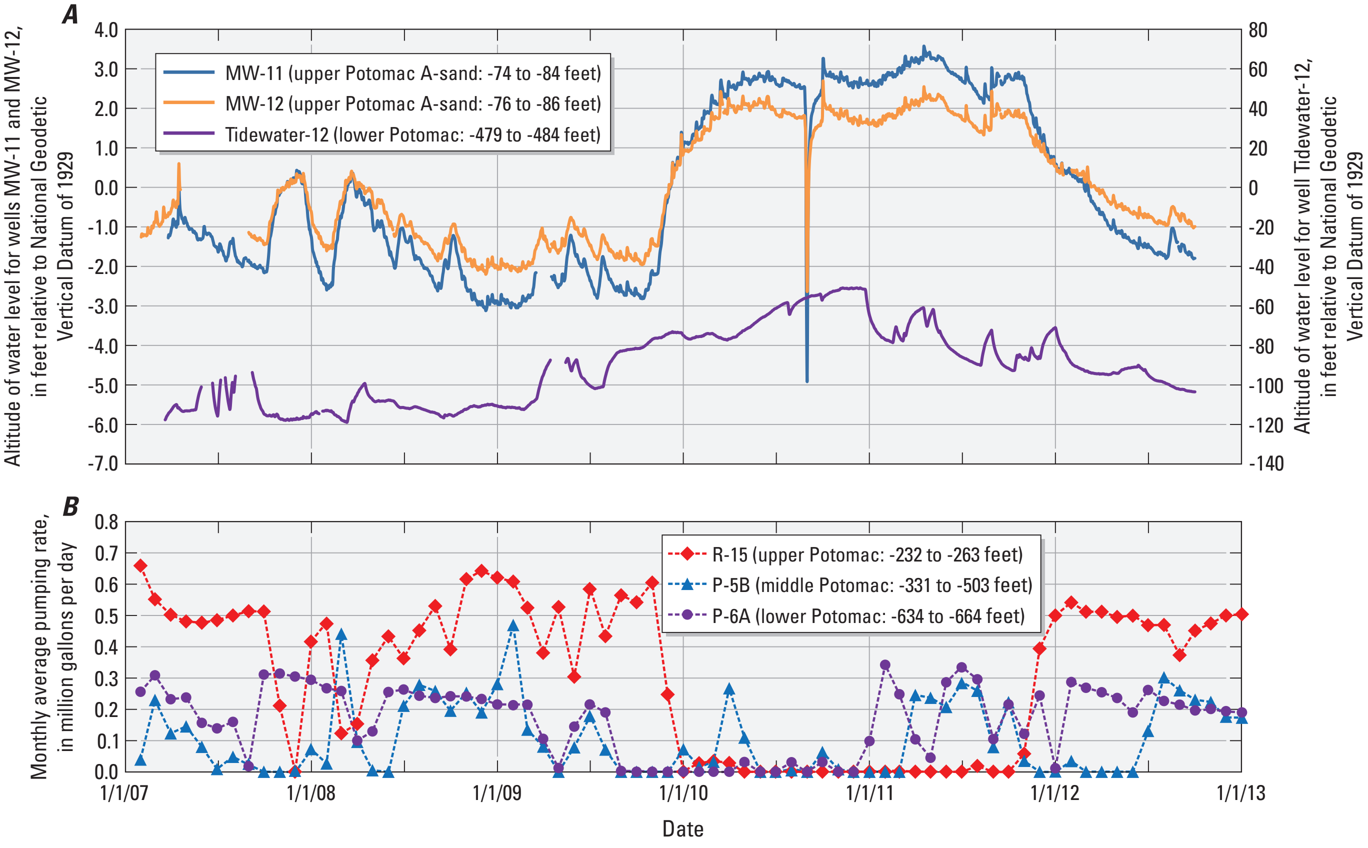


Figure 22. *(A)* Hydrograph showing water-level response to changes in *(B)* pumping rate for production wells screened in the upper (R-15), middle (P-5B), and lower (P-6A) Potomac aquifers near the Standard Chlorine of Delaware, Inc. Superfund Site. (Aquifer name and altitude of screened interval in parentheses.)

upper Potomac at SCD due to their downgradient location and the depth of the screened interval. Well ASR-1 is an aquifer storage and recovery well, where water input and output is fairly equal, although some storage loss to the lower Potomac aquifer likely occurs. Wells AV-1, AV-2, AV-3, and AV-4 are screened in the upper Potomac aquifer but do not appear to affect SCD water levels, even though the pumping rate of 1.4 Mgal/d at AV-1 is greater than the pumping rate at any of the refinery production wells (fig. 2). Their lack of influence on the flow system is likely due to their upgradient location within the regional flow system. AV wells have been pumped at fairly constant rates over time, and a review of the pumping history since 2001 did not reveal any notable period of influence on SCD hydrographs, even when selected wells were shut down for servicing. In contrast, water-level changes were not observed at AV observation wells during the USGS pumping of well OR-6A in August 2010, or during the shutdown of the refinery wells during 2010. The AV well pumping network is likely hydraulically disconnected from upper Potomac aquifer wells located south of Red Lion Creek, further indicating that the creek serves as a flow boundary for the upper Potomac aquifer.

Production Well R-15

Evaluation of water levels in wells screened in the A-, B-, and C-sand aquifers of the upper Potomac Formation near the SCD site has shown that hydraulic heads in the upper Potomac aquifer system are significantly affected by the operating schedule of refinery production well R-15, located south of the site (fig. 4a) and screened within the C-sand aquifer of the upper Potomac Formation (figs. 4b and 23). Correlation between head changes and pumping was first observed in 2007 and early 2008 during two distinct periods of time when the well was idled for servicing. A longer period of shutdown began on November 11, 2009, and data from USGS monitoring wells showed aquifer recovery within the A- and C-sands in the upper Potomac aquifer (fig. 23) (B-sand was not monitored during recovery). Complete recovery was achieved approximately 6 months after pumping in the C-sand stopped. In contrast, 90-percent recovery was achieved in the A-sand 14 days after USGS pumping at well OR-6A.

To further assess the effects of pumping well R-15, an aquifer pumping step test was designed for the well during the restarting period, late in 2011. Approximately equal changes in rate (steps) were made every 2 weeks, beginning with 240

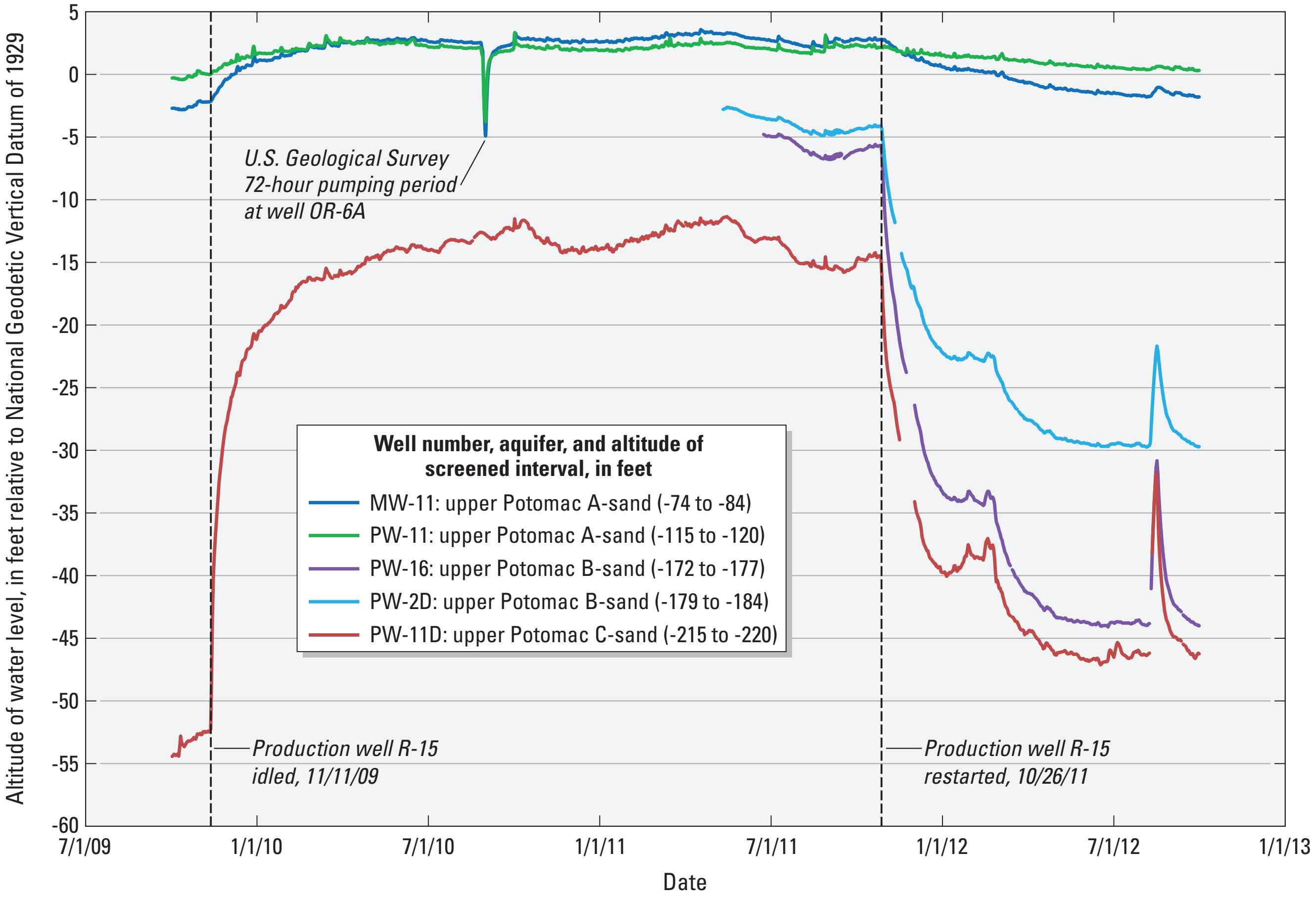


Figure 23. Hydrograph showing upper Potomac aquifer recovery and drawdown for A-, B-, and C-sand intervals in response to production well R-15 operating schedule.

gal/min on October 26, 2011 until reaching 350 gal/min on December 7, 2011. The pumping rate was limited (350 gal/min) by DNREC, in part due to the known effects of well R-15 on upper Potomac water levels. A change in hydrograph slope corresponding to each rate change during the restart period was observed for B- and C-sand monitoring wells, indicating a good hydraulic connection with well R-15, which is screened in the C-sand. A change in the slope of the water-level drawdown curve was not observed for A-sand wells, but water levels in all A-sand wells showed a decline in response to pumping at well R-15. Drawdown was not observed in continuously monitored Columbia aquifer wells (CW-11 and Ion MW-3). Similar to the recovery time period, water-level drawdown was completed in approximately 6 months, and represents a new steady state flow condition within and between the upper Potomac sand layers under pumping influence. The magnitude of drawdown response measured in the observation wells indicates the extent of hydraulic connection to the pumped interval (C-sand). C-sand well PW-11D showed a clear response, as did B-sand wells (PW-16 and PW-2D). The response was greater at well PW-16 than at well PW-2D, which may reflect the relative distance to well R-15, and may also be indicative of differences in hydraulic properties. This is counter to what was observed during the USGS pumping of well OR-6A, when well PW-2D showed a greater response to pumping in the A-sand than well PW-16, indicating that PW-2D is better connected to the A-sand. Another indication of the connection between B-sand and C-sand wells and well R-15 was the short-term response from a 1-week emergency shutdown of R-15 that occurred on August 8, 2012, which can be seen on the hydrograph in figure 23. A small rise is evident at A-sand well MW-11.

Generally, drawdown response in the A-sand was similar to the B-sand in that wells located farthest from the pumping center showed the smallest drawdown (well PW-5 in fig. 9). The cone of depression steepens closer to the pumping center, with large declines measured near the south end of the site (wells MW-11, PW-4D, MW-12, and PW-13), whereas wells located closer to the creek (PW-5 and PW-17) showed less decline (fig. 9), and did not drop below creek stage. Water levels in wells near the creek have remained higher than creek stage since pumping at well R-15 resumed in October 2011, which is similar to the pumping scenario in 2007–09; however, water levels in wells to the south have dropped below creek stage and the flow direction has shifted toward the south. Water-level declines with well R-15 pumping at a steady rate (350 gal/min) have not dropped below levels previously observed in 2009 (fig. 9). At well MW-11, the previous maximum low was approximately -3.0 ft, compared to -1.75 ft, which was observed more recently. Although water levels in wells adjacent to the creek are currently higher than creek stage, potential recharge is still possible because water levels at some wells are lower than creek stage. Potential recharge from the creek/marsh may be mitigated by restoring creek stage to levels observed before the tide gate malfunction (approximately -1.75 ft), which is similar to the lowest current water level observed in any upper Potomac aquifer well.

Refined Local Conceptual Model of Groundwater Flow

The identification of areas of the SCD site where confining units are absent in conjunction with hydrologic evidence of aquifer interconnection has led to refinement of the local conceptual model of groundwater flow at the SCD site. The Merchantville confining unit was initially thought to be a nearly continuous low permeability layer that limited contamination from migrating into deeper aquifers at the site. This conclusion was partially drawn from the lack of water-level response in Columbia wells to an aquifer test conducted in 1990 (Roy F. Weston, Inc., 1992); however, recent detection of benzene and chlorobenzene compounds in sand layers of the upper Potomac aquifer indicates that the clay is discontinuous and drilling and geophysical data indicate that holes may have been eroded through the clay by paleochannels prior to and during the deposition of the Columbia Formation (U.S. Environmental Protection Agency, 2004, 2006). Erosion of the upper Potomac clay also occurred, mostly in the vicinity of Red Lion Creek, which created a focused area of aquifer connection between the Columbia and upper Potomac aquifers. This area is of particular concern at the site because of current and potential future contaminant movement downward into the upper Potomac aquifer.

Description of Components of Conceptual Model

Major features that influence groundwater-flow direction and potential contaminant transport at the SCD site are presented as a refined conceptual model of groundwater flow (fig. 24). This conceptual model represents groundwater flow during the prevailing condition of steady groundwater withdrawal (pumping) from the upper Potomac C-sand layer at production well R-15 (fig. 2). Groundwater flow within the surficial aquifer is generally from topographic high points towards and discharging to Red Lion Creek, although some water recharges the underlying upper Potomac A-sand. In turn, water from the A-sand recharges the B- and C-sand layers, although the connection is not as direct. Flow direction within the A- and B-sands is influenced by pumping and is generally from north to south, differing from the regional flow direction from northwest to southeast. Flow direction within the C-sand is also believed to be from north to south, but cannot be determined from a single well screened within the C-sand. The erosion of confining layers near Red Lion Creek and the resulting extent of aquifer connection near the creek has been demonstrated by looking at various hydraulic stresses on the aquifer system. The dynamics of groundwater flow in the vicinity of Red Lion Creek are complicated by local pumping effects, and by the inter-aquifer connections created by the paleo-Red Lion Creek erosional channel. Recharge to the A-sand is likely enhanced by pumping at production well R-15, but discharge from the A-sand to the creek likely occurs during periods of limited pumping when water levels in the A-sand are higher than creek stage.

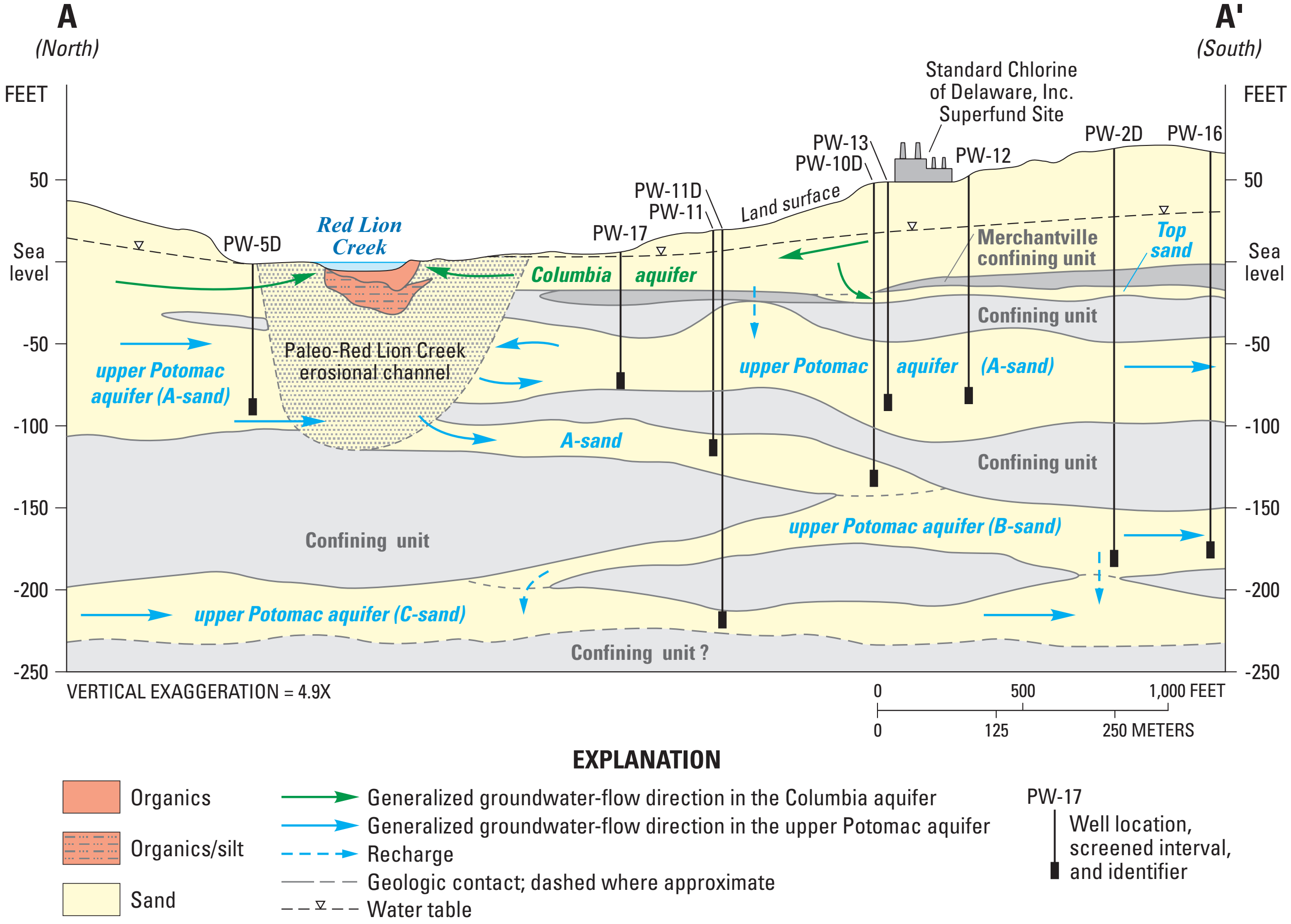


Figure 24. Cross section A-A′ showing refined conceptual model of local groundwater flow, including Red Lion Creek, Columbia aquifer, upper Potomac A-, B-, and C-sand aquifers, selected upper Potomac aquifer wells, and erosional channel of paleo-Red Lion Creek.

Implications for Groundwater Contaminant Movement

The connections between aquifers that were identified have major implications for the long-term movement of contaminants in groundwater near the SCD site. Contaminants detected within the upper Potomac A-sand at several locations have the potential for further movement, depending on the prevailing groundwater-flow direction and head magnitude within the upper Potomac sand layers. The presence of benzene and various chlorobenzene compounds in A-sand wells at the north end of the site (wells PW-14 and PW-17) is attributed to vertically downward transport from overlying contaminated marsh sediments and contaminated Columbia aquifer water. This vertical mixing is due, in part, to strong vertically downward gradients induced by local pumping combined with the absence of confining units in this area. At other A-sand well locations near the SCD site to the east (wells PW-4D, PW-9, and PW-12) and to the west (well PW-13), an effective confining unit (upper Potomac clay) was identified during drilling; however, contaminants were detected below this layer. Their presence is likely a result of lateral groundwater advective transport from other areas to the north where confining units are absent, but may also be attributed to movement of DNAPL downward through microfractures within the confining units. Contaminants have not been detected in the upper Potomac B- and C-sands, indicating that the hydraulic connection from the A-sand to the B- and C-sands is weaker than the connection between the Columbia aquifer and the upper Potomac A-sand.

The relation between creek stage and water levels in the upper Potomac aquifer is important for understanding potential contaminant transport from the creek/marsh to underlying aquifers. The marsh area is a nexus for aquifer mixing where shallow contaminated Columbia aquifer groundwater discharges to surface water, but also recharges the subcropping upper Potomac aquifer in areas where confining units have been eroded (such as near well PW-17, which showed contamination during vertical profiling from the water table to 100 ft below land surface). Recharge is driven by higher water levels in the creek relative to the aquifer, thus, the ability to regulate creek stage changes due to tidal cycling may help to limit the dynamics of both physical and chemical mixing in the marsh area. In particular, a sustained lower creek stage would reduce the potential aquifer recharge of water (and contaminants). Short-term variability in upper Potomac water levels can also be reduced by controlling tidal influences to Red Lion Creek using fully functional tide gates. Changes in aquifer water levels due to increases in creek stage resulting from precipitation runoff are typically of short duration (1-2 days), lasting until the water is discharged to the Delaware River.

Considerable control over the flow system at the SCD site may be achieved by carefully managing the local groundwater pumping regime within the upper Potomac aquifer, particularly at production well R-15. Sustained pumping has resulted in decreased water levels in the upper Potomac aquifer and vertically downward gradients throughout the site, including inside the barrier wall where the Columbia aquifer pump and treat system must maintain a positively upward gradient (with respect to the upper Potomac aquifer) for effective contaminant recovery. Groundwater-flow direction within the upper Potomac aquifer is also largely controlled by pumping at well R-15, with a southward flow toward the production well when operating. Potential long-term contaminant transport in this direction is a concern and contamination detected south of contaminated wetland areas indicates that lateral transport is an issue at the site. Further delineation of the extent of contamination to the southwest of the site (and south of well PW-13) is needed, and is in keeping with the recommendations from the 1995 Record of Decision (U.S. Environmental Protection Agency, 1995). In addition, a characterization of lithology to a depth of 300 ft in this area would be needed to confirm the suspected presence of thick sands (sand channels) inferred from the water-level responses during pumping of well OR-6A. These higher hydraulic conductivity zones may serve as preferential pathways for contaminant transport, and their presence combined with pumping influence will factor into the design of any remedy for addressing deeper groundwater (EPA Operable Unit 4).

Groundwater modeling may prove useful for testing various pumping scenarios within the upper Potomac aquifer to determine the effects on flow direction and changes in leakage (recharge) due to enhanced vertical gradients, which are up to two to three times greater during pumping periods (fig. 17). Future monitoring of changes in vertical gradients may be necessary to evaluate the sensitivity of the flow system to such changes, and to predict potential lateral migration of contaminants resulting from periodic decreases in vertical gradients. Groundwater modeling would also provide insight on the complex recharge mechanisms for this Coastal Plain setting located near the Fall Line.

Summary and Conclusions

The U.S. Geological Survey (USGS), in partnership with the U.S. Environmental Protection Agency, Region 3, and the Delaware Department of Natural Resources and Environmental Control is continuing a multi-year investigation of the hydrogeologic framework and hydrology of the confined aquifer system near the Standard Chlorine of Delaware, Inc. (SCD) Superfund Site. The goals of the ongoing study at the site are to determine the hydraulic connection between the Columbia and Potomac aquifers, determine the direction and rate of groundwater flow in the Potomac aquifer, and identify factors affecting the fate of contaminated groundwater.

Geologic and hydrologic investigation of the upper Potomac Formation near the SCD site from 2005–12 has resulted in a revised site hydrogeologic framework, subdividing the upper Potomac aquifer into three continuous sand layers (A-sand, B-sand, and C-sand), based on lithology and hydraulic responses to precipitation, tidal effects, creek stage changes, and aquifer pumping. A discontinuous sand layer also was identified at the top of the upper Potomac Formation. Interpretations of the flow system in the upper Potomac A-sand were made based on water-level data from a monitoring well network that was installed because chlorobenzene contaminants had been previously detected at the site, typically at an altitude of -85 feet (ft) at multiple locations. Drilling to an altitude of -220 ft at non-contaminated locations provided additional lithologic information to help classify sediments within a complex fluvial environment that includes channel sands ranging in thickness from 10 to 70 ft that may function as preferential groundwater flow paths affecting contaminant transport, and multiple confining units within the upper Potomac Formation ranging in thickness from 20 to 60 ft that may function as effective barriers to contaminant movement. The Merchantville Formation clay was not shown to be an effective confining unit in some areas based on the similarity of water-level responses in the upper Potomac top sand aquifer and the water table. Areas under Red Lion Creek to the northeast of the site show thick sand sequences, an absence of confining units, and a direct hydraulic connection to overlying contaminated sediments. The USGS evaluation of water-level responses in wells during pumping of well OR-6A in August 2010 confirmed the absence of effective confining units near Red Lion Creek, and also demonstrated that shallow groundwater within the barrier wall is mostly isolated from external stresses. Drawdown and recovery responses within the upper Potomac aquifer to the south and west of the site indicate a preferential hydraulic connection in this area.

Efforts to further refine site hydrogeology using well borings paired with geophysical surveys are ongoing. Additional borings to approximately 300 ft below land surface targeting the Potomac Formation would enable a more complete geologic characterization in the vicinity of the SCD site and would also enable further contaminant delineation.

These efforts would also help to classify (locally) the depositional environments of Potomac Formation sediments into various facies, but more importantly, they would help identify paleochannel features formed by amalgamated sands (amalgamated channels) and thick sands (isolated channels), which collectively may form areas of preferential contaminant transport at and near the site.

A variety of hydraulic stresses on the local flow system at the SCD site were identified and evaluated in terms of their relative effect on groundwater flow. Recharge from precipitation to the Columbia and upper Potomac aquifers occurs locally, but water-level variations show greater response to stage loading from Red Lion Creek than to recharge from precipitation, except during large rainfall events. Water levels in the Columbia aquifer varied less than 2 ft during the study, whereas water levels varied up to 6 ft in the upper Potomac aquifer because of pumping. The tide gate malfunction on August 28, 2011 raised the base stage of Red Lion Creek and resulted in a fourfold increase in daily water-level variation within the upper Potomac aquifer. Red Lion Creek and fringing marshes receive discharging groundwater from the surficial aquifer and from the underlying semi-confined upper Potomac aquifer when industrial withdrawals are limited, and water levels are higher than the creek. When major groundwater withdrawals are occurring, water levels in several A-sand wells drop below Red Lion Creek stage, and aquifer recharge from Red Lion Creek may be possible. Groundwater withdrawals also increase vertically downward gradients from the Columbia aquifer to underlying sand layers in the upper Potomac aquifer, and between upper Potomac sand layers. Vertical gradients ranged from slightly upward (0.02) from the A-sand to the Columbia aquifer near Red Lion Creek to strongly downward from the A-sand to C-sand (0.65, during pumping periods).

Continued monitoring of withdrawal rates for nearby production wells, in particular well R-15, will assist in understanding site-related water-level responses and improve future remedial design strategies for deep groundwater. Future data collection and analyses that would yield a more refined understanding of the hydrologic system at the site include: exploratory drilling to a depth of 300 ft, particularly southwest of the site; further analysis of existing surface geophysical data in the context of new lithologic information; and instrumentation of new wells to measure and understand water-level responses in multiple sand intervals of the upper Potomac aquifer. The understanding of the hydrogeologic system and potential contaminant pathways in the vicinity of the SCD site would be further enhanced with development of a groundwater-flow model that incorporates a revised understanding of site stratigraphy and local pumping conditions. This model could be used to predict groundwater traveltimes, assess Red Lion Creek as a flow boundary, and be used to evaluate appropriate withdrawal rates for nearby production wells to align industrial pumping with site remedial goals.

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Appendixes

Appendix 1. Chemicals of concern detected in soils, sediment, and (or) groundwater at the Standard Chlorine of Delaware, Inc. Superfund Site.

Appendix 2. Characteristics of U.S. Geological Survey Potomac Aquifer Study monitoring sites measured at and near the Standard Chlorine of Delaware, Inc. Superfund Site, 2005–12.

Appendix 3. Well characteristics and water-level drawdown and recovery data for wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 28–31, 2010.

Appendix 4. Water-level data for non-U.S. Geological Survey network observation wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 26–September 1, 2010.

Appendix 1. Chemicals of concern detected in soils, sediment, and (or) groundwater at the Standard Chlorine of Delaware, Inc. Superfund Site.

[EPA, U.S. Environmental Protection Agency]

Chemicals of concern identified in 1995 EPA Record of Decision	
Benzene	1,3,5-trichlorobenzene
Chlorobenzene	1,2,3,4-tetrachlorobenzene
1,2-dichlorobenzene	1,2,4,5-tetrachlorobenzene
1,3-dichlorobenzene	Pentachlorobenzene
1,4-dichlorobenzene	Hexachlorobenzene
1,2,3-trichlorobenzene	Nitrobenzene
1,2,4-trichlorobenzene	Toluene
Additional chemicals of concern identified in 2010 EPA Record of Decision	
Dioxin	PCE (Tetrachloroethylene)
Carbon tetrachloride	TCE (Trichloroethylene)
Chloroform	

Appendix 2. Characteristics of U.S. Geological Survey Potomac Aquifer Study monitoring sites measured at and near the Standard Chlorine of Delaware, Inc. Superfund Site, 2005–12.

[USGS, U.S. Geological Survey; DNREC, Delaware Department of Natural Resources and Environmental Control; DGS, Delaware Geological Survey; EPA, U.S. Environmental Protection Agency; Motiva, Motiva Delaware City Refinery; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; bls, below land surface; toc, top of casing; --, no data; TIC, top of inner casing; TPVC, top of polyvinyl chloride (PVC) casing; TSC, top of steel casing; TPVCcollar, top of PVC collar; 4sq., 4-inch square; flush, flush mounted with land surface; up., upper; psi, pounds per square inch; Δ, difference]

Local site name	USGS station number	DNREC permit number	DGS identification number	Latitude (NAD 83) (decimal degrees)	Longitude (NAD 83) (decimal degrees)	Northing (NAD 83) (Delaware State Plane, feet)	Easting (NAD 83) (Delaware State Plane, feet)	Measuring point elevation (NGVD 29) (feet)	Measuring point reference	Outer casing diameter (inches)	Inner casing diameter (inches)	Depth of boring (feet bls)
Red Lion Creek	01482320	--	--	39.6053	-75.6300	584732.08	596052.17	6.78	shelter floor	--	--	--
Ion-MW03	393541075375302	188967	Dc53-93	39.5966	-75.6314	581572.91	595655.61	52.84	TIC	3	2	39
C-31	393552075375601	72650	Dc52-68	39.5979	-75.6323	582025.31	595397.17	62.03	TPVC	8	4	82
CW-4	393558075375503	219241	Dc53-83	39.5995	-75.6318	582631.72	595534.28	55.87	TIC	4sq.	2	69
MW-14	393559075375201	89170	Dc53-68	39.5997	-75.6311	582714.84	595743.80	48.26	TPVC	6	4	60
MW-15	393559075375801	89171	Dc53-67	39.5997	-75.6318	582710.33	595544.15	48.33	TPVC	6	4	67
MW-16	393559075375803	89172	Dc53-66	39.5998	-75.6327	582725.73	595280.04	47.06	TPVC	6	4	66
MW-17	393602075375401	89173	Dc43-28	39.6006	-75.6317	583017.43	595584.79	52.62	TPVC	6	4	72
MW-18	393602075375801	89174	Dc43-27	39.6007	-75.6328	583045.37	595276.16	32.24	TPVC	6	4	54
PMW-48	393602075380101	218228	--	39.6006	-75.6337	583032.83	595001.35	49.56	TIC	4	2	--
PMW-49	393602075380102	218229	--	39.6006	-75.6340	583033.95	594933.39	49.42	TIC	4	2	--
CW-11	393603075375901	228525	Dc42-50	39.6024	-75.6324	583681.30	595390.32	17.47	TIC	6	2	40
SCD-EM-2S	393611075375602	--	Dc43-39	39.6031	-75.6323	583936.51	595406.15	3.36	TSC	--	2	3.78
SCD-EM-2D	393611075375601	--	Dc43-38	39.6031	-75.6323	583936.51	595406.15	4.66	TSC	--	2	9.1
PZ-29	393611075380601	--	--	39.6031	-75.6350	583931.60	594645.93	48.41	TIC	4	1.25	--
OR-6C	393616075381802	--	--	39.6048	-75.6382	584475.47	593743.77	47.09	TPVC	6	4	52
MW-37	393622075375203	178327	Dc43-31	39.6061	-75.6312	585021.39	595729.27	6.03	TPVC	6	4	82
MW-7	393652075380901	81372	Dc42-19	39.6032	-75.6356	583990.06	594473.60	48.70	TPVC	6	4	61.3
PW-7S	393551075381102	218549	Dc52-79	39.5975	-75.6359	581915.77	594373.92	53.60	TIC	4sq.	2	85
PW-4S	393558075375501	218938	Dc53-84	39.5995	-75.6318	582621.11	595549.22	56.46	TIC	4sq.	2	80
PW-3	393541075375301	202312	Dc53-51	39.5966	-75.6313	581563.36	595695.87	51.74	TIC	4	2	147
MW-11	393551075381101	81385	Dc52-56	39.5975	-75.6358	581907.85	594405.97	53.41	TPVCcollar	6	4	136
PW-2	393552075375602	202206	Dc53-50	39.5978	-75.6323	581991.24	595394.64	62.47	TIC	4	2	167
PW-8	393554075375001	219238	Dc53-86	39.5984	-75.6306	582236.65	595885.79	53.38	TIC	4sq.	2	162
PW-9	393555075375701	228523	Dc53-133	39.5987	-75.6325	582322.51	595336.19	52.23	TIC	6	2	148
PW-4D	393558075375502	218725	Dc53-85	39.5995	-75.6318	582616.07	595557.15	56.15	TIC	4sq.	2	150

Appendix 2. Characteristics of U.S. Geological Survey Potomac Aquifer Study monitoring sites measured at and near the Standard Chlorine of Delaware, Inc. Superfund Site, 2005–12.—Continued

[USGS, U.S. Geological Survey; DNREC, Delaware Department of Natural Resources and Environmental Control; DGS, Delaware Geological Survey; EPA, U.S. Environmental Protection Agency; Motiva, Motiva Delaware City Refinery; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; bls, below land surface; toc, top of casing; --, no data; TIC, top of inner casing; TPVC, top of polyvinyl chloride (PVC) casing; TSC, top of steel casing; TPVCcollar, top of PVC collar; 4sq., 4-inch square; flush, flush mounted with land surface; up., upper; psi, pounds per square inch; Δ, difference]

Local site name	USGS station number	DNREC permit number	DGS identification number	Latitude (NAD 83) (decimal degrees)	Longitude (NAD 83) (decimal degrees)	Northing (NAD 83) (Delaware State Plane, feet)	Easting (NAD 83) (Delaware State Plane, feet)	Measuring point elevation (NGVD 29) (feet)	Measuring point reference	Outer casing diameter (inches)	Inner casing diameter (inches)	Depth of boring (feet bls)
PW-1	393559075375802	195516	Dc53-49	39.5997	-75.6319	582706.16	595517.06	48.21	TIC	4	2	154
PW-12	393559075380101	228521	Dc52-127	39.5996	-75.6336	582656.32	595036.66	47.97	TIC	6	2	132
PW-11	393603075375902	228522	Dc42-51	39.6024	-75.6323	583692.57	595397.80	17.48	TIC	6	2	135
PW-13	393603075381501	231310	Dc42-56	39.6009	-75.6375	583128.59	593943.42	45.62	TIC	flush	2	170
MW-12	393604075375301	81386	Dc43-20	39.6009	-75.6308	583148.16	595825.88	55.63	TPVCcollar	6	4	148
PW-10	393609075375601	228524	Dc43-36	39.6008	-75.6329	583089.67	595233.65	30.05	TIC	6	2	107.4
PW-10D	393609075375602	228519	Dc43-37	39.6008	-75.6330	583096.61	595220.57	29.25	TIC	6	2	250
PW-17	393615075380101	231212	Dc42-58	39.6042	-75.6337	584328.55	595006.75	12.73	TIC	6	2	105
PW-14	393616075380501	231211	Dc42-57	39.6044	-75.6346	584398.31	594756.14	9.81	TIC	6	2	69
OR-6A	393616075381801	45620	Dc42-41	39.6048	-75.6382	584548.68	593739.22	43.63	TSC	8	--	180
OR-6B	393616075381803	45619	Dc42-42	39.6045	-75.6382	584453.93	593731.55	47.43	TSC	2	--	--
PW-6S	393616075381804	218553	Dc42-43	39.6047	-75.6382	584505.98	593746.57	45.79	TIC	4sq.	2	107
PW-6D	393616075381805	218554	Dc42-44	39.6047	-75.6382	584513.48	593741.26	45.57	TIC	4sq.	2	180
PW-5S	393622075375201	218550	Dc43-29	39.6061	-75.6312	585037.15	595729.45	7.00	TIC	4sq.	2	71
PW-5D	393622075375202	218552	Dc43-30	39.6061	-75.6312	585039.95	595722.96	6.94	TIC	4sq.	2	110
TY-116B	--	58514	9058514	39.6047	-75.6488	584522.43	590756.86	32.66	TPVC	6	4	128
TY-116C	--	58515	9058515	39.6046	-75.6487	584486.22	590779.83	36.48	TPVC	6	4	127
TY-121A	--	58511	Dc41-21	39.6053	-75.6525	584753.33	589718.06	16.16	TPVC	6	4	98
TY-121B	--	58512	9058512	39.6053	-75.6525	584737.37	589720.19	17.12	TPVC	6	4	57
PW-16	393548075380101	231210	Dc52-173	39.5966	-75.6337	581553.07	595032.66	63.24	TIC	6	2	240
PW-2D	393552075375603	231209	Dc53-187	39.5978	-75.6324	581993.71	595374.66	62.81	TIC	6	2	250
PW-11D	393603075375903	228520	Dc42-52	39.6024	-75.6323	583699.69	595406.56	17.14	TIC	6	2	255
TY-116A	--	58513	Dc42-18	39.6046	-75.6487	584498.43	590781.66	35.29	TPVC	6	4	247
Tidewater-12	393551075375301	--	Dc53-07	39.5977	-75.6306	581953.12	595876.79	58.40	TIC	8	3	701

Appendix 2. Characteristics of U.S. Geological Survey Potomac Aquifer Study monitoring sites measured at and near the Standard Chlorine of Delaware, Inc. Superfund Site, 2005–12.—Continued

[USGS, U.S. Geological Survey; DNREC, Delaware Department of Natural Resources and Environmental Control; DGS, Delaware Geological Survey; EPA, U.S. Environmental Protection Agency; Motiva, Motiva Delaware City Refinery; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; bls, below land surface; toc, top of casing; --, no data; TIC, top of inner casing; TPVC, top of polyvinyl chloride (PVC) casing; TSC, top of steel casing; TPVCcollar, top of PVC collar; 4sq., 4-inch square; flush, flush mounted with land surface; up., upper; psi, pounds per square inch; Δ, difference]

Local site name	Mesured well depth (feet toc)	Δ outer to inner casing (feet)	Outer casing stick-up (feet)	Inner casing stick-up (feet)	Land surface elevation (NGVD 29) (feet)	Depth to top of open interval (feet bls)	Depth to bottom of open interval (feet bls)	Altitude of top of screened interval (feet)	Altitude of bottom of screened interval (feet)	Screened aquifer	Date installed	Responsible agency or company	Period of continous data collection[1,2]
Red Lion Creek	--	--	--	--	--	--	--	--	--	(surface water)	12/1/06	USGS	6/20/07-9/30/12*
Ion-MW03	41.5	-0.21	3.16	2.95	49.89	29	39	21	11	Columbia	9/1/04	Ion Power	10/27/06-9/30/12*
C-31	74.0	-0.45	2.39	1.94	60.09	32	72	28	-12	Columbia	2/5/88	Motiva	--
CW-4	69.4	0.06	2.80	2.86	53.01	62	67	-9	-14	Columbia	5/11/07	EPA	--
MW-14	61.9	-0.29	2.70	2.41	45.85	49	59	-3	-13	Columbia	10/18/91	EPA	--
MW-15	66.8	-0.34	2.42	2.08	46.25	55	65	-9	-19	Columbia	10/21/91	EPA	--
MW-16	67.2	-0.31	2.63	2.32	44.74	55	65	-10	-20	Columbia	10/22/91	EPA	--
MW-17	72.8	-0.19	3.13	2.94	49.68	60	70	-10	-20	Columbia	10/24/91	EPA	--
MW-18	52.6	-0.35	3.02	2.67	29.57	40	50	-10	-20	Columbia	10/23/91	EPA	--
PMW-48	60.2	-0.13	2.11	1.98	47.58	48	58	0	-10	Columbia	--	EPA	10/20/07-9/30/12*
PMW-49	72.0	-0.39	2.12	1.73	47.69	60	70	-12	-22	Columbia	--	EPA	10/20/07-9/30/12*
CW-11	35.0	-0.23	2.09	1.86	15.61	28	33	-12	-17	Columbia	6/28/09	EPA	--
SCD-EM-2S	6.56	--	2.78	--	0.58	3	4	-2	-3	Columbia	5/7/08	EPA	--
SCD-EM-2D	13.4	--	4.31	--	0.35	9	10	-9	-10	Columbia	5/7/08	EPA	--
PZ-29	74.5	-0.30	1.00	0.70	47.71	69	74	-21	-26	Columbia	--	EPA	9/1/10-5/11/11
OR-6C	51.1	-0.22	3.00	2.78	44.31	41	51	3	-7	Columbia	--	Motiva	--
MW-37	51.5	-0.41	2.33	1.92	4.11	30	50	-26	-46	Columbia	5/25/01	EPA	6/23/11-9/30/12
MW-7	58.0	-0.40	2.48	2.08	46.62	47	57	0	-10	Columbia	1/17/90	EPA	--
PW-7S	85.0	-0.03	2.23	2.20	51.40	77	82	-26	-31	up. Potomac–top	3/31/07	EPA	6/6/07-11/18/07 and 6/23/11-9/30/12*
PW-4S	83.8	-0.15	2.74	2.59	53.87	75	80	-21	-26	up. Potomac–top	5/7/07	EPA	6/6/07-9/15/09*
PW-3	138.0	-0.41	2.19	1.78	49.96	125	135	-75	-85	up. Potomac–A	8/5/04	EPA	--
MW-11	138.0	-0.15	1.78	1.63	51.78	126	136	-74	-84	up. Potomac–A	2/24/90	EPA	3/26/07-9/30/12*
PW-2	155.5	-0.27	2.35	2.08	60.39	140	150	-80	-90	up. Potomac–A	7/30/04	EPA	3/17/06-6/5/07
PW-8	159.3	-0.09	2.89	2.80	50.58	152	157	-101	-106	up. Potomac–A	5/15/07	EPA	--
PW-9	140.0	-0.25	2.31	2.06	50.17	133	138	-83	-88	up. Potomac–A	7/9/09	EPA	--
PW-4D	145.0	-0.07	2.08	2.01	54.14	137	142	-83	-88	up. Potomac–A	4/26/07	EPA	6/6/07-9/30/12*

Appendix 2. Characteristics of U.S. Geological Survey Potomac Aquifer Study monitoring sites measured at and near the Standard Chlorine of Delaware, Inc. Superfund Site, 2005–12.—Continued

[USGS, U.S. Geological Survey; DNREC, Delaware Department of Natural Resources and Environmental Control; DGS, Delaware Geological Survey; EPA, U.S. Environmental Protection Agency; Motiva, Motiva Delaware City Refinery; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; bls, below land surface; toc, top of casing; --, no data; TIC, top of inner casing; TPVC, top of polyvinyl chloride (PVC) casing; TSC, top of steel casing; TPVCcollar, top of PVC collar; 4sq., 4-inch square; flush, flush mounted with land surface; up., upper; psi, pounds per square inch; Δ, difference]

Local site name	Mesured well depth (feet toc)	Δ outer to inner casing (feet)	Outer casing stick-up (feet)	Inner casing stick-up (feet)	Land surface elevation (NGVD 29) (feet)	Depth to top of open interval (feet bls)	Depth to bottom of open interval (feet bls)	Altitude of top of screened interval (feet)	Altitude of bottom of screened interval (feet)	Screened aquifer	Date installed	Responsible agency or company	Period of continous data collection[1,2]
PW-1	150.1	-0.12	2.59	2.47	45.74	138	148	-92	-102	up. Potomac–A	11/11/03	EPA	--
PW-12	132.0	-0.33	2.62	2.29	45.68	125	130	-79	-84	up. Potomac–A	8/8/09	EPA	--
PW-11	137.5	-0.22	2.37	2.15	15.33	130	135	-115	-120	up. Potomac–A	8/21/09	EPA	10/1/09-9/30/12
PW-13	165.0	-0.73	0.00	-0.73	46.35	161	166	-115	-120	up. Potomac–A	6/3/10	EPA	8/20/10-9/30/12
MW-12	141.5	-0.33	2.26	1.93	53.70	130	140	-76	-86	up. Potomac–A	6/20/90	EPA	12/15/05-9/30/12*
PW-10	107.4	-0.30	2.76	2.46	27.59	100	105	-72	-77	up. Potomac–A	8/22/09	EPA	--
PW-10D	175.7	-0.21	2.08	1.87	27.38	169	174	-142	-147	up. Potomac–A	8/4/09	EPA	--
PW-17	98.9	-0.35	2.65	2.30	10.43	92	97	-82	-87	up. Potomac–A	6/2/10	EPA	8/27/10-9/30/12*
PW-14	71.5	-0.24	2.57	2.33	7.48	64	69	-57	-62	up. Potomac–A	5/18/10	EPA	--
OR-6A	--	0.00	1.21	1.21	42.42	102	176	-61	-134	up. Potomac–A	--	Motiva	--
OR-6B	183.0	0.00	3.20	3.20	44.23	175	180	-131	-136	up. Potomac–A	--	Motiva	--
PW-6S	108.4	-0.10	1.79	1.69	44.10	102	107	-58	-63	up. Potomac–A	4/20/07	EPA	5/15/07-9/30/12*
PW-6D	180.0	-0.12	1.90	1.78	43.79	172	177	-128	-133	up. Potomac–A	4/19/07	EPA	5/15/12-10/31/07
PW-5S	71.3	-0.03	3.21	3.18	3.82	63	68	-59	-64	up. Potomac–A	3/27/07	EPA	5/15/07-10/12/07 and 10/1/09-9/30/12*
PW-5D	101.8	-0.07	3.12	3.05	3.89	93	98	-89	-94	up. Potomac–A	3/25/07	EPA	4/21/07-5/12/09*
TY-116B	124.7	--	--	--	--	113	123	-78	-88	up. Potomac–A	10/3/84	Tybouts Trust	--
TY-116C	73.1	--	--	--	34.80	60	70	-32	-42	up. Potomac–A	9/25/84	Tybouts Trust	--
TY-121A	89.5	-0.34	2.38	2.04	13.78	77	87	-63	-73	up. Potomac–A	12/4/84	Tybouts Trust	--
TY-121B	53.8	-0.33	2.50	2.17	14.62	43	53	-28	-38	up. Potomac–A	12/5/84	Tybouts Trust	--
PW-16	243.3	-0.25	2.43	2.18	61.06	233	238	-172	-177	up. Potomac–B	6/17/10	EPA	6/23/11-9/30/12*
PW-2D	246.9	-0.48	3.27	2.79	60.02	239	244	-179	-184	up. Potomac–B	6/6/10	EPA	5/11/11-9/30/12*
PW-11D	236.7	-0.24	2.31	2.07	15.07	230	235	-215	-220	up. Potomac–C	7/21/09	EPA	10/1/09-9/30/12*
TY-116A	82.1	--	--	--	--	221	231	-186	-196	up. Potomac–C	9/18/84	Tybouts Trust	--
Tidewater-12	701.0	0.00	3.04	3.04	55.36	534	539	-479	-484	lower Potomac	late 1954	Motiva	3/20/07-9/30/12*

[1] Continuous data collected at selected wells using In-Situ, Inc. Level-Troll 500, or 700 pressure transducers with pressure ranges between 0–5 and 0–30 psi. Other equipment occasionally used, but no longer in service, included Waterlog DH-21, In-Situ, Inc. mini troll, and Solinst level logger pressure transducers.

[2] Dates with * indicate some missing periods of data collection.

Appendix 3. Well characteristics and water-level drawdown and recovery data for wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 28–31, 2010.

[DGS, Delaware Geological Survey; NGVD29, vertical elevation referenced to National Geodetic Vertical Datum of 1929; bls, below land surface; N/A, data not available; N/C, data not calculated; EST, eastern standard time; %, percent; Note: Wells are identified by local site name and DGS identification number if available.]

Local site name	DGS identification number	Distance from pumping well (feet)	Hydrologic unit	Well depth (feet bls)	Land surface elevation (feet NGVD29)	Screened interval (feet bls)	Pre-pumping static water level (NGVD29)	Maximum drawdown (feet)	Date and time of maximum drawdown (EST)	Date and time of 90% recovery (EST)	Time of 90% recovery (days)
Discrete measurements											
CW-4	Dc53-83	2,626	Columbia	67	53.01	62–67	13.32	0.05	8/31/2010 11:28	N/C	N/C
MW-10		1,423	Columbia	N/A	46.33	N/A	10.60	0.04	8/31/2010 12:59	N/C	N/C
MW-13		1,931	Columbia	N/A	46.56	N/A	15.40	0.02	8/31/2010 12:56	N/C	N/C
MW-14	Dc53-68	2,717	Columbia	58	45.85	48–58	12.65	0.06	8/31/2010 17:02	N/C	N/C
MW-16	Dc53-66	2,387	Columbia	65	44.74	55–65	13.11	0.04	8/30/2010 10:49	N/C	N/C
MW-17	Dc43-28	2,398	Columbia	70	49.6	60–70	10.56	0.05	8/31/2010 16:59	N/C	N/C
MW-18	Dc43-27	2,150	Columbia	50	29.57	40–50	10.92	0.05	8/31/2010 16:52	N/C	N/C
MW-21		1,028	Columbia	18	7.41	10–20	2.82	0.17	8/31/2010 09:31	N/C	N/C
MW-22		1,159	Columbia	17	6.69	6.5–16.5	2.89	0.24	8/31/2010 17:22	N/C	N/C
MW-23		1,415	Columbia	26	6.87	16–26	2.47	0.34	8/31/2010 17:26	N/C	N/C
MW-31		1,829	Columbia	N/A	49.16	N/A	11.77	0.02	8/30/2010 07:34	N/C	N/C
MW-33		1,785	Columbia	N/A	45.72	N/A	14.52	0.01	8/31/2010 12:56	N/C	N/C
MW-37	Dc43-31	2,046	Columbia	51	4.11	30–50	1.51	1.18	8/31/2010 12:30	N/C	N/C
MW-38		2,262	Columbia	50	5.32	30–50	1.84	1.76	8/31/2010 12:27	N/C	N/C
OR-6C		74	Columbia	51	44.09	40–50	2.27	0.05	8/28/2010 18:16	N/C	N/C
PMW-41		2,175	Columbia	N/A	45.80	N/A	13.03	0.02	8/30/2010 07:46	N/C	N/C
PMW-42		1,987	Columbia	N/A	45.48	N/A	12.09	0.02	8/30/2010 07:49	N/C	N/C
PMW-43		1,981	Columbia	N/A	49.79	N/A	15.25	0.02	8/30/2010 07:50	N/C	N/C
PMW-44		1,612	Columbia	N/A	45.43	N/A	10.88	0.02	8/31/2010 14:07	N/C	N/C
PMW-47		1,153	Columbia	N/A	45.87	N/A	4.48	0.15	8/31/2010 09:53	N/C	N/C
PMW-50		2,599	Columbia	N/A	48.53	N/A	11.87	0.02	8/30/2010 08:17	N/C	N/C
PMW-51		2,410	Columbia	N/A	48.97	N/A	12.21	0.03	8/30/2010 07:37	N/C	N/C
PW-04S	Dc53-84	2,644	top sand	80	53.87	75–80	13.25	0.06	8/31/2010 11:26	N/C	N/C
PW-07S	Dc52-79	2,709	top sand	85	51.4	77–82	14.19	0.48	8/31/2010 15:39	N/C	N/C
PZ-03		2,163	Columbia	N/A	50.70	N/A	16.33	0.02	8/30/2010 07:44	N/C	N/C
PZ-05		1,292	Columbia	N/A	48.02	N/A	9.57	0.03	8/31/2010 10:28	N/C	N/C
PZ-06		1,241	Columbia	N/A	49.79	N/A	9.16	0.04	8/31/2010 10:32	N/C	N/C
PZ-07		1,172	Columbia	N/A	40.98	N/A	8.55	0.04	8/31/2010 10:24	N/C	N/C

Appendix 3. Well characteristics and water-level drawdown and recovery data for wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 28–31, 2010.—Continued

[DGS, Delaware Geological Survey; NGVD29, vertical elevation referenced to National Geodetic Vertical Datum of 1929; bls, below land surface; N/A, data not available; N/C, data not calculated; EST, eastern standard time; %, percent; Note: Wells are identified by local site name and DGS identification number if available.]

Local site name	DGS identification number	Distance from pumping well (feet)	Hydrologic unit	Well depth (feet bls)	Land surface elevation (feet NGVD29)	Screened interval (feet bls)	Pre-pumping static water level (NGVD29)	Maximum drawdown (feet)	Date and time of maximum drawdown (EST)	Date and time of 90% recovery (EST)	Time of 90% recovery (days)
Discrete measurements—continued											
PZ-08		1,130	Columbia	N/A	50.08	N/A	8.62	-0.02	8/31/2010 10:36	N/C	N/C
PZ-09		895	Columbia	N/A	48.17	N/A	4.12	0.03	8/30/2010 06:56	N/C	N/C
PZ-10		955	Columbia	N/A	47.48	N/A	8.05	0.02	8/31/2010 10:17	N/C	N/C
PZ-12		984	Columbia	N/A	46.53	N/A	3.50	0.10	8/31/2010 09:45	N/C	N/C
PZ-13		1,027	Columbia	N/A	47.18	N/A	6.37	0.07	8/31/2010 10:02	N/C	N/C
PZ-14		1,147	Columbia	N/A	48.11	N/A	6.18	0.05	8/30/2010 06:21	N/C	N/C
PZ-15		1,070	Columbia	N/A	46.33	N/A	3.93	0.11	8/31/2010 09:50	N/C	N/C
PZ-16		1,207	Columbia	N/A	48.51	N/A	5.19	0.10	8/31/2010 09:53	N/C	N/C
PZ-17		1,523	Columbia	N/A	42.78	N/A	7.12	0.05	8/31/2010 10:44	N/C	N/C
PZ-18		1,635	Columbia	N/A	45.08	N/A	8.20	0.03	8/30/2010 06:47	N/C	N/C
PZ-19		1,615	Columbia	N/A	48.36	N/A	9.69	0.03	8/31/2010 10:49	N/C	N/C
PZ-20		2,271	Columbia	N/A	48.69	N/A	11.48	0.03	8/31/2010 13:54	N/C	N/C
PZ-21		2,358	Columbia	N/A	48.39	N/A	14.24	0.02	8/30/2010 08:11	N/C	N/C
PZ-22		2,617	Columbia	N/A	48.80	N/A	16.59	0.02	8/30/2010 08:19	N/C	N/C
PZ-23		2,706	Columbia	N/A	58.90	N/A	17.75	0.02	8/30/2010 08:21	N/C	N/C
PZ-24		2,545	Columbia	N/A	53.98	N/A	18.69	0.03	8/30/2010 07:39	N/C	N/C
PZ-27		2,089	Columbia	N/A	47.61	N/A	11.16	0.04	8/30/2010 08:01	N/C	N/C
PZ-28		1,108	Columbia	N/A	53.72	N/A	8.45	0.01	8/31/2010 10:14	N/C	N/C
PZ-30		1,436	Columbia	N/A	46.28	N/A	8.59	0.03	8/30/2010 06:38	N/C	N/C
TW-28		1,513	Columbia	N/A	49.35	N/A	10.17	0.03	8/30/2010 07:22	N/C	N/C
OR-6A	Dc42-41	Pumping well	upper Potomac–A	176	42.42	102–176	2.10	43.98	8/31/2010 13:31	9/2/2010 06:06	1.69
OR-6B	Dc42-42	95	upper Potomac–A	184	44.23	103–176	2.02	24.50	8/31/2010 13:15	N/C	N/C
PW-02	Dc53-50	3,047	upper Potomac–A	150	60.39	140–150	1.77	6.28	8/31/2010 15:09	N/C	N/C
PW-05D	Dc43-30	2,044	upper Potomac–A	99	3.89	93–98	2.08	3.21	8/31/2010 12:33	N/C	N/C
PW-08	Dc53-86	3,155	upper Potomac–A	158	50.58	152–157	1.37	4.83	8/31/2010 11:30	N/C	N/C
PW-09	Dc53-133	2,740	upper Potomac–A	138	50.17	133–138	1.70	6.44	8/31/2010 17:05	N/C	N/C
PW-10	Dc43-36	2,090	upper Potomac–A	107	27.59	100–105	1.77	6.43	8/31/2010 16:47	N/C	N/C

Appendix 3. Well characteristics and water-level drawdown and recovery data for wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 28–31, 2010.—Continued

[DGS, Delaware Geological Survey; NGVD29, vertical elevation referenced to National Geodetic Vertical Datum of 1929; bls, below land surface; N/A, data not available; N/C, data not calculated; EST, eastern standard time; %, percent; Note: Wells are identified by local site name and DGS identification number if available.]

Local site name	DGS identification number	Distance from pumping well (feet)	Hydrologic unit	Well depth (feet bls)	Land surface elevation (feet NGVD29)	Screened interval (feet bls)	Pre-pumping static water level (NGVD29)	Maximum drawdown (feet)	Date and time of maximum drawdown (EST)	Date and time of 90% recovery (EST)	Time of 90% recovery (days)
Discrete measurements—continued											
PW-10D	Dc43-37	2,075	upper Potomac–A	176	27.38	169–174	1.32	5.22	8/31/2010 16:50	N/C	N/C
PW-12	Dc52-127	2,294	upper Potomac–A	130	45.68	125–130	1.76	6.73	8/31/2010 12:15	N/C	N/C
PW-14	Dc42-57	1,031	upper Potomac–A	69	7.48	64–69	1.77	9.24	8/31/2010 09:30	N/C	N/C
TY-116B		2,982	upper Potomac–A	N/A	N/A	112–122	3.13	1.32	8/31/2010 16:19	N/C	N/C
TY-116C		2,960	upper Potomac–A	N/A	N/A	60–70	1.74	3.24	8/31/2010 16:23	N/C	N/C
TY-121A		4,026	upper Potomac–A	N/A	N/A	77–87	2.97	0.16	8/31/2010 16:07	N/C	N/C
TY-121B		4,023	upper Potomac–A	N/A	N/A	43–53	2.24	0.27	8/31/2010 16:10	N/C	N/C
PW-16	Dc52-173	3,239	upper Potomac–B	238	61.06	233–238	-6.34	0.65	8/31/2010 15:30	N/C	N/C
TY-116A		2,958	upper Potomac–C	N/A	N/A	221–231	-2.87	0.15	8/31/2010 16:20	N/C	N/C
Continuous measurements											
CW-11	Dc42-50	1,864	Columbia	33	15.61	28–33	5.37	0.08	8/31/2010 17:00	N/C	N/C
ION-MW-03	Dc53-93	3,540	Columbia	39	49.89	29–39	17.29	0.05	8/31/2010 05:15	N/C	N/C
PMW-48		1,973	Columbia	59	47.58	N/A	11.11	0.03	8/30/2010 08:04	N/C	N/C
PZ-29		1,097	Columbia	74	47.71	69–74	4.78	5.26	8/31/2010 09:59	N/C	N/C
MW-11	Dc52-56	2,724	upper Potomac–A	136	51.78	126–136	2.06	7.36	8/31/2010 14:30	9/6/2010 01:30	5.46
MW-12	Dc43-20	2,513	upper Potomac–A	142	53.7	130–140	1.43	4.32	8/31/2010 16:30	9/7/2010 01:15	6.36
PW-03	Dc53-51	3,570	upper Potomac–A	138	49.96	125–135	4.10	3.65	8/31/2010 22:30	9/12/2010 06:15	11.32
PW-04D	Dc53-85	2,654	upper Potomac–A	145	54.14	137–142	1.63	5.96	8/31/2010 15:00	9/6/2010 16:15	6.05
PW-05S	Dc43-29	2,050	upper Potomac–A	68	3.82	63–68	2.07	3.13	8/31/2010 12:32	9/5/2010 12:15	4.99
PW-06D	Dc42-44	35	upper Potomac–A	177	43.79	172–177	2.04	28.25	8/31/2010 12:53	N/C	N/C
PW-06S	Dc42-43	44	upper Potomac–A	108	44.11	102–107	2.03	28.18	8/31/2010 13:30	9/3/2010 08:30	2.79
PW-11	Dc42-51	1,865	upper Potomac–A	135	15.33	130–135	1.75	5.91	8/31/2010 13:30	9/4/2010 21:00	4.31
PW-13	Dc42-56	1,440	upper Potomac–A	166	46.35	161–166	2.15	10.29	8/31/2010 13:30	9/4/2010 16:30	4.13
PW-17	Dc42-58	1,288	upper Potomac–A	98	10.43	93–98	1.99	7.76	8/31/2010 13:30	9/3/2010 21:30	3.33
PW-02D	Dc53-187	3,039	upper Potomac–B	240	60.02	235–240	-4.55	2.44	9/1/2010 05:45	9/13/2010 13:00	12.30
PW-11D	Dc42-52	1,873	upper Potomac–C	235	15.07	230–235	-12.64	0.18	8/31/2010 13:45	9/16/2010 09:00	15.80
Tidewater 12	Dc53-07	3,363	lower Potomac	701	55.36	534–539	-56.12	0.00	8/28/2010 13:45	N/C	N/C

Appendix 4. Water-level data for non-U.S. Geological Survey network observation wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 26–September 1, 2010.

[NGVD29, altitude referenced to National Geodetic Vertical Datum of 1929; EST, eastern standard time]

Date and time (EST)	Local site name	Altitude of water level (feet NGVD29)
8/26/2010 15:46	MW-10	10.63
8/27/2010 6:18	MW-10	10.61
8/28/2010 8:14	MW-10	10.60
8/28/2010 14:55	MW-10	10.59
8/29/2010 14:42	MW-10	10.60
8/30/2010 6:39	MW-10	10.60
8/31/2010 12:59	MW-10	10.56
9/1/2010 9:05	MW-10	10.58
8/27/2010 6:06	MW-13	15.39
8/28/2010 8:04	MW-13	15.40
8/29/2010 14:52	MW-13	15.41
8/30/2010 6:35	MW-13	15.40
8/31/2010 12:56	MW-13	15.38
9/1/2010 9:00	MW-13	15.38
8/27/2010 9:44	MW-31	11.80
8/28/2010 11:39	MW-31	11.77
8/29/2010 13:18	MW-31	11.78
8/30/2010 7:34	MW-31	11.75
8/31/2010 14:19	MW-31	11.75
9/1/2010 11:33	MW-31	11.73
8/26/2010 15:33	MW-33	14.56
8/27/2010 6:10	MW-33	14.53
8/28/2010 8:08	MW-33	14.52
8/29/2010 14:40	MW-33	14.55
8/30/2010 6:44	MW-33	14.54
8/31/2010 12:56	MW-33	14.51
9/1/2010 9:02	MW-33	14.51
8/27/2010 9:14	PMW-41	13.04
8/28/2010 10:56	PMW-41	13.03
8/29/2010 13:38	PMW-41	13.03
8/30/2010 7:46	PMW-41	13.01
8/31/2010 14:15	PMW-41	13.02
9/1/2010 10:59	PMW-41	12.99
8/27/2010 9:19	PMW-42	12.11
8/28/2010 10:51	PMW-42	12.09
8/29/2010 13:41	PMW-42	12.11
8/30/2010 7:49	PMW-42	12.07
8/31/2010 11:00	PMW-42	12.08
9/1/2010 10:55	PMW-42	12.07
8/27/2010 9:22	PMW-43	15.27
8/28/2010 10:54	PMW-43	15.25
8/29/2010 13:42	PMW-43	15.24
8/30/2010 7:50	PMW-43	15.23
9/1/2010 10:57	PMW-43	15.22
8/27/2010 9:30	PMW-44	11.11
8/28/2010 10:41	PMW-44	10.88
8/29/2010 13:46	PMW-44	10.91
8/30/2010 7:56	PMW-44	10.91
8/31/2010 14:07	PMW-44	10.86
9/1/2010 10:52	PMW-44	10.90
8/27/2010 6:25	PMW-47	4.50
8/28/2010 8:58	PMW-47	4.48
8/29/2010 12:03	PMW-47	4.45
8/30/2010 6:20	PMW-47	4.40
8/31/2010 9:53	PMW-47	4.33
9/1/2010 7:23	PMW-47	4.31
8/27/2010 8:48	PMW-50	11.89
8/28/2010 11:15	PMW-50	11.87
8/29/2010 14:11	PMW-50	11.87
8/30/2010 8:17	PMW-50	11.85
8/31/2010 13:40	PMW-50	11.85
9/1/2010 11:22	PMW-50	11.84
8/27/2010 9:01	PMW-51	12.22
8/28/2010 11:05	PMW-51	12.21
8/29/2010 13:32	PMW-51	12.21
8/30/2010 7:37	PMW-51	12.18
8/31/2010 13:43	PMW-51	12.18
9/1/2010 11:14	PMW-51	12.17
8/27/2010 9:16	PZ-03	16.34
8/28/2010 10:58	PZ-03	16.33
8/29/2010 13:30	PZ-03	16.34
8/30/2010 7:44	PZ-03	16.31
8/27/2010 7:50	PZ-05	9.60
8/28/2010 9:31	PZ-05	9.57
8/29/2010 12:41	PZ-05	9.58
8/30/2010 7:15	PZ-05	9.55
8/31/2010 10:28	PZ-05	9.54
9/1/2010 8:06	PZ-05	9.53
8/27/2010 7:53	PZ-06	9.18
8/28/2010 9:40	PZ-06	9.16
8/29/2010 12:43	PZ-06	9.17
8/30/2010 7:17	PZ-06	9.14
8/31/2010 10:32	PZ-06	9.12
9/1/2010 8:03	PZ-06	9.12
8/27/2010 7:45	PZ-07	8.50
8/28/2010 9:34	PZ-07	8.55
8/29/2010 12:49	PZ-07	8.54
8/30/2010 7:00	PZ-07	8.52
8/31/2010 10:24	PZ-07	8.51
9/1/2010 8:09	PZ-07	8.51
8/27/2010 7:40	PZ-08	8.71
8/28/2010 9:36	PZ-08	8.62
8/29/2010 12:52	PZ-08	8.67
8/30/2010 7:11	PZ-08	8.65
8/31/2010 10:36	PZ-08	8.64
9/1/2010 8:22	PZ-08	8.62
8/27/2010 7:17	PZ-09	4.14
8/28/2010 9:59	PZ-09	4.12
8/29/2010 13:07	PZ-09	4.10
8/30/2010 6:56	PZ-09	4.09
8/31/2010 10:19	PZ-09	4.10
9/1/2010 8:14	PZ-09	4.08
8/27/2010 7:33	PZ-10	8.07
8/28/2010 9:57	PZ-10	8.05
8/29/2010 13:00	PZ-10	8.07
8/30/2010 7:05	PZ-10	8.04
8/31/2010 10:17	PZ-10	8.03
9/1/2010 8:17	PZ-10	8.03
8/27/2010 6:16	PZ-12	3.50
8/28/2010 8:54	PZ-12	3.50
8/29/2010 11:49	PZ-12	3.49
8/30/2010 6:17	PZ-12	3.45
8/31/2010 9:45	PZ-12	3.40
9/1/2010 7:17	PZ-12	3.36
8/27/2010 6:15	PZ-13	6.36
8/28/2010 9:07	PZ-13	6.37
8/29/2010 11:52	PZ-13	6.39
8/30/2010 6:29	PZ-13	6.33
8/31/2010 10:02	PZ-13	6.30
9/1/2010 7:31	PZ-13	6.30

Appendix 4. Water-level data for non-U.S. Geological Survey network observation wells monitored as part of U.S. Geological Survey 72-hour pumping at well OR-6A near the Standard Chlorine of Delaware, Inc. Superfund Site, August 26–September 1, 2010. —Continued

[NGVD29, altitude referenced to National Geodetic Vertical Datum of 1929; EST, eastern standard time]

Date and time (EST)	Local site name	Altitude of water level (feet NGVD29)
8/27/2010 6:27	PZ-14	6.18
8/28/2010 9:00	PZ-14	6.18
8/29/2010 12:05	PZ-14	6.18
8/30/2010 6:21	PZ-14	6.13
9/1/2010 7:28	PZ-14	6.09
8/27/2010 6:23	PZ-15	3.95
8/28/2010 8:56	PZ-15	3.93
8/29/2010 12:12	PZ-15	3.94
8/30/2010 6:18	PZ-15	3.87
8/31/2010 9:50	PZ-15	3.82
9/1/2010 7:25	PZ-15	3.78
8/27/2010 6:34	PZ-16	5.20
8/28/2010 9:03	PZ-16	5.19
8/29/2010 12:00	PZ-16	5.17
8/30/2010 6:22	PZ-16	5.13
8/31/2010 9:53	PZ-16	5.09
9/1/2010 7:30	PZ-16	5.07
8/27/2010 6:54	PZ-17	7.13
8/28/2010 10:15	PZ-17	7.12
8/29/2010 12:22	PZ-17	7.11
8/30/2010 6:40	PZ-17	7.09
8/31/2010 10:44	PZ-17	7.07
9/1/2010 8:32	PZ-17	7.06
8/27/2010 7:07	PZ-18	8.20
8/28/2010 10:25	PZ-18	8.20
8/29/2010 12:28	PZ-18	8.20
8/30/2010 6:47	PZ-18	8.17
8/31/2010 10:46	PZ-18	8.20
9/1/2010 8:37	PZ-18	8.15
8/27/2010 6:59	PZ-19	9.71
8/28/2010 10:27	PZ-19	9.69
8/29/2010 12:31	PZ-19	9.70
8/30/2010 6:51	PZ-19	9.68
8/31/2010 10:49	PZ-19	9.66
9/1/2010 8:39	PZ-19	9.65
8/27/2010 8:35	PZ-20	11.50
8/28/2010 11:21	PZ-20	11.48
8/29/2010 14:02	PZ-20	11.47
8/30/2010 8:10	PZ-20	11.46
8/31/2010 13:54	PZ-20	11.45
9/1/2010 10:44	PZ-20	11.44
8/27/2010 8:42	PZ-21	14.27
8/28/2010 11:19	PZ-21	14.24
8/29/2010 13:59	PZ-21	14.24
8/30/2010 8:11	PZ-21	14.22
8/31/2010 13:56	PZ-21	14.22
9/1/2010 10:45	PZ-21	14.21
8/27/2010 8:47	PZ-22	16.61
8/28/2010 11:16	PZ-22	16.59
8/29/2010 14:12	PZ-22	16.59
8/30/2010 8:19	PZ-22	16.57
8/31/2010 13:39	PZ-22	16.57
9/1/2010 11:24	PZ-22	16.56
8/27/2010 8:53	PZ-23	17.77
8/28/2010 11:11	PZ-23	17.75
8/29/2010 14:07	PZ-23	17.76
8/30/2010 8:21	PZ-23	17.73
8/31/2010 13:35	PZ-23	17.76
9/1/2010 11:20	PZ-23	17.73
8/27/2010 8:57	PZ-24	18.72
8/28/2010 11:02	PZ-24	18.69
8/29/2010 13:28	PZ-24	18.69
8/30/2010 7:39	PZ-24	18.66
8/27/2010 9:51	PZ-27	11.31
8/28/2010 11:36	PZ-27	11.16
8/29/2010 13:52	PZ-27	11.15
8/30/2010 8:01	PZ-27	11.12
8/31/2010 14:00	PZ-27	11.13
9/1/2010 11:28	PZ-27	11.12
8/27/2010 7:38	PZ-28	8.54
8/28/2010 9:49	PZ-28	8.45
8/29/2010 12:55	PZ-28	8.46
8/30/2010 7:09	PZ-28	8.49
8/31/2010 10:14	PZ-28	8.44
9/1/2010 8:20	PZ-28	8.43
8/27/2010 6:51	PZ-30	8.60
8/28/2010 10:12	PZ-30	8.59
8/29/2010 12:18	PZ-30	8.74
8/30/2010 6:38	PZ-30	8.56
8/31/2010 10:42	PZ-30	8.56
9/1/2010 8:30	PZ-30	8.56
8/27/2010 7:57	TW-28	10.18
8/28/2010 9:25	TW-28	10.17
8/29/2010 12:40	TW-28	10.18
8/30/2010 7:22	TW-28	10.14
8/31/2010 10:30	TW-28	10.14
9/1/2010 8:00	TW-28	10.12
8/28/2010 10:19	TY-116A	-2.87
8/29/2010 10:30	TY-116A	-2.88
8/31/2010 13:10	TY-116A	-3.00
8/31/2010 16:20	TY-116A	-3.02
9/1/2010 8:30	TY-116A	-3.07
8/28/2010 10:18	TY-116B	3.13
8/29/2010 10:32	TY-116B	2.98
8/31/2010 13:11	TY-116B	1.89
8/31/2010 16:19	TY-116B	1.81
9/1/2010 8:31	TY-116B	1.60
8/28/2010 10:20	TY-116C	1.74
8/29/2010 10:28	TY-116C	0.56
8/31/2010 13:09	TY-116C	-1.42
8/31/2010 16:23	TY-116C	-1.50
9/1/2010 8:32	TY-116C	-0.74
8/28/2010 10:05	TY-121A	2.97
8/29/2010 10:12	TY-121A	2.93
8/31/2010 13:24	TY-121A	2.83
8/31/2010 16:07	TY-121A	2.81
9/1/2010 8:20	TY-121A	2.78
8/28/2010 10:04	TY-121B	2.24
8/29/2010 10:11	TY-121B	2.19
8/31/2010 13:22	TY-121B	2.00
8/31/2010 16:10	TY-121B	1.97
9/1/2010 8:21	TY-121B	1.98

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