SUPPLEMENTAL REMEDIAL INVESTIGATION GROUNDWATER REPORT (PART 1)
FORMER YORK NAVAL ORDNANCE PLANT
1425 EDEN ROAD
YORK, PA 17402

Prepared for:

Harley-Davidson Motor Company
Operations, Inc.
York, PA

VOLUME 1 OF 3
TEXT

September 2011

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Groundwater Sciences Corporation

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Respectfully submitted,

Stephen M Snyder

Stephen M. Snyder, P.G.

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LIST OF ACRONYMS AND ABBREVIATIONS

11DCA	1,1-dichloroethane
11DCE	1,1-dichloroethene
111TCA	1,1,1-trichloroethane
1112PCA	1,1,1,2-tetrachloroethane
µg/kg	micrograms per kilograms
µg/L	micrograms per liter
Act 2	Land Recycling and Environment Remediation Standards Act, Act 2 of 1995, 35 P.S. § 6026.101
AGI	Advances Geosciences Inc.
AMF	American Machine & Foundry Company
AMO	AMO Environmental Decisions, Inc.
AMSL	above mean sea level
AOC	area of concern
AST	aboveground storage tank
bgs	below ground surface
BPA	Burn Pile Area
BTEX	benzene, toluene, ethylbenzene, xylenes
CEA	chloroethane
cis12DCE	cis-1,2-dichloroethene
COC	constituents of concern
CPA	Central Plant Area
Cr+3	trivalent chromium
Cr+6	hexavalent chromium
CVOC	chlorinated volatile organic compounds

DCA	dichloroethane
DCE	dichloroethene
DCR	Department of Conservation and Recreation
DERP	Defense Environmental Restoration Program
DG	down gradient
DGPS	differential global positioning system
DNAPL	dense non-aqueous phase liquid
DSA	drum storage area
DQO	data quality objectives
EBldg2	East Building 2
EDD	electronic data deliverable
EI	electrical imaging
EPM	equivalent porous medium
EPRA	Eastern Perimeter Road Area
foc	fraction of organic carbon
FS	Feasibility Study
FSP	field sampling plan
ft^2	square feet
FUDS	Formerly Utilized Defense Site
fYNOP	former York Naval Ordnance Plant
GAC	granular activated carbon
gpd	gallons per day
gpm	gallons per minute
GPS	global positioning system
GWTP	Groundwater Treatment Plant

GWTS	groundwater extraction and treatment system
Harley-Davidson	Harley-Davidson Motor Company Operations, Inc.
HSWA	Hazardous and Solid Waste Amendments
IWTP	industrial wastewater treatment plant
KCF	KCF Groundwater, Inc.
Koc	coefficient
Langan	Langan Engineering and Environmental Services, Inc.
MC	methylene chloride
MCBA	Metal Chip Bin Area
MDL	method detection limit
mg/kg	milligrams per kilogram
mm	millimeter
MOA	Memorandum of Agreement
MSC	Medium Specific Concentration
MSL	mean sea level
MTBE	methyl tertiary-butyl ether
MW	monitoring well
NAD	North American Datum
NBldg4	North Building 4
NCP	National Contingency Plan
NETT	North End Test Track
NIR	Notice of Intent to Remediate
N.O.P.	Naval Ordnance Plant
Norfolk Southern	Norfolk Southern Railway Company
NPA	North Plant Area

NPBA	Northern Property Boundary Area
NPDES	National Pollutant Discharge Elimination System
OWCA	Old Waste Containment Area
PADEP	Pennsylvania Department of Environmental Protection
PADER	Pennsylvania Department of Environmental Resources
PA	Pathway Analysis
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PCE	tetrachloroethene
PID	photoionization detector
POTW	publicly owned treatment works
PTA	packed tower aerator
QA	quality assurance
QC	quality control
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
REWAI	R.E. Wright Associates, Inc.
REWEI	R.E. Wright Environmental, Inc.
RFA	RCRA Facility Assessment
RFI	RCRA Facility Investigation
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
SA	source area
SAIC	Science Applications International Corporation

SBldg4	South Building 4
SIM	selective ion monitoring
Soils RI	Supplemental Remedial Investigation Soils Report (SAIC, December 2009b)
SPBA	Southern Property Boundary Area
SRBC	Susquehanna River Basin Commission
SRI	Supplemental Remedial Investigation
SVE	soil vapor extraction
SVOCs	semi-volatile organic compounds
SWMU	Solid Waste Management Unit
SW-WPL	Southwest corner of the West Parking Lot
S_y	specific yield
TCA	1,1,1-trichloroethane
TCE	trichloroethene
TCL	target compound list
TPH	total petroleum hydrocarbons
TVOCs	total priority pollutant volatile organic compounds
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
UST	underground storage tank
UTM	Universal Transverse Mercator
UW	University of Waterloo
VADCR	Virginia Department of Conservation and Recreation
VC	vinyl chloride
VOCs	volatile organic compounds
WBldg2	West Building 2

WPA	West Property Area
WPL	West Parking Lot
YNOP	York Naval Ordnance Plant
ZPR	Zinc Plating Room

EXECUTIVE SUMMARY

This Supplemental Remedial Investigation Groundwater Report (Part 1) (SRI Report) presents the detailed results of a groundwater Supplemental Site-Wide Remedial Investigation (SRI) completed during the period 2007-2008 at the former York Naval Ordnance Plant (fYNOP) located in York, Pennsylvania (Site) and includes recent groundwater chemistry and remedial operations data through December 2010. This report summarizes the environmental investigations completed on-Site from 1984 through 2006, and draws conclusions from analysis of the entire body of information from 1984 to 2010. The report contains a description of the site specific geology, hydrogeology, nature and extent of chemicals of concern (COCs) and the fate and transport of the COCs in the aquifer. Also included are an exposure pathway assessment and recommendations for further investigation to close data gaps. A companion report on soils was completed in December 2009.

The aquifers underlying the Site are composed of fractured quartzitic sandstone and karstified carbonate rock. The karstified carbonate rock, which underlies the Central Plant Area (CPA) portion of the Site is well connected as a result of high fracture permeability and well distributed solution channels. Chlorinated volatile organic compounds (CVOCs) were introduced to the ground surface in the form of dense nonaqueous phase liquid (DNAPL) through spills, leaks, and on-site disposal from the 1940s into the 1980s and are pervasive throughout the Site at concentrations that exceed Pennsylvania Department of Environmental Protection (PADEP) groundwater medium specific standards (MSCs). The solution channels have appeared to allow deep (as deep as 200 feet below ground surface) vertical migration of DNAPL into the aquifer. In addition to the numerous CVOCs and their related compounds, chromium and cyanide occur above PADEP MSCs, but have limited distribution in the groundwater on site.

Results of an evaluation of the performance of an interim groundwater extraction system operational on Site since the 1990s are included. The system appears to effectively prevent off-Site migration of groundwater from all areas of the Site except the South Property Boundary Area (SPBA) where studies indicate no human receptors are impacted. The performance evaluation is caviated by the potential that the vertical extent of CVOCs and the vertical extent of karst solution channels in the carbonate aquifer may be deeper than currently delineated. Over 38,000 pounds of

CVOCS have been removed by the groundwater extraction system. The average rate of removal over the last 5 years is approximately 1,500 pounds per year.

This report demonstrates that large reductions in COC concentrations have occurred in groundwater, with trichloroethene (TCE), the most widely distributed CVOC, reducing in concentration by 90 to 99% in most wells. However, the reduction required to meet Pennsylvania Department of Environmental Protection (PADEP) medium specific concentrations (MSCs) has not been met in most wells.

Estimates of the mass remaining in the aquifer on Site using trend analysis exceed 60,000 pounds, and may be substantially underestimated because DNAPL pools appear to be present. On the order of 2,000 pounds of this mass occurs as dissolved in groundwater. The remaining mass is adsorbed onto and diffused into the matrix of the aquifer or is in the form of suspected DNAPL pools. These undissolved sources of mass are very slowly released to the groundwater passing through the site.

Section 8 of this report is a summary of the technical conclusions in Sections 1 through 7 designed to provide an overview to a reader familiar with the environmental conditions on Site. References to key figures throughout the report are made in Section 8, and the PDF version of this section contains links to those figures that will open in a separate window if activated.

Stakeholders Harley-Davidson and United States Army Corp of Engineers (USACE) concur that additional studies are necessary to evaluate certain identified data gaps, specifically the vertical extent of CVOCs in the aquifer, the depth of karst channels in the aquifer, the effect of karst channels on groundwater flow and contaminant migration, and the interaction of storm water and surface water with the karst aquifer. In addition, more definition of source areas is recommended in two locations prior to commencing with the feasibility study (FS).

1 PROJECT DESCRIPTION

This Supplemental Remedial Investigation Groundwater Report (Part 1) (SRI Report) presents the detailed results of a groundwater Supplemental Site-Wide Remedial Investigation (SRI) completed during the period 2007-2008 at the former York Naval Ordnance Plant (fYNOP) located in York, Pennsylvania (Site) and includes recent groundwater chemistry and remedial operations data through December 2010. This report summarizes the environmental investigations completed on-Site from 1984 through 2006, and draws conclusions from analysis of the entire body of information from 1984 to 2010. The groundwater SRI is part of an overall Site-wide remedial investigation and feasibility study (Site-wide RI/FS) being performed at the Site under the auspices of the One Cleanup Program jointly administered by the United States Environmental Protection Agency (USEPA) and the Pennsylvania Department of Environmental Protection (PADEP).

The fYNOP Site is currently occupied by the Harley-Davidson Motor Company Operations, Inc. (Harley-Davidson) facility. A site location map is provided on Figure 1.0-1. Work during the SRI was completed in accordance with the Field Sampling Plan (FSP) for Supplemental Remedial Investigations (Science Applications International Corporation [SAIC], July 2006) and the Quality Assurance Project Plan (QAPP) (SAIC, June 2006). The QAPP describes the specific quality assurance (QA) and quality control (QC) activities, and the FSP provides sampling procedures, methods, and details. The QAPP has recently been updated (SAIC, December 2009c) to reflect changes that have occurred during the performance of the Supplemental Site-Wide RI.

The FSP for the SRI was developed according to applicable guidance (United States Army Corps of Engineers [USACE], 2001, and USEPA, November 1999). USEPA QA/R-5 components are addressed in both the FSP and QAPP. Although the FSP does not specifically follow the 1984 Hazardous and Solid Waste Amendments (HSWA) to the Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) model, solid waste management units (SWMUs) designated by the RCRA Facility Assessment (RFA), prepared by A.T. Kearney (Kearney, January 1989), are used in the FSP to organize the investigation.

For scheduling purposes, and because groundwater investigation activities continued well beyond the completion of soil investigations, the Supplemental Site-Wide RI reporting was divided into a soil investigation report and a groundwater investigation report. The draft soils Supplemental Site-Wide RI report was submitted to regulators on December 2, 2009 (SAIC, December 2009b) and was approved as the final version of that report in a joint letter from PADEP and USEPA dated March 17, 2010.

Much of the scope of the groundwater SRI was discussed in meetings with the USEPA at Harley-Davidson on May 1 and 7, 2003. Notes from those meetings are included in Appendix A of the FSP. In addition, scoping and guidance from the PADEP were provided during subsequent team meetings. This report has been prepared by Groundwater Sciences Corporation (GSC) on behalf of Harley-Davidson with assistance, where noted in the report, by SAIC and KCF Groundwater, Inc. (KCF). Project coordination was performed by AMO Environmental Decisions, Inc. (AMO). Official public information about the facility can be found at the public web-link, http://yorksiteremedy.com.

During the process of preparing this report, the data presentation and analysis were shaped by meetings between the GSC technical team, Ralph Golia of AMO and Jim Lolcama of KCF. In these meetings, results and preliminary conclusions were presented and discussed. As a result, additional assignments were made to the members of the technical team and to KCF. KCF provided analysis of borehole stratigraphy, karst conditions, and chemical transport. Text sections were written by KCF, and provided to GSC, which were woven into the report.

1.1 Objectives

The objectives of the Site-wide RI/FS are to evaluate potential sources of soil and groundwater impacts, determine the fate and transport characteristics of known constituents of concern, and to provide sufficient information and analysis for an evaluation of the risk that the constituents of concern (COCs) pose to human health and the environment. The results of the investigation will also be used to conduct a risk assessment and identify and evaluate remedies that will minimize risks to human health and the environment.

The overall project objective of the SRI was to obtain sufficient data to allow implementation of a Site-wide feasibility study (Site-wide FS) and ultimately select a final remedy for the fYNOP Site. It is intended that the Site-wide FS will consider remedial alternatives in the context of a Site-wide solution. This Site-wide evaluation of remedial alternatives is directed by an agreement between Harley-Davidson and the United States Government, under which the Site is being investigated and remediated.

1.2 Regulatory Framework

Harley-Davidson began remedial environmental investigations at the site in 1984. Initially, work was reported to and reviewed by the Pennsylvania Department of Environmental Resources (PADER), Waste Management Division. In 1989, USEPA performed an RFA of the facility. As a result of this assessment, 73 SWMUs were identified, needing further investigation. These SWMUs were a combination of major areas of concern (AOCs) discussed in hydrogeologic reports and former and existing manufacturing facilities and processes. The locations of these SWMUs are shown on Figure 1.0-2 as blue squares, which in some cases overlap where processes, like tanks, are closely spaced. This figure also points out the location and describes 31 AOCs that may have contributed to observed contamination in groundwater at the Site. Individual numbered SWMUs are not referenced in this report, as they are in the Supplemental RI Soils Report (SAIC, December 2009). Rather, this report deals with AOCs, which may encompass numerous SWMUs.

Harley-Davidson entered into a Settlement Agreement with the United States (represented by USACE) on January 24, 1995 pursuant to authority delegated under the Defense Environmental Restoration Program (DERP) Formerly Utilized Defense Site (FUDS) program. This Settlement Agreement established a cost sharing arrangement between Harley-Davidson, as the present Site owner, and the United States, as the past owner, for costs incurred in response to environmental contamination at the facility. A Trust Fund was established to handle the cost sharing of those response actions. The Settlement Agreement further provided that Harley-Davidson would manage the project at the York facility and that the project would be carried out in substantial compliance with the National Contingency Plan (NCP) as defined by 40 CFR §300.700.

On May 20, 2002, fYNOP committed to USEPA's "Facility Lead Program" under the RCRA Corrective Action Program in response to USEPA's invitation to participate. That commitment was subsequently modified when fYNOP entered into the One Cleanup Program established by the USEPA Region III and the PADEP, pursuant to a Memorandum of Agreement (MOA) dated April 24, 2004.

The One Cleanup program initiative began on February 7, 2005, when fYNOP submitted a Notice of Intent to Remediate (NIR) to PADEP under the Department's Land Recycling Program established by the Land Recycling and Environmental Remediation Standards Act, Act 2 of 1995, 35 P.S. § 6026.101 (Act 2). Public notice of the NIR under Act 2 was published in the *Pennsylvania Bulletin* on March 19, 2005. Participation in the program was acknowledged by letters dated July 15, 2005, and September 28, 2005, from James J. Burke of USEPA and Eugene A. DePasquale of PADEP to Sharon R. Fisher of Harley-Davidson. USEPA and PADEP also acknowledged the 1995 Settlement Agreement and recognized that site assessment and remediation under the One Cleanup Program would be consistent with the NCP.

In September of 2005, USEPA completed a letter called Documentation of Environmental Indicator Determination. The findings of that letter indicated the following:

"Based on a review of the information contained in this EI Determination, 'Current Human Exposures' are expected to be 'Under Control' at the Harley-Davidson Motor Company facility, USEPA ID # PAD 001 643 619, located at 1425 Eden Road, York, Pennsylvania under current and reasonably expected conditions. This determination will be re-evaluated when the Agency/State becomes aware of significant changes at the facility."

1.3 Site Setting and History

The fYNOP is located in Springettsbury Township in York County, Pennsylvania, and is currently an active motorcycle manufacturing facility situated on approximately 230 acres. As shown on Figure 1.0-3, the facility is bordered on the south by Route 30; on the west by Eden Road, a railroad line and northward flowing Codorus Creek; and on the east and north by residential properties. The West Parking Lot (WPL), Central Plant Area (CPA), and numerous other site features are called out on this figure. The eastern third of the site is undeveloped woodlands. The central and northern areas are occupied by buildings supporting manufacturing activities. The southern and western portions of the property are parking areas.

The Site was initially developed in 1941 by the York Safe and Lock Company, a United States Navy contractor, for the manufacture, assembly, and testing of 40 millimeter (mm) twin and quadruple gun mounts, complete with guns. In 1944, the Navy took possession of the York Safe and Lock Company facility. The Navy owned and operated the facility as the York Naval Ordnance Plant (YNOP) until 1964, switching operations after World War II to overhaul war service weapons and to manufacture rocket launchers, 3-inch/50-caliber guns, 20-mm aircraft guns, and power drive units for 5-inch/54-caliber guns. In 1964, the Navy sold the YNOP to American Machine and Foundry Company (AMF), who continued similar manufacturing. In 1969, AMF merged with Harley-Davidson. In 1973, Harley-Davidson moved its motorcycle assembly operations to the AMF York facility. In 1981, AMF sold the York facility to Harley-Davidson. Harley-Davidson has continued motorcycle assembly operations at the York facility since 1981.

The surface of the Site is immediately underlain by either fill (associated with site industrial and roadway construction), residual soil produced from the weathering of the underlying bedrock, or alluvium. From R.E. Wright Associates, Inc. (REWAI, September 1986) natural residual soils are comprised of sandy silt, clayey silts, and silt loam deposits from four primary soil series (Duffield, Glenelg, Elk, and Chester). These soil series are derived primarily from parent bedrock formations consisting of quartzitic sandstone and limestone.

Two geologic rock types underlie the Site. Solution-prone (karst) gray carbonate bedrock (limestone and dolostone) underlies the flat lowland (western) portion of the Site. Quartzitic sandstone underlies the more steeply sloping hills and upland area on the eastern part of the Site. The limestone is a karstic carbonate aquifer with groundwater migrating through solution-enhanced discontinuities and overlying unconsolidated materials. The quartzitic sandstone is a much less permeable aquifer; with minimal primary porosity, groundwater flows through tight bedding plane partings, joints and fractures, which are not solution-enhanced as they are in the carbonate bedrock. Groundwater flow is generally westward, from the upland area at the eastern part of the Site toward Codorus Creek; however, localized groundwater flow is also controlled by an active groundwater extraction and treatment system on-Site, that otherwise intercepts groundwater flow to Codorus Creek.

Groundwater investigations beginning in 1986 revealed the presence of volatile organic compounds (VOCs) in groundwater directly under the Site. The interim remedy for addressing the VOCs in groundwater included groundwater capture via extraction wells and treatment of the groundwater using air stripping in association with thermal treatment or carbon adsorption to control off-gasses, followed by on-Site discharge of the treated groundwater back into an unnamed tributary of Codorus Creek, locally called Johnsons Run. The groundwater extraction and treatment system (GWTS) was constructed in 1990 and has continued operations to date. The status of the GWTS is reported to the PADEP and USEPA via annual reports. The discharge point for treated groundwater was moved from Johnsons Run to the Codorus Creek after National Pollutant Discharge Elimination System (NPDES) renewal permitting in 2007. The location of the discharge point is shown on Figure 1.0-3.

1.4 Summary of Previous Investigations and Remediation

Numerous environmental investigations and remedial efforts have been conducted at the Site. Starting in 1984, Harley-Davidson began an investigation of potential environmental impacts in the eastern portion of the facility (Gettysburg Electronics, November 1984). Investigations of Site groundwater began in 1986 (REWAI, September 1986), followed by other subsequent groundwater investigations (REWAI, January 1987, August 1987, December 1989, May 1990, and July 1991). Due to the presence of VOCs in groundwater, a GWTS was designed and constructed in 1990 and has been in operation since that time. Various soil remedial efforts have also been conducted on-Site and are specified in the Soils RI report (SAIC, December 2009b).

In 1998, a Site-wide RI was initiated. The results of that study—including more detailed summaries of soil, groundwater, sediment, and surface water sampling—are provided in a draft report entitled "Interim Site-wide Remedial Investigation Report, Harley-Davidson Motor Company, York, Pennsylvania Facility" (Langan Engineering and Environmental Services, Inc. [Langan], July 2002). The purpose of the RI work was to characterize the Site for the development of appropriate remedial measures. This was facilitated through the investigation of potential source areas, further development of the conceptual model, and evaluation of migration and exposure pathways. The report resulted in the need to prepare a comprehensive document that compiled the remedial site activities completed and developed a scope of work to address data gaps. The fYNOP team (Harley-Davidson, USACE, and consultants AMO and SAIC) addressed that need with the Field Sampling Plan for Supplemental Remedial Investigations (SAIC, July 2006).

Two soil vapor intrusion studies were conducted for fYNOP by Langan in 2005 and 2007. The results of the soil vapor model using conservative assumptions and Site-specific characteristics indicate that the vapor pathway due to volatilization and migration of constituents in groundwater is not complete. The reports of those investigations conclude there is no apparent on-Site or off-Site risk to human health via the vapor intrusion pathway associated with the property. In addition, an off-Site soil vapor intrusion investigation was performed. The off-Site investigation was outlined in a letter to the USEPA dated June 29, 2007. All soil-vapor results were below the PADEP soil gas screening criteria, which reaffirms that there is no off-Site human health risk via the vapor intrusion pathway associated with the Harley-Davidson property in this area. The conclusions of these vapor intrusion studies may have to be re-visited following a revision of the PADEP's vapor intrusion guidance currently underway.

In December 2009, a report entitled Draft Supplemental Remedial Investigations Soils Report was completed (SAIC, December, 2009b). This report was accepted by EPA and PADEP as complete under the One Clean-up Program, as recorded in a letter from both agencies to Ms. Sharon Fisher of Harley-Davidson dated March 17, 2010. Areas of soil exceedances of PADEP Medium Specific Concentrations (MSCs) for direct contact (nonresidential) and soil to groundwater (residential used aquifers) were delineated. Summary maps from that report are included in the beginning of Section 4 of this report.

1.5 Groundwater Constituents of Concern

Remedial investigations and activities at the Site have indicated that the primary COCs due to concentration, detection frequency, and potential for off-Site migration are chlorinated solvents, including tetrachloroethene (PCE), trichloroethene (TCE), and 111trichloroethane (TCA), and degradation products of these VOCs. Less frequent detections of hexavalent chromium, lead, benzene, ethylbenzene, methyl tertiary-butyl ether (MTBE), 1,4-dioxane, and cyanide have also been detected in groundwater samples from Site monitoring wells. The distribution of these constituents in groundwater suggests that they have originated from multiple sources.

1.6 Report Organization

This report focuses on the groundwater investigations that have been completed including both the historical studies and the recently completed Supplemental Site-Wide RI. Included in this report and relative to the groundwater investigations are sediment sampling, and surface water sampling. The remainder of this report is organized in seven additional sections, as described below:

- The field activities and investigations conducted during the Supplemental Site-Wide RI are discussed in Section 2.

- Section 3 provides a description of the geology, hydrogeology, and karst weathering that provide the framework for groundwater migration and contaminant transport in the groundwater on and off Site.

- Section 4 discusses the Site-wide distribution of groundwater constituents of concern, as well as the chemistry trends in individual areas of interest. Where relevant to provide background or groundwater investigation decisions, groundwater results or investigations are briefly discussed.

- Section 5 discusses the Fate and Transport of the groundwater constituents of concern.

- Section 6 describes the progress that's been made at the Site since groundwater extraction activities began in 1990.

- Section 7 is an exposure pathway analysis for groundwater.

- Section 8 is a summary of findings and recommendations for next steps regarding groundwater.

- Section 9 is a listing of references.

2 SUPPLEMENTAL REMEDIAL INVESTIGATION ACTIVITIES

The work scope for this phase of investigations was described in the document *Field Sampling Plan for Supplemental Remedial Investigations* (SAIC, July 2006). Figure 2.0-1, taken from the FSP, shows the field activities as planned. In addition to the activities described in the FSP, hydrodynamic testing was conducted on the aquifer to evaluate the effectiveness of the WPL groundwater extraction system. Continuous monitoring of water levels in wells installed along the Codorus Creek was begun during the WPL hydrodynamic testing, and continued for approximately seven months. (As a result of these studies, a groundwater divide has been added to Figure 2.0-1 separating groundwater flow back towards the on-Site pumping cone of depression beneath the WPL from flow towards Codorous Creek.) Also, a more detailed understanding of the geologic setting was obtained through field inspection of outcrops and review of geologic mapping publications, detailed analysis of geologists' logs of the wells drilled and the development of a 3-D visualization model of the site.

All field data collection and database management were completed by SAIC in 2007 and 2008. Many of the maps and early versions of the text of introductory sections of this report were initially drafted by SAIC, and the background and procedural information from the Draft Supplemental Soils Remedial Investigation Report were used or modified in the preparation of this report. GSC acknowledges the work conducted by SAIC and the access and cooperation of SAIC as the report writing and analysis were transferred to GSC.

2.1 Monitoring Well Installation

Twenty-nine groundwater monitoring wells were proposed to be installed on-Site and off-Site as part of the investigative work during the Supplemental RI. The proposed locations of the new wells are shown on Figure 2.0-1, which is taken from SAIC's Field Sampling Plan (2006). Seven wells were targeted to be installed in saturated overburden, while twenty-two wells were planned to be installed into bedrock. All twenty-nine wells were installed in the planned locations. In two off-Site locations, monitoring wells were installed adjacent to the planned wells, to specifically characterize groundwater in thick unconsolidated material or solution features above planned bedrock monitoring wells. These two locations include:

- Well MW-109S, located in the area of well MW-109 on Figure 2.0-1 in the southeastern corner of the study area, that is installed in unconsolidated material to a depth of 65 feet below ground surface (ft. bgs); and
- Well MW-100S located west of the Site along the Codorus Creek that is installed in a mud-filled solution cavity at a depth range of 46 to 51 ft. bgs, with a second well screen (MW-100I) set to monitor limestone at a depth range of 61 to 66 ft. bgs, and a third well screen (MW-100D) set to monitor bedrock a depth range of 104 to 114 ft bgs.

Soon after the installation of the Supplemental RI wells, two additional wells designated MW-116 and MW-117, were installed in the northwestern portion of the Site. MW-116 and MW-117 were installed outside the east and west walls, respectively, of the Industrial Wastewater Treatment Plant (IWTP) in Building 41. These wells are not shown on Figure 2.0-1, since they were not part of the FSP. These wells were installed as a result of an interim action being carried out in this building however their well logs and the groundwater information collected from them are included in this report because of the timing of their construction.

Wells installed during and after the Supplemental RI are numbered consecutively, starting with MW-94 and ending with MW-117. A summary of well information, including surface completion information, depth to bedrock, materials penetrated, void intervals, and screened intervals for all wells, active and abandoned, installed on the property is presented as Table 2.1-1. Appendix A is a compilation of all logs for wells installed on the property, active and abandoned, including the new wells.

2.1.1 Location of Levee Wells on Conduit Features

An important component of the Supplemental RI was to investigate the relationship of Codorus Creek to the groundwater at the Site. Four sets of multi-level wells were placed on the eastern bank (flood control levee) of Codorus Creek. These wells were placed in locations that would increase the potential that they would intersect karst weathering features that are preferential groundwater flow paths. The wells were located using information gathered from fracture trace analysis, a thermal survey of water in the Codorus Creek, and Electrical Imaging, a geophysical methodology that can differentiate subsurface conditions. Appendix B includes a narrative of the results of the analysis and selection procedure.

2.1.1.1 Thermal Survey of Codorus Creek

A thermal surface water study was conducted on the Codorus Creek in August 2007 to delineate groundwater discharge points associated with subsurface conduits in the karst limestone bedrock (carbonate aquifer) that underlies the area of the creek and the flat lowland (western) portion of the Site. The survey covered a 2,500-foot length of the creek immediately west of the Site, as shown on Figure 2.0-1. Due to the karst nature of the carbonate aquifer beneath the project area, groundwater may discharge to the creek downgradient of the Site from discrete conduits (the nature of the karst conduits in the carbonate aquifer is described in Section 3.3 of this report). Temperature differentials identified near the bottom of the creek may indicate the location of the discharge of groundwater from a karst conduit.

2.1.1.2 Electrical Imaging Survey

The objective of the electrical imaging survey was to provide data on potential preferred groundwater flow pathways to support selection of locations for groundwater characterization well pairs. The results of this survey were used in conjunction with the fracture trace analysis results and the thermal survey of Codorus Creek to assist in the site selection of monitoring well pair locations along the east bank of Codorus Creek. In solution-prone carbonate rocks where karst weathering has developed in the aquifer, low resistivity anomalies can indicate discontinuities such as fractures, water- or sediment-filled solution cavities, and zones of greater depth to bedrock. These conditions often represent preferential pathways for groundwater flow in solution-prone carbonate rock.

SAIC conducted the EI survey in September of 2008. Five EI survey lines were laid out parallel to the creek and the west property line of the Site. The results of the survey are included in Appendix B.

2.1.1.3 Well Location Selection

Figure 2.1-1 shows the results of the fracture trace analysis, the Codorus Creek thermal survey, and the EI survey. All three studies are indirect methods of identifying locations of preferential groundwater flow features. As shown on Figure 2.1-1, results of these three methods identified three areas, designated as segments A, B and C along the west side of Codorus Creek, for possible monitoring well locations as follows:

- Segment A - This area hosts a cluster of thermal anomalies scattered among the bedrock outcrops through which a fracture trace runs. An EI anomaly occurs approximately 120 feet to the south of the fracture trace. If the fracture trace were shifted southeastward 75 feet (the accuracy of the fracture trace location is approximately 100') the trace would cross the EI anomaly and would line up the EI anomaly with the denser cluster of thermal anomalies.

- Segment B - The high density of thermal anomalies in the creek is coincident with a high frequency of EI anomalies in EI Traverse 1 closest to the creek. Linear trends between EI anomalies on Traverses 1 through 4 and clusters of thermal anomalies suggest the subsurface presence of groundwater conduits.

- Segment C - A cluster of thermal anomalies immediately adjacent to a broad EI anomaly (in-line distance 2200, [See Appendix B, Figure B4.0-3]) ties closely with the fracture trace mapped through the area. If the fracture trace position is shifted approximately 100 feet to the southwest, it would reasonably coincide with the EI and thermal anomalies.

Four well pair/cluster locations as shown on Figure 2.1-1 were selected based on these the EI results, and are denoted on the EI Traverse 1 profile. The locations were distributed across the 2500 foot reach of the east side of Codorus Creek, using the flood control levee as access. The wells targeted EI anomalies that were believed to indicate well-developed karst weathering features and had good potential to be connected to preferential flow pathways that extend to the west from the fYNOP Site.

2.2 Geologic/Karst Investigation

GSC personnel located bedrock outcrops and recorded structural features such as bedding, joints, and discontinuities on and immediately surrounding the Site. Geologic publications of the area were scrutinized, and a detailed map of the regional geology was prepared from available mapping in order to gain a better understanding of Site-specific bedrock stratigraphy and the orientation of bedrock structures. Considerable effort was directed toward characterizing the weathering of the carbonate bedrock beneath the Site and understanding the effect of karst weathering on the carbonate bedrock aquifer. A bedrock surface contour map was constructed; fracture orientations and the depth and positions of dissolution features were evaluated; and a 3-D visualization model was developed to assist in the understanding and description of the aquifer.

KCF scrutinized well logs of on-Site wells and constructed cross sections in order to better understand the on-Site stratigraphy and characteristics of the epikarst (the weathered layer of limestone bedrock) and karst solutioning in the aquifer.

2.3 Codorus Creek/WPL Groundwater Extraction System Evaluation

Harley-Davidson has operated and maintained a series of groundwater collection wells along its western property boundary since 1994. The collection well network was designed to maintain groundwater capture and prevent the off-Site flow of VOC-impacted groundwater. Water level data (collected from on-Site wells) have historically been collected and analyzed on a semi-annual basis and have suggested groundwater containment.

On the basis of the fracture trace, thermal survey, and EI survey described in Section 2.1, ten groundwater monitoring wells (at four different locations) were installed in the winter of 2007/spring of 2008 on the flood control levee on the east side of Codorus Creek. Groundwater quality analyses performed on these ten well in the spring of 2008 indicated the presence of VOCs (TCE and PCE predominated, with concentrations in the hundreds of parts per billion in the center two well clusters). As a result, a scope of work was developed to utilize the new wells to gain an understanding of groundwater flow in this previously unmonitored area. Specifically, these tests and observations were used to evaluate:

- Head differentials between the Codorus Creek and wells completed at various depths within the carbonate bedrock aquifer to determine whether there is an upward or downward gradient from the creek to these monitored intervals. Water levels were measured during seasonal low groundwater conditions, during apparent recharge periods, and during seasonal high groundwater conditions.

- Influence of the groundwater extraction system on the flood control levee wells during seasonal low groundwater conditions.

- Reactions and interactions of the surface water and groundwater during precipitation and high stream conditions.

The scope of work included the following:

- A continuous water level recorder was installed in Codorus Creek near the outfall of Johnson Run.

- Continuous water level recorders (In-Situ Troll 500 or 700) were installed in the 10 monitoring wells located along the levee on the east side of Codorus Creek. In addition, water level recorders were installed in 16 wells in the vicinity of the WPL and the CPA.

- Phase I – Starting on October 13, 2008, water levels were recorded by the continuous water level recorders in Codorus Creek, 10 levee area wells (Group A) and 16 WPL area wells (Group B) as shown on Figure 2.3-1 and listed in Table 2.3-1. Manual water levels were also measured weekly in 45 wells (Group C), also as shown on Figure 2.3-1 and listed on Table 2.3-1. During this time the groundwater extraction system had been operating as designed for many months, thus allowing an examination of impact of normal operation of the pumping wells on the groundwater.

- Phase II – Pumping Wells CW-8, CW-9, CW-13, CW-15A, and CW-17 were shut down on October 27, 2008. The wells remained off until November 19, 2008, while water levels were automatically recorded in the 26 Group A and Group B wells and in the Codorus Creek. In addition, manual water levels were measured in the same Group C wells monitored during Phase I daily for the first four days. Additional rounds of manual levels were collected on Monday, Wednesday and Friday of the following week (three events).

- After normal pumping operations resumed on November 19, 2008, continuous and manual water levels were recorded in all wells until December 11, 2008.

- Phase III – Long term water level monitoring of the ten Group A wells along Codorus Creek and the Codorus Creek level continued for approximately 6 months, until mid-May 2009. Monthly manual water levels were measured in Groups B and C.

Water levels from the manual rounds of measurements are presented in Table 2.3-2. Hydrographs of water levels and analysis of the data are presented and discussed in subsequent sections. Data collected for well couplets MW-50S&D and MW-51S&D showed erratic data for which an explanation has not been determined. This data was included later in this report but not analyzed.

2.4 Groundwater Monitoring

Groundwater monitoring completed as part of the Supplemental RI included completion of two groundwater sampling rounds. The first round of groundwater sampling was performed in April/May of 2008, after the installation of the wells constructed as part of the supplemental groundwater remedial investigation. This comprehensive sampling round included collection of groundwater samples from all available wells (156 wells) and analysis of the samples for a full suite of COCs, including the parameters listed in FSP. The second groundwater sampling round that included collection of samples from 125 wells was performed in September/October 2008. The scope of the sampling during the second round was carefully reduced, eliminating wells with a long consistent record, and reducing parameters where there is a good understanding of the COCs in that area. Since the Supplemental RI sampling, there have been two additional groundwater monitoring rounds consisting of annual sampling and analysis of a subset of wells identified as Key Wells. The list of Key Wells that are sampled annually includes wells considered to be in key locations to provide an understanding of on-Site and off-Site groundwater quality. A point was made to include the new wells installed during the Supplemental RI, to lengthen the record for those wells. Key Well sampling occurred in June/July 2009 and June/July 2010.

Water levels in all available wells on-Site and selected wells off-Site were measured prior to each round of sampling, regardless of whether or not the well was to be sampled during the sampling event. Water levels for the first and second Supplemental RI groundwater monitoring rounds (Round 1 and Round 2), and the Key Well round for 2009 are listed in Table 2.4-1. Purge data for Round 2 and the June 2009 Key Well event are included in Table 2.4-2. Purge data for Round 1 was not included because it was not captured electronically in the field, and would require data entry from the field log books.

All water level and laboratory data collected during the Supplemental RI were collected following the strict procedures provided in the project QAPP (SAIC, December 2009c), which included water level measurement procedures, laboratory analysis methods, chain of custody lists, method detection and reporting limits and data presentation requirements.

Groundwater chemistry data for the entire period of record is included in Tables 2.4-3 through 2.4-6.

2.5 Investigation Procedures and Data Management

All field data collection and database management were completed by SAIC in 2007 and 2008. Many of the maps and early versions of the text of introductory sections of this report were initially drafted by SAIC, and the background and procedural information from the Draft Supplemental Soils Remedial Investigation Report were used or modified in the preparation of this report. GSC acknowledges the work conducted by SAIC and the access and cooperation of SAIC as the report writing and analysis were transferred to GSC.

Environmental data were obtained through the collection of representative samples which were subjected to both on-site and off-site analysis per the methods described in the project QAPP (SAIC, 2009c) and in Section 5.0 of the FSP (SAIC, July 2006).

2.5.1 Procedures

Procedures for field sampling, chain-of-custody, laboratory analysis, and reporting of data are described in a separate QAPP (SAIC, 2009c). Specific analytical method objectives and sample QC criteria were provided in the QAPP.

The FSP provided the details of the field activities and quality assurance/quality control (QA/QC) measures that were used during monitoring and sampling associated with the Supplemental Site-Wide RI at the fYNOP. Monitoring wells were sampled using a well yield matched purge technique (SAIC, July 2006, pp.184-189). Additionally, the FSP provided the data quality objectives (DQOs) and the standards of comparison for indoor air, Site-wide soil, Site-wide groundwater, and Site-wide sediment and surface water.

2.5.2 Data Management

In order to include all of the historical investigations, remedial actions, and resulting sample data, an effort was started prior to the initiation of the Supplemental Site-Wide RI to compile and standardize all of the historical sampling data. AMO compiled data from various sources consisting of historical reports, report tables, laboratory reports, laboratory electronic data deliverables (EDDs), and the Site-Wide RI project database. Included in the compiled database are data from several different laboratories that were used throughout the years of investigation. The reporting standards varied between the laboratories, as well as from year to year. Additionally, approved laboratory analysis methods have changed, depending on the specific project requirements at the time and as a result of changes in regulations and improvements in analytical methods. The details of the data sources and the laboratory methods have been included in the master database. Since the data originated from different laboratories, additional details of the data are required to be considered such as the different reporting and detection limits, how the laboratory reported results below the method detection limits (MDLs), and differing laboratory qualifiers. All attempts were made to standardize the data when appropriate and possible. The master database is maintained on a server at the SAIC offices in McLean, Virginia, and is web accessible (https://www.fYNOP.com) by approved stakeholders (password protected).

All laboratory data collected during the Supplemental Site-Wide RI were collected following the strict procedures provided in the project QAPP, which included laboratory analysis methods, COC lists, method detection and reporting limits, and data presentation requirements. The QAPP provides a sample nomenclature that was used to uniquely identify each sample that was designated for laboratory analysis. The purpose of the sampling nomenclature is to provide a tracking system for the retrieval of unique analytical and field data for each sample. This sample nomenclature is maintained in the project master database. Sample names include a site designator, area or project designator, sample collection type (i.e., MW for monitoring well), sample number, sample depth interval or sample round, and sample type (i.e., "0" for primary investigative sample). The QAPP includes a table (SAIC, 2009c pp. 44-45) with lists for each portion of the sample nomenclature.

During the compilation of the database, in an effort to assure that no data was lost or left out, some duplicate data was added to the database. The majority of the duplicates occurred because SAIC's database covering data collected from 1986-1998 was copied into Langan's database by Langan. During the process, however, sample and analysis dates were altered. When both databases (Langan's and SAIC's) were compiled along with other data, the duplication occurred. The Langan database included legitimate data from the RI investigation completed by them between 1998 and 2001, and it became a tedious task to include the legitimate data and purge the altered records. Other duplicate issues were discovered and carefully corrected as the database was plotted on maps and compiled on tables, referencing original reports, and field log books. This work was completed by SAIC in 2008 and 2009.

During the Supplemental Site-Wide RI, all samples for laboratory analysis were collected by SAIC and provided to TestAmerica of Pittsburgh, Pennsylvania. As part of the QA/QC process, EDDs from the laboratory were entered into the fYNOP database, which is stored in the ARC IMS system and checked for completeness against the chain of custody record. Laboratory data packages were further validated at SAIC to determine if laboratory qualifiers were properly applied. All of the data was evaluated for completeness, then 10% of the data was validated, reviewing technical holding times, blanks, duplicates, laboratory control samples, matrix spike samples, surrogates, and calibration to standards. Verified electronic analytical data with qualifiers were then entered into the fYNOP database and stored on the SAIC server. Laboratory records are retained at TestAmerica for a period of five years after the report is issued.

3 PHYSICAL CHARACTERISTICS OF THE fYNOP STUDY AREA

This section describes the physical characteristics of the fYNOP site. The following subsections describe the site topography, physiography, geology, and hydrogeology, relying on previous work performed at the site including those studies described in Section 2.

3.1 Topography and Drainage

The Site is located in central York County, north of the City of York, PA. This area is drained by the Codorus Creek, a tributary to the Susquehanna River. As shown on Figure 1.0-1, the ground surface topography at the Site and surrounding area ranges from an elevation of 565 feet above mean sea level (amsl) in the northeastern corner of the Site, to an elevation of 340 feet amsl at Codorus Creek (reference Figure 1.0-1). Hills rim the fYNOP Site on the north and east, forming somewhat of a bowl-like configuration. The eastern one third of the Site is fairly steeply sloping to the west (4 to 20%), forming an upland area to the east of the flat-lying Central Plant Area (CPA). From the base of the hills to the Codorus Creek, the land surface underlying the CPA slopes very gently (0.5%) to the west. To the point where Codorus Creek crosses US Route 30 it drains 237 square miles of central and southern York County. The Codorus Creek flows northward past the Site, carving a fairly steep canyon through the upland area north of the Site. The main stem of Codorus Creek then flows eight miles eastward to its confluence with the Susquehanna River.

3.2 Physiography and Geology

The fYNOP Site is located in a geologically complex area known as the Piedmont Province, a physiographic and geologic region occupying the southern portions of York and Lancaster Counties in Pennsylvania. Plate 3A presents the regional geology surrounding the project area, and specifically captures the course of the Codorus Creek from where it passes the Site to where it joins the Susquehanna River (in the extreme northeast corner of the map). The Piedmont Province is composed of two sections: the Lowland Section and the Upland Section. The Lowland Section, locally known as the York Valley, is the area in which much of the fYNOP Site is located and is immediately adjacent to the Piedmont Upland Section, locally known as the Hellam Hills. The eastern portion of the fYNOP Site is situated in part of the Upland Section. The geology is notably different in these two areas with predominantly carbonate bedrock units and minor shale and sandstone units occurring in the lowland section and non-carbonate silici-clastic bedrock units composed of resistant phyllite, sandstone and quartzitic sandstone occurring in the upland area. Both areas are complexly folded and faulted.

3.2.1 Stratigraphy

Although bedrock exposures on-Site are extremely rare, two main geologic formations have been identified under the plant property from borehole data. A solution-prone gray carbonate unit is located in the flat lowland section of the property. This unit has been mapped by the Pennsylvania Geologic Survey as the Cambrian-aged Vintage Formation which is composed almost exclusively of dolostone (Stose and Jonas, 1939). Site investigation activities have revealed a variety of rock types within this unit including dolostone, and gray (calcite-rich) crystalline limestone with quartz veins. Detailed studies have documented that the Vintage Formation is composed of a comparatively pure, fined-grained limestone in the top section and mostly a blue-gray knotty dolomite in the lower portion (Stose and Stose, 1944), which was observed in cores from boring MW-61 drilled in the southwest corner of the site. The lowest portion of the basal dolomite has been observed to contain a white quartzose marble that grades into the underlying quartzitic sandstone. This observation is supported by findings during the drilling of the relatively deep on-Site monitoring well MW-73, located within the footprint of Building 3 (refer to Figure 1.0-3), which encountered a white marble at a depth of approximately 85 feet. Wells drilled in the eastern portion of the Site reveal that the contact of the Vintage Formation with the underlying Antietam Formation is gradational (sandy limestone present) with interbeds of quartzite and limestone and sandstone overlying limestone. Bedding in the Vintage Formation beneath the Site is expected to exhibit a variable strike and dip because of the intense folding that has occurred in the area; however, the general direction of dip is to the west and southwest across the Site.

Quartzitic sandstone of the Antietam Formation has been identified as underlying the more steeply sloping hills in the eastern part of the Site. In York County, this sandstone unit is a massive, grayish-green, argillaceous, fine- to medium-grained, quartzitic sandstone (Stose and Jonas, 1939). Outcrops of this more resistant unit are rare on the Site. Stose recorded a strike and dip reading in the Antietam Formation at an outcrop near the northern boundary of the Site or immediately north of the boundary. The measurement, shown in Figure 4 of Stose & Stose, 1944 (and added to the geologic map in this report [Plate 3A]), shows a northwest-southeast strike and a dip of 20 degrees west. This dip measurement indicates the Antietam Formation dips beneath the Site at depth and may be useful, in conjunction with wells penetrating the formation contact, to estimate the base of the Vintage Formation. The outcrop measured by Stose and Stose has not been located in the field.

A third, less extensive geologic formation is mapped under the northeastern portion of the Site. The Harpers Formation is shown on Plate 3A mapped together with the Antietam Formation by the Pennsylvania Geological Survey. The Harpers Formation is composed of a dark greenish-gray phyllite with some albite-mica schist and has been observed to grade into the overlying Antietam Formation (Stose and Stose, 1944). Occasional quartz sandstone layers are observed within the phyllite, which is well exposed northwest of the fYNOP Site on the west side of the Codorus Creek valley along Black Bridge Road. The Harpers phyllite was encountered during on-Site drilling in the area between MW-18S&D and MW-9 and at CW-1/1A and CW-7/7A. In addition, phyllite was encountered at depth in MW-98, the northernmost well installed during the Supplemental Site-Wide RI on the Codorus Creek levee.

Two other geologic formations found in the vicinity of the fYNOP Site are the Kinzers Formation and the Chickies Formation. While both of these formations do not subcrop beneath the Site, they are near enough to be significant in the Site geologic and hydrogeologic setting.

The Kinzers Formation, which stratigraphically overlies the Vintage, is primarily a limestone formation with a shale unit that forms the low hills located west of Codorus Creek near the intersection of Route 30 and Interstate 83. The Kinzers Shale unit was not differentiated on the geologic mapping layers provided by the Pennsylvania Geologic Survey, however Stose mapped the shale unit of the Kinzers in his 1944 publication. Because that unit may affect regional groundwater flow, the shale unit was added to Plate 3A in the area immediately to the west of the Site.

The older Chickies Formation, a vitreous quartzite and conglomerate unit with an interval of slate, occurs north of the Site and is exposed in the active Kinsley Quarry located north of Eden Road and east of the railroad and Codorus Creek. It is mapped as being in fault contact with the Antietam/Harpers and Vintage formations north and east of the Site.

Unconsolidated overburden materials have developed from the underlying bedrock throughout the Site. These overburden materials range in thicknesses from 15 feet to greater than 60 feet. Portions of the Site also have alluvial deposits, which include more coarse-grained sediments interspersed among the predominantly fine-grained residual soils.

Weathering, more specifically called karst development, has taken place within the carbonate bedrock in the form of dissolution of carbonate minerals, particularly along fractures and bedding planes. This dissolution was evidenced by numerous voids encountered during the drilling of borings and monitoring wells within the carbonate bedrock. The natural (non-fill) overburden materials in the carbonate terrain range in thickness from 15 feet to 60 feet, and are comprised of silt and clay, some or all of which had formed as the residual material from carbonate bedrock weathering, and transported alluvial sediment. In addition, several sinkholes have occurred on the fYNOP property, which are a typical occurrence within areas of soluble carbonate rocks. The solution cavities and fractures often contain mud, silt, and rounded 0.5 to 2-inch quartz and limestone gravels and cobbles, as recorded in numerous boring logs from wells drilled on-Site.

Terzaghi, et al (1996) state that, “the weathering products … of limestone, dolomite and marble consist almost entirely of the insoluble portion of the parent rock. They usually form a nearly structureless residuum, generally clayey but sometimes sandy or pebbly, with no transition to the undissolved, unweathered rock. However, although sharp, the contact may be extremely irregular… Very soft clay is often found in the bottom of incipient or collapsed sinkholes. The overlying material is usually stiffer and is often covered by colluvium.”

3.2.2 Structural Geology

Structurally, the Site is located at the western end of the westward-plunging Mount Zion anticline which is defined by the subcrop of the Antietam and Harpers formations (Plate 3A). The Mount Pisgah hills located east of the site were formed by the faulting of older and more resistant quartzites and conglomerates of the Chickies Formation over the Antietam and Harpers formations of the Mount Zion anticline by the Highmount Overthrust and the Glades Overthrust (Stose and Stose, 1939). The Chickies Formation, though not found beneath the fYNOP Site, subcrops immediately north of an east-west strike-parallel normal fault that brings the Chickies into unconformable contact with the Antietam and Vintage formations about 200 feet north of the Site. The rocks in the area immediately north of the normal fault are part of the westward plunging Chickies Rock anticline which is also truncated by the previously-mentioned overthrusts. This fault is a significant structural feature that extends westward across the Codorus Creek valley. It is truncated by a northwest-southeast oriented normal fault, known as the Plank Road Fault (Stose and Stose, 1939), located approximately 1,200 feet east of the Site. Together, these two faults define the northern and eastern edges of the fault block on which the fYNOP Site is located. The fault located south of the Site is the Gnatstown Overthrust which trends westward along the northern edge of the York Valley and is terminated by the Plank Road Fault southeast of the Site.

An aerial photograph fracture trace analysis was completed a number of years ago for the fYNOP Site to identify likely fracture zone locations and their orientation in the carbonate limestone aquifer, and to correlate them, where possible, with karst weathering features in the bedrock. A photogeologic fracture trace is defined by Lattman (1958) as a “natural linear feature consisting of topographic (including straight stream segments), vegetal, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern or tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces.”

Black and white 10- by 10-inch contact prints of aerial photographs taken in September 1937 were obtained at a scale of 1:20,000. The historical aerial photographs were used to map fracture traces and lineaments to allow these features to be observed with minimal disturbance by Site development that reportedly began in 1941. The photographs were viewed obliquely and in stereo at various magnifications. Fracture traces were mapped and marked directly on the photographs. The photographs were digitally scanned, imported into the Arcview®, and superimposed on the Site topographic base map, rotated, and scaled for best-fit. Straight line segments were aligned with the mapped fractures on the photographs and saved as an Arcview® shape file. A total number of 16 fracture traces were identified from the aerial photographs.

Mapped fracture trace locations and orientations overlying the Site base map are illustrated in Figure 2.0-1 and Plate 3A.

The fracture traces showed two sets of orientations, trending North 50-70º East (9 fracture traces) and trending North 35-55º West (6 fracture traces). A single fracture trace was oriented North 22º East. When fracture sets are tightly grouped into a few orientations, as these are, it is reasonable to expect that the fracture traces reflect a structural fabric within bedrock and beneath the Site. As such, unmapped fractures and discontinuities may be present in the bedrock and residual structures may be present in the residual soil parallel to these fracture trace orientations.

3.2.3 Karst Features in the Carbonate Bedrock

The high degree of variability in the elevation of the top of bedrock, called a "cutter and pinnacle" bedrock surface, and the occurrence of numerous apparent caverns and solution channels within the bedrock at the Site indicate processes that are described as karst development. Figure 3.2-1 shows a typical pinnacled bedrock surface, from the J. E. Baker Quarry, located west of the Site. Epikarst is the zone of chemically weathered bedrock that overlies competent limestone and dolostone. After White, 2004, the base of the epikarst is considered to be the horizon where solutionally widened fractures and bedding plane partings narrow to bedrock relatively unmodified by dissolution. The cutter and pinnacle karst bedrock surface structure develops as slightly acidic (corrosive) groundwater finds recharge pathways into the bedrock, and slowly dissolves the carbonate rock to form channels or cutters in the rock surface. The cutters subsequently became filled with residuum and/or transported sediment.

The epikarst layer functions to direct infiltrating groundwater to vertical conduits, which allows for the introduction at depth of fast infiltrating aggressive waters. This rapid influx of recharge dissolves the rock in such a way that fractures may be enlarged into conduits, or solution cavities and caverns, which are openings within bedrock below the soil/bedrock interface (Bakalowicz, 2004). In general, studies of karst bedrock settings have indicated the rate of dissolution of the carbonate rock declines with depth as the groundwater reaches carbonate mineral saturation (Palmer, 2004). However, in the Mid-Atlantic region, including at the fYNOP Site, substantial solution cavities can be found to depths of 200 feet or greater. The following subsections will describe in greater detail the processes that control karst development and the karst features at the Site will be compared to those typical of karst sites found in the literature.

3.2.3.1 Data Analysis Methods

To aid in this analysis of data from the site, figures and tables have been excerpted from published literature to provide a foundation for better understanding the karst development at the Site. Sources for these excerpts are provided in the list of references at the end of this report.

In order to provide a visual perception of karst development at the soil/bedrock interface as well as the vertical distribution of conduit development at this Site, two approaches were taken. GSC constructed a three-dimensional visualization of the fYNOP Site using Rockworks 15 by RockWare Inc. and KCF constructed a series of eight cross sections running east-west and north-south across the Site. To construct the Rockworks model, physical data for each well, including geographic coordinates, surface elevation, and depth to competent bedrock (i.e., depth to the base of the overburden unit as shown on the well log), borehole depth, and conduit (void) intervals were entered into Rockworks' Borehole Manager module. A grid model was then generated using the inverse-distance algorithm in the "Stratigraphy Model" of Rockworks. The resulting grid model was converted to both 3-D and 2-D visualizations.

A cold-to-hot color scheme with 64 levels was used for the 3-D color visualization with warm colors (reds) indicating lower epikarst surface (i.e., top of bedrock) elevations and cool colors (blues) indicating higher elevations. The 2-D surface contour visualization was developed from the grid model using a contour spacing of 2 feet.

(The 3-D visualization can be viewed by clicking on this LINK if the reader is reading this report as a PDF document by paging through the files in consecutive order. Otherwise, the complete model can be found on the disc accompanying this report.)

To describe the occurrence of solution features in the carbonate bedrock, KCF constructed a series of eight cross sections. These cross sections are reproduced in Appendix C. The locations of these cross sections are shown on Figure C-1. KCF's cross sections, designated A-A' through H-H', are then provided on Figures C-2 through C-9. Geologists' logs from a total of 115 monitoring wells and collector wells prepared by R.E. Wright, SAIC, and Langan were used in the construction of these cross sections to illustrate the representative characteristics of karst features in the bedrock and the location of the geologic contact of carbonate with quartzitic sandstone bedrock. The cross sections were developed by plotting the total thickness of karst in the bedrock at each well, and the locations of geologic contacts, using a graphical rendering program to show the elevations in the bedrock of soft void-fill material, soft/weathered rock zones, open water-filled voids, fractured and broken bedrock, the water table, and geologic contact of carbonate rock with sandstone/quartzite and phyllite. A vertical exaggeration of 10:1 was utilized to better view the karst features in vertical detail.

The heterogeneity of the karst at the Site, where karst formations in bedrock can vary sharply across distances of only several feet, makes it impossible to accurately extrapolate or interpolate connections between one karst feature and another in an adjacent boring. However, the individual cross sections support the occurrence of karst features in the form of open and filled voids throughout the carbonate bedrock. Therefore, the karst features have not been extrapolated beyond boreholes, or interpolated between boreholes; the geologic logs have been rendered on the cross sections as they were recorded by the project geologist. The cross sections are therefore without bias towards one interpretation of the data or another.

The bottom of the karstification of the Vintage dolomite is not known at this time, and therefore the cross sections currently do not define a bottom to the karst features. Experience with the depth of penetration of karst weathering in the mid-Atlantic area carbonate bedrock is approximately 250 feet, although exceptions are found. This would put the estimated base of the karst slightly below the locations of the deepest known karst beneath the Site.

3.2.3.2 Carbonate Rock Dissolution

The development of karst features in carbonate rocks is fundamentally associated with the dissolution of calcium carbonate (calcite) in limestone and calcium-magnesium carbonate (dolomite) in dolostone. The initial step in the dissolution of carbonate rock is associated with the formation of weak carbonic acid as carbon dioxide (CO_2) dissolves in pore water (see Figure 3.2-2 after White, 1988). This reaction occurs within the vadose zone where percolating water dissolves CO_2 gas present in soil pores. The carbonic acid then ionizes to form a bicarbonate ion (HCO_3^-) and a proton (H^+). The HCO_3^- remains in solution while the H^+ adsorbs to the solid phase carbonate rock, where it reacts with a carbonate ion on the surface of the carbonate rock. This reaction results in the release of a second bicarbonate ion along with a calcium ion, which both diffuse back into the solution (White, 1988, pp. 140-141).

The dissolution of the carbonate rock continues until the solution reaches calcite saturation for limestone or dolomite saturation for dolostone. Figure 3.2-3 depicts the pathways to equilibrium for unsaturated karst waters (White, 1988, p.205) with a plot of pH versus HCO_3^- concentration. The equilibrium pathways are shown for open and closed systems and various initial CO_2 pressures. The open system refers to one in which CO_2 can be added to the solution, reflecting conditions above the water table. The closed system then relates to equilibrium pathways for groundwater below the water table where CO_2 gas cannot be added to the solution. Figure 3-2.3 shows that, at bicarbonate alkalinities within the normal range for groundwater in carbonate rocks (i.e., less than 400 ppm), water with pH values less than 7.0 will almost certainly be undersaturated with respect to both calcite and dolomite solubility.

There are insufficient bicarbonate concentration data from the Site to create a plot similar to that in Figure 3.2-3, but there are pH data for the monitoring wells at the Site that allow for a comparison of pH versus depth of the monitoring interval. Figure 3.2-4 shows a plot of monitoring depth versus pH from 61 carbonate aquifer wells sampled at the Site in June and July of 2009. A horizontal line corresponding to a pH of 7.0 and a vertical line corresponding to a depth of 80 feet bgs have been drawn on this figure to separate the data into four quadrants. As shown on this figure, only five of 28 pH readings from monitoring intervals at depths less than 80 feet exhibit pH values above 7.0, suggesting that groundwater in the top 80 feet of the carbonate aquifer is undersaturated with respect to both calcite and dolomite. Conversely, for monitoring intervals deeper than 80 feet bgs, there is a near even distribution of pH values above a pH of 7.0 (17 wells) and below (15 wells). This distribution suggests increased overall saturation of the groundwater beneath a depth of 80 feet. However, nearly half of the pH values are still less than 7.0 and the pH in the deepest monitoring interval is 6.7 at a depth of 235 feet bgs. Based on these observations, it appears that a significant percentage of the groundwater present at depths of approximately 235 feet bgs is undersaturated with respect to calcite and dolomite. This conclusion must be confirmed by future concurrent groundwater analyses for pH and bicarbonate. However, if confirmed, these data would indicate that carbonate dissolution associated with karst development is still occurring at depths below 200 feet bgs at the Site.

3.2.3.3 Development and Spatial Distribution of Karst Features

Various models have been proposed to explain the development of karst features above and below the water table. Figure 3.2-5 (White, 1988, p.267) presents the three prevalent theories proposed in the early 20th century-Vadose Theory, Deep Phreatic Theory and Watertable Cave Theory. White notes that each of these theories was championed by various early researchers. However, he goes on to explain that in the 1950s and 1960s, researchers, including White, began to conceive of conduit development as a kinetic process that is highly dependant on the hydrology and geology of the carbonate aquifer, with none of these models being exclusively correct.

In accordance with this kinetic model, Figure 3.2-6 (White, 1988, p. 274, adapted from Ford and Ewers [1978]) shows four states of phreatic (i.e., at or below the water table) cave development. Depending on the geology, the four models shown on this figure result in very deep conduit development (bathyphreatic), deep conduit development, mixed phreatic and water table components and an ideal water table cave. Worthington (2004) further examined the effects of fracture geometry on the depth of conduit development and flow. Figure 3.2-7 (after Worthington (2004), Figure 6), shows an initial flow field (A) with dimensions of 200 m deep by 1500 m long. Depending on the fracture frequency and stratal orientation of bedding, the depth of conduit flow, as shown in D is predicted by Worthington to be as much as 200 m (i.e., >600 feet) below the water table.

The preceding discussion provides references that confirm the development of karst conduits and caves at substantial depths below the water table. As such, it demonstrates that the Vadose Theory (which views all karst development as occurring above the water table) does not explain all means by which karst features develop, including in particular, such development below the water table. Since one stricture of the Vadose Theory was that gravitational water reaching the water table is either already saturated with respect to calcite or quickly becomes saturated after mixing with shallow groundwater, White (2002) and other researchers examined the kinetics of fracture and conduit enlargement and determined that changes in the kinetics of the dissolution reaction described above in section 3.2.3.2 facilitate fracture and conduit enlargement at significant depths below the water table. The following excerpts from White (2002) explain this process:

“When the water is undersaturated, the reaction kinetics is roughly first order. When the water is approaching saturation [about 85%], the reaction order increases to near fourth order. This break is of profound importance in the development of conduit permeability.” (White [2002] p.93)

‘When unsaturated water enters a fracture, there is a rapid reaction and uptake of dissolved carbonate. If the kinetics is strictly linear, the argument [of the Vadose Theory] goes that the water would quickly become saturated, dissolution would cease, and there would be no dissolutional enlargement of fractures deep within the aquifer. There would be surface karst but no caves. However, if the rate shifts from first order to fourth order when the water is only 85% saturated, the rate slows down by some orders of magnitude, thus permitting slow, laminar flow to carry the slightly undersaturated water deep into the aquifer. Dissolution continues along the entire flow path but at a slow rate. The significant concept is the ‘‘breakthrough’’ of all possible pathways through the aquifer along joints, joint swarms and bedding plane partings, one pathway will, only by chance, have a slightly larger average initial aperture than the others. This pathway will gradually enlarge until its aperture is such that water with less than the 85% saturation can penetrate the entire aquifer. When this happens, the kinetics shifts from fourth order to first order and the rate of dissolution dramatically increases. In effect, the shift in kinetics triggers a runaway process which allows the chosen pathway to enlarge rapidly. This is the kinetic threshold or kinetic trigger that explains why the number of fully developed conduits is usually (but not always) much smaller than the number of fractures. (White [2002] p.94)

Figure 3.2-8 (after White [1988] Figure 9.12, p.287) shows a schematic rate curve for conduit development. At the origin on this graph, the initial fracture aperture prior to any enlargement due to solutioning is assumed to be on the order of 10-25 microns. Over a period of time estimated by White to be 3000 to 5000 years, the initiation of fracture aperture widening occurs until the aperture reaches 5-10 mm. As noted on this graph, this aperture size is associated with “critical thresholds”. The nature of these critical thresholds is summarized in White (2002, p. 94) as follows:

The evolution from fractures to conduits is discontinuous. There are three thresholds that appear when the aperture reaches to roughly 0.01 m.

(a) Hydrodynamic threshold: The onset of turbulent flow and resulting loss of Darcian behavior.

(b) Kinetic threshold: A shift in dissolution rate from the fourth order kinetics to linear kinetics. [as discussed above]

(c) Transport threshold: Apertures and flow velocities become sufficient for the transport of clastic material.

After these thresholds have been exceeded, Figure 3.2-8 shows that enlargement of the conduit proceeds over a period of 10,000 to 100,000 years, leading, in the case of conduit development below the water table, to a flooded conduit with dimensions greater than 3 m and possibly as high as 50 m. Because the transport threshold has also been exceeded, sediment transport and deposition occurs within the enlarging conduit concurrent with the enlargement of the conduit. Finally, as noted, exceeding the hydrodynamic threshold also results in potential turbulent flow within the individual conduits, with the resultant loss of Darcian behavior for flow within the conduit itself.

With these processes in mind, White (2002) summarizes the hydrologic classification of carbonate aquifers in the table shown in Figure 3.2-9 (White [2002] after White [1969]) basing cave (conduit) type on flow type and hydrologic control. Based on the results of investigations completed at the Site, the carbonate aquifer beneath the fYNOP property appears to match the flow type II. Free flow, B. Deep, 1. Open. The hydrologic characteristics of this flow type are “thick, massive soluble rocks” with a “karst system extending to considerable depth below base level” (i.e., 200+ feet below Codorus Creek) and “soluble rocks extend[ing] to land surface”. Based on Figure 3.2-9 this flow type and set of hydrologic controls would generate karst features typified by “integrated conduit cave systems” with “flow ..through flooded conduits”. Abandoned caves are also likely to be “sediment-choked”.

In addition to this classification of carbonate aquifers by White, Ford (1999) reproduced and modified a chart originally published by Palmer (1991) describing the plan view patterns of caves (conduits) based on a matrix of the type of recharge and the type of pre-solutional porosity. This matrix is presented as Figure 3.2-10. First of all there is no evidence of upwelling hypogenic fluids (thermal water from deep-seated source) beneath the Site, so the right-hand column of this matrix does not apply. With respect to the other types of recharge, there is evidence at the Site for both diffuse recharge and recharge via karst depressions.

Of particular interest is the network pattern associated with diffuse recharge through sandstone. As described in the sections on stratigraphy and structure, the Antietam quartzite/sandstone is present along contacts with the Vintage Formation, with the Antietam subcropping east of the CPA while the Vintage subcrops under the CPA, NPA and WPL. Where their conformable contact extends below ground surface, the Antietam underlies the Vintage, although there is borehole evidence of interlayering of sandstone and limestone along the contact, especially in the southeast corner of the site. The general east to west flow of groundwater (discussed in a later section) results not only in shallow acidic groundwater flowing across the contact, but also upwelling acidic groundwater from the Antietam to the Vintage all along their contact at depth below the western portion of the Site. This diffuse recharge to the Vintage from the Antietam may have contributed to the development of a network pattern of fissures due to enlargement of fractures by upwelling acidic groundwater crossing the contact from the Antietam to the Vintage. As noted on Figure 3.2-10, further enlargement may then occur due to recharge from other sources as described above.

The preceding discussion provides a basis for understanding the development of deep karst features to depths of more than 200 feet below the base level of Codorus Creek without any need to suggest that somehow base level for groundwater flow beneath the Site had been hundreds of feet lower during the development of these deep karst features over the past one million years. This is especially important since no current understanding of the regional geology or erosional and depositional history of south-central Pennsylvania would provide a basis for such a change in base level at the Site.

3.2.3.4 Description of Karst Features at the fYNOP

The description of karst features at the fYNOP Site will rely on figures generated from output of the Rockworks 2-D and 3-D models and the KCF cross sections presented in Appendix C. Figure 3.2-11 shows a detailed view of the top of the bedrock surface based on the 2-D visualization contouring. The topographic contours shown on this figure are for the top of bedrock surface based on interpolation between the available boreholes drilled into the bedrock. As such, these contours do not depict the full variability of this surface as reflected in Figure 3.2-1. Rather, it shows large scale variations in this surface including larger karstic features.

Figure 3.2-11 also shows the locations of wells that penetrated solution cavities or caverns in rock below the top of bedrock. These locations are shown as colored discs underlying the well symbol. Also shown are the locations of wells that penetrated a sufficient thickness of carbonate bedrock to have encountered karst features, if they were present, but the total thickness of any voids encountered was less than 1.0 feet. The solution cavities that comprise the karstic voids are found in various conditions: open, or partly or completely filled with sand, silt, clay, alluvial gravel and weathered rock debris.

Figure 3.2-12 shows the plan view output of the 3-D color visualization with warm colors (reds) indicating lower epikarst surface (i.e., top of bedrock) elevations and cool colors (blues) indicating higher elevations. On this figure, the hotter colors depict localized bedrock depressions or sinking points anticipated to correspond to locations of more concentrated groundwater recharge.

Finally, Figures 3.2-13 to 3.2-16 present four three dimensional views of the Site based on the Rockworks model output that includes not only the color visualization of the top of epikarst, but also the total depth interval of each monitoring and the discrete intervals of voids (conduits) penetrated in each well. Each of these figures include one view looking obliquely downward at the top of epikarst and a second view looking obliquely upward at the underside of this color-coded layer.

Beginning with Figure 3.2-11, the most prominent top of bedrock karst feature this figure shows is an irregular-shaped bedrock surface depression located west of the geologic contact of carbonate bedrock with quartzitic sandstone and phyllite. It is delineated by highlighting the 330-foot elevation closed depression contour in this area, and is keyed in the legend as “Bedrock Surface Depression Following Bedrock Contact”. The broad depression, shown as 200 to 800 feet in width, has a general north to south orientation, curving to the west at its northern extent, as the geologic contact curves to the west. The depression contains some of the localized bedrock depressions or sinking points depicted on Figure 3.2-12 into which concentrated groundwater recharge has formed the deeply penetrating solution conduits which pervade the bedrock. The substantial dissolution of the bedrock surface in this area, up to a depth of 76 feet, has likely been created by corrosive groundwater recharge and storm water runoff from the Antietam Formation quartzitic sandstone and Harpers phyllite upland area in the eastern portion of the Site, flowing onto the lower-elevation carbonate bedrock area beneath the western portion of the Site. Some notable features/observations regarding this broad, epikarstic feature in the center of the Site include:

- MW-77 is located in this depression. Langan (July 2002) shows that bedrock was not encountered at MW-77 in a 67-foot deep corehole, with overburden consisting of alluvial gravel and sand. Outside of this depression, bedrock is typically encountered at about 25 ft. bgs.

- MW-25, also located in this feature, has clay and gravel to 58 ft. bgs with no bedrock being encountered. Adjacent deep well MW-115 encountered bedrock at a depth of approximately 24 feet, forming the "rim" of the trough.

- During the drilling of MW-87 that was terminated at a depth of 98 ft. bgs, an estimated 50-foot thick cavern was encountered from 45 to 95 feet beneath a thin bedrock cover; alternatively SAIC describes this as possibly a deep penetrating cutter feature. (A “cavern” is a large cave structure buried inside of bedrock, as compared to a “cutter” which is a channel feature in the rock surface that may extend to substantial depths but is nonetheless not covered or capped by competent bedrock.) Bedrock is found at a depth of about 40 ft. bgs in the surrounding areas outside of the cutter feature, such as at CW-18. The cavern/cutter contains rounded gravel.

Using the closed contours at elevation 330 feet amsl across the Site as the indicator of zones where the top of bedrock is significantly deeper, the features labeled “Bedrock Surface Depression-330 Contours” on Figure 3.2-11 indicate closed depressions underlying the northwestern corner of Building 2 and the northern half of Building 4. Also, the northwest corner of the WPL, the west-central section of the WPL, and the southwest corner of the WPL have closed depressions below elevation 330 feet amsl, indicate karst development within the carbonate bedrock in the westernmost portion of the property and between the property and Codorus Creek.

As noted above, Figure 3.2-12 shows the path of infiltrating groundwater being directed along the soil-bedrock interface to sinking points into the karst aquifer. The lower elevation of the epikarst surface and solution cavities associated with these features also generally correlate with concentrated fracture trace patterns. After Palmer (2004), the groundwater sinking areas may be enhanced and deepened in areas of intersection of large scale and deeply penetrating bedrock fractures and master joints.

Figure 3.2-11 shows that the locations of the solution cavities of various total thicknesses are widespread throughout the Site. The few well locations with no void thickness greater than 1.0 feet appear to be more prevalent in the southwestern corner of the area studied and near the contact between the Vintage Formation and the Antietam Formation in the vicinity of Buildings 3 and 14.

The suggestion from this view of karst development is that well locations exhibiting karst features are well-distributed across the Site. For 65 wells examined, only 13 had total void thickness less than 1.0 foot. This corresponds to a 0.80 probability of encountering a void in the 65 wells drilled in the carbonate aquifer to sufficient depth to encounter a conduit if one is present at that location. By contrast, Worthington (2004) indicates a much lower probability of penetrating a conduit in any given borehole based on the following excerpt:

…evaluation of conduits is much more difficult where recharge to a karst aquifer is only by percolation and where springs are not visible (e.g., where an aquifer discharges into large rivers, lakes or along coasts). Boreholes are very useful in evaluating matrix and fracture flow, but are very problematic in evaluating conduit flow because of the low probability (0.01-0.02) of a borehole intersecting a conduit.

The contrast between the probability of encountering a conduit as anticipated by Worthington based on his experience (0.01-0.02) and that demonstrated from the drilling history at the fYNOP Site (0.80) strongly suggests that the frequency of conduit occurrence beneath the fYNOP Site is extraordinary. This observation from conduit occurrence shown on Figure 3.2-11 is strongly reinforced by the 3-D views of void occurrence in boreholes shown on Figures 3.2-13 to 3.2-16 and KCF's cross section views on Figures C-2 to C-9 in Appendix C. These observations may support the likelihood that the distribution of conduits beneath the fYNOP Site may be similar to the network development identified on Figure 3.2-10 as resulting from diffuse recharge through sandstone with further or primary enlargement by recharge via karst depressions generating "branchworks" at several levels.

3.2.3.5 Depth of Karst Development

The depth of karst solutioning is evident from the solution channels and caverns encountered in carbonate bedrock to a depth of 212 ft. bgs at MW-75D, located in the southwest corner of the WPL. The filling materials in the solution channels in the MW-75D borehole are sand, silt, clay, alluvial gravel and weathered rock debris. Also in the southwestern portion of the WPL, drilling of test recovery well CW-20 (SAIC, June 2008) encountered carbonate bedrock with stacked caverns totaling 79.5 feet in thickness to a depth of about 200 ft. bgs. Below these stacked voids, a one-foot void was encountered at a depth of 213 ft. bgs within more competent rock. The CW-20 borehole was terminated at a depth of 214 ft. bgs (see Plate 3B after Plate 2 of SAIC, June 2008).

From SAIC (May 2004), well locations MW-93S and MW-93D, located approximately two hundred feet north of MW-75D, encountered relatively shallow carbonate bedrock. Solution channels of 0.5 feet were found at depths of 30 ft. bgs and 39.5 ft. bgs, respectively. A 6.5 foot solution channel opening was encountered at a depth of 48 ft. bgs, and a more than 18-foot high cavern was encountered at a depth of 142 ft. bgs. The base of the cavern lies below a depth of 160 ft. bgs. Loose sediment fills the cavern to within one foot of its top.

As discussed above, this depth of karst development to more than 200 feet below the local base level of Codorus Creek cannot be attributed to draining of the Vintage Fm aquifer to a base level more than 200 feet lower than the current base level. It can, however, quite possibly be attributed to the factors considered by White (1988) in identifying his deep conduit development model (Figure 3.2-6) and by Worthington (2004) in considering the effects of fracture and bedding orientation on depth of conduit development (D on Figure 3.2-7) and again by White (2002) in characterizing the various conduit development regimes based on flow type and hydrologic controls (Figure 3.2-9). As shown on this last figure, the hydrologic characteristics of the flow type represented by the fYNOP Site are “thick, massive soluble rocks” with a “karst system extending to considerable depth below base level” (i.e., 200+ feet below Codorus Creek) and “soluble rocks extend[ing] to land surface”. Based on Figure 3.2-9 this flow type and set of hydrologic controls would generate karst features typified by “integrated conduit cave systems” with “flow ..through flooded conduits”. Abandoned caves would also likely to be “sediment-choked”. These characteristics of conduit development are amply exhibited by the documented conduit development at the fYNOP Site based on the borehole data as presented on Figures 3.2-11 and 3.2-13 to 3.2-16, as well as the KCF cross sections in Appendix C.

3.3 Hydrogeology

This subsection describes the hydrogeology of the Site including the observed characteristics of the carbonate rock aquifer, the effects of karst features beneath the Site and the calculated recharge rate.

3.3.1 Conceptual Site Model of Groundwater Flow

The stratigraphy, structural geology and karst development described in the previous sections are the basis for the aquifer conditions and groundwater flow through the site. Groundwater generally migrates from east to west, from the high topographic areas underlain by quartzitic sandstone to the carbonate aquifer that underlies the western half of the site. Aquifer transmissivity, the property of the aquifer that describes the ease with which groundwater moves through the saturated subsurface materials, is very different between these two geologic materials. The quartzitic sandstone transmissivity is lower due to the groundwater migrating through minor partings associated with bedding planes, joints and fractures with relative higher resistance compared to the carbonate aquifer because the openings are not solution-enhanced. Because the materials of the carbonate aquifer are prone to dissolution by migrating groundwater, transmissivity in this aquifer is greatly enhanced, and groundwater moves with relative ease through the aquifer. In fact, the dimensions of the conduits identified in boreholes are such that flow in these features may be turbulent rather than laminar, resulting in non-Darcian flow in individual conduits.

Plates 3C and 3D are groundwater elevation contour maps for the water table at the Harley-Davidson Site developed from groundwater level measurements from June and December 2009. These contour maps are from the Groundwater Extraction and Treatment System Annual Operations Report for 2009 (SAIC, March 2010).

As shown on these plates, groundwater beneath the Site flows from the upland area in the eastern portion of the Site westward toward Codorus Creek. Based on the groundwater elevation contours shown on Plates 3C and 3D, the operation of groundwater extraction wells appears to prevent groundwater flow from the WPL to Codorus Creek. In the North Property Boundary Area (NPBA), flow directions are locally modified by active groundwater extraction wells; however, groundwater appears to flow off the Site to the west of MW-18. In the southeastern corner of the Site, groundwater flows offsite to the south.

Water table gradients are steep (6 to 10%) in the upland regions underlain by quartzitic sandstone and diminish to a relatively flat gradient (1% or less) once the groundwater flows into the area underlain by carbonate rocks. Groundwater in the upland area flows mainly through the interconnected network of fractures, joints, and bedding planes.

Once the groundwater encounters the carbonate rocks, groundwater flow is directed along fractures, dissolution cavities, interconnected conduits, and weathered zones in the rock. The regional groundwater flow through the property follows a general west-southwesterly direction. Locally, the groundwater flow through the karst bedrock is widely variable following the pathways of solutionally enlarged conduits. However, responses to pumping tests and migration pathways traced by groundwater chemistry indicate a well-connected aquifer as a result of numerous highly interconnected conduits, as described in the previous section.

Groundwater flow is redirected locally by the system of capture wells in the WPL. The combination of pumping from the extraction wells and the discharge of Site storm water to a wetland area between the western property line and the Codorus Creek have created a divide between the creek and the Site. Groundwater on the east side of the divide migrates toward the Site, and groundwater on the west side of the divide migrates westward toward the Codorus Creek.

3.3.2 Aquifer Characteristics

This subsection addresses the characteristics of the quartzitic sandstone and carbonate aquifers beneath the Site as they affect groundwater flow and other processes associated with chemical fate and transport which are discussed in Section 5.

3.3.2.1 Transmissivity and Specific Yield from Aquifer Tests

Transmissivity values of 100 to 200 gallons per day per foot (gpd/ft) were measured in wells penetrating the Antietam Formation on-Site (REWAI, May 1990; REWAI, July 1991). Transmissivity values of 8,000 to 28,000 gpd/ft were measured in pumping wells in the Vintage

Formation (REWAI, May 1990; REWAI, July 1991). These values represent the bulk characteristics of the bedrock units.

Specific Yield (S_y) is the volume of water stored in an unconfined aquifer, such as underlies the Site. S_y values in the carbonate aquifer ranged from 0.01 to 0.03 as a result of pumping test calculations on wells CW-8 and CW-9 (REWAI, July 1991). This is a typical S_y value for a karstified aquifer in Cambro-Ordovician carbonates in south–central Pennsylvania. For CW-20, specific yields of 0.004 (at CW-9) and 0.01 (at MW-93D) were measured. It is also typical that S_y calculations in a karst aquifer will vary for individual observation wells, depending on the connectivity between the pumping well and the observation well.

3.3.2.2 Porosity, Hydraulic Conductivity and Aquifer Storage

Worthington (2000 and 2003) describes karst aquifers as three-porosity systems corresponding to matrix, fracture and conduit porosity. The following discussion of porosity, hydraulic conductivity and aquifer storage in the carbonate aquifers he studied is excerpted from Worthington (2003). His use of the term “channel” is equivalent to the term “conduit” as otherwise defined in this report.

Worthington et al (2000) examined matrix, fracture and channel flow in four carbonate aquifers. The four aquifers are:

a) a Silurian dolostone aquifer in a glaciated area, where there have been a large number of studies at a PCB spill site (Smithville, Ontario).

b) the Mississippian aquifer at the world's most extensive known cave (Mammoth Cave, Kentucky).

c) the most important aquifer in Britain (the Cretaceous Chalk).

d) a tropical Cenozoic limestone aquifer (Nohoch Nah Chich, Yucatan, Mexico). In recent years scuba divers have mapped more than 60 km of submerged channels in this cave.

Porosity and permeability results from these four aquifers are given in Tables 3.3-1 and 3.3-2, respectively. In all four cases more than 90% of the aquifer storage is in the matrix and more than 90% of the flow is in channels (Table 3.3-3), with fractures playing an intermediate role. Thus there are considerable similarities between the four aquifers.

Table 3.3-1: Matrix, Fracture and Channel Porosity in Four Carbonate Aquifers			
Area	Porosity (%)		
	Matrix	Fracture	Channel
Smithville, Ontario	6.6	0.02	0.003
Mammoth Cave, Kentucky	2.4	0.03	0.06
Chalk, England	30	0.01	0.02
Nohoch Nah Chich, Mexico	17	0.1	0.5

Table 3.3-2: Matrix, Fracture and Channel Permeability in Four Carbonate Aquifers			
Area	Area Hydraulic conductivity (m s-1) ((ft d-1))		
	Matrix	Fracture	Channel
Smithville, Ontario	1 x 10-10	1 x 10-5	3 x 10-4 (85)
Mammoth Cave, Kentucky	2 x 10-11	1 x 10-5	3 x 10-3 (850)
Chalk, England	1 x 10-8	4 x 10-6	6 x 10-5 (17)
Nohoch Nah Chich, Mexico	7 x 10-5	1 x 10-3	4 x 10-1 (2834)

Table 3.3-3: Principal Flow and Storage Components in Four Carbonate Aquifers		
Area	Fraction of storage in the matrix, %	Fraction of flow in channels, %
Smithville, Ontario	99.7	97
Mammoth Cave, Kentucky	96.4	99.7
Chalk, England	99.9	94
Nohoch Nah Chich, Mexico	96.6	99.7

These values reported by Worthington will provide a basis of comparison to values from the fYNOP Site.

3.3.2.2.1 Porosity and Aquifer Storage

Although groundwater flow within the bedrock units beneath the Site is almost exclusively within discontinuities that comprise the secondary porosity of these units, they do also exhibit primary porosity. Beginning with porosity of the sandstone sedimentary rock at about 30% and depending on the degree of infilling with quartz, the quartzitic sandstone primary porosity may range anywhere from very low, on the order of a few percent or even much less, to over 10 %.

In the early stages of burial and diagenesis, carbonates may exhibit high porosity (i.e., over 30%). During millions of years of burial, diagenetic processes reduce that porosity to much lower levels depending on the age of the carbonate unit. This factor appears to account for much of the variation in matrix porosities listed in Worthington's Table 3.3-1 above. Most studies of carbonate porosity are directed toward better understanding oil and gas reservoir rocks at great depth. However, recent studies have been completed at the University of Waterloo in Waterloo, Ontario regarding the primary (matrix) porosity of Silurian-age carbonate bedrock at a contamination site in the Michigan Basin of Ontario. The results of these studies were presented in two master's theses, Plett, 2006 and Kennel, 2008. Tables from these two theses are reproduced in Appendix E. Plett, 2006 reports a range of matrix porosity for dolostone from 0.8 to 15.3% with an average of 6.8%. Based on results from 246 samples, Kennel, 2008, reports a range in dolostone porosity of 1.2 to 20.9%, with an average of 9.8. These results are similar to those in Worthington's Table 3.3-1 for apparently older carbonate units in Ontario (6.6%) and Kentucky (2.4%). Based on these various values for matrix porosity, a value of 7% will be assumed for calculation of relative water in storage in each type of porosity.

Matrix porosity is an important value with regard to long term storage of water and chemicals of concern, as discussed in later sections. However, matrix porosity in the carbonate aquifer is not considered effective porosity for the purpose of groundwater flow through the site.

Values for unconsolidated, generally uncompacted soils, as presented in Freeze and Cherry, 1979, can give representative values for the residuum and sediments that comprise the fill within voids in the carbonate rock and the unconsolidated soil overburden. Depending on the sorting of the material, such values range from 25% for coarser-textured material such as sand or gravel, to 70% for uncompacted clay. Residuum from carbonate solutioning typically contains a high clay fraction, so much of this material can be expected to exhibit high intergranular porosity (i.e., associated with pores bounded by soil grains). For the residuum and sediments containing coarser sedimentary particles, each of those particles will also exhibit the same matrix porosity as that of their parent rock (i.e., a fragment of dolostone would exhibit the same matrix porosity as the competent dolostone from which it was eroded). For purposes of calculating overall porosity and relative volume of water in storage in each type of porosity, a value for all unconsolidated materials in solution cavities is assumed to be 25%, while the residuum porosity, which is generally more compacted, is assumed to be 20%.

In order to calculate the percentage of the carbonate rock that is comprised of conduits, geologists' logs for 87 wells penetrating carbonate were examined to determine the cumulative length of borehole that penetrated a bedrock void and then to determine what percentage of the voids were sediment-filled. The total length of borehole penetration of the carbonate aquifer is 5,702 feet. Of that footage, 888 feet were determined to have penetrated voids in the rock, indicating void/conduit porosity of 16%. This is an astounding number compared to the values reported by Worthington above as 0.003% to 0.5%. This is yet another indication of the high degree of karst development in the carbonate aquifer at this Site.

Of the 888 feet of borehole that penetrated voids, 560 feet, or 63%, of the void space was sediment-filled. Assuming 25% porosity for the sediment and 100% porosity for open voids, the average porosity of the void space is approximately 53%. Since the total void space constitutes 16% of the total volume of the aquifer, it contributes 53% x 0.16 = 8.5% to the total porosity of the aquifer.

Assuming the porosity of the rock matrix is 7.0% and it comprises 84% of the total aquifer volume, the bedrock matrix contributes approximately 6.0% to the total porosity of the aquifer. Adding this value to the porosity contributed by filled and unfilled voids yields a total of 14.5%. Based on the values for fracture porosity listed by Worthington in Table 3.3-1 above, it is expected to contribute less than 1% to the overall aquifer porosity. Accounting for this in the calculation does little more than justify rounding the total aquifer porosity to 15%. With respect to effective porosity of the aquifer, however, for the purpose of calculating the volume of water migrating through the aquifer, the matrix porosity would be excluded.

Based on these calculations, 33% of the groundwater in storage within the carbonate aquifer is contained within the primary porosity of the bedrock and 67% is contained in a combination of filled voids, open voids and fractures. This is substantially out of line with the values reported by Worthington in Table 3.3-3 above for the four carbonate aquifers he studied and once again indicates the exceptional degree of karst development that has occurred at this Site.

With respect to effective porosity of the aquifer, however, for the purpose of calculating the volume of water migrating through the aquifer, the matrix porosity would be excluded, yielding an effective porosity of 9%.

3.3.2.2.2 Hydraulic Conductivity

In the carbonate rock, on the scale of individual solution features, the hydraulic conductivity ranges from virtually impervious rock to solution channels that support open conduit flow. Therefore, while it would be possible to calculate the hydraulic conductivity of this aquifer by simply dividing the transmissivities by an assumed aquifer thickness of 250 feet, the calculated hydraulic conductivity values (i.e., 5-15 ft/day) would nonetheless be a bulk property of the aquifer and not a characteristic of any unit thickness of fractured and solutioned bedrock. If it is assumed that the transmissivity values derived from aquifer tests is attributable only to the portion of the aquifer comprised of voids (filled and unfilled) then the calculated hydraulic conductivities would be 31-94 ft/day. Extending this reasoning further, if the transmissivity were only attributable to the open voids in the aquifer, then the calculated hydraulic conductivities would be 83-250 ft/day.

By comparison to Table 3.3-2 of Worthington (2000) above, which lists channel (conduit) hydraulic conductivities ranging from 17 ft/day to 2800 ft/day, even the enhanced values calculated above fall within the lower end of that range. Notably, they also fall within the moderate to high range of hydraulic conductivities for aquifer materials that exhibit Darcian flow characteristics. Worthington does not explain how he measures or determines channel hydraulic conductivities.

3.3.2.3 Velocity of Groundwater Flow

Figure 3.3-1 shows the results of tracer tests performed at the fYNOP Site by Crawford and Associates, Inc. in 2000 (Crawford, 2000 in Langan, 2002). As shown on this figure, the groundwater flow velocities from these tests ranged from a low of 5 ft/day to a high of 67 ft/day. These velocities are relatively low compared to velocities commonly reported for conduit or channel velocities as determined by tracer tests, and actually fall within the range of groundwater velocities associated with Darcian flow. Given the very high conduit porosity, including substantial filled void porosity, it is likely that these lower velocities are due to substantially more well-integrated conduits available to transmit the groundwater flow as compared to typical karst aquifers where the total conduit porosity is orders of magnitude lower, as reported by Worthington (2000).

The on-Site velocities were measured while the groundwater extraction system was operating, thus the velocities are induced by pumping, and would certainly be faster than natural flows.

3.3.3 Boundaries of the Carbonate Aquifer

Figure 3.3-2 shows the topographic divide upgradient to the north and east of the Site. In general, groundwater from these areas migrates onto the Site and forms the upper boundary condition of the of the aquifer system. The quartzitic sandstone aquifer composed of the Antietam Formation drains into the carbonate aquifer composed of the Vintage Formation.

The lower limit to the carbonate aquifer and the karst weathering features beneath the Site is not known at this time. However, the following evidence is summarized towards starting to define the lower boundary of the epikarst. The normal fault structure which expresses itself north of the property boundary (see Figure 3.3-2) displaces the Vintage dolomite downwards on the south side of the southward dipping fault contact. The displacement positions the dolomite in fault contact with the Antietam-Harpers sandstone-phyllite in the northwest corner of the Site, and the Chickies quartzite in the northeast portion of the Site. The fault contact as it gently dips southward beneath the Site at a shallow angle would be the lowermost possible limit of epikarst development beneath the northwest portion of the Site. The dip of that fault was estimated at 15 degrees south, based on drilling at MW-98 along the Codorus Creek.

Beneath the north-central and south-central portions of the Site, the Antietam quartzitic sandstone underlies the Vintage dolomite, and would be the lowermost possible limit of karst development beneath these areas. No specific information regarding the depth of the quartzitic sandstone beneath the CPA or the WPL is known, however, as discussed in Section 3.3.4, a marker bed that may indicate a proximity to the bottom of the carbonate aquifer was detected at 90 to 100 feet beneath Building 3 in MW-73, and 240-270 feet beneath the North end of Building 4 (NBldg4) in MW-49D. The remainder of carbonate aquifer beneath the Site has no defined limiting geologic boundary to karst formation.

To the south, the carbonate aquifer is laterally extensive, and the southern boundary condition is tentatively defined by a groundwater flow path perpendicular to groundwater contours from the southeast corner of the property to the Codorus Creek.

Under natural (nonpumping) conditions groundwater flow through the Site would be westward and discharge to the Codorus Creek, which would be the western boundary condition for Site groundwater. A discussion regarding the potential for Site groundwater to migrate underneath Codorus Creek is provided later in this section.

3.3.4 Vertical Gradients

The vertical gradients at the Site are measured by taking water levels in paired or clustered wells that are open to different depths. A number of well pairs on-Site, often designated by a number followed by an S or D (for shallow and deep) provide an opportunity to measure the vertical gradient. Upward gradients occur commonly at or near the base of the hill near the contact between the quartzitic sandstone and the carbonate rocks, as seen in well pairs MW-67 S&D (near Building 30), and MW-86 S&D (near Building 14) (see Plates 3C and 3D). As groundwater moves westward into the carbonate aquifer, the vertical gradient reverses and is downward. The transition zone can be seen to the west of Building 14 in well pairs MW-86, MW-70, MW-103 and MW-102 during active groundwater extraction.

A large vertically downward gradient measured in June of 2009 along the southern property line at MW-40 S&D is most likely caused by infiltration from water stored in the unlined storm water collection basin at this location, as it was not repeated during December 2009. This basin was lined in December 2010 to minimize the frequent development of sink holes in that area. Downward vertical gradients also occur in well pairs in the WPL.

A vertically upward gradient was measured at the well pairs located next to Codorus Creek with respect to the water level in the creek. Those wells were installed as part of an investigation to understand the relationship of the creek to the groundwater, and will be discussed in detail in another subsection.

Shutdown/restart testing of extraction wells in the carbonate aquifer was conducted to determine the hydrodynamic impact of the groundwater extraction system on horizontal and vertical gradients in the groundwater flow system beneath the Central Plant Area (CPA), the WPL, and the area between the WPL and Codorus Creek. As described in Section 2.3, continuous water level recorders were installed in twenty-six wells and piezometers, and the Codorus Creek. Manual rounds of water levels were collected on these wells plus forty-five additional wells and one additional creek level station, as shown on Figure 2.3-1. From October 13 to October 27, 2008, groundwater level conditions were monitored with all groundwater extraction wells operating normally. Manual rounds of water levels are recorded in Table 2.3-2.

Figures 3.3-3A through F are hydrographs showing groundwater elevations in the wells monitored during the testing. Figure 3.3-3G is included for completeness, but was not analyzed because the data is not considered valid. Adjacent wells and well couplets and triplets are grouped together to permit assessment of vertical gradients within the carbonate bedrock aquifer. Levee wells between the creek and on-Site piezometers and the pumping wells were also added to each graph to evaluate horizontal gradients associated with capture in the critical east-west direction; the discussion of horizontal gradients based on these graphs is presented in subsection 3.4.

Pumping Conditions: Beginning with shallow well pairs, a downward gradient was observed from the residuum to the bedrock over the area of pumping influence, as noted in well pairs MW-93 S&D on Figure 3.3-3A, and MW-39S&D on Figure 3.3-3B. Within the carbonate bedrock aquifer, the vertical gradient is not consistently upward or downward during pumping conditions, and is presumed to be a reflection of the connectivity of the individual piezometers with the network of fractures and solution channels penetrated by the pumping wells. For example, on Figure 3.3-3A, which shows the hydrographs of the wells in the SW WPL where numerous stacked solution cavities occur, MW-37D is screened at depth of 131-141 ft. bgs, with adjacent wells MW-75S and CW-20 screened at 168-173 and 205-215 ft. bgs, respectively. In this case, the shallower well exhibits the lowest water level under pumping conditions, while CW-20, which is the deepest, exhibits a slightly higher groundwater elevation, and MW-75S has a water level above CW-20. A similar condition occurs between the well triplet in the Building 58 Area, where MW-113, the deepest well (screened from 131-151 ft. bgs) has the highest water level. MW-80, the shallowest well (screened from 20.5 to 40.5 ft. bgs), has the next highest water level, while MW-87, screened from 75 to 95 ft. bgs has a slightly lower water level during pumping operations. The pattern of vertical gradients at both of these locations is nonetheless generally consistent with extraction from collection wells installed to depths that are shallow or intermediate in depth compared to the monitoring intervals in the deepest piezometers in each cluster.

Non-Pumping Conditions: Vertical gradients in the recovered aquifer appear to be minimal, with less than 0.1 ft differential in most well pairs. This is illustrated on Figures 3.3-3A, B and D, where hydrograghs of groundwater elevations for well pairs coalesce during the time the pumping wells are shut down. In most cases a slight downward gradient was reflected, and less vertical differential was measured, compared to during pumping conditions.

3.3.5 Unstressed Water Table Configuration

During the shutdown/restart test described in section 2.4, pumping wells were deactivated for three weeks, starting on October 27, 2008, and the aquifer was allowed to recover to non-pumping conditions. Hydrographs of continuous water levels indicate the aquifer completely recovered within approximately 10 days (Figure 3.3-3A shows this trend most clearly) and water levels were beginning to decline in response to the regional groundwater recession (natural drop in groundwater levels that occurs between recharge [rainfall] events).

Figure 3.3-4 shows contours of the recovered non-pumping water table measured on November 10, 2008. This date was selected because a full round of water levels were recorded, all wells appear to have completely recovered from pumping, and the influence of precipitation that occurred just prior to the shutdown and again later in the monitoring period was avoided. The undisturbed (non-pumped) water table is shallow at about 13 to 20 ft. bgs. Under such conditions, the water table in the carbonate terrain lies several feet to more than 10 feet above the top of rock and therefore, occurs mostly within the overburden materials, although pinnacles of rock can rise above the water table.

In the northern portion of the monitored area, from the NPA (MW-30) to CW-17, there is a 5 foot elevation difference in the recovered water table, which is a gradient of 1.2%. However, the gradient from CW-17 to the Codorus Creek is only 0.4%.

From the Building 58 Area (east of the south end of Building 2) to the western property line, there is less than 2 feet of elevation difference, which is a gradient of approximately 0.1%. The flat gradient is an indication of the high transmissivity of the carbonate aquifer under the CPA, the WPL and the area west of the WPL. The area of steeper gradients in the north and particularly east of CW-17 may be attributed to lower aquifer transmissivity east of CW-17 caused by possible thinning of the carbonate aquifer to the north.

Under the WPL, the gradient generally slopes to the northwest. A single one-foot contour line meanders through the southern portion of the WPL in response to MW-93S, which has a somewhat higher water level in the overburden at that location. Also of interest is the lower water level in MW-7, which penetrates the top of weathered limestone bedrock. The 342 and 343 feet amsl groundwater potentiometric contours trend back to the southeast to honor the MW-7 water level. A similar condition was observed in the non-pumping water table in 1990 (see Figure 3.3-5). The trend parallels the orientation of the fracture traces mapped through the northern end of the WPL. The water level in CW-17, 370 feet to the northwest of MW-7, was measured to be within 3/100 of a foot of MW-7. Assuming the water level measurements are generally accurate to the nearest 1/10 ft, these wells have essentially the same groundwater elevations. CW-17 penetrated a shallow open cavern from 32 to 64 ft. bgs. It may be that the cavern in CW-17 is part of an extensive conduit system preferentially connected in a southeast to northwest direction through the northern WPL which is directing natural groundwater flow through this area and controlling the water level in MW-7.

3.3.6 Groundwater Flow Rate Through the Karst Aquifer

The estimate of groundwater flowing through the Site offers a basic check on the understanding of the Site hydrogeology. These calculations of estimated flow were used to design the groundwater pump and treat system for the WPL, and to develop a conceptual hydrogeologic model for the Site.

The volume of groundwater that flows through the aquifer was estimated by REWAI (July 1991) using the following two methods.

1. A graphical hydrograph baseflow separation technique was used to calculate the groundwater component of the Codorus Creek, using the total flow records at the

Pleasureville gaging station, and adjusting them for discharges from publicly-owned treatment works (POTWs) and Harley-Davidson's wastewater treatment plant. Groundwater baseflow was calculated at 556,000 gallons per day per square mile (gpd/mi^2) (0.86 cubic feet per second/square mile [cfs/mi^2]) for the basin. The percentage of carbonate and noncarbonate rocks in the basin was coincidentally equal to the percentage of carbonate and noncarbonate rocks in the recharge area of the site. Multiplying this unit area recharge value for the Codorus Creek times the area upgradient of the western property line of the Site yields an average annual recharge rate of approximately 275,000 gpd (0.425 cfs), or about 190 gallons per minute (gpm).

2. The empirical hydraulic flow formula developed for porous media by Darcy was used to calculate groundwater flow beneath the site using measurements obtained from water table mapping and aquifer tests. Using an average lateral gradient through the WPL (0.0097) and an average transmissivity from three pumping tests on-Site in the carbonate aquifer (21,000 gpd/ft), the rate of groundwater flow beneath the site was estimated to be 285,000 gpd, or about 198 gpm.

Aquifer transmissivities vary significantly within this carbonate aquifer, and the average of the three tests does not necessarily provide a trustworthy estimate of the average aquifer transmissivity beneath the WPL. In this case, however, the match to the average annual calculation using the baseflow separation method is very good, and provides a general check on the quantity of groundwater flowing through the site. In addition, site groundwater appears to react in an equivalent manner to a porous media on a site-wide scale, based on responses to pumping of the WPL groundwater extraction system, and migration of groundwater chemistry in the available observation and monitoring points.

A third general calculation of groundwater flow through the WPL was conducted as part of this supplemental RI analysis using updated literature and methods that use computer programs to perform stream baseflow separations, followed by a computerized model which used an iterative process to model recharge from various aquifers in the Susquehanna River Basin. The surface area upgradient of the Site was calculated and differentiated by geologic formation. Using recharge rates calculated by Gerhart and Lazorchick (undated) in their study of the aquifers of the Conestoga

Valley immediately east of the project area in Lancaster and Berks Counties, the estimate of groundwater flowing through the Site was 253,000 gpd, or about 175 gpm. The calculation and the contributing area are shown on Figure 3.3-2. This method had the added benefit of separating recharge that originated from the non-carbonate formations to the north and east (called allogenic recharge) and recharge that fell directly on the carbonate formation (called autogenic recharge).

3.3.7 Karst Loss and Karst Influence

Stream baseflow separation techniques, one of the methods which have been used on the Site to determine groundwater flow rates, rely upon a number of assumptions about stormwater flow and groundwater flow. Stream flow is composed of water that flows across the surface (overland flow) and water that discharges to the stream from the aquifer (groundwater runoff). Stream baseflow separation uses the rapid rate at which overland flow reaches streams to differentiate groundwater discharges to streams, which is delayed by the infiltration and generally slower underground pathways, from surface runoff which reaches streams far more quickly. However, the combination of conduit flow permeability and recharge enhanced by karst loss can result in water entering and passing through the aquifer very quickly. Therefore, where conduit flow and karst loss are significant properties of the aquifer, a portion of the water which enters and flows through the aquifer can erroneously be categorized as surface water runoff when using the baseflow separation technique.

From Virginia Department of Conservation and Recreation (VADCR) (1999), karst loss is the term given to the enhanced recharge of overland flow into the epikarstic conduits which underlie karst terrain. The enhanced recharge enters into the groundwater flow system through karst features such as swallets, sinkholes, exposed karst openings in bedrock, epikarstic openings in the bedrock surface beneath the overburden, and through stream and creek losses and leaking ponds. Although swallets, sinkholes and exposed openings in the bedrock are generally quickly repaired on the Site by the Harley-Davidson operations, and stormwater is managed through a network of surface channels and storm sewer pipes, the subsurface conditions in the aquifer make karst loss a potentially significant factor. Some additional perspective on this factor will be provided in the discussion in the next subsection of water level monitoring during the shutdown/restart test at the Site.

3.4 Carbonate Aquifer Extraction System Capture Evaluation

Comparing the amount of groundwater estimated to flow through the WPL to the amount of groundwater being pumped and treated by the groundwater extraction system provides a general check on the viability of the system to stop off-Site migration. As stated in Section 3.3.6 the average annual groundwater recharge/flow through the Site for the main plant and WPL is estimated to be between 253,000 and 285,000 gpd. The average annual groundwater extraction rate is 386,000 gpd. On average, therefore, groundwater extraction is 140% of the groundwater budget, which is sufficient to cover seasonal fluctuations in groundwater flow. The excess water over the majority of the year is drawn from north, south and west of the Site.

Even though the overall extraction rate for the groundwater remediation system was designed to substantially exceed the average annual recharge rate for the Site, there is nonetheless some potential uncertainty in the estimates of recharge rate due to hydrologic factors such as karst loss. For this reason, this subsection will address analysis of additional data necessary to confirm that the groundwater extraction system is capturing groundwater flow in the WPL area.

Verification that this design basis has led to effective capture of groundwater flowing beneath the Site has been completed based on analysis of groundwater elevation data under pumping and non-pumping conditions, including observations of water level recovery and drawdown that occurred during the shutdown and restart test of the extraction system performed in 2008 (see section 2.3). Groundwater elevation data have been analyzed based on graphical examination of horizontal gradients among various wells based on time series plots of water level monitoring data collected during this shutdown/restart test.

In addition to analyzing the results of this shutdown/restart test, patterns of groundwater piezometric levels have been examined by drawing equipotential contours in both plan view and cross section. This portion of the analysis examines such contours in plan view for recent pumping (October 20, 2008) and in two east-west cross sections, one each across the northern and southern portions of the Site.

3.4.1 Analysis of Equipotential Contours

Figure 3.4-1 is a map of the area of the Site that encompasses the CPA, the WPL, and the off-Site area between the western Site boundary and Codorus Creek. Groundwater table contours show interconnected cones of depression around pumping wells CW-8 in the TCA Tank Area and CW-9, CW-13, and CW-17 in the WPL. Pumping water levels ranged from elevation 325 ft. amsl in CW-15A to 333 ft. amsl in CW-17. The combination of pumping from the extraction wells and the discharge of Site storm water to a wetland area between the western property line and the Codorus Creek are believed to have created a groundwater flow divide between the creek and the Site. Groundwater on the east side of the divide migrates toward the Site, and groundwater on the west side of the divide migrates westward toward the Codorus Creek.

This same pattern of groundwater flow can be observed on Cross Sections A-A' (Figure 3.4-2) and B-B' (Figure 3.4-3), which run in an east-west direction through the south end of the WPL and the north end of the WPL, respectively. Piezometric isocontours are presented to depict an interpretation of groundwater flow conditions with depth beneath the Site. The cross sections show approximately 200 feet of depth beneath the Site, which is the limit of vertical information available on-Site. The 200' depth is penetrated by two wells along Cross Section A-A' (MW-32D, MW-75D), with three additional wells penetrating to 150 feet. Section B-B' depicts a similar number of deep wells (MW-49D and MW-74D). The piezometric data shown in these two cross sections is believed to adequately characterize the piezometric levels in the top 150 to 200 feet of the aquifer.

Cross Section A-A' runs from the Antietam Formation (quartzitic sandstone) on the east side of the section, into the Vintage Formation (limestone and dolomite). The section runs through the Building 58 Area, TCA Tank Area and the southwest corner of the WPL (SW-WPL) and from there through the levee to Codorus Creek. It also connects groundwater extraction wells CW-8 and CW-9. Piezometric contours are essentially vertical across the section, indicating generally horizontal migration through the aquifer. The exceptions are represented by the contours wrapped around the pumping wells, indicating flow toward the pumping well open interval.

Cross Section B-B' runs through the NETT, which is underlain by Antietam Formation, through the north end of Building 4 and the northern end of the WPL, then extending through the levee to

Codorus Creek. The section runs through the West Building 2 (WBldg2) Corridor, the NBldg4 Area, and the Burn Pile Area, in the northwest corner of the WPL. It also connects groundwater extraction wells CW-15A and CW-17.

Piezometric contours coalesce around pumping well CW-15A, as shown on the cross section, however the limited connectivity of CW-15A to the karst network of conduits results in the low yield (3.5 gpm on average) and limited drawdown measured in the surrounding portions of the aquifer. Pumping of CW-17 nominally at 60 to 70 gpm from the shallow open solution channel results in strong vertically upward gradients, and is the dominant feature causing vertically upward gradients during pumping operations in the north end of the WPL. Piezometric contours shown on Cross Section B-B' are not vertical, as they are in Cross Section A-A', and indicate a strong vertically upward movement in the aquifer under pumping conditions. This may be in response to pumping from the large shallow conduit penetrated by CW-17, which would tend to draw groundwater from this shallow zone. It also may be resulting from thinning of the carbonate bedrock aquifer under the north end of the WPL and NPA compared to the southern end of the WPL and CPA, as a result of the south dipping fault contact with the Chickies/Harpers Formation from the north, and the west dipping conformable contact with the Antietam Formation from the NETT area to the east.

The pattern of piezometric isocontours shown on both of these cross sections, including the presence of the groundwater divide depicted on them between the extraction wells and the creek, strongly support the conclusion from the plan view contour map that the operation of the extraction well system in the carbonate aquifer captures groundwater flow within that unit at least to the depth investigated to date.

3.4.2 Graphical Analysis of Time Series Water Level Data

During pumping conditions, as shown on Figures 3.3-3A through F before October 27, 2008 and after November 19, 2008, water level plots for the levee wells on each of these six graphs show piezometric levels that are consistently higher than the groundwater elevations in monitoring wells in the various on-Site well groupings also shown on these graphs. The only exception is during the short-term initial restart period when water levels were adjusting to the inception of extraction activities. This relationship among these wells persists even during and following rainfall events and the associated recharge to the carbonate aquifer. Therefore, this analysis of data from the shutdown/restart test supports the conclusion that the divide between the western property boundary and the creek is persistent.

3.4.3 Aquifer Drawdown

The influence that groundwater extraction exerts on groundwater levels in the carbonate aquifer has been further demonstrated by constructing a contour map of drawdown calculated from data collected as part of the shutdown/restart test. In this instance, "drawdown" has been calculated as the difference between the pumping water levels prior to shutdown and the recovered water levels after shutdown, but prior to any significant recharge event. Drawdown so defined has been contoured and displayed on Figure 3.4-4. Table 3.4-1 lists areas and selected wells that also summarize these responses.

From this table and the posted and contoured data on Figure 3.4-4, the following observations can be made:

- Every one of the seventy-one wells monitored during the shutdown test exhibited water level recovery on the order of one foot or more that is attributable to drawdown from pumping.

- At least two feet of drawdown occurred in monitoring wells deeper than 200 ft. bgs in all four areas for which data are listed in Table 3.4-1.

Table 3.4-1: Drawdown in Collection and Monitoring Wells by Area					
Area	**Location**	**Monitoring Depth (ft.)**		**Drawdown (ft.)**	
		MW Range	**Ind. Well**	**MW Range**	**Ind. Well**
Burn Pile Area	Areawide	3-250		2.67-4.76	
	CW-13		59.6-70		15.19
	CW-17		32-65		8.50
	MW-39S		3-30		4.47
	MW-39D		53-100		4.76
	MW-74S		175-201		3.34
	MW-74D		220-250		2.67
North Building 4	Areawide	12-220		2.57-8.49	
	CW-13		59.6-70		15.19
	CW-15A		18-68		18.81
	CW-17		32-65		8.50
	MW-7		13-35		8.49
	MW-51S		34-51		7.34
	MW-50D		157-170		4.75
	MW-49S		134-158		2.76
	MW-49D		201-220		2.57
Southwest WPL	Areawide	11-215		3.45-6.72	
	CW-9		47-50		13.04
	MW-37S		11-33		4.30
	MW-37D		125-141		6.64
	MW-75S		151-190		5.90
	MW-75D		200-217		6.69
	CW-20		205-215		6.61
TCA Tank Area (CPA)	Areawide	7-220		2.16-3.75	
	CW-8		99-128		8.21
	MW-28		8-55		3.66
	MW-32S		133-148		3.75
	MW-32D		196-220		3.40

- Drawdown in observation wells in the WPL area ranged from 3.5 to 8.5 feet (excluding MW-51D and -50S, for which data are considered to be invalid [see Figure 3.3-3G) because of the erratic behavior of the water level recordings.

- Drawdown in the BPA and the NBldg4 area attenuates with depth due, at least in part, to the thinning of the aquifer, and the comparatively shallow depth of the extraction wells in this area.

- Drawdown in monitoring wells in the SW-WPL area is not attenuated with depth, indicating better vertical connection between the shallow extraction well (CW-9) and monitoring wells as deep as 205-215 ft. bgs.

- There is generally lower drawdown (on the order of three to four feet) in the TCA Tank Area in spite of the higher extraction rate at CW-8 and drawdown in this area is not appreciably attenuated with depth, both suggesting higher transmissivity and vertical connectivity in this area.

- Outside of the areas listed in Table 3.4-1, more than one foot of drawdown was measured in monitoring wells as far east as the Building 58 Area and west to the levee wells (MW-99S&D and MW-100S,I&D) between the WPL and Codorus Creek.

3.4.4 Discussion of Groundwater Extraction System Effectiveness

Groundwater piezometric levels in observation wells during operation of the groundwater extraction system indicate sufficient influence to maintain capture in the portion of the carbonate aquifer that has been investigated. There is little drawdown differential with depth in the southern WPL, indicating an extensive connected aquifer. In the northern portion of the aquifer, there is a distinct upward gradient, indicating groundwater is drawn vertically upward to the extraction wells. The monitoring points respond in a predictable manner, indicating the wells are being consistently influenced by the pumping system. Although some karst aquifers can be penetrated by disconnected or poorly connected sets of conduits, or contain karst blocks of rock that are poorly connected to conduits, and result in considerable heterogeneity, observations to date suggest that the carbonate bedrock aquifer beneath the CPA and the WPL responds to pumping as a relatively homogeneous aquifer. The fact that the estimated groundwater flow through the aquifer is exceeded by the amount of groundwater extraction further suggests that the groundwater extraction system is effective at preventing off-Site migration of groundwater carrying COCs.

However, there are three concerns regarding the prevention of off-Site migration of groundwater. First, the depth of extraction wells is relatively shallow compared to the likely depth of karst development in the carbonate aquifer. In fact, the maximum depth of monitoring wells in five areas on-Site (Building 58 Area, TCA Tank Area, SW WPL, WBldg2 Corridor and NBldg4) is no greater than 220 ft. bgs while the likely depth of karst development could reasonably be 250 ft. bgs and the maximum depth to the bottom of the Vintage Formation might be on the order of 500 to 700 ft. bgs. Although the groundwater extraction system clearly imparts drawdown in these areas and most likely causes upward vertical gradients in these areas of the Site, without knowing the full depth to which groundwater flow in the karst aquifer occurs, there is no assurance that capture of all groundwater flow in the carbonate aquifer is complete.

A second concern is the loss of capture during storm events. As discussed in Section 3.3.7, a karst aquifer can experience very large and rapid influxes of storm water to the aquifer, directed to the epikarst through swallets, sinkholes, exposed karst openings in bedrock, and epikarstic openings in the bedrock surface beneath the overburden. This volume of water, described as karst loss previously in this report, is potentially not completely included in the calculation of groundwater flow through the Site. This situation could result in much larger volumes of water flowing through the aquifer for a period of hours or days following high recharge events (rainfall and snow melt) than can be extracted by the pumping system.

Evidence that the system can maintain capture through a moderate rainfall event can be observed on Figure 3.3-3A. The hydrographs for MW-37D, MW-75S and CW-20 show responses to a one-inch rainfall which occurred in late November 2008. Water level rise in these piezometers was just over one foot in the two deeper wells and just over two feet in the shallowest well, MW-37D. (Note: Apparently during this event there was also a brief shutdown of CW-9, which produced an abrupt spike and decline in water levels in these wells.) Most importantly, the graphs on Figure 3.3-3A shows that at no time did the water level in any of these wells in the SW-WPL area exceed the water level in the corresponding levee wells, MW-100S,I,&D.

While the storm event is recharging the aquifer, the storm sewer system is recharging the wetlands to the west of the WPL, between the WPL and the Codorus Creek. The degree of recharge from the wetland to the water table has not been determined. However, it is speculated that a mound develops on the water table under the wetlands as a result of recharge. This condition may aid in preventing off site migration of groundwater from the WPL, since the mound would tend to slow westward migration of the groundwater.

Another complication is the cessation of 100,000 gallons per day of non-contact cooling water from the Harley-Davidson plant. Since the beginning of the operation of the groundwater extraction system, water has been discharged to the wetlands on a continuous basis. All observations and pumping records of the groundwater extraction system are under those conditions. With the cessation of the process water discharge in early July 2011, the configuration of the water table and the pattern of drawdown and capture may change.

The third and final concern is that there are significant concentrations of Site COCs present in the wells monitoring groundwater along the east side of Codorus Creek. This issue will be discussed in Section 5.

3.5 Role of Codorus Creek as a Discharge Boundary

Under natural conditions (without the operation of the groundwater pump and treat system), groundwater flowing through the Site flows westward toward and discharges to the Codorus Creek. Codorus Creek naturally receives groundwater along its course, which makes up the flow in the creek after surface water runoff has ceased. Normally, groundwater from both sides of a stream converges on and discharges to the stream, with the opposing gradients preventing groundwater from crossing the stream.

As documented above, the operation of the groundwater extraction system on the Site has likely intercepted virtually all groundwater flowing within the carbonate aquifer above a depth of approximately 200 feet bgs. Data also indicate that the operation of this system has not completely reversed the groundwater gradient between the creek and the Site in spite of the fact that the centerline of the cone of depression is less than 1000 feet from the creek. However, this is believed at least in part to be due to the discharge of storm water and non-contact cooling water to the wetland between the creek and the Site, thus reinforcing a groundwater divide beneath it. Nonetheless, Codorus Creek still represents a discharge zone for groundwater flow in the carbonate aquifer from the area west of the groundwater divide.

For the Codorus Creek to no longer represent a discharge boundary for shallow groundwater flow on its east side in the portion of the aquifer affected by on-Site extraction, a pumping center west of the creek, such as the Roosevelt quarry, would have to exert sufficient influence on the groundwater levels in the aquifer on the west side of the creek that the natural gradient would be reversed and groundwater could then be drawn beneath the creek from east to west. For this to occur, exfiltration from the creek would have to occur at such a low rate that it would not create a sufficient mounding condition to prevent east to west flow beneath the stream, or the conduit within which groundwater flow beneath the stream was occurring would have to be isolated from the interconnection of the flow system and the creek, as it is currently understood.

3.5.1 Thermal Survey of Codorus Creek

A thermal surface water study was conducted on the Codorus Creek in August 2007 to delineate groundwater discharge points associated with subsurface conduits in the karst limestone bedrock (carbonate aquifer) that underlies the area of the creek and the flat lowland (western) portion of the Site. The survey covered a 2,500-foot length of the creek immediately west of the Site, as shown on Figure 2.0-1. Due to the karst nature of the carbonate aquifer beneath the project area, groundwater may discharge to the creek downgradient of the Site from discrete conduits. Temperature differentials identified near the bottom of the creek may indicate the location of the discharge of groundwater from a karst conduit. The methodology and details of the survey are included in Appendix B.

The thermal survey data has been subdivided into three sections designated Section A through Section C, based on the characteristics of the data. A discussion of the distribution of temperature anomalies for each of these segments shown on Figure 3.5-1 is provided below:

- Section A - Most of the rock outcrops that appear in the stream (identified by gray squares on Figure 3.5-1) occur in the southern 700 feet of the surveyed length. Low temperature anomalies were fairly evenly distributed throughout this area. A mapped fracture trace also cuts at an angle through this area. A blue triangle on Figure 3.5-1 located near the northern limit of the area of rock outcrops denotes the location of a 6” diameter hole near the eastern bank of the stream, similar to a muskrat hole. A technician observed the submerged hole and placed his hand inside. He could physically detect a significantly cooler temperature to the water in the hole. The location was established by GPS, but the temperature was not measured with an instrument.

- Section B - Low temperature anomalies are fairly evenly distributed along the western side of the creek, while on the east side they are clustered in two areas. A possible explanation could be that discharges of groundwater from the east side of the creek are fed by the limited recharge in the area west of the groundwater divide due to the effects of the groundwater extraction system operating in the WPL, while discharges from the west reflect a larger recharge area. Low temperature anomalies on the east side of the creek occur in two clusters, which may indicate groundwater discharges from preferential flow paths.

- Section C - The northern portion of the surveyed creek is characterized by two segments of the creek where no low temperature anomalies occur for hundreds of feet. Just to the south of the intersection of a fracture trace with the creek, which runs through the center of Section C, there is a cluster of anomalies on both sides of the creek. The cluster could indicate a high permeability zone within the bedrock, from which groundwater discharges to the creek. However, small streams enter the Codorus Creek on both sides of the creek, and could be providing cooler water. The slight bend in the stream to the west (marked on Figure 3.5-1) is the location where the fault contact between the Harpers Phyllite and the Vintage Limestone is mapped. The position of the fault and the change in rock type is the likely cause for the location of these small streams, pushing carbonate groundwater to the surface, as its northward migration is resisted by the less permeable phyllite.

3.5.2 Review of Water Level Records

This review of water level records for the Site has been performed to determine if there is any evidence in the existing data for a stress in the system (other than the on-Site pumping and the stream) that is affecting water levels on the west side of the creek. The ten piezometers installed in karst conduits along the east side of Codorus Creek provide useful information for this evaluation. The wells were placed in karst conduits because they would represent likely pathways of preferential groundwater flow from the Site to the creek, and would be areas most likely to be influenced by a pumping center on the west side of the creek, or be pathways that could potentially be isolated from the creek.

Hydrographs of stream and groundwater levels at depth in the aquifer in the piezometers installed beneath the creek on the levee are shown in Figures 3.5-2 and 3.5-3. The period of record monitored is from early October 2008 through the middle of May 2009. The October 2008 through May 2009 period provides a record of the stream and groundwater levels during periods of minimal precipitation and recharge to the groundwater, and during periods of high recharge and large runoff events, as well as under pumping and non-pumping conditions.

Figure 3.5-2 includes hydrographs of nested piezometers MW-98S,I&D, which are the northern-most wells along the levee. Also included are piezometers MW-99S&D, which are located 300 feet to the south of the MW-98 triplet. The hydrograph of Codorus Creek (Codorus 2), measured at a point between these well sets, is also presented. Water levels in the wells for the majority of the monitoring period are shown to be at a higher elevation than the level in the creek. This represents an upward gradient from the groundwater to the creek, and suggests discharge of groundwater to the creek. This discharge condition held true under pumping and non-pumping conditions, and during the majority of the variable seasonal conditions monitored from October 2008 through May 2009. The exception to this condition only occurs during large rainfall events, such as the 2.3-inch rainfall event that occurred on December 10 and 11, 2008. During this and other sizeable precipitation events in October 2008 and March 2009, the stream level exceeded the rising groundwater levels for a brief period of time, on the order of a day or two. In these cases the stream stage is higher than the groundwater, and the stream has the potential to recharge the aquifer.

It is noteworthy that water levels in the wells are highly responsive to rainfall events, as would be expected in a karst aquifer. The responses are an indication of “karst loss” discussed earlier in Section 3.3, potentially associated with the discharge of storm water to the wetland adjacent to these wells. Another observation is that the highest water level in this area (the top line on the graph, representing the water level elevation in MW-98D) represents the water level in the Harpers Phyllite, which underlies the carbonate rocks of the Vintage formation. This indicates that groundwater from the deeper and less permeable phyllite discharges upward to the more permeable karstified limestone aquifer.

Similar conditions are true in the northern sets of piezometers shown on Figure 3.5-3. In this case, however the continuous Codorus Creek level (Codorus 2) monitors the water level 1,000 and 1,700 feet down stream, so the differential between the piezometric levels in the wells and the creek hydrograph are exaggerated. However, the manual measurements taken at Codorus 1 were stream water levels of Codorus Creek measured at the Route 30 bridge, which is 300 feet upstream of MW-101, and 1,000 feet upstream of MW-100, clearly showing a persistent upward gradient during the majority of the monitoring period, again suggesting groundwater discharging to the creek. Most notable in the hydrographs of MW-100S,I&D is that when pumping is halted, the upward gradient (the differential between the groundwater level and the creek level) increases. The point to be made here is that there is no evidence in the hydrographs for these wells and the creek to suggest that the water levels along the west side of the creek are responding to any stresses in the aquifer other than the creek and the on-Site extraction system. Obviously, the karst aquifer is believed to extend to a much greater depth than the deepest levee wells, so it remains to be seen if this relationship will hold at those depths.

3.5.3 Topographic and Stratigraphic Considerations

The Codorus Creek flows northward from the Site, crossing from an area underlain by carbonate bedrock into an area underlain by bedrock consisting of phyllite and quartzite, located north of the Site and north of well triplet MW-98. Unlike the carbonate bedrock beneath the area of Codorus Creek, west of the Site, the bedrock to the north is not solution prone. As a result, the hills to the north are supported by the phyllite and quartzite, and the creek has carved a narrow canyon through the non-carbonate clastic rocks on its way to the Susquehanna River (see Plate 3A). As shown on Cross Section C-C’ (Figure 3.5-4), the carbonate rocks to the south ramp up over the phyllite at a 15 degree angle (Cross section C-C’ shows a vertical exaggeration of 2.5). The permeability of the phyllite is lower than the carbonate, and the groundwater gradient is from the phyllite into the carbonate, based on the water level in MW-98D, described in the previous section. In addition, the zone of carbonate rocks in proximity with the phyllite may tend to be more intensely karstified due to the acidic water discharging from the phyllite, causing a high permeability zone along this change in rock type. This is suggested by the stacked solution channels in MW-98. Thus northward migration of groundwater would be discouraged by the low permeability phyllite and quartzite, and groundwater would tend to follow higher permeability zones in the solutioned carbonate bedrock to the surface, discharging to the Codorus Creek. The position of the small tributary streams to Codorus Creek which enter from both the east and west sides of the Creek a few hundred feet upstream of the phyllite contact indicate groundwater from the carbonate aquifer is being forced to the surface upgradient of the fault contact with the less transmissive Harpers Phyllite.

The carbonate formation continues under the creek to the west. Groundwater migration westward beneath the creek could be induced by a large pumping center (a large water supply well or dewatering operation) or by lower head in an adjacent carbonate stream basin. The Roosevelt Quarry located approximately 12,000 feet (about 2 ¼ miles) to the southeast, extracts large volumes of groundwater for dewatering purposes. An attempt to locate pumping records of the quarry from the Susquehanna River Basin Commission (SRBC) was not successful. Mining maps of the Roosevelt Quarry were obtained from the Department of Environmental Protection District Mining Operations office in Pottsville, PA, which shows that the quarry floor is 225 ft. amsl, approximately 110 feet below the elevation of Codorus Creek in the area of the Site. Although it is unlikely that the Roosevelt Quarry pumps sufficient water to induce flow from that distance, since quantities are unknown, a westward flow of groundwater under the creek due to off-Site groundwater extraction is raised as a possibility.

An examination of published bedrock geologic mapping for the region indicates the presence of the Kinzers Formation a few hundred feet to the west of the Codorus Creek. The Kinzers Formation, which stratigraphically overlies the Vintage, is primarily a limestone formation with a basal shale unit (Kinzers Shale) that forms the low hills located west of Codorus Creek near Route 30 and Interstate 83. The Kinzers Shale unit was not differentiated on the geologic mapping layers provided by the Pennsylvania Geologic Survey. Stose mapped the shale unit of the Kinzers in his 1944 publication, and his original mapping was added to Plate 3A. The shale is potentially significant to the westward migration of groundwater from the Site because it is a non-carbonate unit, and may serve as a barrier to groundwater flow.

A geologic cross section was constructed between the Roosevelt Quarry to the west and the Site. It is presented as Figure 3.5-5, and is shown at no vertical exaggeration, two times vertical exaggeration and 20 times vertical exaggeration. Figure 3.5-6 shows the location of the cross section in map view on the geologic map of the region. The Kinzers Shale unit is shown to support a topographic rise to the west of the Codorus Creek. In the position as shown from the geologic mapping, it would tend to prevent the influence of dewatering in the Roosevelt Quarry from reaching the Codorus Creek at the fYNOP Site.

On the basis of the analysis and review described above, flow to the north and west under Codorus Creek appears to be unlikely. However, additional verification of this conceptual model may be necessary through determination of the extent of pumping from the Roosevelt Quarry, field verification of the mapping and effectiveness of the Kinzers Shale to serve as a barrier to northerly and westerly groundwater flow and /or drilling of deeper wells near the creek, followed by tracer testing.

4 NATURE AND EXTENT OF GROUNDWATER CONTAMINATION

Figure 4.0-1 is an annotated map of the fYNOP property showing the groundwater AOCs. The areas of the Site are labeled with general descriptions of the activities that occurred that resulted in impacts to the groundwater. More detailed description of the activity and surface/soil related investigations are described in detail in the Soils RI (SAIC, December 2009b). Individual numbered SWMUs are not referenced in this report, as they are in the Supplemental RI Soils Report (SAIC, December 2009). Rather, this report deals with AOCs, which may encompass numerous SWMUs.

Activities have been widespread throughout the Site, and have resulted in over twenty suspected and confirmed source areas for the groundwater constituents of concern. Overall, these activities and associated suspected and confirmed source areas have resulted in seven general areas of the Site where COCs have been identified in groundwater. A summary of these seven areas is included below:

- **Northeastern Property Boundary Area (NPBA)** – Vapor degreaser wastes were distributed along the NPBA as a form of dust control on the perimeter road and weed control along the perimeter fence, according to interviews of employees of the facility familiar with that practice. Vapor degreaser wastes were also reportedly poured into groundhog burrows as a rodent control measure.

- **Eastern Area** – In addition to dust control and rodent control along the Eastern Perimeter Road other locations in the Eastern Area of the Site that reportedly contributed to the COCs in groundwater include a former cyanide spill area, and a former landfill area.

- **Southeastern Property Boundary Area (SPBA)** – The COC presence in groundwater in this portion of the Site is due to similar dust control and rodent control activities as were performed in the NPBA and the Eastern Area.

- **North End of the Test Track (NETT)** – Liquid wastes were stored in drums in the area north and west of Building 14 called the NETT. Leaks and spills from the drums were common, according to employees who maintained and eventually removed the drums in the 1970s. Also, bomb line grease, cyanide waste and liquid waste were reportedly disposed in open pits.

- **North Plant Area (NPA)** – Locations that likely contributed COCs in this portion of the Site include: the Old Waste Containment Area that was used to store liquid wastes; the IWTP that was used to treat wastewater; a former metal chip bin area that resulted in releases of cutting oils, according to interviews of employees of the facility familiar with that practice; and a gasoline underground storage tank (UST) area where gasoline was released from subsurface piping. The NPA is characterized by a small plume of TCE and PCE that occurs northwest of Building 42 (MW-31D); a small plume of TCE and PCE that occurs under the IWTP (Building 41); and elevated concentrations of unleaded gasoline components (i.e., benzene, toluene, ethylbenzene, MTBE and xylenes) that are present in groundwater under the UST and fueling dispenser between former Buildings 42 and 45.

- **CPA** – Locations that likely contributed COCs in this portion of the Site include: the former Building 2 vapor degreaser (near MW-55) and the TCA tank area (near CW-8) in the southern half of Building 2; cutting oil tank, the former wastewater sumps located in the corridor east of Building 2; the former chrome/zinc plater area and the area of Building 58 near the southeast corner of Building 2; the corridor west of Building 2; and the North Building 4 plating/sludge and vapor degreaser area. A highly concentrated plume of chlorinated solvents occurs in the groundwater between Buildings 2 and 4 north of Building 91. This plume commingles with a plume with similar constituents caused by activities involving the former northern vapor degreaser in the northwestern corner of Building 4. A plume of PCE trends northwestward from the southwestern corner of Building 4, also the former location of a vapor degreaser. Also commingled with this plume is chromium, which is a result of spills and leaks from a plating operation in Building 4, just south of the former northern vapor degreaser.

- **WPA** – This portion of the Site includes the WPL and Burn Pile Area (BPA). The western boundary and the western edge of the WPL were landfilled and used as a disposal area for liquid and solid waste. The highest concentrations of chlorinated solvents (42 parts per million) in the groundwater on Site occur in the southwest corner of the WPL. Prior to the operation of the interim groundwater extraction system in the WPL, TCE, PCE and TCA reached wells that are located along the levee on the east side of Codorus Creek, a distance of approximately 500 feet from the property line. The BPA is the designation for the northwestern corner of the Site, where disposal of solid and liquid is suspected. High concentrations of CVOCs were found in the soil west of new Eden Road proximate to the BPA in the area of well location MW-96S&D (Area B – CVOC disposal area).

This section will discuss the distribution of COCs in groundwater on a Site-wide basis, and then break the Site down into the seven listed geographical and common-use areas to describe in more detail the historical water quality trends of specific areas of interest.

4.1 Site-Wide Distribution of Chemicals of Concern

As explained in Section 2, one complete round of groundwater sampling that consisted of collection of samples from all accessible wells (156 wells) was performed in April/May of 2008, after the installation of the wells constructed as part of the supplemental groundwater remedial investigation. A second round of groundwater sampling (125 wells) was performed in September/October 2008. The second round was carefully reduced, eliminating wells with a long consistent record, and reducing parameters where there is a good understanding of the COCs in that area. Since the supplemental RI sampling, there have been two rounds of Key Well sampling and analysis. The Key Well sampling rounds included the new wells installed during the supplemental RI, to lengthen the record of groundwater quality data for those wells. Key well sampling occurred in June/July 2009 and June/July 2010.

The maps and text in this report consider data collected through the 2009 Key Well sampling round. For tables and graphs, all historical data was included through the 2010 Key Well round.

4.1.1 Chlorinated Volatile Organic Compounds

Figure 4.1-1 shows a graduated symbol posting of total Priority Pollutant volatile organic compounds (TVOCs) to show a distribution of the total VOC concentrations detected in groundwater samples collected in June/July 2009. TVOCs are primarily made up of TCE, PCE, TCA and their degradation products, cis12DCE and vinyl chloride (VC). All graduated symbol maps use chemistry data from the first round sampling of the Supplemental RI, to take advantage of the most complete round of wells sampled. TVOCs are concentrated in the WPL area and CPA, with concentrations along the NPBA and SPBA. TCE, PCE and TCA were used as solvents in vapor degreaser operations in at least three locations across the Site. The vapor degreasers were used to prepare metal parts for painting and plating.

4.1.1.1 TCE, PCE and TCA Source Areas

Chemical ratios and concentrations of prominent CVOCs are illustrated using graduated pie charts, shown on Figures 4.1-2 and 4.1-3. These charts provide a synopsized view of the distribution, relative concentrations and ratios of the chlorinated compounds. Three factors impact the relative concentrations of CVOCs in groundwater at a given location:

1. The original proportion of TCE, PCE and TCA solvent in the waste material released or co-disposed as a dense non-aqueous phase liquid or DNAPL.
2. Degradation by biotic and abiotic dechlorination of dissolved TCE, PCE and TCA concentrations, which changes PCE to TCE, TCE to cis12DCE, and cis12DCE to VC, and TCA to 11DCE or 11DCA, and 11DCA to chloromethane.
3. Migration of dissolved concentrations and commingling of plumes from source areas.

The primary concern of this subsection of the report is the first factor, but an understanding and consideration of the second and third factors are necessary to sort out separate source areas. Section 5, the section on fate and transport of COCs, provides more detailed discussion regarding degradation and migration, but some basic principles are described in this section.

Figure 4.1-2 shows the three parent compounds and the degradation products of the parents. Degradation can only occur in the dissolved state (degradation does not occur in a DNAPL accumulation zone or pool). CVOCs in solution migrating with groundwater must move with the hydraulic gradient, however, in a karst aquifer that pathway may be tortuous, guided by solution-enhanced discontinuities in the rock. Degradation is not reversible. Therefore, for example, if PCE increases in a down-gradient direction, it is likely a result of a different source.

Figure 4.1-3 was constructed to assist with consideration of the original proportion of TCE, PCE and TCA. The pie charts on this figure show the relative concentrations of just the three parent compounds. Concentrations of degradation compounds have been converted or “normalized” to their molar equivalent mass and added to the parent. Although TCE is a degradation product of PCE, it was also the primary chlorinated solvent used at the Site, so it was kept separate from PCE.

Known and suspected source areas of TCE, PCE and TCA solvents have been identified within portions of the seven general areas of the Site where COCs have been identified in groundwater. Known source areas are the locations of historical activities, aerial photo evidence, or concentrations in soil that indicate a source area. A suspected source area was located in response to an observation of high concentrations in the groundwater requiring a nearby source, but where no source is known. As described above, chemical ratios of parent CVOC compounds and their degradation products were used to differentiate specific known and suspected source areas to the extent possible.

Known and suspected source areas of TCE include:

- Along the perimeter road in the NPBA , including a suspected area south of the perimeter road;
- In the southeastern corner of the Site, up-gradient of monitoring well MW-64S&D;
- In the NETT, under the former drum storage area and the former bomb line grease disposal pit;
- Near Building 58;
- In the East Building 2 (EBldg2) Corridor, west of Building 46;
- In the WBldg2 Corridor;
- Under the IWTP;

- In the NBldg4 Area;
- In the southwest corner of the WPL; and
- In the northwest corner of the WPL and BPA.

Known and suspected sources of PCE include:

- Along the perimeter road in the NPBA, but much less extensively distributed than TCE;
- In the southeastern corner of the Site, up-gradient of monitoring well MW-64S&D;
- Along the southern property boundary, east of monitoring well MW-43S&D;
- In the WBldg2 Corridor;
- Under the IWTP;
- In the NBldg4 Area;
- In the southwest corner of the WPL; and
- In the northwest corner of the WPL and BPA.

Known and suspected sources of TCA include:

- West of Building 2 in the TCA Tank Area; and
- In the NBldg4 Area.

4.1.1.2 Site-Wide Distribution of TCE, PCE and TCA Dissolved in Groundwater

Figures 4.1-4 through 4.1-7 show contour maps of TCE, PCE, TCA and cis12DCE concentrations. The groundwater chemistry data were generally contoured using the concentrations of four sampling events (2007 Key Well, 2008 Supplemental Round 1, 2008 Supplemental Round 2, and 2009 Key Well). In rare cases, outliers, either due to differentials with depth or pumping/non-pumping conditions, were not honored during contouring. In addition, chemistry data from abandoned wells was considered in the construction of concentration contours where replacement wells had not been constructed. Concentration trends in the abandoned wells and in adjacent active wells were used to predict 2008-2009 concentrations in abandoned wells. Concentrations contours represent the highest value at any depth in the aquifer. Plates 4A, 4B, 4C and 4D show a large scale version of the chemical concentration maps, including the four sets of data and screened interval of the aquifer, considered during the construction of the contours. On the plates, the value in the chemical data box used to construct the contour is highlighted. For comparison, the figures and plates also depict the approximate locations of the known and suspected source areas for TCE, PCE and TCA listed in Section 4.1.1.1.

Showing the general concentration distribution of CVOCs in a karst aquifer, like the aquifer at this site under the CPA, NPA and WPL is often discouraged due to the potential for discrete flow paths in solution enhanced conduits. It is acknowledged that lateral and vertical differences in chemical concentrations can be expected in fractured and karst aquifers, and that construction of concentration contours are a generalization. However, lateral and vertical differences in CVOC chemistry are not prevalent in the Site data, except where DNAPL conditions are suspected and are a result of the elevation of the source locations rather than conduit directed groundwater flow. Contour lines represent concentrations expected in the groundwater within the interconnected fractures and solution channels in the saturated zone.

TCE (Figure 4.1-4) exhibits the widest distribution of the COCs across the Site, with concentrations of greater than 1,000 µg/L in the WBldg2 Corridor, the NBldg4 Vapor Degreaser Area, the southwest corner of the WPL, the northwest corner of the WPL (Area B), the area of Building 58 within the Central Plant Area, the NPBA and the southeastern corner of the Site. Lower concentrations occur down-gradient (in the direction of groundwater migration) of these high concentration areas in the northeast corner of the site, the NETT Area and a few smaller localized spots.

The PCE concentration contour areas shown on Figure 4.1-5 and Plate 4B, exhibit a somewhat smaller footprint than the TCE areas, although concentrations are similar or higher than TCE near apparent source areas. This is likely due to the more limited distribution of PCE (it was used for a shorter period of time on Site as a vapor degreaser solvent than TCE) and to the lower solubility of

PCE (240 mg/l) compared to TCE (1,400 mg/l). Concentrations of PCE greater than 1,000 µg/L have been detected in groundwater samples collected from beneath the WBldg2 Corridor, the NBldg4 Vapor Degreaser Area and the southwest corner of the WPL. Lower concentrations of PCE are present in groundwater down-gradient of these high concentration areas, west of the south end of Building 4, the southeastern corner of the Site and a few smaller localized spots.

TCA was the last of the chlorinated vapor degreaser solutions to be used at the plant. The distribution of concentrations greater than 1,000 µg/l of TCA is limited to the NBldg4 area and the southwest corner of the WPL (see Figure 4.1-6 and Plate 4C). The solubility of TCA is 1,250 mg/l, similar to TCE. TCA in detectible concentrations is notably absent from the NPBA, the SPBA, and does not occur in small localized spots across the Site. It is suspected that changes in waste disposal practices before the advent of TCA usage on-Site resulted in the minimized distribution. It is notable that the location of one of the highest historical concentrations of TCA near the Building 2 TCA Tank Area (TCA Tank) (100,000 µg/L [MW-32D in 1990]) now has a limited presence in groundwater (17J µg/l in 2008).

Concentrations of cis12DCE are contoured on Figure 4.1-7 and Plate 4D. Cis12DCE is a degradation product and an indication of biological anaerobic dechlorination of PCE and TCE. Concentrations greater than 1,000 µg/l appear in the WBldg2 Corridor, the NBldg4 Vapor Degreaser Area and the southwest corner of the WPL. One well (MW-117) down-gradient of the IWTP also contains high concentrations of cis12DCE. Lower concentrations are present in groundwater down-gradient of these high concentration areas, as well as in the northwest corner of the WPL (Area B), the area of Building 58 in the CPA, the NPBA and a few smaller localized spots. The distribution of this compound is more variable than TCE and PCE, with adjacent wells and paired wells (wells sampling different depths at the same location) showing very different cis12DCE concentrations. Deeper wells typically have higher concentrations than adjacent shallow wells. But there are exceptions, particularly when there are high parent concentrations near the surface (such as Area B). Discussion will continue regarding this compound in Section 5 under the discussion of Transformation by Reductive Dechlorination.

Site-related CVOCs have been identified off-Site in the following areas:

- TCE was detected in groundwater samples collected from former residential wells on the north side of Paradise Road north of the NPBA. Concentrations have been reduced by the groundwater extraction system in that area.

- TCE and PCE have been detected in groundwater samples collected from monitoring wells south of the southeastern corner of the Site.

- PCE, TCE and their degradation products have been detected in groundwater samples collected from monitoring wells along the east side of Codorus Creek, west of the WPL.

4.1.2 Other Chemicals of Concern

Although CVOCs pose the majority of concern regarding COCs in groundwater on the fYNOP Site, there are a few other chemicals that exceed PADEP MSCs for used residential aquifers. Because of the scattered nature of the non-CVOC compounds, the concentrations and distribution were shown with graduated symbols rather than isoconcentration contours:

- Chromium, used for plating of metals exceeds the MSC of 100 µg/l west of the former plating operations in the northwestern corner of Building 4 (wells MW-51S and MW-7) and along the southeast side of Building 2 (MW-57). Figures 4.1-8 and 4.1-9 display the concentrations of dissolved hexavalent chromium (Cr+6) and dissolved total chromium (Cr +3 plus Cr+6) across the Site. Wells with exceedances are relatively shallow, with deeper wells not indicating exceedances. Both locations are adjacent to known historical plating operations. Soils have been remediated for plating metals in both of these areas.

- Cyanide was used on-Site as a component of electroplating solutions for nickel and chrome plating. Cyanide waste was found during an exploratory excavation in the NETT. Metal canisters of cyanide waste were recovered after disposal in the MW-2 Area (within the Eastern Area). PADEP’s Medium Specific Concentration (MSC) for cyanide in used residential aquifers is 200 µg/l. All 156 wells were analyzed for free and total cyanide during Round 1 of the Supplemental RI sampling. Results exceeding 10% of the MSC (> 20 µg/l) during Round 1 (April/May 2008) are posted on Figure 4.1-10. Groundwater sampling locations where cyanide exceeded the applicable MSC are MW-2, near the aforementioned disposal and recovery; MW-65S (northeast of the Eastern Landfill in the Eastern Area); and MW-51S, immediately down-gradient (west) of the zinc plater in Building 4.

- 1,4-Dioxane is a stabilizer added to TCA product. Although 601/8260 laboratory methodologies report it as a Priority Pollutant VOC, the reporting limit is higher than the regulatory guidance. Therefore 19 wells were analyzed for 1, 4-Dioxane using Method 8270 Selective Ion Monitoring (SIM) during Round 1 supplemental RI sampling (May 2008). The results are included in Table 2.4-7, along with additional analyses since the Round 1 sampling. The wells sampled were near historical locations where significant concentrations of TCA were detected.

  1,4-Dioxane has a PADEP MSC for residential used aquifers of 5.6 µg/l. This guideline is exceeded at three locations on the Site, as illustrated on Figure 4.1-11:

  1. NBldg4 – Groundwater beneath and down-gradient of the vapor degreaser in the northwest corner of Building 4 contain the highest concentration detected on Site (1,300 µg/l in MW-49S in May 2008; 300 µg/l in July 2009). Samples from six wells in this vicinity exceeded the MSC.

  2. TCA Tank – The location of historically high concentrations of TCA were reduced significantly by the operation of groundwater extraction well CW-8. Residual concentrations of 1,4-Dioxane exceeding the MSC were detected in 5 wells in this location.

  3. Building 58 Area – Groundwater from two wells in this location (MW-80 and MW-87) had concentrations that exceeded the MSC. A third well (MW-113) was sampled in July 2010 and also exceeded the MSC.

- There was a historical leak of gasoline from piping related to UST T-4 located west of Building 45 in the NPA. This resulted in concentrations of benzene, toluene, ethylbenzene, xylenes and MTBE in MW-77 (see Figure 4.1-12). Benzene and MTBE exceed PADEP MSCs for residential used aquifers in this well. No other groundwater samples on-Site detected gasoline components at concentrations of concern. Off-site wells MW-109S and MW-109D have concentrations of gasoline components, including concentrations that exceed the MSCs for benzene and MTBE as a result of a known gasoline leak from the Rutters Store at the intersection of North Sherman Street and Arsenal Road.

- During the first round of the Supplemental RI sampling in April and May 2008, metals were run using method SW846 6010B. This method does not produce a sufficiently low reporting limit, in particular, for thallium. As a result, thallium, which is not a fYNOP COC, was detected above the PADEP MSC for residential used aquifers in numerous wells on-Site and off-Site during Round 1. All detections were flagged as estimated. For Round 2 (September/October 2008) method SW846 6020, which has a lower detection limit, was used, and wells with estimated values of thallium were rerun. All wells reanalyzed during Round 2 had no MSC exceedances for thallium. For that reason, thallium is not discussed in the report as a COC.

- Semi-volatile organic compounds (SVOCs) were detected above the detection limit in ten wells during Round 1 of the Supplemental RI groundwater sampling; however, subsequent analyses during Round 2 confirmed none of the Round 1 detections of SVOCs:

    - Wells MW-49S, MW-50D and CW-15A, located near the NBldg 4 Degreaser Area had concentrations that exceeded PADEP MSCs for residential used aquifers of bis (2-ethylhexyl) phthalate, nitrobenzene or pentachlorophenol.

    - Bis (2-ethylhexyl) phthalate was detected in MW-116, immediately west of the IWTP.

    - Wells MW-32D, MW-37S, MW-37D, MW-55 and CW-8, located near the Building 2 TCA Tank had sample analyses that detected SVOCs. The sample from CW-8 exceeded the PADEP MSC for residential used aquifers for bis (2-ethylhexyl) phthalate; the sample from MW-55 exceeded the same standard for nitrobenzene.

- Wells MW-37S, MW-37D and MW-75S located in the southwestern corner of the WPL had sample analyses that detected SVOCs. In all cases, the detections were flagged as estimated, and exceedances of the standards were below the laboratory reporting limit.

Figure 4.1-13 posts SVOCS from the Supplemental RI sampling Round 1 that exceed PADEP MSCs for residential used aquifers. In all cases, these locations correlate to locations with high concentrations of CVOCs, and for that reason, there has been minimal focus on SVOCs as COCs on-Site. Most detections of SVOCs are below reporting limits (flagged with a J), or are bis (2-ethylhexyl) phthalate, a common lab contaminant. The exception is nitrobenzene. Nitrobenzene was detected immediately down-gradient of the NBldg4 Vapor Degreaser Area at concentrations of 170 and 190 µg/l (MW-50D and MW-49S, respectively). Well MW-55, near the Bldg 2 Vapor Degreaser detected a nitrobenzene concentration of 190 µg/l. However, in all cases, reanalysis during Supplemental RI sampling Round 2 (October 2008) did not detect nitrobenzene or other SVOCs in these wells.

4.2 AOC-Specific Groundwater Quality

The AOCs for the Supplemental Site-Wide RI were developed, in part, from a list of 73 SWMUs obtained from the 1989 RFA prepared by A.T. Kearney (Kearney, January 1989). Other AOCs were added to this list from historic Site information. Figure 1.0-2 shows the general location of each SWMU/AOC.

This subsection discusses the known history of each AOC, including environmental investigations or remediation performed. The AOCs were discussed in Chapter 3 of the Soils RI (SAIC, December 2009b) in their numerical order, and in the same order as the Supplemental RI Field Sampling Plan (SAIC, July 2006). For this groundwater report, the order of discussion follows a geographical pattern, starting in the east and migrating westward. Descriptions of many SWMUs were not carried over from the Soils RI if they do not have a significant groundwater impact. In addition, the AOCs were grouped into major divisions of the plant, and discussion is biased toward the areas that have impact on groundwater quality. Previously introduced Figure 4.0-1 offers a quick reference to the locations of these groundwater AOCs, while Plate 4E provides more detail of the sample locations.

Each of these sections contains a description of the Supplemental RI investigations conducted relating to groundwater, if any. Also, current groundwater quality conditions and historical trends are discussed. The groundwater quality for each well is available in Tables 2.4-3 through 6. The record of water quality in the AOCs discussed in this section was graphed since 1986 for selected wells in the respective areas. For each well graphed, the following separate graphs were plotted:

- Concentrations of PCE, TCE, cis12DCE and VC plotted on an arithmetic concentration scale. PCE and TCE are chemicals formerly used as products on-Site, and disposed as waste, and therefore referred to as parent compounds. As previously mentioned, TCE can also be a degradation product of PCE, cis12DCE is a degradation product of TCE, and VC is formed as a result of further degradation of cis12DCE.

- Concentrations of TCA, 11DCA, 11DCE and chloroethane (CEA) plotted on an arithmetic concentration scale. TCA is the parent compound, while 11DCA, 11DCE and CEA are degradation products of TCA.

- Concentrations of PCE, TCE, cis12DCE and VC plotted on a logarithmic (log) concentration scale. Trends can sometimes be detected better if data is plotted on a log scale, particularly at lower concentrations.

- Concentrations of TCA, 11DCA, 11DCE and CEA plotted on a logarithmic concentration scale.

- Concentrations of PCE, TCE plus the addition of degradation products cis12DCE and VC normalized to the moles of TCE, and TCA plus the addition of degradation products 11DCA, 11DCE and CEA normalized to the moles of TCA on a log concentration scale. By normalizing to the moles of the parent product, an indication of the trend of the preserved mass of the COCs can be observed.

The graphs were then collated into appropriate groupings of wells. Plate 4E serves as an index to the collated groups of graphs, which occur in Appendix D of this report entitled Chemical Concentration Trend Graphs.

4.2.1 Northern Property Boundary Area (SWMU 12)

The NPBA is located in the northeast corner of the Harley-Davidson property, as shown in Figure 4.0-1, and is physically up-gradient and relatively remote from the industrial plant operations. The NPBA is identified as SWMU 12 in the 1989 RFA (Kearney, January 1989). VOCs (primarily TCE and some PCE) were first detected in groundwater in 1986. Several attempts have been made to determine the location of source(s) of these VOCs via soil gas and limited soil sampling, without much success. One soil sample (NPB-OB-2) at a depth of 8 to 10 feet exceeded the soil-to-groundwater MSC for 1122-tetrachloroethane (see Soils RI for details).

VOCs in the groundwater are believed to have originated from dumping (road oiling and weed control) along the perimeter dirt roadway. According to interviews of personnel who worked at the plant while the Navy and AMF operated it, there is also a potential for disposal of “coolant” in groundhog holes in the NPBA. A series of groundwater collection wells were installed in 1988 and have been in operation since November 1990 to prevent off-Site migration. The details of the groundwater collection wells, their operation, and effects on the groundwater flow in this area are reviewed every year, and presented in the annual Operations and Maintenance report. Further discussion of the effectiveness of the NPBA groundwater extraction system is included in this report in Section 5.3

Investigative activities began in April 1986, when chlorinated solvents were detected in monitoring well MW-3 (632 μg/L TCE) (REWAI, September 1986). This detection led to further investigations of the groundwater quality in the NPBA and off-Site to the north. TCE and PCE have historically been the predominant VOCs detected in groundwater at the NPBA. The highest total VOC concentration reported prior to commencement of groundwater extraction was at MW-20S (9,970 μg/L).

Four off-Site residential wells to the north of the NPBA, named RW-1 through RW-4, were sampled during early studies in the NPBA (REWAI, August 1987). These wells, with the exception of RW-4, were not in use as domestic water supplies at the time of the initial sampling, but had been used as residential water supplies in the past (personal communication with owner Seigler). In 1986 RW-2 had a TCE concentration of 2,070 µg/L while RW-3 had a TCE concentration of 2,137 ug/l in 1987. RW-4 was in continuous use from prior to 1986 until October 2007. RW-4 was sampled quarterly since 1988, and showed no detections of Site-related COCs.

Figure 4.2-1 (Figure 2-3 from REWAI, August 1988) shows the static groundwater table contours, while Figure 4.2-2 (Figure 2-4 from REWAI, August 1988) shows the piezometric levels in profile view along the north property line. The water table was documented in 1988 as typically occurring in the unconsolidated material overlying quartzitic sandstone bedrock at a depth ranging from 15 to 40 feet bgs. Artesian conditions were encountered at well MW-18S (REWAI, August 1988). Groundwater flow in the NPBA migrated in a northeast to southwest direction beneath the NPBA prior to operation of the groundwater extraction system.

A seismic survey was completed on a 1,000-foot long section of the NPBA roadway, between wells MW-9 and CW-5, during 1988 to identify the depth to bedrock in this region, in preparation for design and installation of extraction wells. The water table is below the top of bedrock, and the aquifer is fracture controlled, with bedding plane partings and weathering along cleavage planes being the likely discontinuities along which aquifer permeability has developed. Hydraulic testing in this area indicated that the aquifer is anisotropic, with an average transmissivity of 160 gallons per day per foot (gpd/ft) (REWAI, May 1990). This information was used to design a groundwater recovery network consisting of nine extraction wells.

Groundwater extraction at the NPBA commenced in November 1990, with the goal of preventing off-Site contaminant migration and with the potential to pull back contaminants from off-Site. The nine extraction wells (CW-1, CW-1A, CW-2, CW-3, CW-4, CW-5, CW-6, CW-7 and CW-7A) pump groundwater to the NPBA control building where individual pumping rates are controlled and measured. The groundwater from each well is combined to a common 3-inch diameter pipe, which transmits the water a distance of 2,300 feet to the groundwater treatment system. During 2008, the NPBA extraction system removed approximately 6.5 million gallons of groundwater at an average rate of approximately 541,000 gallons per month, equivalent to about 12.3 gpm. This volume is slightly higher than the five-year average (2004-2008) withdrawal from the NPBA of 11.6 gpm.

Overall, the NPBA pumps approximately 4 percent of the total volume of groundwater withdrawn at the Site.

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from the following NPBA locations: monitoring wells MW-9, MW-10, MW-11, MW-12, MW-16S&D, MW-18S&D, MW-20S/M/D, collection wells CW-1, CW-1A, CW-2, CW-3, CW-4, CW-5, CW-6, CW-7 and CW-7A, off-Site residential wells RW-2 and RW-4, and springs, S-6 and S-7. Access to sample off-Site former residential wells RW-1 and RW-3 was not obtained.

During the 2007-2009 sampling events, TCE was detected above the PADEP MSC of 5 µg/L in NPBA monitoring well locations MW-9, MW-10, MW-12, MW-16S&D, MW-18S&D and MW-20S&M, with a maximum concentration of 1,800 µg/l in MW-18D. PCE exceedances above the PADEP MSC were noted in monitoring wells MW-16S and MW-20S with a maximum concentration of 620 µg/l (MW-16S). Cis12DCE was noted above the applicable PADEP MSC in wells MW-10 and MW-18S&D with a maximum concentration of 770 µg/l (MW-18D). Other VOC exceedances above applicable PADEP MSCs included methylene chloride (MC) (MW-16S, MW-18 S&D) and vinyl chloride (VC) (MW-18 S&D). NPBA extraction wells yielded maximum exceedances of TCE (330 µg/l), PCE (160 µg/l) and MC (5.5 µg/l).

The record of water quality in the NPBA was graphed since the 1986 for most of the wells in this area. The graphs were collated into the following groups and appear in the Chemical Concentration Trend Graphs provided in Appendix C:

- NPBA-PW: Pumping Wells (CW-1 thru 7, 1A and 7A);
- NPBA-W: Monitoring Wells in the western half of the NPBA (MW-16S&D; MW-18S&D); and
- NPBA-E: Monitoring Wells in the eastern half of the NPBA (MW-3, -9, -10, -11, 20S, M&D).

As indicated by the concentration trend graphs, it is obvious that TCA was not a component of the waste disposed in the NPBA. While PCE is present, particularly in the central portion of the NPBA (around CW-5 and 6), TCE is the primary CVOC, and is not likely that degradation of PCE contributed significantly to the TCE concentrations, because of the low initial concentrations of PCE in most wells. In general, pumping wells decreased in the concentrations of TCE and PCE over the period of record. In some locations, such as wells CW-3 and CW-6, TCE and PCE concentrations have decreased while cis12DCE concentrations have increased. Mole normalized parent concentrations generally show steady decreasing trends (examples are data for wells CW-7 and CW-7A) although nearby CW-1 shows a minimal decreasing trend.

Monitoring wells have more erratic trends as compared to pumping wells. Many wells (MW-11, MW-16D, MW-20S, MW-20M and MW-20D) show steady decreasing trends. A number of wells show the apparent presence of a higher concentration slug being pulled through the area, resulting in a rise and subsequent fall of concentrations (MW-10, MW-12, MW-18 S&D). MW-16S appears to be experiencing a slug of high concentration PCE, which has not currently peaked. Changes in water quality such as these were the reason that suspected sources of TCE were added to Figure 4.1-4 south of MW-10 and west of MW-18S&D.

Exceedances of metal constituents in NPBA monitoring wells above applicable PADEP MSCs include total and dissolved arsenic, beryllium, chromium, nickel and lead. Monitoring wells MW-16S, MW-18S, MW-18D, MW-20M and MW-20D had exceedances for one or more of these total metals. Dissolved metals were sporadically detected, and not confirmed by repeat sampling. Turbidity was very high in these samples (see Table 2.4-2) and is believed to be the cause for the metals detections.

No VOC exceedances were noted in the NPBA off-Site residential wells and springs sampled during Supplemental RI activities. RW-4 yielded exceedances of total and dissolved lead (maximum value of 28.9 µg/L for total lead), believed to be a result of the low pH of the water and the lead used in the residential plumbing.

4.2.2 Southern Property Boundary Area

The AOC identified as the SPBA is located along the southern property boundary of the facility, as shown in Figure 4.0-1. Historical accounts indicate that liquid waste was used to control weeds along the perimeter road and to reduce the dust on the road. Other specific AOCs within the SPBA include impacted soils discovered while constructing a sanitary sewer line, which was installed during the construction of the Softail Plant (this was most likely an example of the historical disposal methods mentioned above), and a former drum storage area (DSA).

The Sanitary Sewer Area is located along the southern property boundary of the facility. According to a 1964 aerial photograph of the Site, the course of the perimeter road formerly routed through this area. Prior to 1974, the perimeter road was altered to its current course in this location, due to the realignment of Route 30 (Reference Figures 3.4-1 and 3.4-2 of the Soils RI). During the construction of a sanitary sewer line connection from the Softail facility (Building 3) southward to an existing manhole near the United States Army Reserve Center (SAIC, April 2003), VOCs were detected by monitoring with a photoionization detector (PID). A soil sample from the excavation was collected and indicated 1,800 milligrams per kilogram (mg/kg) PCE at a depth of 7 feet bgs. Approximately 285 tons of impacted soils were removed from the sanitary sewer excavation and disposed off-Site as part of the sewer line construction/installation. Details of this area, including additional source investigations are found in the Supplemental Soils RI Report.

The AOC identified as the SPBA/DSA is located along the southern property boundary of the Site and is approximately 1.5 acres in size and bounds both sides of the service road extending south from Buildings 13 and 70. Historical accounts and aerial photographs from 1974 indicate that drums were stored along this road. These can be seen on Figure 3.4-3 of the Soils RI. The contents of the drums are not known. Investigations detailed in the Supplemental Soils RI report indicate no soil degradation was discovered in this AOC.

Groundwater studies were conducted in the SPBA during 1991 to characterize the distribution of COCs and to evaluate remedial alternatives. Four multilevel piezometers, a single piezometer and two test groundwater recovery wells (MW-40 S&D, MW-41 S&D, MW-42 S&D, MW-43 S&D, MW-44, CW-10 and CW-11) were installed and sampled (REWAI, July 1991). Groundwater samples collected from these wells contained a maximum total VOC concentration of 863 μg/L (MW-43D), with TCE making up almost 70 percent of all VOCs. No metals issues exist in the SPBA currently, and based on current conditions throughout the site, it is suspected that the early sample may have had high turbidity, causing elevated metals in that sample.

Two rock types (limestone and quartzitic sandstone), having distinctly different hydrogeologic properties, are found underlying the SPBA. The quartzitic sandstone is found beneath the more steeply sloping hill/upland area, located approximately 500 feet northeast of MW-43S and extending eastward. The limestone is located beneath the flat lowland area, which underlies the primary manufacturing facilities at the Site. Limestone is also found immediately south of the eastern-most extent of the SPBA (south of the Harley-Davidson property), and underlying the quartzitic sandstone at well MW-64, in the southeastern corner of the Site. The estimated location of the contact is shown on all figures and plates referenced in this section. This contact was developed from Site-specific information, consisting of drilling logs, and observations by SAIC during construction of the Softail facility (Building 3). Borehole evidence suggests that the contact between the quartzitic sandstone and the limestone is conformable, with interlayered beds of limestone and quartzite/sandstone occurring in several wells along the contact.

The depth to the groundwater table beneath the portion of the SPBA underlain by quartzitic sandstone, ranges from 56 feet bgs in the southeast corner of the site (near MW-22) to 32 feet bgs near the contact with the limestone. The groundwater flow direction in the quartzitic sandstone is generally toward the south. A downward hydraulic vertical gradient has been identified in the quartzitic sandstone and is suspected to be due to the proximity of the higher transmissivity limestone (REWAI, July 1991).

The depth to the groundwater table beneath the portion of the SPBA underlain by limestone ranges from 33 to 35 feet bgs. Shallow groundwater flow near the quartzitic sandstone/limestone contact is from the east (quartzitic sandstone) toward the west (limestone). However, the groundwater gradient within the limestone is nearly imperceptible. A slight downward vertical gradient is evident in this portion of the SPBA (see Plates 3B and 3C).

During the 1991 investigation, two constant rate pumping tests were performed (CW-10 and CW-11). A transmissivity of 112 gpd/ft was calculated for the aquifer at CW-10, which is located within the quartzitic sandstone of the Antietam Formation. A transmissivity of 28,000 gpd/ft was calculated at CW-11, which is located within the limestone aquifer. The 1991 investigation resulted in a recommendation to design and install a groundwater pump and treat system to prevent the off-Site migration of VOC-impacted groundwater (REWAI, July 1991). A feasibility study was conducted to evaluate options for installing and operating a pump and treat system in the SPBA.

Beginning in 1995, R.E. Wright Environmental, Inc. (REWEI) performed off-Site investigations south of the Harley-Davidson property (REWEI, April 1997). As part of that investigation, four well pairs were installed along the southern boundary (MW-61 through MW-64). Evidence from that report indicates that TCE and other chlorinated solvents may be migrating off the Harley-Davidson property. The highest levels of VOCs were detected in MW-63S and MW-64D (1,600 µg/L and 1,800 ug/L TCE, respectively). Elevated levels of TCE and other compounds were also detected in off-Site wells at the former Cole Steel property (wells CS-3, CS-4 and CS-7) and at the Giambalvo Pontiac dealership (well RW-5). The report suggested that Site constituents were migrating off-Site along the SPBA. It recommended treatment or connecting Giambalvo to public water and conducting additional investigations in the area of MW-62 and MW-63, in order to better define the off-Site groundwater flow direction. Giambalvo was connected to public water in January 1999.

A dye trace study was conducted during the Site-wide RI (Langan, July 2002). Five different dyes were injected at different locations across the Site. The dye injected near the SPBA was the only dye that was not captured by the active groundwater treatment system. This supports the conclusion that groundwater is migrating from the eastern and southern portions of the Site off-Site toward the south. The dye injected along the SPBA was detected in the Site sanitary sewer, but a pathway for introduction into the sewer was not identified, and the dye is commonly found in household products that could be found in municipal waste water.

Sanitary sewer plans were acquired from Springettsbury Township for the lines south and east of MW-64D extending along Sherman Street, Canterbury Lane, Arsenal Road, south along Route 83 and north along the eastern Harley-Davidson property boundary. The dye trace sample locations established within the sanitary sewer during the previously completed dye study are along the downstream sections of the sanitary sewer lines reviewed. The sewer line elevations from the plans were compared to the groundwater table elevation contours constructed from the groundwater elevation data collected on June 10, 2005. The groundwater elevation contours are extended to the property boundaries due to the data set used for the construction and the sewer lines are along the property boundary and off-Site. Based on the review and comparison of the groundwater and sewer elevations, the present data set is inconclusive whether the sewer lines are below the groundwater table along Mill Creek and Codorus Creek; therefore, it is unclear if groundwater is at an elevation that would enable infiltration into the sanitary sewers.

During Supplemental RI activities completed in 2007 and 2008, five off-Site monitoring wells were installed to delineate the VOC impact identified at MW-64D and to further evaluate potential off-Site migration. These well locations, MW-108 S&D, MW-109 S&D and MW-110, are illustrated on the plates supporting this section. Monitoring Well MW-108 S&D was installed east of MW-64D near the intersection of Canterbury Lane and North Sherman Street. MW-109 S&D and MW-110 were installed southeast and southwest of MW-64D, respectively, within a grass strip between Route 30 and Arsenal Road (a small access road paralleling Route 30, which is also known as Arsenal Road). Well couplet MW-108 S&D was installed to a total depth of 68.5 feet bgs and 149 feet bgs, respectively. Well couplet MW-109 S&D was installed to a total depth of 65 feet bgs and 100 feet bgs, respectively, and monitoring well MW-110 was installed to a total depth of 55 feet bgs.

- Monitoring wells MW-108 S&D, MW-109 S&D and MW-110 were sampled twice during 2008 supplemental RI activities and also during the 2009 and 2010 Key Well sampling rounds. Monitoring well MW-108S yielded detections of the following total metals (in order of increasing concentration): cadmium (8.1 µg/L), beryllium (44.5 µg/L), arsenic (93.4 µg/L), nickel (352 µg/L) and lead (446 µg/L). These metals were detected in similar concentrations in both Supplemental RI Round 1 (April 2008) and Round 2 (September 2008). No dissolved metals were detected at levels of concern in these same samples, and high turbidity is expected to be the explanation for these elevated metals concentrations.

- Methylene chloride was noted in MW-109S at a concentration of 9.2 µg/L. Samples from MW-110 indicated concentrations of TCE and PCE at 84 µg/L and 69 µg/L, respectively. Exceedances of applicable PADEP MSCs for benzene and MTBE (gasoline constituents) were noted in MW-109 S&D at maximum concentrations of 200 µg/L (MW-109S) and 35 µg/L (MW-109D) respectively, as a result of a known gasoline spill at the Rutters store, immediately north of this well.

Additional groundwater samples were collected during Supplemental RI and Key Well sampling rounds completed between 2007 and 2009 from both on-Site and off-Site SPBA well locations. On-Site wells include: MW-1, MW-22, MW-40 S&D, MW-43 S&D, MW-64 S&D and MW-85. Off-Site wells include RW-5 (located at the Giambalvo car dealership,) Cole D, Cole F and MW-4 (located at the former Cole Steel facility). Groundwater samples were analyzed for VOCs, total and dissolved metals and total and free cyanide. The results of CVOC constituents are posted on Plates 4A through D.

- TCE was detected in MW-1, MW-22, MW-43D, MW-64 S&D and MW-85 while PCE was detected in only MW-43D and MW-64 S&D.
- Other VOCs detected above the PADEP MSCs in the SPBA were cis12DCE (MW-85) and methylene chloride (MW-40S, MW-64S).
- Metals exceedances of arsenic and lead were noted in several on-Site wells. Total lead was noted in MW-40S, MW-43S and MW-64S with a maximum concentration of 73.4 µg/L (MW-64S). Total arsenic was noted in MW-64S at a concentration of 12.4 µg/L. These same metal issues were not present in the dissolved sample analyses, suggesting turbidity in the samples to be the reason for the metals. Turbidity remains a factor in the sampling and analysis of SPBA on-Site wells for metals. Monitoring well MW-40S, for example, was purged for four and one half hours prior to sampling and a turbidity reading of 868 NTU was noted. Field water quality measurements, including turbidity, are presented in Table 2.4-2 for selected recent rounds of sampling.

Several off-Site monitoring wells located south of US Route 30 were included in the Supplemental RI investigation. These include wells located at the former Cole Steel manufacturing facility and the Giambalvo car dealership. At the former Cole Steel facility, TCE and PCE were detected in off-Site monitoring wells Cole D, Cole F and MW-4 (Cole) with maximum concentrations of 22 µg/L (MW-4 (Cole)) and 42 µg/L (Cole D), respectively. The well located at the Giambalvo property, RW-5, yielded concentrations of TCE and PCE at concentrations of 57 µg/L and 8 µg/L, respectively.

The record of water quality in the SPBA was graphed since 1986 for ten wells in this area. The graphs were collated into an SPBA group and appear in the Chemical Concentration Trend Graphs provided in Appendix C. The wells graphed were the newly constructed well MW-110, existing wells MW-43 S&D, MW-64 S&D. Also wells MW-41 S&D and MW-42 S,M&D, abandoned in 2002 during the construction of Building 3, were graphed.

- No significant concentrations of TCA are or were present in the wells in the SPBA.
- TCE and PCE appear to be codisposed, or disposed in the same general locations.
- Very little cis12DCE occurs in the wells in the SPBA, an indication that anaerobic reductive dechlorination is not occurring.
- Most wells have shown steady reductions in concentrations of CVOCs (specifically abandoned wells MW-41 S&D and MW-42 S, M&D). Existing wells tend to show a similar trend. The exception to this is MW-64D, where concentrations of TCE and PCE are similar without a decreasing or increasing trend at nearly 1,000 and 600 µg/L, respectively.
- MW-43 S&D are screened in the limestone aquifer. MW-43S screens a small void near the top of bedrock, while MW-43D did not encounter fractures or solution channels and is a very low yielding well. While MW-43S has detected virtually no CVOCs over the years, MW-43D continues to measure 200 to 300 µg/L of TCE, suggesting that the source for this well is not in the local overburden, but migrating with groundwater in the limestone bedrock.

Wells to the north of the SPBA (MW-2, MW-15, MW-91 and MW-92) show higher ratios of PCE to TCE than MW-64 S&D and MW-22, as illustrated on Figures 4.1-2 and 4.1-3. Most likely this is a result of disposal overprinting of different sources from different release points, and commingling of plumes rather than reductive dechlorination of PCE to TCE. The lack of cis12DCE presence in groundwater in this area supports commingling of different PCE and TCE sources rather than reductive dechlorination. The ratio of PCE to TCE is similar for wells MW-64, MW-110 and MW-4(Cole). The ratio of PCE to TCE is also similar for wells MW-2, MW-91, MW-92 and Cole D. These groupings of similar ratios suggest separate sources for each group.

MW-85 is located in the southwest corner of the Site near US Route 30 next to the stormwater basin. Concentrations of TCE went from 200 µg/l to not detected from between 2000 and 2008. The aquifer in this location is has low permeability, with no karst weathering, and the well has a low yield. Cis12DCE concentrations are nearly 100 percent of the CVOCs in this well. There is no vinyl chloride.

4.2.3 Eastern Area

The Eastern Area is located in the east-central portion of the Harley-Davidson property, as shown on Figure 4.0-1. The area is the steeply sloping hillside that runs from the eastern property line westward to the base of the hill, between NPBA and the SPBA. Although separate sections were written for the numerous SWMUs and AOCs in this area for the Soils RI report, for the purposes of this groundwater discussion, it is combined into one section. The SWMUs and AOCs within this area consist of the following:

- Reforested Area
- Eastern Perimeter Road Area (EPRA)
- Former Cyanide Spill Area (MW-2) (SWMU 16)
- Landfill Area (SWMU 17)
- Former Miscellaneous Disposal Areas (SWMUs 18 – 21)
- Bunkers and Shell Ranges (Firing Ranges)

In all cases, these areas are underlain by the quartzitic sandstone of the Antietam Formation. Residuum and colluvium thickness above bedrock ranges from 6 to 40 feet, with the thinner unconsolidated materials in the higher elevations along the EPRA and the thicker unconsolidated material at the base of the slope (west of the landfill and underlying the shell ranges. The depth to groundwater beneath the Eastern Area, is approximately 60 feet bgs at the eastern perimeter road, and five feet bgs at the western toe of the landfill. The groundwater gradient slopes to the southwest, and the presumed direction of groundwater flow is to the southwest, which is perpendicular to the presumed strike of bedding (NW-SE strike, dipping 20° west).

The EPRA and adjacent MW-2 area, the Landfill Area and the Building 14 Firing Range are described in this section. The Former Miscellaneous Disposal Areas and the Bunkers and Shell Ranges (other than Building 14) were adequately described in the Supplemental Soils RI and do not have an independent impact on groundwater quality, and therefore are not described in detail in this report.

4.2.3.1 Eastern Perimeter Road Area

The AOC known as the EPRA is located along the eastern boundary of the Harley-Davidson property, as shown in Figure 4.0-1. It covers an area of approximately one-half mile in length. It is a continuation of the northern and southern perimeter roads and has a common history with these areas.

Historical waste disposal practices along the perimeter road and fence line are suspected of being sources of groundwater contamination. According to the January 1987 REWAI report, local residents and employees indicate that waste solvents were used to control weed growth along the fence line, while liquid wastes were used to control dust along the perimeter road.

During Supplemental RI and Key Well sampling rounds completed between 2007 and 2009, groundwater samples were collected from wells MW-65 S&D, MW-14 and MW-15 in the Eastern Perimeter Road Area. MW-65S, the northern most of the EPRA wells, had TCE at 99 µg/L (see Plate 4A). MW-14, further south, had trace concentrations of TCE and PCE. Further to the south along the perimeter road, PCE (Plate 4B) is the predominant CVOC in MW-15 at 460 µg/L. The relative ratios of these compounds are illustrated on Figure 4.1-2.

Wells further south, and hydraulically down-gradient of the EPRA (MW-2, MW-91 and MW-92) show increasing ratios of TCE compared to MW-15 (all PCE) with concentrations of PCE ranging between from 100 to 240 µg/L, and TCE ranging from 14 to 53 µg/L. Most likely this increase in the proportion of TCE is a result of disposal overprinting of different sources from different release points, and commingling of plumes rather than reductive dechlorination of PCE to TCE, since there is no cis12DCE in samples collected from these wells. Conditions that result in reductive dechlorination of PCE to TCE and TCE to cis12DCE are similar and it would be unusual that no cis12DCE would be detected if reductive dechlorination was responsible for the increase in TCE concentrations.

4.2.3.2 Former Cyanide Spill Area

SWMU 16, identified as the Former Cyanide Spill Area, is located near monitoring well MW-2 on the eastern edge of the property, as shown in Figure 4.0-1. The area is generally down-gradient and to the west of the EPRA. The RFA (Kearney, January 1989) report on SWMU 16 described it as being located 75 feet east of monitoring well MW-2. Two separate burial areas, less than 100 feet apart, were discovered and exhumed in 1984. Details of the remediation and soil sampling/investigation are included in the Supplemental Remedial Investigations Soils Report (SAIC, December 2009b).

In April 1986, the location of monitoring well MW-2 was coincidentally drilled in close proximity to the site of the exhumed waste, without knowledge of the wastes that had been buried at that location. The first groundwater samples collected from MW-2 in April 1986 contained total cyanide (1,060 μg/L), TCE (405 μg/L) and PCE (672 μg/L). Elevated levels of cyanide and chlorinated organic compounds continue to be detected above applicable PADEP MSCs in groundwater samples collected from well MW-2 as part of recent Key Well groundwater sampling.

Additional groundwater monitoring wells were installed in this area in 1987, with two wells (MW-15 and MW-22) installed near to MW-2. Monitoring well MW-15 was located up-gradient from MW-2 and contained generally the same suite of VOCs (primarily TCE and PCE). Well MW-22 was installed down-gradient from MW-2 and contained TCA and 11DCE in addition to TCE and PCE. Sampling data for both locations indicated that cyanide was not detected at a concentration above laboratory reporting limits (REWAI, August 1987).

The parameters detected in well MW-22 are consistent with those previously detected in former south property boundary wells MW-41S and MW-44. The presence of TCA and 11DCE at MW-22 suggests that a separate source of CVOCs exists between MW-22 and MW-2 (REWAI, August

1987). This is probably evidence of the rodent control disposal methods related by former employees.

During the RI in 1999, two additional groundwater monitoring wells (MW-91 and MW-92) were installed between MW-2 and MW-22 (Langan, July 2002). The initial sampling conducted of these wells in 2000 indicated that TCE and PCE were present at concentrations exceeding their PADEP MSC values. TCA was not detected at either of the newly installed sampling locations.

During supplemental RI remedial investigation activities completed in 2007 and 2008, monitoring well MW-111 was installed to a total depth of 149 feet bgs. MW-111 was installed west and down-gradient of MW-2, and up-gradient of Building 3 in order to replace MW-21, abandoned to make way for the construction of Building 3. Sampling of MW-111 yielded a detection of TCE at 33 µg/L, above the MSC of 5 µg/L. Groundwater samples collected from existing wells during Supplemental RI and Key Well sampling rounds completed between 2007 and 2009, yielded only one well location (MW-2) with groundwater sample concentrations above the applicable PADEP MSC for total cyanide, including a maximum concentration of 1,300 µg/L. Exceedances of applicable PADEP MSCs for TCE and PCE were detected in samples from well MW-92 at maximum concentrations of 71 µg/L and 240 µg/L, respectively.

4.2.3.3 Landfill Area

The Landfill Area is located in the eastern portion of the property immediately north of a steep-sided road and encompasses approximately 2.5 acres, as shown on Figure 4.0-1. It is located directly north of the former Cyanide Spill Area.

The shallow groundwater beneath the landfill and up-gradient of the landfill flows within the underlying quartzitic sandstone bedrock. The shallow groundwater down-gradient of the landfill (near wells MW-17, MW-68 S&D and MW-67S) flows within the unconsolidated material composed of colluvial/residual quartzitic sandstone soils. The depth to shallow groundwater in this area varies from 5 feet bgs (down-gradient of the landfill) to 55 feet bgs (up-gradient of the landfill). In general, the depth to groundwater becomes shallower in a westerly direction from the eastern property boundary (up-gradient of the Landfill Area) toward the contact of the quartzitic sandstone and the limestone (down-gradient of the Landfill Area). The presence of a shallow groundwater table down-gradient of the landfill is marked by the presence of numerous springs between the Landfill Area and the quartzitic sandstone/limestone bedrock contact area. Several monitoring wells at the Site exhibit artesian groundwater flow near the foot of the slope (coincident with the contact between the quartzitic sandstone and the limestone). Well MW-67D, which intercepts the quartzitic sandstone bedrock at a location 500 feet southwest of the landfill, is one well that exhibits artesian groundwater levels.

During the remedial investigation efforts in 1998, two additional groundwater monitoring wells (MW-65S and MW-65D) were installed up-gradient of the Landfill Area (Langan, July 2002). Two nested piezometer pairs (MW-66 S&D and MW-67 S&D) and one deep bedrock monitoring well (MW-68) were also installed and sampled during the remedial investigation (Langan, July 2002). Piezometer pair MW-66 S&D is located immediately down-gradient (at the toe of the lower edge) of the landfill while piezometer pair MW-67 S&D is located further down-gradient from the former landfill. MW-17/MW-68, which were installed due west and topographically below the landfill, do not appear to be in the path of groundwater migration from the landfill, due to the southwesterly groundwater migration path.

Groundwater samples collected from up-gradient well MW-65S have significant concentrations of TCE (99 µg/L in MW-65S during Round 1 [April 2008]), indicative of historical waste disposal practices presumably along the perimeter road and fence line. MW-66 S&D, located at the toe of the landfill show minimal concentrations of TCE (10 µg/L in MW-66S during Round 1 [April 2008]), suggesting that the landfill is not a significant source of COCs. Further down the groundwater gradient, samples of groundwater from MW-67S contain concentrations of TCA (260 µg/L), 1,1,2 trichloroethane (7 µg/L, and the only detection of this compound on the Site), 11DCE (39 µg/L), PCE (27 µg/L) and TCE (72 µg/L) when first sampled in 1999. During Round 1 of the supplemental RI sampling, TCA is reduced to 26 µg/L, there are traces of 1,1,2 trichloroethane and 11DCE, 4.3 µg/L of PCE and 29 µg/L of TCE.

Ratios of CVOCs are consistent (nearly all TCE) between MW-65 S&D, and down-gradient wells MW-66 S&D, MW-1, MW-68 and MW-67D, suggesting a common source (see Figure 4.1-2). Analysis of groundwater samples from well MW-67S indicate the presence of TCA, that must have had a different, and probably very local source.

4.2.3.4 Building 14 Firing Range

Historical and descriptive information about Building 14 was taken from two N.O.P. drawings titled "Proof Shop Building 14 Plan" and "Proof Shop Building 14 Sections and Elevations." The drawings were dated April 18, 1952, and numbered Y.P.W. 344. According to the drawings, Building 14 consisted of a firing room and an assembly room, which took up the majority of the southern rectangular portion on the building. A long, narrow northern extension (18 feet wide by 328 feet long) is the firing range and extends from the firing room to the sand hopper and elevator. Part of the firing range is underground. See the Soils RI for details.

Minimal environmental investigation has been completed for Building 14. Potential environmental concerns regarding groundwater are related to the northern end of the firing range. Based on experience with Building 16, it is possible that sand used as a backstop and contained in the sand hopper/target room may have concentrations of lead. The volume of sand left in the building is unknown. Building 14 has considerable structure underground in the vicinity of the target building and the sand hopper, including a sump beneath the sand elevator and hopper that goes to elevation 385 feet mean sea level, which is approximately 15 feet below the groundwater table elevation in this area.

In addition to the sand hopper, there are springs along the course of the building. Springs that occur in the basement of this building were sampled in 1987 for VOCs. Spring S-1 contained 338 µg/L of TCE, while S-2 contained 571 µg/L of TCE. Springs 3 and 4 are located to the west and southeast of Building 14, respectively. Springs 1 and 2 were reported to be dry during the Site-wide RI sampling in 1998 and 2000. Spring S-3 was located 100 feet west of Building 14. It was sampled twice during the Site-wide RI . Total lead was 1,000 µg/L during the 1998 sampling, but is believed to be caused by high sediment in the sample, as suggested by the high total iron (177,000 µg/L), the lack of soluble lead, and 16 µg/L of total lead in the repeated sample (March 2000).

On January 11, 2006, SAIC investigators inspected Springs S-1 through S-4. Springs S-1 and S-2 are actually sump pits in Building 14. They were found to be dry. S-3 was not found, and is expected to have been destroyed or dried up by the improved storm drainage system constructed at the time that a new substation for Building 3 was installed. Near the recorded location of Spring S-

4, which is located southeast of Building 30, a drainage pipe was found discharging a small flow of water into a concrete drainage channel.

Springs S-1 and S-2 were scheduled to be sampled during Round 1 of the Supplemental RI (April/May 2008); however, no water was available.

One shallow groundwater well (MW-104) was installed down-gradient of the north end (target building and sand hopper) of Building 14 to a total depth of 28 feet bgs. The purpose of the boring was to test the water quality for lead immediately down-gradient of the presumably groundwater-saturated sand reclamation tower at the end of the firing range. The boring penetrated unconsolidated materials consistent with residuum from the underlying quartzitic sandstone. Chlorinated solvents PCE and TCE were detected at concentrations of 7.5 and 36 µg/L, respectively, in the Round 1 sampling (May 2008). Although total lead exceeded the groundwater PADEP MSC at 10.7 µg/L in one sample (Oct 2008), three other samples for total lead and all four analyses for dissolved lead indicated no exceedances of the PADEP MSC in the groundwater.

4.2.4 North End Test Track (SWMU 15)

SWMU 15, identified as the NETT is located north of the existing Softail plant, and immediately west of the Building 14 Firing Range target building and sand hopper, as shown in Figure 4.0-1. It is named for its location on the northern turn of the former motorcycle test track that was in the area. Asphalt pavement remnants of the test track are still present in this area.

According to the RFA (Kearney, January 1989), SWMU 15 is estimated to include an area of approximately 40,000 ft^2 with several distinct disposal areas. Several of these units are relatively small (less than 100 feet in diameter) and include the Cold Nose Compound Disposal Area, Cyanide Sludge Disposal Area, Plating Sludge Disposal Area, Bomb Line Grease Lagoon, and the Fly Ash and Sodium Cyanide Drum Disposal Area. In addition, a large former Drum Storage Area, estimated to have stored on the order of 10,000 drums, was present in the 1970s. Details of historical activities in this area related to usage and activities that could have contributed to environmental impacts are detailed in the Soils RI Report (SAIC, December 2009b).

Groundwater Investigations in the NETT Area are described below:

Investigative activities began in the NETT during 1986. One groundwater monitoring well (MW-4) was installed and the initial laboratory analyses performed on a sample from MW-4 indicated that TCE and TCA were the primary constituents at this location. The maximum reported concentrations for these parameters were 1,482 μg/L and 343 μg/L, respectively. PCE was also detected, with its maximum concentration reported at 25 μg/L (REWAI, September 1986).

The groundwater table beneath the NETT Area was present at a depth of approximately 25 feet bgs in 1986. The groundwater surface at MW-4 in the NETT Area is located within unconsolidated materials and residual sandstone soils, with the water table gradient sloping to the southwest (REWAI, September 1986).

Wells MW-19 (up-gradient) and MW-26 (down-gradient) were installed and sampled during subsequent investigations. All well locations are shown on Plates 4A through E. The concentrations and variety of VOCs detected in MW-4 and MW-26 (down-gradient of the NETT) were similar at both locations. The concentrations at MW-19 and two springs located up-gradient of the test track were only one-third of the levels seen in the down-gradient wells (REWAI, August 1987). These observations suggest that a source of VOCs exists between the location of MW-19 and the locations of MW-4 and MW-26.

A recommendation was made in 1988 to install a groundwater extraction system west (down-gradient) of the north end of the test track (REWAI, August 1988). During installation of the NPBA groundwater system, a spare groundwater transmission line was installed from the NETT Area to the groundwater treatment building in anticipation of utilizing it for groundwater extraction in the NETT. A remedial system has not been installed in this area, pending completion of a Site-wide RI/FS. The spare line was used to pipe groundwater collected from the Building 3 lift station to the Groundwater Treatment Plant (GWTP).

During the remedial investigation conducted between 1998 and 2002, a well couplet (MW-70 S&D) was installed at the NETT (Langan, July 2002). This well couplet was located approximately halfway between the former location of MW-4 (abandoned) and the current location of MW-19. The initial laboratory analyses conducted in 1999 indicated the presence of TCE and PCE at levels that exceed their PADEP MSCs. TCE was the predominant VOC detected at a maximum concentration 220 µg/L (MW-70S), while PCE was detected at a maximum concentration of 43 µg/L in this same well. TCA was only detected in well MW-70S at a concentration of 12 µg/L.

A second well couplet (MW-71 S&D) was installed during the Site-wide RI southeast of former MW-4. TCE and cis12DCE were detected in a sample from MW-71S at concentrations of 1,840 µg/L and 2,510 µg/L, respectively. MW-71D VOC concentrations were lower, with concentrations of TCE and PCE at 332 µg/L and 19 µg/L, respectively. Well couplet MW-71 S&D was decommissioned during on-Site construction activities completed in 2001.

During supplemental RI activities completed in 2007 and 2008, 2 well couplets were installed in the NETT area, MW-102 S&D and MW-103 S&D. Well couplet MW-102 S&D was installed down-gradient from the former lagoon and in a position near the former location of abandoned well couplet MW-71 S&D. Well couplet MW-103 S&D was installed near the south end of the NETT in an attempt to determine if the source of VOCs in MW-26 is from the NETT activities, and in order to better characterize the horizontal and vertical extent of the NETT plume. Monitoring well couplet MW-102 S&D was installed to a total depth of 65 feet bgs, and 99 feet bgs, respectively. Monitoring well couplet MW-103 S&D was installed to a total depth of 86 feet bgs and 107 feet bgs, respectively.

Monitoring well couplets MW-102 S&D and MW-103 S&D were sampled twice during 2008 remedial investigation activities and once as part of the 2009 Key Well sampling round. Samples were analyzed for VOCs, cyanide (total and free) and total and dissolved metals. Volatile detections were present in both well pairs. Maximum concentrations of TCE, PCE and 11DCE detected in MW-102S were 82 µg/L, 27 µg/L and 62 µg/L respectively. TCE, PCE and methylene chloride detections in MW-102D were 180 µg/L, 14 µg/L and 6.6 µg/L, respectively. Sampling of well MW-103S yielded maximum TCE, PCE and methylene chloride concentrations of 280 µg/L, 39 µg/L and 9.5 µg/L, respectively and sampling of well MW-103D yielded TCE and PCE concentrations of 120 µg/L and 12 µg/L, respectively. TCA was not detected in samples from well pairs MW-102 S&D or MW-103S&D. Cyanide was not detected in any samples collected from well pairs MW-102 S&D and MW-103 S&D.

Other NETT wells and springs sampled during Supplemental RI and Key Well sampling events completed between 2007 and 2009 include MW-19, MW-26, MW-69, MW-70 S&D, MW-86 S&D, MW-104, and springs at Building 14 S1&S2 (S1 & S2). TCE concentrations in the above referenced locations range from ND in S1 to 440 µg/L in MW-26 (May 2008). PCE values ranged from not detected to 50 µg/L at MW-70S. The concentrations of these compounds are plotted on Plates 4A and B. Other VOCs detected included 11DCE, methylene chloride and cis12DCE.

Figure 4.1-2 shows a considerable variety of ratios between PCE and TCE, which could be caused by the numerous small source areas rather than anaerobic dechlorination, since the ratio of cis12DCE is very small or not present in most wells in the NETT Area. MW-102S appears to be the only well in this area that has a significant ratio of TCA and its abiotic daughter product 11DCE.

CVOCs from monitoring well MW-26 were graphed to examine the long term trend in this area (See NETT Graphs, in the Chemical Concentration Trend Graphs provided in Appendix C), since it is the only well with a considerable record length. First sampled in 1987, the highest concentration of TVOCs was 9,768 µg/L in 1991. TCE currently makes up 83% of the TVOCs in MW-26, with the concentration trend graphs showing steady declines, with the most recent TVOC value at 447 µg/L.

4.2.5 North Plant Area

The NPA consists of several small SWMUs/AOCs with coalescing study areas. The NPA contains the following AOCs (SWMU numbers are from Kearney, January 1989):

- Old Waste Containment Area (OWCA) (SWMUs 2 – 11)
- Building 67 Container Storage Area (SWMUs 23 – 25)
- Mobile Tankers 1 and 2 (SWMUs 26 & 27)
- Waste Solvent Boilers (Building 10, Power House) (SWMUs 28 & 29)
- Former Coal Storage Area - Northwest of Building 10
- Industrial Wastewater Treatment Plant, Building 41 (SWMUs 30 – 42)

- Building 40 Hazardous Waste Storage Facility (SWMU 74)
- Former Drum Storage Areas (Buildings 51 & 67) (SWMUs 43 – 46)
- Metal Chip Bin Area
- Underground Storage Tank T-4
- Building 57

A detailed history of these SWMUs and AOCs and the COCs in the soils can be found in the Supplemental Soils RI (SAIC, December 2009b).

The groundwater table beneath the NPA occurs at a depth of approximately 20 feet bgs. The groundwater surface is located within unconsolidated materials and residual limestone soils that provide good vertical communication with the underlying fractured limestone bedrock. Groundwater flow direction beneath the NPA is to the west. The area is hydraulically down-gradient from the NETT Area and up-gradient of the NBldg4 and the WPL.

Investigative activities began in the NPA during 1986. One groundwater monitoring well (MW-5) was installed and the initial laboratory analyses performed on samples from this well indicated that TCE and cis12DCE were the primary constituents.

4.2.5.1 Old Waste Containment Area

AMF and Harley-Davidson previously operated a temporary hazardous waste storage facility identified as the Old Waste Containment Area (OWCA) (Figure 4.0-1) and located in the western end of the NPA. This former storage facility housed six steel storage tanks, listed in the 1989 RFA as SWMUs 2 through 7. SWMUs 8 and 9 are sumps within the containment structure, SWMU 10 is the loading/unloading area, and SWMU 11 is the sump in the loading/unloading area.

The former configuration of the OWCA facility is shown in Figures 3.2-1 and 3.2-2 of the Soils RI report (SAIC, December 2009b). Three of the storage tanks were above ground, and three were partially buried. They were used to store acids, bases, cyanides, waste oils, and waste solvents until the facility was replaced in 1995. A few occurrences of spills were reported at the OWCA during its use and are detailed in the Soils RI report. During 1995, the OWCA was decommissioned by REWEI (REWEI, November 1995). PADEP approved the final soil remediation plan for the OWCA in a letter dated January 26, 1999. SAIC completed the final remediation activities, including the removal and RCRA closure of the tanks at the OWCA during October 1999 (SAIC, June 2000).

As part of closure activities for the Old Waste Containment Area (OWCA) in 1995, two new groundwater monitoring wells were installed (MW-59 and MW-60). These two wells plus two existing wells (MW-31S and MW-36S) were sampled to evaluate the potential for groundwater contamination from the OWCA. Three primary VOCs were detected (TCE, PCE and cis12DCE). The highest concentrations of TCE (10,000 μg/L), cis-1,2-DCE (8,400 μg/L), PCE (1,800 μg/L), were detected at MW-60, which is located immediately south of the OWCA. The highest concentration of vinyl chloride (220 μg/L) detected in a groundwater sample from this area of the Site was also from MW-60 location. Similar suites of VOCs were detected at each well; however, concentrations of VOCs in the up-gradient monitoring well (MW-31S) were significantly different (see Figure 4.1-2). VOCs found in the groundwater beneath the OWCA were not found in OWCA soils at concentrations high enough to have been the source (REWEI, November 1995). Wells MW-59 and MW-60 were abandoned in April 2001 to accommodate a stormwater pipe construction project. Concentrations of TCE and PCE in MW-59 in April of 2000, the last sample analyzed from these wells, were 250 μg/L and 76 μg/L, respectively. Results of April 2000 sampling of MW-60 indicated concentrations of TCE and PCE of 970 μg/L and 210 μg/L, respectively.

4.2.5.2 Metal Chip Bins Area (MCBA)

The Metal Chip Bins were concrete structures that received oily metal shavings from shaping operations. The oil drained from the chips into a grate-covered concrete channel. The channel drained to a partially buried tank. In 1991, an investigation was conducted in this portion of the Site. High concentrations of total petroleum hydrocarbons (TPH) were found in the soils north of the Chip Bins. Two groundwater monitoring wells (MW-52 and MW-53) were installed and sampled during that investigation. VOCs were not detected in well MW-53. VOCs detected in groundwater from MW-52 included TCE (78 μg/L), cis12DCE (100 μg/L), VC (57 μg/L) and 11DCA (71 μg/L). The VOCs detected at this location were believed to have originated somewhere other than the MCBA (REWAI, January 1993).

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from monitoring points MW-52 and MW-53. Vinyl chloride was noted in a groundwater sample collected from well MW-52 at 2.2 µg/L, but was surprisingly free of other CVOCs, given the known up-gradient concentrations in the groundwater beneath the NETT Area. Total lead was detected in the groundwater sample from well MW-52 at 16.1 µg/L, however high turbidity in the sample (see Table 2.4-2) is the most likely explanation.

On May 14, 2010, monitoring wells MW-52 and MW-53 were abandoned to make way for a stormwater facility in the area.

4.2.5.3 Central Portion of the North Plant Area

During the Site-wide RI, four additional wells were installed in the central portion of the NPA (MW-78, MW-82, MW-83 and MW-84) (Langan, July 2002). The initial sampling of MW-78 in 1999 indicated that VOCs were not present in the shallow aquifer at this location. TCE and/or cis-1,2-DCE were detected at elevated concentrations in wells MW-82, MW-83 and MW-84.

Groundwater samples from shallow and residuum wells in the eastern (up-gradient) two-thirds of the NPA have none or very low concentrations of VOCs. VOCs in the bedrock wells throughout the eastern two-thirds of the area are at concentrations that suggest the contaminants were transported from an up-gradient source area, most likely the NETT Area.

During the Supplemental RI investigation work completed in 2007 and 2008 monitoring well MW-116 was installed on the west end of Building 41. Monitoring well MW-117 was installed near the east side of Building 41 during the Building 41 East Pipe Trench investigation (SAIC, December 2009a). Monitoring wells MW-116 and MW-117 were installed to a total depth of 50.8 feet and 29.5 feet bgs, respectively. Sampling of well MW-116 yielded concentrations above applicable PADEP MSCs for TCE (570 µg/L), PCE (310 µg/L), cis12DCE (1,200 µg/L), vinyl chloride (37 µg/L), 11DCE (46 µg/L) and methylene chloride (140 µg/L), while sampling of well MW-117 yielded a concentration above the PADEP MSC for TCE (39 µg/L).

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from monitoring points in the North Plant Area. Of these wells, concentrations above applicable PADEP MSCs for volatile, and/or metal constituents were noted in groundwater samples from monitoring wells MW-82, and MW-84. A groundwater sample from MW-82, located along the extreme northern corner of the property, contained 39 µg/L of TCE. TCE, PCE and cis12DCE were detected in MW-84 at maximum concentrations of 160 µg/L, 7 µg/L, and 130 µg/L, respectively.

4.2.5.4 Underground Storage Tank T-4

In the fall of 1991, Harley-Davidson removed or closed in place seven USTs at the York facility (REWAI, March 1992b). The excavation of one of the seven tanks uncovered evidence of leaking gasoline. The tank was designated by Harley-Davidson as UST T-4 and had a state registration of 67-00823 No. 006. UST T-4 was a 3,500-gallon gasoline tank originally installed in 1973, immediately west of Building 45, and served a gasoline fueling dispenser. A total of 1,200 tons of hydrocarbon-impacted soil was excavated from the area. Due to underground utilities and other conditions, no additional excavation was possible, and some hydrocarbon-impacted soil was left at this location.

The excavation was filled with crushed stone, and pipes were installed in the fill to facilitate vacuum extraction. The soil gas extraction system was operated from October 1996 through the end of September 1997 but was inactive during the winter months. In all, the system operated for a period of four months. In December 1997, confirmatory soil samples were collected. A number of parameters, including benzene, cumene, toluene and naphthalene, exceeded PADEP soil action guidelines at that time.

Groundwater down-gradient of UST T-4 contains benzene, toluene, ethylbenzene, and xylenes (BTEX) components (constituents of gasoline). Well MW-77 was sampled during 1999, and contained 2,100 µg/L of benzene, 180 µg/L of toluene, 100 µg/L of ethylbenzene and 600 µg/L of xylenes.

Analyses of gasoline parameters benzene, toluene, ethylbenzene, xylenes, cumene, naphthalene and MTBE were conducted in groundwater samples from wells MW-77, MW-79, MW-53, MW-83, MW-31S and MW-31D during Rounds 1 and 2 of the Supplemental RI, and results are posted on Figure 4.1-12. MW-77 analyses yielded exceedances of gasoline constituents benzene (2,000 μg/L), MTBE (790 μg/L) naphthalene (110 μg/L) and 1,2,4-trimethylbenzene (44 μg/L). With the exception of an unrepeated estimated concentration of benzene below the laboratory reporting limit in MW-83 (0.72J), there were no other detections of gasoline parameters in this set of wells. Also of note, samples of groundwater from MW-77 contained no CVOCs.

4.2.5.5 Chemistry Trends in the NPA

Graphs of CVOCs for wells in the NPA are included in Appendix C. The predominant COC is TCE. Most wells show a strongly decreasing trend, not only in the parent product, but also in cis12DCE. The presence of cis12DCE and vinyl chloride suggests that reductive dechlorination is responsible for the decreasing trends.

4.2.6 Central Plant Area

The CPA consists of the portion of the plant generally defined as being located east of the WPL, south of the NPA, north of the South Parking Lot and west of the new Softail Manufacturing area, basically the area covered by Buildings 1, 2 and 4. The CPA incorporates multiple SWMUs inclusive of the following:

- SWMU 1, TCA Tank Area
- SWMU 22, North Building 4, Plating Sludge/Vapor Degreaser Area
- SWMUs 47 – 52, Building 2 (East Corridor) former Wastewater Sumps
- SWMUs 53 – 60, Building 4 Wastewater Sumps
- SWMUs 61 & 62, Building 2 Settling Tanks
- SWMU 63, Building 2 Sumps, Chrome Plater Area (Building 66)
- SWMU 64, Building 4 Sumps, Zinc Plater Area
- SWMU 65, Chrome Plater Tank Scrubber (Building 66)

- SWMUs 66 – 67, Building 2 Dust Collectors
- SWMUs 68 – 71, Building 4 Dust Collectors
- SWMU 72, Building 2 Accumulation Area
- SWMU 73, Building 4 Accumulation Area

The CPA portion of the Site has historically been the location of the majority of Site manufacturing activities. Groundwater degradation in this area is more likely a result of spills or leaks of product, and less likely disposal of waste. The SWMUs listed above have been grouped together in this section due to the similarity of groundwater quality, which indicates a general CVOC presence. Specific details regarding the individual SWMUs can be found in their individual sections within the Supplemental RI Soils report. After a general discussion of the characteristics of the groundwater beneath the CPA, details of the historical and current conditions are discussed for specific areas.

The groundwater surface (water table) beneath the CPA was determined to occur at a depth of approximately 15 to 20 feet bgs, sloping to the south-southwest (REWAI, August 1987). The groundwater surface (water table) is located within unconsolidated materials and residual limestone soils that provide good vertical communication with the underlying fractured and solutioned limestone bedrock. Current groundwater elevation data (see Plate 4A) indicates that groundwater flow beneath the CPA is generally toward the west due to the influence of active groundwater recovery wells. The gradient is approximately 1 to 4%, which is relatively flat, due to the high transmissivity of the aquifer.

In order to describe these activities, the CPA is broken into a number of areas where industrial activities defined the source areas of the COCs.

4.2.6.1 Building 2 Former TCA Tank Area and Vapor Degreaser (SWMU 1)

SWMU 1, identified as the TCA Tank Area, is located along the western exterior wall of Building 2, as shown in Figure 4.0-1. This area of the facility is the former location of a 2,500-gallon TCA aboveground storage tank (AST). This tank supplied the solvent for a vapor degreaser located a few hundred feet due east, inside Building 2.

Groundwater samples collected from well MW-28 in the TCA Tank Area in 1987 indicated elevated concentrations of TCA (30,800 micrograms per liter [µg/L]). This discovery led to investigations and remediation activities in this immediate area and within Building 2.

Interviews from former Navy and AMF employees indicate that the degreaser was installed by AMF between 1963 and 1965. The degreaser used three different chlorinated solvents over the years, including TCE, PCE and TCA, in that order. The degreaser was used to clean grease and oil from metal parts. It consisted of a solvent heating/condensing unit, a circulation pump, and a degreaser tank set within a concrete containment pit. The vapor degreaser was dismantled on June 29, 1994, and replaced with an aqueous-based parts washer. For additional details of the history of the activities in the TCA Tank/Bldg 2 Vapor Degreaser area, including the soils investigation, refer to the Supplemental RI Soils Report (SAIC, December 2009b).

Additional investigative activities were implemented at the CPA in 1990. Seven monitoring wells were installed and sampled in the vicinity of MW-28, and one collection well, CW-8, was installed and tested to determine aquifer characteristics. The results of this investigation delineated an area of TCA groundwater contamination that could be remediated by pumping collection well CW-8.

Groundwater extraction was initiated at CW-8 (located south of Building 91) in November 1990. The goal of pumping CW-8 was to prevent TCA migration and remove VOCs from the groundwater in this area. Initially, extraction well CW-8 was pumped at a rate higher than necessary to maintain capture, since there was available treatment capacity in the new groundwater treatment plant, before the initiation of planned groundwater extraction in the WPL. Groundwater from this well was conveyed a distance of approximately 1,000 feet through a 3-inch diameter pipe to the GWTP (Building 41). The initial goal was to reverse the direction of migration prior to pumping groundwater at the WPL, which would have potentially pulled the western edge of the TCA tank plume further west. With the startup of the WPL system the available treatment capacity at the treatment plant was reduced, so the pumping rate of CW-8 was reduced to a level that maintained capture of the TCA plume.

Investigations continued in this area, focusing on the vapor degreaser operation to the east. In 1993 wells were constructed on the east side (MW-54) and on the west side (MW-55) of the vapor degreaser, and initial samples were collected in July 1993. The elevated VOC concentrations in groundwater detected at MW-54 (TCE 1,000 µg/L, TCA 30,000 µg/L, 11DCE 10,000 µg/L and 11DCA 750 µg/L) compared to lower concentrations detected at MW-55 (TCE 450 µg/L, TCA 2,400 µg/L, 11DCE 4,200 µg/L and 11DCA 50 µg/L) suggest that the contamination originated near the degreaser and moved westward toward groundwater extraction well CW-8 (REWEI, July 1995).

Groundwater extraction at a second well (CW-16) was initiated in February 1995 to contain and remediate groundwater beneath the former Degreaser Area located inside Building 2, 150 feet east of CW-8. In June 2002, extraction well CW-16 was removed from service. The pump at this well failed and was not repaired due to its location in a busy manufacturing area, the ability of CW-8 to maintain capture, and the potential that groundwater extraction in the TCA area will be reconfigured or eliminated as a result of the RI findings.

Subsequent groundwater sampling performed in the TCA Tank Area since the implementation of groundwater remediation has indicated a change in the general groundwater quality data. The dominant VOC present in this area has clearly shifted from TCA to TCE. In 1987, TCA accounted for 95 percent of the total VOC concentration in groundwater. In 2002, TCA accounted for 4 percent of the total VOC concentration while TCE accounted for approximately 70 percent of the total VOC concentration. In general, TCA concentrations are decreasing in this area while TCE concentrations remain elevated. This information suggests that groundwater impacted by a source of TCE is being drawn toward the TCA Tank Area due to groundwater extraction at CW-8. Graphs of these wells are included in the Concentration Trend Graphs provided in Appendix C.

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from monitoring points within the TCA tank area. Exceedances of volatile, semi-volatile, and/or metal constituents were noted in monitoring wells MW-28, MW-32 S&D, MW-33, MW-34 S&D, MW-35 S&D, MW-54, MW-55 and collection wells CW-8 and CW-16. Constituents which exceeded PADEP MSCs included 11DCE, Bis (2-Ethylhexl) Phthalate, cis12DCE, nitrobenzene, PCE, TCE, methylene chloride, vinyl chloride, 1,4-

dioxane, and metals, hexavalent chromium and lead. TCA concentrations did not exceed the PADEP MSC in this area.

The maximum concentration of TCE during sampling for the supplemental RI was noted at MW-32D (970 µg/L). The maximum concentration of PCE in this area was detected in MW-54 (79 µg/L), while the maximum concentration of 11DCE was found in MW-55 (3,000 µg/L). Other volatile and semi-volatile exceedances during this sample period were noted in MW-32D (450 µg/L cis12DCE and 21 µg/L vinyl chloride) MW-54 (58 µg/L 1,4-dioxane) and MW-55 (190 µg/L nitrobenzene and 86 µg/L methylene chloride). Concentrations of metals above applicable PADEP MSCs were noted in MW-55 (12.1 µg/L total lead and 310 µg/L hexavalent chromium), presumably due to high turbidity during sampling. Dissolved metal analyses of this well recorded no exceedance of MSCs.

Trend graphs of the groundwater CVOC chemistry for wells in the TCA Tank/Bldg 2 Degreaser Area are collated into two groups:

- Wells within the TCA Tank Spill Area (CW-8, CW-16, MW-28, MW-32S & D, MW-54 and MW-55); and
- Wells down-gradient (west) of the TCA Tank Spill Area (MW-33, MW-34 S&D, MW-35 S&D)

All graphs for wells in the TCA Tank/Bldg2 Degreaser Area show the rapid depletion of TCA. In extraction well CW-8, this occurred after one year of pumping. For surrounding monitoring wells in close proximity to CW-8, the timing of the TCA reduction was similar. For wells more distant from CW-8, the decline in TCA concentration was more gradual. Well MW-54, which is near the vapor degreaser, had part per million concentrations of TCA and/or its degradation products (TCA-series CVOCs) when drilled in 1994, which was 4 years after groundwater withdrawals began at extraction well CW-8, suggesting the aquifer improvement caused by pumping of CW-8 did not reach that far to the east. TCA concentrations reduced rapidly in MW-54 after CW-16 was added as an extraction well.

Also shown in most graphs for wells in the TCA Tank/Bldg2 Degreaser Area is the rapid increase in TCE concentrations. CW-8 showed an increase in TCE concentrations from 150 µg/L at the end of 1993 to 1,000 µg/L at the end of 1995. TCE concentrations in CW-8 now range between 200-400 µg/L, and clearly show a steady sustained level, indicating a nearby source that is not being rapidly depleted.

Figure 4.2-3 is previously introduced Cross Section A-A’ that runs through the TCA Tank Area in an east-west direction. The schematic piezometric isocontours (equipotentials) are intended to depict an interpretation of general trends in groundwater flow conditions during operation of extraction well CW-8, in the TCA Tank Area, and extraction well CW-9, located further west in the WPL. Likewise, general chemistry trends are represented by the TCE isoconcentration contours inferred from known data points. The cross section shows high concentrations of TCE at depth in the aquifer below the TCA Tank.

The current interim action of pumping extraction well CW-8 has served its original purpose of removing the concentrated TCA contamination at this location. Continued pumping is currently removing TCE from an unknown source.

4.2.6.2 Building 2 East Corridor

The area identified as the Building 2 East Corridor is located along the eastern exterior wall of Building 2, as shown in Figure 4.0-1. This area of the facility is the former location of six in-ground wastewater tanks which are listed as SWMUs 47 through 52 in the RFA (Kearney, January 1989). The tanks originally contained acid and alkaline wastes, chrome rinse wastes, and cyanide wastes. Adjacent to the tanks is the location of the former Cutting Oil Tank. Shallow groundwater and soil contained elevated concentrations of chlorinated solvents (primarily TCE), extending beneath the building. Activities in the East Corridor were primarily related to soils investigations and remediation (Refer to the Supplemental RI Soils Report for details).

Prior to the construction of Building 65, the Nickel, Chrome, and Zinc plating facility, an investigation was conducted on the east side of Building 2 in 1993 (REWAI, October 1994). A perched water table was detected in borings at depths of 5 to 15 feet bgs. Perched groundwater was not analyzed for COCs. Analytical results of groundwater from well MW-58, screened in unconsolidated material, indicated a TCE concentration of 3,900 µg/L. The detection of TCE in well MW-58 suggested a nearby source of TCE in the soil. Well MW-58 was abandoned in order to construct the new building, after only one sample was taken from the well.

During supplemental RI remedial investigation activities completed in 2007 and 2008, monitoring well MW-94 was installed to a total depth of 17 feet bgs to characterize the groundwater in the area of SWMUs 47 through 52. Groundwater samples collected during 2008 and 2009 sampling rounds yielded exceedances of applicable PADEP MSCs for certain VOCs and metal constituents. TCE, PCE and cis12DCE were detected in samples collected from MW-94 at maximum concentrations 340 µg/L, 23 µg/L and 380 µg/L, respectively. Concentrations of chromium, lead, nickel, arsenic, and beryllium were detected in samples collected from MW-94 at 187 µg/L, 123 µg/L, 117 µg/L, 35.5 µg/L and 7.7 µg/L, respectively, in the second round of Supplemental RI sampling (September 2008). Results of a subsequent sampling and analysis round (July 2009) revealed no concentrations of concern for metals.

4.2.6.3 Former Chrome Plater Area in Building 66 (SWMU 63) and Building 58 Area

According to the RFA (Kearney, January 1989), SWMU 63 is described as sumps surrounding process areas in Building 2 that contain degreasers, dust collectors, or electroplating tanks. However, for clarification for this investigation, this SWMU is considered to include the chrome and nickel platers that were in the southeast corner of Building 66. Because of its proximity and the contribution of CVOCs to the Building 66 Area, the Building 58 Area is also discussed in this section. The location is shown on Figure 4.0-1. This area of Building 66 was formerly used as a chromium and nickel plating facility, which was removed in 1996. After removal, soils impacted by metals were excavated and properly disposed off-Site. Building 58 has no known history of manufacturing, but is the location of high concentrations of CVOCs in groundwater.

One temporary well (TW-B6) and one permanent well (CW-18) were constructed inside Building 66 in order to assess groundwater impacts. A groundwater sample collected from TW-B6 on July 13, 1995, was analyzed for metals and VOCs. This sample detected 260 µg/L hexavalent chromium, 68 µg/L lead, 450 µg/L zinc, 13 µg/L PCE and 210 µg/L TCE. A groundwater sample collected from CW-18 on April 10, 1996, was also analyzed for metals and VOCs. This sample detected 660 µg/L nickel, 19 µg/L 11DCE, 11 µg/L PCE and 600 µg/L TCE. No chromium or hexavalent chromium was detected in this sample from CW-18. CW-18 was constructed in a manner suitable for future pumping, if remedial alternatives were to require groundwater extraction at this location.

Monitoring well MW-57, located south of Building 66, contained concentrations of chromium, copper, lead, and nickel, in addition to the ubiquitous VOCs. Only the lead concentration (110 µg/L) exceeded the PADEP MSC. A sample of this well in 1999 detected only very low concentrations of chromium. Monitoring well MW-87 to the east (up-gradient of Building 66) detected low concentrations of chromium, copper, cyanide, nickel, and zinc, likely as a result of sample turbidity. Sampling of well MW-54, 300 feet to the west, indicated no detectable concentrations of metals in 1993, and only a trace concentration of zinc (26 µg/L) in 1999.

During the Site-wide RI (Langan, July 2002), wells MW-80 and MW-87 were drilled east of Building 66, between Buildings 58 and 59. Deep well MW-87 penetrated an apparent collapsed solution cavity. It is screened in gravelly material, and contains part per million concentrations of TCE (1,300-1,700 µg/L. Shallow well MW-80 has much lower concentrations of TCE (180 µg/L). During the Supplemental RI characterization well MW-113 was drilled in this area in an effort to define the lower limit of COC impact. The well screened an interval of 131 to 151 feet bgs. Sampling and analysis of this deeper well indicated TCE concentrations similar to well MW-87.

MW-88 is located south of Building 2, and southwest of wells MW-80, MW-87 and MW-113. Groundwater at this location contains a few hundred parts per billion of TCE. The ratio of chlorinated compounds and the mole adjusted product ratio suggest that the source of the COCs in well MW-88 is the same as MW-87 and MW-113 (See Figures 4.1-2 and 4.1-3). The inferred groundwater flow direction from the MW-87/MW-113 area to MW-88 is to the southwest, making migration with the natural groundwater flow the likely mechanism for transport.

Trend graphs of the groundwater CVOC chemistry for wells MW-57, MW-80, MW-87, MW-88, MW-113 and CW-18 were plotted and grouped together. The graph group is called BLDG 58-66, and is illustrated on Plate 4E and found in the Chemical Concentration Trend Graphs provided in Appendix C. Unlike most wells at the Site, there is no apparent trend common to these wells.

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from existing wells to assess impacts from the plating activities in Building 66. Wells analyzed include MW-54, MW-80, MW-57, MW-87, CW-8, CW-16 and CW-18. Figures 4.1-8 and 4.1-9 display the concentrations of dissolved hexavalent chromium (Cr+6) and total chromium (Cr +3 plus Cr+6) across the Site. All of these wells detected estimated (J) values of dissolved total chromium. Dissolved hexavalent chromium was detected in only MW-57 at 71 µg/L, below the PADEP MSC of 100 µg/L.

4.2.6.4 West Building 2 Corridor

Monitoring Well MW-27 was installed in 1987 in the corridor between Buildings 2 and 4 near the northern extent of these buildings. Groundwater analyses from this well consistently show approximately 500 µg/L of PCE and 30 to 160 µg/L of TCE, along with their degradation product cis12DCE. Two groundwater monitoring wells (MW-81S and MW-81D) were installed a few hundred feet to the south in this corridor, just north of Building 91 in August 1999, as part of the Site-wide RI (Langan, July 2002). Sampling at that time indicated elevated concentrations of TCE, PCE, cis12DCE, and 11DCE. TCE was the most prominent of the VOCs detected, with concentrations ranging from 1,500 µg/L (MW-81D) to 3,300 µg/L (MW-81S). Speculation as to the origin of the CVOCs include migration of DNAPL in the karstic bedrock from North Building 4, or an unknown process or disposal location either in the corridor or in the northern end of Building 2. To better define the extent of the concentrated CVOCs in this area, characterization well MW-114 was installed during the supplemental RI activities, and is screened at a depth of 90-144 feet bgs.

Water quality results during the supplemental RI sampling were as follows:

- TCE was the prominent VOC detected, with 8,300 µg/L detected in the first sample of MW-114. Sampling of well MW-81S indicated a TCE concentration of 2,800 µg/L, while MW-81D had a TCE concentration of 1,200 µg/L. Relatively elevated concentrations of cis12DCE accompanied the TCE detections.

- PCE concentrations in groundwater samples from wells MW-81S and MW-81D (50 µg/L in both wells) were relatively low compared to MW-114 (950 µg/L). For well MW-27, PCE was still the most prominent VOC detected, with the concentrations of PCE and TCE unchanged from initial sampling in 1987.

- TCA is absent from the samples from wells in the West Building 2 corridor, but traces of TCA degradation products 11DCE and 11DCA are present in samples from wells MW-114 and MW 81S.

The ratio of CVOCs (Figure 4.1-2) and molar-corrected parent products (Figure 4.1-3) suggest that the source of the CVOCs for the WBldg2 Corridor was not the same as the NBldg4 Degreaser Area.

Trend graphs of the groundwater CVOC chemistry for wells MW-27, MW-81 S&D and MW-114 were plotted and grouped together. The graph group is called WBldg2 Corridor is illustrated on Plate 4E, and is found in the Chemical Concentration Trend Graphs provided in Appendix C. Concentrations of CVOCs, in particular TCE, are not declining, suggesting a nearby source.

4.2.6.5 North Building 4

Three groundwater AOCs are delineated in the NBldg4 Area, shown on Figure 4.0-1, including the Northern Vapor Degreaser, the Building 4 Sumps and Zinc Plater Area and the Southern Vapor Degreaser. Details of the investigation regarding the activities that occurred in this area are included in the Supplemental RI Soils Report. A brief history of the area and the groundwater investigations that focused on this area are provided in the following subsections.

4.2.6.5.1 Northern Vapor Degreaser

Vapor degreasers were operated in the northwest corner of Building 4 from the late 1940s through 1994. According to interviews with former plant employees, the first degreaser in this area originally used TCE as the solvent for many years and then switched to PCE for a period of 1 to 1.5 years. In the early 1970s, the solvent was switched to TCA (REWEI, January 1995). The solvents for this degreaser were stored in an aboveground tank located along the northwest corner of the building exterior (Figure 3.10-2 of the Supplemental Soils RI Report [SAIC, December 2009b]). After flood damage in 1972, AMF replaced this vapor degreaser with a new smaller unit at the same location, which remained until 1994 when it was decommissioned and replaced with an aqueous parts washer. Prior to installing the smaller degreaser, AMF reportedly backfilled the base with metal plating sludge containing cyanide and sealed the vault with concrete (Kearney, January 1989; REWEI, January 1995). In January 1984, Harley-Davidson exhumed 60 to 80 tons of the plating sludge, soil, and debris, from the vault, which was disposed at an off-Site hazardous waste facility (Kearney, January 1989).

MW-7 was one of eight original environmental characterization wells drilled on the property in 1986. It is located in the WPL, 200 feet southwest of the NBldg4 area. The first samples collected from this well detected 600 and 2,076 μg/L of TCE, 1,040 μg/L of cis12DCE, and 35 to 106 μg/L of PCE. Monitoring well (MW-48) was installed and sampled at the north end of Building 4 during the 1990 WPL investigation. Part per million levels of TCE (240,000 μg/L), PCE (11,600 μg/L), TCA (90,400 μg/L) and 11DCE (20,400 μg/L) were detected during this investigation. The possibility of non-aqueous phase TCE at the MW-48 location was suspected due to the concentrations of CVOCs detected in this area (REWAI, July 1991).

Groundwater extraction from well CW-15A began along with the WPL groundwater extraction system in May 1994 and continues to date. Initial groundwater concentrations in this well were TCA (110,000 μg/L), TCE (190,000 μg/L) PCE (11,000 μg/L) with accompanying high concentrations of 11DCE and 11DCA.

During Supplemental RI activities, groundwater samples were collected from CW-15A, and MW-49 S&D in the area of the Northern Vapor Degreaser. Maximum concentrations of TCA (6,300 μg/L) and 11DCE (2,700 μg/L) were noted in samples from wells CW-15A and MW-49S, respectively. Concentrations of TCE (13,000 μg/L), cis12DCE (15,000 μg/L), and methylene chloride (360 μg/L) were identified in samples from well MW-49S. PCE was detected in a sample from well CW-15A at a concentration of 1,600 μg/L. Other volatile constituents, 1,4-dioxane and nitrobenzene, were detected in MW-49S at 1,300 μg/L and 190 μg/L, respectively. Semi-volatile compounds bis(2-ethylhexl) phthalate (9 μg/L) and pentachlorophenol (3.7 μg/L) were detected in samples from wells CW-15A and MW-49S, respectively.

Previously introduced Cross Section B-B’ is reintroduced as Figure 4.2-4 adding the concentrations of TCE and PCE at depth in the aquifer below the degreaser area, and the general chemistry trends are represented by the TCE isoconcentration contours inferred from known data points. The high concentrations at depth may commingle with concentrations up-gradient to the east, the location of the WBldg2 Corridor, although the ratio of CVOCs (Figure 4.1-2) and molar-corrected parent products (Figure 4.1-3) suggest that the source of the CVOCs for the WBldg2 Corridor was not the same as the NBldg4 Degreaser Area.

4.2.6.5.2 Building 4 Wastewater Sumps (SWMUs 53 – 60), Zinc Plater Area (SWMU 64)

Nine underground wastewater tanks were located near the north end of Building 4, along the exterior west wall of the building, as shown in Figure 4.0-1. These tanks were designated as SWMUs 53 through 60 as part of a RFA (Kearney, January 1989). Several of the tanks had not been used for many years. Harley-Davidson replaced these existing wastewater tanks, located along the west side of Building 4 with new aboveground tanks in 2004. Investigations in this area by SAIC had identified the presence of elevated concentrations of heavy metals and volatile organics in the soil surrounding these tanks. New aboveground process tanks had been constructed, and Harley-Davidson removed the underground tanks, including soils with concentrations of COCs exceeding PADEP MSCs prior to the initiation of the Supplemental Site-Wide RI.

The Zinc Plating Room (ZPR) was located in the northern half of Building 4, along the inside western wall as shown in Figure 4.0-1. The ZPR is located immediately inside of Building 4 from the wastewater sumps. This area was 40 feet by 96 feet and housed the zinc plating operations from 1981 to approximately 1995 (REWEI, July 1996). Prior to 1981, cadmium, chromium, and copper plating operations were conducted in the western half of the ZPR for 20 to 30 years. The eastern half of the ZPR contained cleaning tanks at the north end, which contained hydrochloric acid. Cyanide was also used in this room as part of the plating process. Over the years, the concrete floor near columns B-13 and B-14 had become seriously deteriorated by acids and liquids that ran onto the floor from the various tanks. A new concrete floor was poured on top of the old floor in 1981.

Monitoring well MW-47 was installed and sampled west (down-gradient) of the Building 4 wastewater sumps. A review of the results from the initial sampling of MW-47 in 1990 indicated moderate levels of TCE and PCE (28 μg/L and 61 μg/L, respectively). Chromium was detected in MW-47 in 1990 at a concentration (2,500 μg/L) above its MSC of 100 μg/L (REWAI, July 1991). A 1995 sample of groundwater from well MW-47, located 50 feet west of the ZPR, detected 4,000 μg/L of total chromium and 4,400 μg/L of hexavalent chromium.

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from monitoring and collection wells in the area of the Building 4 wastewater sumps and Zinc Plater Area. Of the wells sampled, exceedances of applicable PADEP MSCs for VOCs and/or metal constituents were identified in samples collected from monitoring wells MW-45 and MW-47. Sampling and analysis of monitoring well MW-47 indicated exceedances of applicable MSCs for TCE (260 µg/L), PCE 150 (µg/L), cis12DCE (110 µg/L) and 11DCE (8.9 µg/L). Sampling and analysis of well MW-45 indicated exceedances of applicable PADEP MSCs for TCE and PCE at concentrations of 63 µg/L and 150 µg/L, respectively. Detected concentrations of dissolved total chromium (Cr+3 plus Cr+6) exceeded the MSC of 100 µg/L in samples collected from MW-47 (2,310 µg/L) and MW-51S (356 µg/L). An elevated concentration of dissolved total chromium was also detected below the MSC in a sample from well MW-7 (92.7 µg/L) (see Figures 4.1-8 and 9).

4.2.6.5.3 Building 4 Southern Degreaser and Tank

One vapor degreaser and one aboveground TCA tank were formerly located at the southern end of Building 4. According to a report prepared in 1991, the degreaser and the 2,500-gallon exterior tank were installed and permitted in 1987 and used TCA exclusively (REWAI, July 1991). Both the tank and the degreaser were removed in December 1990. The degreaser was located inside the building, while the aboveground TCA tank was located at the exterior southwest corner of the building. There are no known historic releases from the degreaser or the TCA tank. The concrete secondary containment structure that formerly contained the TCA tank still exists at the southwest corner of the building and is currently used as a fish pond for goldfish.

A 2-inch monitoring well (MW-46) was installed to a depth of 39 feet bgs adjacent to the former TCA tank containment dike in 1990. A composite soil sample collected by hand auger methods during the construction of that well did not detect VOCs. Analysis of a groundwater sample collected from that well in May 1990 indicated high levels of TCE (2,200 µg/L) and PCE (4,400 µg/L), with lower concentrations of TCA (120 µg/L).

Seven soil borings were completed in the area of the degreaser and TCA tank during the Supplemental RI. No PADEP MSCs were exceeded in soil samples collected and analyzed from these seven soil borings. Details are included in the Supplemental RI Soils report.

During Supplemental RI and Key Well sampling events completed between 2007 and 2009, groundwater samples were collected from MW-46 in the Building 4 Southern Degreaser and Tank Area. Exceedances of TCE, PCE and methylene chloride were noted in MW-46 at maximum concentrations of 68 µg/L, 500 µg/L, and 22 µg/L, respectively.

The ratio of CVOCs (Figure 4.1-2) and molar-corrected parent products (Figure 4.1-3) demonstrate that PCE concentrations in this area of the Site increase to the south. The high historical concentration, and the current ratio and concentration of PCE in groundwater from MW-46 suggest a PCE source in this area of the Site.

4.2.6.5.4 Building 4 Summary

Trend graphs of the groundwater CVOC chemistry for wells in the TCA Tank/Bldg2Degreaser area were collated into a group of wells immediately proximal to the NBldg4 area and the wells along the west side of Bldg4, including MW-45, MW-46, MW-47, MW-49 S&D, MW-50 S&D, and MW-51 S&D. The well locations are shown on Plate 4E and the graphs are in Appendix C (The Chemical Concentration Trend Graphs section under BLDG 4). A review of the Trend Graphs suggests the following:

- MW-45 and MW-46, to the south of, and not directly impacted by the north vapor degreaser, show order of magnitude reductions in CVOC concentrations.

- The graphs of MW-47 shows evidence of a plume of TCE-concentrated water migrating through the well between 2004 and 2007, accompanied by an increase in 11DCE and TCA. Recent concentrations indicate steady increasing concentrations of CVOCs.

- The graphs of MW-49 S&D show decreases in concentrations of TCE and TCA, although samples from these wells had not been analyzed since initial samples were collected in 1992.

- MW-50 S&D are located northwest of the NBldg4 vapor degreaser in the direction of groundwater extraction well CW-17. The graph of MW-50D shows evidence of a slug of groundwater concentrated with TCE and 11DCA being pulled through this well between 2000 and 2005, then steadily declining. MW-50S experienced a steady decline since initiation of sampling, with a major increase in TCE and PCE occurring from 2002 to 2007.

- MW-51 S&D are located southwest of the NBldg4 vapor degreaser in the direction of groundwater extraction well CW-13. The graphs show steady declines since initial sample analyses conducted in 1991. Concentrations of CVOCs jumped upward after the replacement of CW-14 with CW-17 in September of 1995. MW-51D was not sampled during that time frame.

Additional efforts to characterize the groundwater quality in the CPA have identified several potential contaminant source areas as summarized below:

- **TCA Tank Area**, west side of Building 2, south of Building 91: Primarily a TCA spill and leakage area near the previous aboveground storage tanks that provided product for the vapor degreaser in Building 2.

- Activities at the former **Building 2 degreaser** located 150 feet east of the TCA tank resulted in a source of TCE, TCA and degradation products.

- The location of the former **Cutting Oil Tank**, east of Building 2 is an apparent source of TCE and other organic solvents.

- The west side of Building 2 (**WBldg2 Corridor**), north of Building 91 (MW-81 S&D) has concentrations of chlorinated VOCs with no known immediately up-gradient source.

- **NBldg4**: Part per million concentrations of TCE, PCE and TCA associated with losses from the vapor degreasing operations are found in the groundwater immediately beneath the building. In addition, former plating operations in the north end of Building 4 resulted in chromium in the groundwater.

- The south end of Building 4 (**SBldg4**) immediately adjacent to the former Solvent tank and vapor degreaser operation (MW-46) has concentrations of chlorinated VOCs in the groundwater. It is more likely that the source is near the degreaser operation than from an unknown up-gradient source.

4.2.7 Western Property Area

The WPA is defined as that portion of the property located west of the original Eden Road and the fenced plant area. Figure 4.2-5 identifies the current features and historical locations of areas of interest. This area includes a large paved employee parking area, known as the WPL, an abandoned electrical substation, and a new elevated roadway, which routes Eden Road around the WPL, along Harley-Davidson's western property boundary. Harley-Davidson's property (and the WPL) is bounded to the west by an active railroad owned by the Norfolk Southern Railway Company (Norfolk Southern). Further to the west are a wetlands area, the flood control levee and Codorus Creek. A tributary known as Johnson's Run flows westward toward Codorus Creek along the north end of the WPA. A quarry, owned by Sand Bank Hill, LLC, and a National Guard armory building are located north of Johnson's Run. A property owned by 84 Lumber adjoins the southern boundary of the WPA. Two recently constructed storm water detention basins are located in the southwest and northwest corners of the WPA. These storm basins were lined with synthetic liners to prevent storm water infiltration and to minimize sinkhole activity. Storm water flows westward via three piped outlets beneath the railroad into the wetland area located between the railroad and a constructed flood control levee and finally into the Codorus Creek.

According to the 1989 RFA (Kearney, January 1989), the WPL is identified as SWMU 14. The WPL area includes the parking area located between the original Eden Road, which ran immediately west of Buildings 1 and 4, and the railroad right-of-way.

Historical aerial photographs show that significant landfilling occurred in the WPL beginning sometime after September 1937 and ending sometime before March 1968. By 1957, two-thirds of the current WPL area was used for parking, and only the southwest quadrant of the parking lot was unpaved.

Harley-Davidson interviewed several former employees of the YNOP and AMF between 1990 and 1991 to identify areas of potential environmental concerns over the entire facility. Numerous interviewees indicated a BPA, variously called "burn pile," "west magnesium burn pile," "magnesium burn area," and "paint filter burn area" located in the northern-most end of the WPL. Also in the WPL was an area identified as "Naval Ordnance Plant (N.O.P.) Dump," generally to the south of the BPA; and a “firefighter training area,” generally to the east of the BPA and west of the former electrical substation.

During 2004, Springettsbury Township, as part of a Pennsylvania Department of Community and Economic Development funding project, rerouted Eden Road along the western edge of the Harley-Davidson property.

The Supplemental RI Soils report provides numerous maps and data summaries of the WPL. The reader should refer to that report if more detail is desired. Sources and suspected sources of groundwater contamination, shown on Plates 4A-C consider the soils information.

4.2.7.1 West Parking Lot

Environmental investigations in the WPL started in 1986, with the installation of three groundwater-monitoring wells (MW-6, MW-7, and MW-8). Analyses of groundwater from these wells indicated that groundwater had been impacted by chlorinated solvents. VOC concentrations in these wells included 2,076 µg/L TCE and 1,040 µg/L cis12DCE in a sample collected from well MW-7, and 944 µg/L TCE, 750 µg/L PCE and 1,040 µg/L cis12DCE in a sample collected from well MW-8. Sampling of well MW-6, north of the WPL and west of the NPA, indicated extremely minor impact from fYNOP COCs (TCA and 11DCA at 4 and 16 µg/L, respectively).

Additional investigative activities were conducted at the WPL in 1990. Three multilevel piezometers (MW-37 S&D, MW-38 S&D and MW-39 S&D) and one test recovery well (CW-9) were installed along the western perimeter of the WPL. All groundwater samples collected during this investigation contained TCE and PCE. The MW-37 piezometer cluster also contained elevated concentrations of TCA while the MW-38 and MW-39 clusters contained elevated concentrations of cis12DCE. PCE was the prominent VOC at the MW-37 well cluster while TCE and cis12DCE were the prominent VOCs in groundwater samples collected at well clusters MW-38 and MW-39.

Shallow groundwater beneath the WPL was measured at a depth of approximately 16 feet bgs in 1991, prior to any groundwater remediation. Shallow groundwater beneath the WPL flowed to the west toward the Codorus Creek (REWAI, July 1991). An original groundwater contour map from that report is included as Figure 3.3-5. The groundwater table surface is located within unconsolidated materials and residual limestone soils that provide vertical communication with the underlying fractured and solutioned limestone bedrock (REWAI, July 1991). TCE, PCE, and TCA have historically been the prominent VOCs detected in groundwater at the WPL.

A pumping test was conducted on test well CW-9. Results indicated a transmissivity of 9,300 gpd/ft and a S_y of approximately 0.02, typical for a karstified aquifer in Cambro-Ordovician carbonates in south–central Pennsylvania (REWAI, July 1991). A groundwater extraction and treatment system was subsequently designed and installed for the WPL Area. The purpose of the WPL groundwater extraction system is to prevent off-Site migration of groundwater containing dissolved VOCs and (including CW-15A) to control the migration of VOCs in a plume located near the northwest corner of Building 4. Extraction wells CW-9, CW-13, CW-14 and CW-15A (near Building 4) began operation in May 1994. Extraction well CW-14 was replaced by well CW-17 in September 1995, due to excessive sediment buildup in the CW-14 well.

Extracted groundwater from the WPL wells is conducted via underground piping to the groundwater treatment system located in Building 41. The wells are individually piped to the groundwater treatment plant so that flow control, flow measurements and water samples may be obtained for each well at this central location. The combined pumping rate of the four wells in 2009 was 200 gpm. The groundwater extraction and treatment system is discussed in detail in Section 5.4.

During the Site-wide RI performed at the Site between 1998 and 2002, two nested piezometer pairs (MW-74 S&D and MW-75 S&D) were installed at the WPL (Langan, July 2002) at known areas of high concentrations of CVOCs, in order to assess the vertical extent of CVOC presence beneath the WPL. Initial sampling performed at MW-74 S&D, located in the northern WPL near well pair MW-39 S&D detected TCE concentrations of 110 and 240 μg/L, respectively, at depths of 175 to 201 feet bgs and 220 to 250 feet bgs, respectively. Initial sampling performed at the southern well pairs (MW-75 S&D) indicated that TCE and PCE were present at part per million concentrations. TCE, PCE and TCA concentrations in groundwater samples from MW-75S were measured at 15,000 μg/L, 30,000 μg/L and 1,200 μg/L, respectively. Subsequent sampling indicated a similar sustained level of CVOCs in well MW-75S. TCE, PCE and TCA concentrations in groundwater samples from MW-75D were initially measured at 3,200 µg/L, 6,200 µg/L and 240 µg/L, respectively.

A detailed investigation of soil and fill along the south, west and north perimeters of the WPL and the Burn Pile Area (to be described in the next subsection) was conducted in preparation for the construction of Eden Road in 2004. Concentrations of polychlorinated biphenyls (PCBs), metals and CVOCs were found in this area and reported in SAIC, May 2004. The soils supplemental RI report (SAIC, December 2009b) describes the constituents of fifteen areas labeled A through O. Wells MW-93S and MW-93D were installed in April 2004, during the Eden Road investigation. This two-level cluster well was installed immediately west of high concentrations of VOCs and PCBs found in the soil (Areas J and K of SAIC, May 2004). TCE and PCE were the prominent VOCs detected at the MW-93S and MW-93D cluster. The TCE and PCE concentrations detected in a sample collected from well MW-93S were 8.8 µg/L and 16 µg/L, respectively. The TCE and PCE concentrations detected in a sample collected from well MW-93D were 430 µg/L and 340 µg/L, respectively.

In 2006, a test extraction well CW-20 was installed in the southwestern corner of the WPL, near well pairs MW-39 S&D and MW-75 S&D (SAIC, June 2008). The intended purpose of this extraction well was for recovery of VOC-impacted groundwater and to enhance the containment of groundwater. Testing was conducted to determine the impact of the test well and the existing extraction wells on the surrounding aquifer and to gather data to use in the design of a modified well pumping network. An aquifer pumping test was conducted on extraction well CW-20 and a second pumping test was run on the existing WPL extraction wells while monitoring the wells surrounding CW-20.

CW-20 was pumped at a rate of 60 gpm. A transmissivity of 5,200 gpd/ft was calculated for this well. Specific yields of 0.09 and 0.37 were calculated using wells immediately adjacent to the pumping well (MW-75D and MW-37D, respectively). Measurements from more distant wells (greater than 140 feet) yielded specific yields of 0.004 (at CW-9) and 0.01 (at MW-93D). After 72 hours of pumping, 1.59 feet of drawdown was measured at well location MW-8, 280 feet to the northeast of CW-20. In contrast, 0.48 feet of drawdown was measured at well MW-38D, 280 feet to the northeast of CW-20. These data are an indication of a preferential flow pathway in a northeast to southwest direction orientation from the CW-20 well head. This direction is consistent with the location of a mapped fracture trace. The northeast-to-northwest drawdown ratio is approximately 2:1, which is equivalent to the directional transmissivity contrast.

A second groundwater pumping test was subsequently conducted to compare the aquifer influence of the existing WPL collection wells (CW-9, CW-13, CW-15A and CW-17) in this southwest corner of the WPL to the influence of CW-20. Pumping wells were shut down and the aquifer was allowed to equilibrate. Then the WPL wells were operated normally while water levels were measured. At 72 hours of pumping, drawdowns of 2.94 feet (MW-37D) and 2.92 feet (MW-75D) were measured in deep wells proximate to well CW-20. These values exceed the maximum drawdown recorded at 72 hours for the same locations (1.93 feet at MW-37D and 2.22 feet at MW-75D). Shallow well MW-37S recorded drawdown of 1.85 feet during the WPL pumping test, compared to 1.22 feet during the CW-20 pumping test. These results suggest that groundwater capture in the southwest corner of the WPL is being maintained by the existing WPL extraction system.

Harley-Davidson’s SRBC permit authorizing pumping wells and pumping rates was modified to include CW-20 in the WPL groundwater extraction scheme. Action to connect CW-20 to the groundwater extraction system is pending further evaluation, which will be considered during the FS.

4.2.7.2 Burn Pile Area

The BPA is located north-northwest of the WPL and was historically used as a burn area to incinerate combustible waste materials. Historical aerial photographs were used to identify a general area of disturbance. Early investigations (REWAI, July 1991, March 1992a; Langan, July 2002) in this management area have included geophysical surveys, soil gas surveys, test pits, and soil borings/sampling. The results of the interim RI concluded that much of the BPA is covered with up to three feet of fill, comprised of various debris such as cinder blocks, wood, metal, concrete, glass, and containers. In addition, coal, slag, gray sludge, and resinous material were found in this area. The fill and soil material contain various chemicals including VOCs, SVOCs and metals. The COCs in the soils and fill include several polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene, TCE, PCE and metals (antimony, cadmium, lead, and nickel). In addition, the resinous material identified in one test pit was found to contain xylenes and PCBs.

A groundwater monitoring well (MW-76) was installed in the northwest corner of this area in 1999 (Langan, July 2002). Results of sampling and VOC analysis indicated 50 µg/L of TCE and 20 µg/L of PCE in the groundwater at the MW-76 location. This well was abandoned in early 2004 due to the planned Eden Road relocation construction.

4.2.7.3 Area B

Surface soil within Area B, which encompassed an area of approximately 9,000 ft^2 west of the BPA, was found to contain debris, elevated concentrations of VOCs, metals and PCBs. The subsoil within Area B also contained elevated concentrations of VOCs, which were not planned to be addressed as part of the Eden Road construction. Following completion of the construction activities, temporary fencing was installed to limit access by workers or trespassers. A geosynthetic cap was installed over this area in the fall of 2005. Contractors installed approximately 9,000 ft^2 of 40-mil polypropylene liner over the entire area and covered the liner with 18 inches of clean subsoil and 6 inches of topsoil. The cap provides for reduced infiltration of s0rface water and eliminates the direct contact exposure pathway. The location is called out on Figure 4.2-5. It is also illustrated as the source area for TCE and PCE underlying and northwest of Eden Road in the northwest corner of the property on Figure 4.1-4 and Plate 4A.

4.2.7.4 WPL/BPA Supplemental RI Investigations

A series of three wells, MW-105 in the northwest corner of the BPA, MW-106 in the central portion of the WPL near the western property line, and MW-107 in the southwest corner of the WPL were installed in the overburden to evaluate the potential that groundwater could find a preferential pathway off-Site in saturated unconsolidated materials above the bedrock. Since rounded cobbles and gravels had been encountered in solution channels in numerous wells in the carbonate aquifer, the investigation explored the possibility that an alluvial deposit of sediments with moderate to high permeability could have been deposited on top of the karstic bedrock surface.

Monitoring well MW-105 was installed as an overburden well on the eastern edge of Area B at a total depth of 22 feet bgs where auger refusal was encountered. Soils encountered during drilling consisted of silt to silty sand with minor gravels and minimal saturated thickness. MW-106 was installed to total depth of 28 feet bgs, where split-spoon refusal was encountered. The bottom five feet of the hole (the saturated portion) penetrated silty angular to subangular gravel. MW-107 was installed to a depth of 23 feet bgs where split-spoon refusal was encountered in limestone. The wellbore at the MW-107 location encountered clay residuum.

Based on these results, there appears to be some variety of grain size within the unconsolidated materials above the bedrock surface in the WPL, including coarser subangular material that could have been derived from an alluvial source. However, an alluvial channel that could preferentially direct significant groundwater flow was not identified.

Maximum concentrations of TCE, PCE and cis12DCE were detected in MW-105 at 280 µg/L, 1200 µg/L and 120 µg/L, respectively, suggesting groundwater impacts due to adjacent Area B soils. Analysis of groundwater samples collected from MW-106 indicated maximum concentrations of TCE and PCE of 110 µg/L and 10 µg/L, respectively. Analysis of groundwater samples collected from MW-107 indicated concentrations of TCE and PCE of 16 µg/L and 23 µg/L, respectively.

During Supplemental RI investigation activities completed in 2007 and 2008, four wells were installed in Area B of the West Parking Lot to evaluate the impact of the high concentrations of CVOCs identified in shallow soil in this area and represent the groundwater quality of abandoned well MW-76. Well pair MW-96 S&D was installed to depths of 40 and 90 feet bgs, respectively. Monitoring well MW-95 was installed to a total depth of 51 feet bgs along the north edge of Area B. MW-105 was discussed previously as a shallow well drilled to evaluate the potential for alluvial deposits. Area B monitoring wells were sampled twice during 2008 remedial investigation activities and once as part of the 2009 Key Well sampling event. TCE was the only compound detected above a PADEP MSC in the sample collected from well MW-95 with a maximum concentration of 34 µg/L. TCE, PCE and methylene chloride detections in MW-96D were 460 µg/L, 32 µg/L and 6.9 µg/L, respectively. Maximum concentrations of TCE, PCE and methylene chloride detected in MW-96S were 1400 µg/L, 590 µg/L and 17 µg/L, respectively.

MW-97 was installed in the west central WPL area near MW-106. Groundwater samples collected from MW-97 during 2008 and 2009 sampling events yielded concentrations of TCE, PCE, cis12DCE, methylene chloride and vinyl chloride at maximum concentrations of 420 µg/L, 26 µg/L, 270 µg/L, 16 µg/L and 4.1 µg/L, respectively. MW-106, screened from 18 to 28 feet bgs, had TCE concentrations of 79 to 110 µg/L, with concentrations of PCE about an order of magnitude lower.

Southern WPL wells exhibited numerous exceedances of TCE, PCE, TCA, 11DCE, cis12DCE, methylene chloride, with single occurrences of semi-volatile constituents benzo (g,h,i) perylene, and dibenzo (a,h) anthracene. Maximum concentrations of TCE, PCE, TCA and methylene chloride detected in MW-75S samples included 10,000 µg/L, 32,000 µg/L, 1,000 µg/L and 5,000 µg/L, respectively. Cis12DCE was detected in samples collected from well MW-75D at a maximum concentration of 840 µg/L.

In summary, as shown on Plates 4A through 4D, high concentrations of TCE, PCE and their degradation product cis12DCE are concentrated west of the north end of Building 4, in the northwest corner of the WPL, and in the southwest corner of the WPL as a result of separate sources. Pie diagrams showing clearly different ratios of CVOCs support that conclusion as do the general distribution and the inferred groundwater gradient.

4.2.7.5 Codorus Creek Levee Wells – WPL

Four well groups were installed along the eastern side of the Codorus Creek levee as part of the 2007 and 2008 supplemental RI remedial investigation activities. Well triplet MW-98 S/I/D was installed to total depths of 68 feet bgs, 105 feet bgs and 172 feet bgs, respectively. Monitoring well pair MW-99 S&D was installed to total depths of 74.3 feet bgs and 142 feet bgs, respectively. Well triplet MW-100 S/I/D was installed to total depths of 51 feet bgs, 66 feet bgs and 114 feet bgs, respectively. Well pair MW-101 S&D was installed to total depths of 40 feet bgs and 115 feet bgs, respectively. These nested piezometer couplets and triplets were installed to assist in evaluating groundwater capture and to evaluate chemical flux to the creek. As described in Section 2, the wells were successfully positioned on groundwater preferential flow paths (conduits), located using a combination of fracture trace analysis and Electrical Imaging. Cross section C-C’, shown on Figure 4.2-6 shows the locations and depths of the wells on the electrical imaging modeling.

Starting in the north, analysis of groundwater collected from well MW-98S and well MW-98I from the solution channels screened by these wells, detected maximum concentrations of TCE at 26 µg/L and 30 µg/L, respectively. PCE was detected in samples from well MW-98S and MW-98I at 5.7 and 9.4 µg/L, respectively. MW-98D penetrated the Harpers Phyllite, a much less permeable noncarbonate rock unit underlying the limestone. PCE was not detected, and the TCE concentration was below the analytical laboratory reporting limit, with an estimated maximum detection of 0.23J. As depicted on Plate 4A and Figure 4.1-4, TCE concentrations in the MW-99 and MW-100 multi-level wells exceed 100 µg/L. There is no apparent pattern regarding concentration differentials with depth. PCE concentrations in MW-99 S&D are on the order of 10 µg/L, while at MW-100 S,I&D PCE concentrations are around 100 µg/L. The groundwater quality analyses in the southern most Levee well pair (MW-101 S&D) detected maximum concentrations of 23 µg/L and 30 µg/L, respectively for TCE, and 4.2 µg/L and 8.8 µg/L, respectively for PCE.

4.2.8 Building 3 (Softail Plant)

Harley-Davidson expanded its facility through the construction of a new Softail production plant beginning in 2001. This new facility was constructed in the eastern portion of the Site, in the vicinity of the former test track. Due to the potential for shallow VOC-impacted groundwater to discharge to the surface and to the lowest floor of the facility, a groundwater collection system was designed as part of the project. The groundwater collection system for the Softail site consists of a shallow interceptor trench (or toe drain), a deep interceptor trench and drain, and a capture well (CW-19). All three components of the groundwater collection system are designed to direct flow to a pumping station. From the pumping station, the groundwater is transported via underground piping to the groundwater treatment facility located in Building 41. Groundwater collection via this system was initiated in March 2002. Volume of water collected from this system is highly variable, ranging from 0.8 to 1.3 million gallons per year.

4.2.8.1 Toe Drain System

The northeast corner of the Softail site was identified as the area with the most potential for groundwater to discharge to the surface after final grading. To prevent the potential for human contact with the groundwater, a toe drain was installed at the bottom of the slope cut. This was designed to collect groundwater from this area, thus lowering the groundwater levels and minimizing surface discharges down-gradient of the toe drain. The toe drain was constructed as a shallow trench drain filled with gravel and 4-inch perforated PVC piping. The toe drain trench was lined with geotextile fabric to minimize sediment from entering the piping. An impermeable layer was placed on top of the trench to reduce infiltration of surface water into the drain. The toe drain was connected to the lift station described in Section 4.2.8.4.

In late 2010, in conjunction with the construction of the northern addition to Building 3, the toe drain was rerouted and a seep interceptor drain was added.

4.2.8.2 Deep Trench Drain

The deep trench drain was installed along the eastern perimeter of the building due to the high probability of groundwater levels encountering the lower floor of the facility. The deep trench drain is sloped to gravity drain to the lift station. The depth varies from 22 feet to 26 feet bgs. Four cleanouts were installed along the 760-foot length of piping. The deep trench drain was constructed of perforated PVC piping in a trench filled with coarse gravel. Prior to installation of the piping and drainage course, the trench was lined with a geotextile fabric to minimize sediment mixing with the gravel.

4.2.8.3 Capture Well (CW-19)

A capture well (CW-19) and force main were installed in the paint sludge pit area of the new plant. The paint sludge pit area consists of a 27-foot deep pit used to house the paint sludge holding tank. CW-19 was installed 7 feet deeper than the pit so that the well could be programmed to begin pumping prior to the groundwater level reaching the elevation of the bottom of the pit. The force main was installed to transfer groundwater captured in the well to the lift station. The force main was installed with a slope toward the lift station so that groundwater does not remain in the line after the well pump stops running. Groundwater has not risen to the level that the pump in CW-19 has been required to operate due to the effectiveness of the deep trench drain.

4.2.8.4 Lift Station

The lift station is located north of the Softail building. The lift station receives groundwater from the toe drain system and the deep trench, and conveys it to the groundwater treatment plant in Building 41. The lift station controls and pumping operations have been automated and pump operation can be controlled remotely.

Sampling of groundwater collected by the lift station was initially performed in June 2003 in response to a reporting requirement for the SRBC. Two groundwater samples were collected from the lift station in 2004 and analyzed for VOCs. A review of the results from the June and December 2004 sampling events indicate that TCE is the most dominant VOC present at this location (2.4 µg/L during both sample events). The analytical results from June and December 2004 are recorded in the 2004 Groundwater Extraction and Treatment System Annual Operations Report (SAIC, March 2005).

4.2.8.5 Building 3 Area Groundwater Migration

Numerous monitoring wells were abandoned during the construction of Building 3. Two wells were installed in this area during the Supplemental RI to determine the impact on the groundwater flow and COC migration. MW-111 was installed to the east of Building 3, and east of the toe drain in the sandstone aquifer. MW-111 is west and down-gradient of MW-2, and was installed to replace MW-21, abandoned to make way for the construction of Building 3. MW-111 yielded MSC exceedances of TCE at 33 µg/L. Analyses of three groundwater samples from well MW-111 for total and free cyanide yielded results below the detection limit. MW-112 was installed at the southwest corner of Building 3, and west of the deep drain in the limestone aquifer to a total depth of 120 feet bgs. TCE was detected in groundwater sampled from this well at a maximum concentration of 10 µg/L.

Groundwater from the toe drain and the deep trench drain were sampled separately by catching water in a container as it drained from the pipes entering the lift station in May 2008 (Supplemental RI sampling Round 1). No target compound list (TCL) analytes exceeded groundwater MSCs. TCE and PCE were detected at 3.1 and 2.1 µg/L respectively.

5 CONTAMINANT FATE AND TRANSPORT

This report section combines the information provided in the previous two sections into an analysis of the contaminant fate and transport mechanisms that may explain the current distribution of COCs at the Site and predict future trends. This section begins with a discussion of the fate and transport mechanisms potentially affecting releases of COCs at the Site and then examines evidence for how these mechanisms are affecting sources, plumes and the effectiveness of current remedial measures.

5.1 Description of Fate and Transport Mechanisms

The following subsections present a discussion of the various fate and transport mechanisms that affect the distribution and transport of COCs that are classified as chlorinated VOCs (i.e., CVOCs). As such this subsection discusses the fate and transport mechanisms that apply to CVOCs as DNAPLs and as dissolved mass in groundwater at the fYNOP. In this discussion, reference will be made to Figures 5.1-1 and 5.1-2, which summarize the geology, hydrogeology and fate and transport mechanisms that are essential to understanding the pattern of occurrence and concentrations of COCs in the various environmental media that have been impacted by historical releases at fYNOP. Figure 5.1-1 addresses the carbonate aquifer portion of the Site and off-Site areas to the west, and Figure 5.1-2 addresses the noncarbonate aquifer. As stated in Section 4 there are other Site-related COCs (gasoline components, chromium, 1,4-Dioxane) in groundwater at fYNOP. These compounds have different fate and transport properties than DNAPLS, and are not specifically addressed in this section, because of the minor impact those compounds will have on subsequent steps and final remedies at the Site.

Columns #1 and #2 on Figure 5.1-1 summarize the geology and hydrogeology associated with the carbonate aquifer and the overlying soil and residuum. As described in Section 3.3, the area underlain by the Vintage Formation has a surficial soil or fill layer underlain by residuum. The surface of the bedrock is highly solutioned, and exhibits a cutter and pinnacle surface, with residuum and alluvium infilling between pinnacles. The water table is found in the residuum above the average bedrock surface elevation, with a few pinnacles reaching above the water table. Above the water table, the vadose zone is characterized by the presence of both air and water in the pore spaces and is also termed the “unsaturated zone”. Below the water table, the geologic materials are shaded blue on Column #1, indicating saturation of the intergranular and intragranular porosity of the soils and the primary (matrix) and secondary (fracture and/or solution-enhanced) porosity of bedrock in the saturated zone. Open water-filled voids may occur within the residuum and solution-enhanced cavities in the bedrock may be completely or partially filled with residuum and/or sediment. Open voids and bedrock cavities containing sediment will be filled with water below the water table.

Columns #1 and #2 on Figure 5.1-2 summarizes the geology and hydrogeology associated with the noncarbonate aquifer and the overlying soil and residuum in the Antietam Formation. The soil and residuum are relatively thin compared to that developed in the carbonate rock. The soil-bedrock surface roughly parallels the ground surface, in contrast to the highly irregular bedrock surface in the carbonate rocks. In addition, the change from soil to rock is gradational, with the top of bedrock being partially decomposed by weathering processes. As a result, joints, fractures, and bedding planes in the bedrock are somewhat enlarged near the soil-bedrock interface. This weathered condition dissipates with depth. The water table in the area underlain by quartzitic sandstone occurs exclusively within the bedrock.

The following subsections describe the transport and fate mechanisms that affect the movement and distribution of CVOCs in the solid (soil and bedrock), aqueous (pore water and groundwater), and vapor (soil air) phases affected by releases of COCs.

5.1.1 Dense Non-aqueous Phase Liquid Transport

The most significant COCs at this Site were released in the form of DNAPLs which are, by definition, immiscible in water and exhibit a higher specific gravity than water. These DNAPLs include the principal halogenated solvents used at this Site - PCE, TCE and TCA. This subsection describes the anticipated transport mechanisms associated with releases of DNAPL to soil and bedrock materials characteristic of this Site.

At the fYNOP Site, the factors affecting the transport of a DNAPL release are highly dependent on the geologic characteristics at the location of the release. For this reason, the following discussion of the anticipated transport of DNAPLs released at this Site will address those mechanisms in each of the geologic environments depicted separately on Figures 5.1-1 and 5.1-2.

Carbonate Rock and Residuum: As shown in Column #1 and annotated in Column #3 on Figure 5.1-1, initially DNAPL released to the subsurface soil in source areas will seep vertically downward within the unsaturated zone. However, separate phase liquid can also move horizontally depending on the vertical variation in water content of the soil and its texture and structure. As the DNAPL release approaches the top of the capillary fringe (saturated zone above the water table where water is retained under capillary forces that corresponds to the top of the saturated zone shown on Figure 5.1-1), it will begin to spread laterally due to the difficulty of displacing water contained in water-filled voids in the saturated zone. If sufficient accumulation occurs at the water table, the DNAPL will penetrate into the saturated zone. DNAPL will then move downward within the saturated soil column, again potentially deflected horizontally in response to changes in soil texture. Where vertical erosion channels exist in the regolith, DNAPL will migrate rapidly downward, following these channels.

If the DNAPL encounters the top of bedrock or just a finer-textured soil layer such as clay or silt underlying the upper soil or fill, it may spread out and form a zone of continuously DNAPL-saturated soil within which most of the water has been displaced. Such an accumulation is commonly referred to as a “pool” but should more accurately be referred to as a DNAPL accumulation zone. This is in contrast to a zone of DNAPL residual concentration in which DNAPL occupies a portion of the pore space or fracture opening together with water and, in the vadose zone, with vapor. Feenstra and Guiguer in Chapter 7 of Pankow and Cherry, 1996 indicate that DNAPL may occupy 50 to 70% of the pore space in an accumulation zone, but typically less than 10% of the pore space in a residual zone.

The principal control over the lateral migration of DNAPL, within the epikarst layer as shown on Column 1 of Figure 5.1-1 is the pinnacled soil-bedrock interface. The DNAPL will form an accumulation zone in closed depressions in the bedrock surface, or be directed along this relatively impermeable interface, deeper into the karstified aquifer. The DNAPL will then migrate through vertical and lateral solution channels that are open (filled with water) or filled with water-saturated residuum and sediment (sand, silt, clay, gravels and rock fragments). Vertical movement of DNAPL in open voids is essentially unimpeded by capillary forces due to the size of the opening. The principal drivers of that downward transport are the DNAPL’s greater specific gravity than the water that fills the voids and its immiscibility in water. By contrast, movement of DNAPL into and through granular residuum is strongly controlled by the size and geometry of pores and pore throats in that material. DNAPL accumulation zones in open voids may contain literal “pools” of separate phase liquid while the DNAPL mass per unit volume of accumulation zones in residuum is capped by the porosity of the residuum itself.

DNAPL can also migrate vertically and laterally into water-filled discontinuities (i.e., joints, bedding-plane partings and fractures in the bedrock) that are not solution-enhanced. The ease with which DNAPL will penetrate into such discontinuities is strongly controlled by the aperture of the parting in the rock, much as it is controlled by the geometry of pore throats in granular soils (Kueper and McWhorter, 1991).

As discussed in Section 3.3.2, these carbonate rocks may exhibit average matrix porosity between 6% and 9%. However, the geometry of those pores is such that mobile DNAPL will more easily follow discontinuities that comprise the secondary porosity, including solution-enhanced discontinuities of the rock rather than penetrating into the primary pores contained in the rock matrix itself.

Another DNAPL transport mode unique to karst aquifers is the bulk transport of DNAPL in water flowing at high velocities through open voids (Loop and White, 2001). Bulk transport can occur in open (sediment-free) portions of solution cavities during elevated flow conditions when water flows over a DNAPL pool and entrains droplets of free product. Likewise, open channel flow may entrain sediment particles together with DNAPL that may be present due to DNAPL penetration into the porous residuum or sediments that occupy the bottom of the channel.

Quartzitic Sandstone and Residual Soil: Figure 5.1-2 shows the simpler pathway of DNAPL releases over and within the quartzitic sandstone (non-carbonate) aquifer. The DNAPL seeps vertically downward through the soil and residuum layer, where textural and structural contrasts control lateral migration, as described for the carbonate aquifer. As it encounters the weathered rock zone, DNAPL is directed laterally by the porosity contrast between the residuum and the rock, forming accumulation zones, and preferentially following discontinuities in the weathered bedrock. The primary porosity of the heavily weathered quartzitic sandstone bedrock may be greater than that of the carbonate rock resulting in greater potential for DNAPL to enter the pore spaces within the rock. However, the principal migration pathway within the quartzitic sandstone is still expected to occur through discontinuities corresponding to fractures, joints and bedding planes.

In most areas underlain by quartzitic sandstone of the Antietam Formation, the water table occurs in the weathered bedrock or competent bedrock geologic zones. As in the residuum in the area of the Site underlain by carbonate bedrock, DNAPL will accumulate at the water table until it overcomes the capillary pressures and displaces the water contained in discontinuities in the bedrock and continues to migrate downward. As the DNAPL migrates downward into competent (unweathered) bedrock, it will encounter increasing resistance to migration through tight discontinuities and reduced primary and secondary porosity. In fact, it is likely that the primary porosity of the unweathered quartzitic sandstone may be lower than that of the carbonate bedrock beneath the Site. Thus the potential for DNAPL to penetrate into the matrix of unweathered quartzitic sandstone is expected to be low.

As DNAPL migrates along pathways in both the carbonate and quartzitic sandstone aquifers and their residual soils, the available mobile DNAPL will be reduced by retention in accumulation zones and as trapped globules and ganglia in soil and fractures along the migration pathway in what are termed DNAPL residual zones. Eventually this process of retaining DNAPL along migration pathways will occur until insufficient mobile DNAPL remains to support further downward migration. DNAPL migration typically occurs fairly rapidly to this state of equilibrium, at which point the DNAPL in the subsurface is held in place by capillary forces in accumulation and residual DNAPL zones.

5.1.2 Aqueous Phase Transport

Once a DNAPL release has reached equilibrium in the subsurface such that, with the exception of entrainment in high velocity open-channel flow, separate phase transport is no longer relevant, the mass of DNAPL is gradually diminished by two mechanisms shown in Columns #4 and #5 on Figures 5.1-1 and 5.1-2. These are: 1) dissolution in pore water in the vadose zone and groundwater in the saturated zone; and 2) evaporation to soil vapor in the vadose zone. This subsection will deal with the first of these two mechanisms.

Dissolution of the DNAPL in pore water and groundwater will create an aqueous (dissolved) phase of the CVOC that typically will extend along the entire DNAPL migration pathway(s). In the area directly impacted by a DNAPL release (i.e., a source area), aqueous concentrations near the interface of water and DNAPL will approach the solubility of the CVOC. However, when the DNAPL is a mixture of more than one CVOC, such as PCE, TCE and TCA, Feenstra and Guiguer in Chapter 7 of Pankow and Cherry, 1996 note that the solubility of each constituent in the mixture must be adjusted downward based on the mole fraction of that CVOC in the mixture.

Figure 5.1-3 (after Figure 7.2, Feenstra and Guiguer in Chapter 7 of Pankow and Cherry, 1996) shows that dissolution from a DNAPL pool is rate limited by aqueous diffusion, while dissolution from residual DNAPL within pores of granular soils (as shown) or partially filling bedrock fractures is enhanced by the flow of groundwater around the DNAPL globules and ganglia. This configuration results in exposure of greater surface area per volume of DNAPL to dissolution by flowing groundwater and a mechanism to sweep away the dissolved fraction of the CVOC. However, Figure 5.1-4 (after Figure 7.10, Feenstra and Guiguer in Chapter 7 of Pankow and Cherry, 1996) shows that even in a residual zone there are dead-end pores, and in the case of bedrock, dead-end fractures, within which globules or ganglia of DNAPL will remain after the most easily dissolved material has been removed. Dissolution of this remaining mass of DNAPL in residual zones will also be rate-limited by aqueous diffusion as in the case of dissolution from pools.

Once DNAPL has come into contact with pore water and gravitational water in the vadose zone and groundwater in the saturated zone, and an aqueous (dissolved phase) of the CVOCs develops by direct dissolution from the DNAPL, Column #4 on Figures 5.1-1 and 5.1-2 depicts the aqueous transport mechanisms associated with the movement of CVOCs dissolved in water. Essentially there are two principal mechanisms for aqueous phase transport of dissolved COCs. These are advective flow and diffusion. Aqueous phase advective transport (i.e., transport of dissolved CVOCs in flowing groundwater) is responsible for the movement of dissolved CVOCs from the source into the plume over comparatively large distances. Aqueous diffusion, on the other hand, accounts for movement of dissolved phase CVOCs over comparatively short distances from either the source or the plume into pores of the surrounding aquifer material through which advective transport is otherwise not occurring on any meaningful scale. Figure 5.1-5 (Kennel, 2008) shows conceptually the relationship among these mechanisms in fractured bedrock containing a point source and a plume of CVOCs.

5.1.2.1 Aqueous Phase Advective Transport

Aqueous phase advective transport is the process that generates a plume of dissolved CVOCs extending from the source area to the point of discharge to surface water or an extraction well. At any given location beneath the Site there are two natural sources of water. These are recharge derived from infiltration of precipitation at the ground surface and upgradient groundwater flow ("lateral advection" on Figures 5.1-1 and -2). Within the vadose zone, infiltration moves downward as gravitational pore water draining freely to the water table. In a DNAPL source zone, this gravitational water can dissolve soluble compounds directly from separate phase liquid associated with a DNAPL source in the vadose zone and transport that dissolved mass downward into the saturated zone. Upgradient groundwater flow entering a given area can either be clean if it has not already been impacted by a source or it can contain dissolved CVOCs either from contacting an upgradient DNAPL source in the saturated zone or as a result of mixing with contaminated recharge also at some upgradient location.

As shown on Figure 5.1-1 there is also potential for vertical advection of groundwater downward into and through the very permeable fractured and solution-enhanced zones in the carbonate bedrock. This potential exists because there is a slight vertical downward gradient within the carbonate aquifer during pumping, and because conduit flow can occur in response to minimal head differential. The gradient prior to inception of pumping is unknown, but after recovery from pumping in November 2008, some well pairs showed a modest downward gradient and some showed a modest upward gradient.

In the noncarbonate bedrock, infiltrating water from precipitation in the vadose zone migrates vertically, as it does overlying the carbonate rocks, and may dissolve soluble compounds directly from the separate phase liquid and transport that dissolved mass downward into the saturated zone. Vertical percolation of infiltrating water to the water table is through the discontinuities within the quartzitic sandstone. Lateral advection through the discontinuities in the rock (bedding plane partings, joints and fractures) is the primary transport mechanism; however, downward vertical advection is possible due to the downward gradient measured in most well pairs screened in the quartzitic sandstone of the Antietam Formation. Groundwater migrates from the quartzitic sandstone into the carbonate aquifer, which serves as an effective drain for the quartzitic sandstone aquifer due to the higher transmissivity and lower head potential in the carbonates.

5.1.2.2 Aqueous Phase Diffusion

In addition to horizontal and vertical groundwater flow, dissolved CVOCs can be transported by aqueous diffusion into groundwater contained in pores bounded by individual soil particles in the residuum or sediments and into the primary (matrix) porosity of the bedrock in response to a chemical concentration gradient. This can occur in both the DNAPL source area and the plume emanating from it.

5.1.2.2.1 Matrix Diffusion in the DNAPL Source Area

Studies of DNAPL fate at the University of Waterloo (UW) have shown that DNAPL held in bedrock fractures by capillary forces may, depending on the characteristics of the surrounding rock matrix, diffuse over time into the pore water contained in the rock (Kennel, 2008). Figure 5.1-6 taken from Kennel, 2008 shows that given sufficient time and the proper characteristics of the rock matrix surrounding a fracture, this process, otherwise termed “matrix diffusion”, can result in the complete elimination of the separate phase liquid from individual fractures. Where this occurs, the mass of CVOCs previously present as DNAPL in the fractures is then present as aqueous phase, high concentration dissolved CVOC in pore water within the rock matrix adjacent to the fracture that previously contained the DNAPL.

At fYNOP, matrix diffusion will occur not only into the solid rock surrounding fractures and open voids, but also where DNAPL is in contact with porous granular material, including the residuum and sediment that partially or completely fill voids in the carbonate bedrock (4A on Figure 5.1-1). In the case of diffusion into the residuum and sediment, the process will be two-stage. First the dissolved CVOCs will diffuse into the intergranular water-filled pores bounded by grains of soil. As the aqueous concentrations build up within these pores, the CVOCs will then begin to diffuse into the intragranular pores (i.e., the pores associated with the primary porosity of individual soil grains that are eroded fragments of sedimentary rocks). This process will continue for as long as there is a chemical gradient between the concentrations of groundwater in contact with DNAPL and the aqueous concentrations within the intergranular and intragranular pore water. Since many DNAPL releases have remained unremediated for several decades, there can be substantial transfer of mass from the separate phase to the aqueous phase by aqueous diffusion, with the latter becoming the repository of a significant percentage of the mass originally released to the environment.

At any given DNAPL site, it is difficult enough to approximate the mass of DNAPL that has been released to the environment, let alone being able to assess the extent to which matrix diffusion has diminished the percentage of the mass remaining as separate phase liquid. As will be discussed in a later section, the best that can be done is to examine Site data for evidence of separate phase liquid and the occurrence of matrix diffusion. What is certain is that once separate phase DNAPL comes into contact with a geologic medium that exhibits interconnected pores containing clean pore water, a chemical concentration gradient exists that will result in the diffusion of mass from the dissolving DNAPL into the adjacent pore water.

Figure 5.1-7 depicts a conceptual model of three stages in this source area evolution within the carbonate bedrock aquifer. Stage One is the emplacement of the DNAPL source following a release to the environment of separate phase solvents. This stage shows a deep vertical DNAPL transport pathway with the development of residual DNAPL zones and accumulation zones along that pathway, including penetration into fractures and voids in the carbonate bedrock and pore spaces in the residuum and the occurrence of actual DNAPL pools in open voids. Stage Two of that process depicts the initial stages of mass transfer from the DNAPL to pore water in the rock matrix and within the intergranular porosity of the residuum and sediments. Finally, Stage Three depicts the nearly complete dissipation of the DNAPL component of the source by aqueous diffusion into pore water. Included in this stage is the diffusion of CVOCs into the intragranular pores within the individual fragments of sedimentary rock that comprise a portion of the residuum and sediment. As noted above, it is difficult to know what stage this process has reached at any one site or at various points of DNAPL release on the same property. As discussed in a later section, strong evidence exists at the fYNOP Site to suggest that DNAPL source material has not been completely dissipated and is still present in several source areas.

5.1.2.2.2 Matrix Diffusion in the Plume Area

Beginning with Stage One of the source development shown in Figure 5.1-7, a dissolved plume of the CVOCs contained in the released DNAPL forms immediately by dissolution in groundwater and advection down gradient from the source area. Matrix diffusion also occurs within this plume area as shown on Figure 5.1-5. Within the plume area generated by advective transport in fractures and solution conduits, matrix diffusion will also occur in response to the substantial chemical gradient between the open conduits in the carbonate aquifer, within which advective transport of dissolved CVOCs preferentially occurs, to the adjacent solid rock, residuum or sediment, all of which typically exhibit lower hydraulic conductivity than the open fractures and therefore do not represent the principal pathways for plume migration. As a result, groundwater flowing in fractures and containing dissolved CVOCs is in direct contact with groundwater contained in pores of the adjacent rock matrix, residuum and sediment, thus creating a chemical diffusion gradient from the water in the fracture to the water in these pores.

The matrix diffusion process resulting from this contrast is shown on Figure 5.1-8 (Kennel, 2008). For example in the carbonate aquifer, as shown on Figure 5.1-1, CVOCs diffuse from groundwater flowing in fractures and solution conduits into the residuum, the clastic sediments and the rock matrix. In the noncarbonate aquifer (Figure 5.1-2), aqueous diffusion into the matrix of the quartzitic sandstone also occurs as a result of the groundwater migrating through the discontinuities in the bedrock. Kennel has also documented the aqueous phase concentrations in matrix pore water in his study. Figure 5.1-9 (Kennel 2008) shows a depth profile of TCE concentrations in matrix pore water identified by his study. As shown on this figure, concentrations of TCE as high as 50,000 ug/L are shown to occur in pore water adjacent to fractures associated with active migration of TCE in the plume.

By contrast with the high concentrations expected to be produced in the matrix pore water in the source area, the concentrations in pore water adjacent to fractures conveying dissolved CVOCs away from the source area will typically diminish with distance from the source area as the concentrations in the plume diminish downgradient. If the concentrations of CVOCs in fracture flow decline for any reason, such as the inception of groundwater remediation, there will be a reversal of the diffusion gradients from the rock matrix back out to the fracture flow. This will result in reverse diffusion from the rock matrix back into the fracture as depicted in the diagram on the right side of Figure 5.1-8.

5.1.3 Vapor Phase Transport Processes

Column #5 on Figure 5.1-1 and 5.1-2 depicts the various processes relating to CVOC transport within a vapor-phase component of CVOC mass in the subsurface. The development of the vapor phase results from two mechanisms: direct evaporation of CVOCs from residual DNAPL in the vadose zone and volatilization of CVOCs from groundwater at the water table.

Evaporation from residual DNAPL in the vadose zone is controlled by the vapor pressure of each individual compound. In the immediate vicinity of the DNAPL source, this process should produce vapor phase concentrations that are near each substance's saturation concentration in air. By contrast, volatilization of VOCs from the water table will be controlled by the concentration of each compound in the groundwater and its Henry's Law constant. In general, direct evaporation from residual DNAPL will be expected to produce higher vapor phase concentrations than volatilization from groundwater. This is due in large part to the relatively low solubility of these substances in groundwater.

Once in the vapor phase, the principal transport mechanism, as shown in Column #5 of Figures 5.1-1 and 5.1-2, is vapor diffusion. Transport by this means will occur primarily in response to the chemical concentration gradient between comparatively high vapor concentrations in the soil air versus negligible concentrations of these substances in atmospheric air. Vapor diffusion will therefore be primarily upwards to the ground surface from DNAPL source zones in the vadose zone and dissolved CVOCs at the water table. The result is diffusive losses of VOC mass to the atmosphere. The development of this vapor phase in the vadose zone is shown on Figure 5.1-7 by orange shading in the region between the water table and the ground surface in Stages Two and Three on Figure 5.1-7.

In addition to vapor diffusion, vapor transport may occur as a result of advection. This mechanism may occur across the concrete slab of buildings built over a source or plume in response to a difference in air pressure across the slab. Advective transport of vapors may also result from "barometric pumping", whereby changes in atmospheric pressure result in a pressure gradient from the soil air to the atmospheric air resulting in the movement of some volume of the soil air containing CVOC vapors as opposed to just the molecules of VOCs as is the case for diffusion.

Vapor phase advective transport may also be induced through the operation of remedial systems including a soil vapor extraction system or a sub-slab depressurization system. For example, the former soil vapor extraction (SVE) system in the NBldg4 area artificially induced a vacuum beneath the building slab and extracted CVOCs by advective transport.

5.1.4 CVOC Fate Processes

Column #6 on Figure 5.1-1 and 5.1-2 depicts the fate processes that result in the loss of CVOCs by degradation, temporary storage by sorption, or transformation in both the saturated and unsaturated zones.

5.1.4.1 Partitioning from Soil Vapor to Pore Water in the Vadose Zone

As shown in Column #6 on Figure 5.1-1, in the vadose zone, some portion of the mass of CVOCs contained in soil vapor will partition to the pore water that coats each of the individual soil grains. As in the case of the volatilization from the water table that contributed to the development of the vapor phase presence of CVOCs, this process of partitioning of CVOC mass from the vapor phase to the pore water is controlled by the Henry's Law constant of each of the CVOCs.

5.1.4.2 Sorption on Formation Solids

Column #6 of Figure 5.1-1 shows that sorption of VOCs onto the organic carbon fraction of formation solids occurs in both the saturated and unsaturated zones. In the saturated zone this is by direct partitioning from the aqueous phase to the solid phase whether in the presence of DNAPL or not. In the vadose zone this may occur directly from the aqueous phase to the solid phase if DNAPL is present in contact with pore water. Otherwise, this process first requires partitioning from soil vapor to pore water as discussed above, then partitioning from pore water to the solid phase.

Little information is available regarding the organic carbon content of carbonate and quartzitic sandstone bedrock at the Site. However, the studies at the University of Waterloo performed by

Plett (2006) and Kennel (2008) included determinations of the fraction organic carbon (foc) in the matrix of the Silurian dolostone that was the subject of their studies. Appendix E includes tabulations of the results of their determinations of foc. Table 2.3 from Plett (2006) indicates a range of foc in dolostone of 0.003-0.125 %, averaging 0.017 %, which suggests low sorption potential. However, the data in Table 3.2 of Kennel (2008) (Appendix E) provides values for various components of the dolostone bedrock. For the dolostone matrix, Kennel reports values for 74 samples ranging from 0.01 to 0.10 % and averaging 0.02 %, which is very similar to Plett's results. For a single sample from a stylolite layer, he reports 3.5 %, but most importantly, for 15 samples of fracture surfaces he reports a range of 0.08 to 6.36 % with an average value of 2.31 %, indicating significant sorption potential on fracture surfaces. In fact, these data suggest that the sorption potential on the surface of fractures in the dolostone is more than 100 times greater than the sorption potential of the dolostone rock matrix.

All other things being equal, the tendency for each of the CVOCs to sorb onto dolostone matrix or fracture surfaces will be in proportion to the magnitude of their water/organic carbon partition coefficient (Koc). Table 5.1-1 lists each of these substances along with their Koc values as published in 025 PA Code § 250, Appendix A, Table 5. The higher the Koc, the greater the tendency for the substance to sorb to the organic carbon fraction of formation solids. Thus, PCE should be the most strongly sorbed CVOC at this Site and, if the distribution of organic carbon is similar to that in the UW studies, adsorption of this CVOC and the others should be concentrated on the surface of fractures and voids in the carbonate bedrock.

Table 5.1-1: Organic Carbon Partition Coefficients

Compound	Koc (mL/g)
Tetrachloroethene	300
Trichloroethene	93
cis-1,2-Dichloroethene	49
1,1,1-Trichloroethane	100
1,1-Dichloroethane	52
1,1-Dichloroethene	65

In addition to sorption onto organic carbon, Loop and White (2001, p. 121) report that CVOCs may also adsorb to the surface of metal oxide coatings. Such coatings are most prevalent in the quartzitic sandstone of the Antietam Formation, but can also be present in the carbonate bedrock aquifer. Similar to adsorption onto carbon, this process removes mass from the CVOCs being transported with the groundwater.

The significance of this mechanism cannot be assessed for the fYNOP Site in the absence of site-specific determinations of foc for granular materials (residuum and sediment), the rock matrix and the surfaces of fractures, as was done by the University of Waterloo at their site. However, if conditions are similar at fYNOP, sorption onto fracture surfaces would remove some fraction of the mass dissolved in groundwater passing through those fractures and could, as discussed later, comprise a component of secondary sourcing once concentrations begin to decline and desorption occurs. If the residuum and/or sediments are found to exhibit significant foc, then sorption and desorption associated with these materials may also be at least as significant, particularly if it results in sorption retarded reverse diffusion.

5.1.4.3 Reductive Dechlorination of PCE, TCE and TCA

Under reducing (anaerobic) conditions, the principal chlorinated solvents found in the groundwater at the Site can undergo biotic reductive degradation and be transformed into less chlorinated compounds. These reactions are mediated by natural bacteria. The sequence of reductive dechlorination for the ethenes is: PCE→TCE→cis12DCE→VC→Ethene. Experience at other PCE DNAPL sites indicates that when PCE is the parent compound, the dechlorination proceeds preferentially to cis12DCE over TCE. Therefore, when groundwater monitoring data indicate that PCE is the principal CVOC in a source area or plume, if TCE is present at concentrations greater than cis12DCE, this may indicate that TCE is present as a second, co-disposed solvent rather than a degradation product of the PCE.

The sequence of reductive dechlorination for the ethanes is: TCA→11DCA→CEA→Ethane. It should also be noted, as discussed in the next subsection, that TCA also transforms abiotically to 11DCE.

In most aquifers, the rate of each transformation step slows as reductive dechlorination proceeds so that the concentrations of the later transformation products (i.e. cis12DCE, VC, 11DCA) can appear to increase relative to the concentrations of the parent solvents. In some cases the increase in the relative concentrations of the transformation products occurs with increasing distance from the source zone (provided geochemical conditions continue to favor reductive dechlorination), and may occur also with increasing time at a given location as biogeochemical conditions may become more favorable with time.

Most frequently these transformations occur in source areas where the CVOCs were co-disposed with other organic compounds (e.g., petroleum products). The biotic degradation of these other substances typically creates the sulfate-reducing or methanogenic geochemical conditions necessary for reductive dechlorination of CVOCs to occur. However, once the assemblage of parent compounds and daughter products is transported away from the source area, frequently the conditions within the plume area are no longer conducive to reductive dechlorination and the transformation process ceases. In this case progressive changes in the ratio of the parent compounds to the daughter products do not continue to occur with increasing distance downgradient.

5.1.4.4 Abiotic Transformation of TCA to 11DCE

Early research on the formation of 11DCE from TCA performed by Vogel and McCarty (1987) determined that TCA released to the environment and dissolved in groundwater will undergo an abiotic hydrolysis reaction that forms 11DCE (about 20%) and acetic acid (about 80%). The rate of this reaction is not dependent on bacteria or the geochemical conditions in the groundwater.

Various researchers (Gauthier and Murphy, 2003, and Murphy and Mohsen, 2010) have indicated that the half-life for the TCA→11DCE reaction depends solely on the groundwater temperature.

This transformation begins to occur as soon as the TCA dissolves in groundwater and proceeds at a rate that is unchanged so long as the temperature of the groundwater remains unchanged. Since groundwater temperature is fairly constant at most sites, Smith et al, 1994, suggested that the ratio of 11DCE to TCA might be used to determine when TCA was first dissolved in groundwater and by extension, when the initial release of TCA to groundwater occurred.

Unlike the transformations associated with reductive dechlorination discussed above, the transformation of TCA to 11DCE will continue to progress as the dissolved TCA is transported away from the DNAPL source regardless of any changes in geochemical conditions. This is true whether that transport mode is advection within the plume or diffusion into the matrix pore water in the bedrock or the pore water within the residuum and the sediment, both in the source area and in the plume. Transport within the plume will be accompanied by progressively higher ratios of 11DCE to TCA with downgradient distance provided the travel time in the plume to the point of discharge to surface water or an extraction well is significant compared to the half-life of TCA concentration reduction at the ambient groundwater temperature.

If residence time within the plume is fairly short compared to the half life of TCA and the TCA DNAPL source has been in place for many years or decades, then matrix diffusion of TCA in the source area is not only more likely to yield much higher ratios of 11DCE to TCA, but also higher concentrations of 11DCE. This is due primarily to the slow pace of aqueous diffusion which makes residence time for TCA in matrix pore water much longer than in a plume characterized by relatively rapid transport from the source to the point of discharge to surface water or an extraction well. The result is an increase in 11DCE concentration with distance away from a fracture surface as TCA diffuses into the rock matrix and transforms to 11DCE. Figure 5.1-10 presents a theoretical set of 11DCE and TCA diffusion profiles with distance from the fracture surface to depict this process.

The profiles at time equals T1 indicate the distribution of TCA and 11DCE concentrations while the concentration of TCA freshly dissolved from DNAPL in the fracture remains high. Since the maximum concentration of 11DCE in the rock matrix will continue to increase and there is little or no 11DCE in groundwater flowing in the fracture, a chemical concentration gradient will develop for 11DCE diffusion both further into the rock matrix as well as back into the fracture (time equals T2). The increase in 11DCE concentrations in the flowing groundwater may accelerate following the startup of a groundwater extraction system for source remediation when the concentration of freshly dissolved TCA in fracture flow declines (time equals T2). At that point TCA will begin to diffuse back out of the rock matrix, but as it does, it will continue to transform to 11DCE creating a stronger and stronger chemical concentration gradient for 11DCE diffusion both into and out of the rock matrix. As this process continues to progress, this back diffusion will result in increasing concentrations of 11DCE in groundwater flowing in the fracture (time equals T3) which will be observed in groundwater monitoring data as an initial increase in the 11DCE to TCA ratio, which nonetheless will still be less than 1.0.

Eventually, depending on the extent of TCA concentration reduction in the fracture flow, the ratio of 11DCE to TCA will increase to greater than 1.0. This is especially true since forward diffusion of both 11DCE and TCA into clean pore water in the rock matrix will also continue during this entire time, with the transformation of TCA to 11DCE occurring continuously. At some stage in the process, the mass of these two CVOCs in the rock matrix will be comprised almost entirely of 11DCE back diffusing from the rock matrix to the fracture flow (time equals T5). If the concentration of TCA in the fracture flow has since been diminished by remediation to a very low level, the ratio of 11DCE to TCA will be much greater than 1.0 and 11DCE will be the predominant CVOC of these two observed in monitoring data of fracture flow.

5.1.4.5 Aerobic/Anaerobic Oxidation

The principal solvent parents (PCE, TCE and TCA) will not undergo biodegradation under oxidizing conditions in groundwater. Under suitable conditions, cis12DCE and VC undergo degradation by aerobic or anaerobic oxidation without the formation of readily identifiable degradation products. As shown on Figure 5.1-1 and 5.1-2, depending on the depth to the water table, cis12DCE and VC may degrade aerobically in the vadose zone, lessening their potential significance as constituents of concern for vapor intrusion into occupied structures.

5.1.5 Secondary Sourcing

Several of the processes identified on Figures 5.1-1 and 5.1-2 have been noted as being “reversible”. These include the following:

- Aqueous diffusion into pore water within the carbonate and non-carbonate rock matrix, the residuum, and the sediments that partially or completely fill voids in the carbonate rock both in DNAPL source areas and CVOC plume areas;
- Partitioning from soil vapor or DNAPL to pore water in the vadose zone; and
- Sorption onto the organic carbon fraction of formation solids and metal oxide coatings in both the saturated and unsaturated zone.

All of these processes effectively work to store mass in the solid phase of the soil and bedrock. The extent to which any of these processes stores mass and maintains that mass in storage relies on either the continuing presence of DNAPL as a primary source of aqueous and vapor contamination or simply the presence of groundwater with concentrations of the constituents as high or higher than those that originally determined the levels of sorbed and diffused mass. Once groundwater concentrations have declined appreciably due to the effects of remediation, these processes will be reversed, at which point the associated fate and transport mechanisms are termed reverse diffusion and desorption.

As groundwater and soil vapor concentrations continue to decline, the processes of desorption and reverse diffusion will return previously stored mass to the flowing groundwater in the saturated zone and gravitational water in the vadose zone. Because this mass is stored in the solid phase and available to re-enter the aqueous phase, it constitutes a secondary source of contamination to groundwater that may retard the rate at which groundwater concentrations can decline over time. As such, these processes are typically the cause of the tailing effect often observed in groundwater monitoring data at CVOC remediation sites.

5.2 CVOC Fate and Transport at fYNOP

Disposal or spillage of DNAPL is the likely sourcing for the dissolved plumes of CVOCs distributed in groundwater throughout the Site. From these source areas, the primary aqueous transport process of distribution is advection, or migration of the dissolved CVOCs with the groundwater. Prior to operation of the pump and treat system, groundwater in the CPA/NPA/WPL migrated generally westward toward the Codorus Creek through residuum and solution-enhanced pathways in the carbonate bedrock.

Although source areas were generally discussed in Section 4, this subsection applies the theoretical discussion of fate and transport mechanisms presented in the previous subsection to the analysis of groundwater monitoring data from the fYNOP Site collected both before and after the inception of remediation. In analyzing these data it will be important to understand the location of both extraction and monitoring wells with respect to source areas as well as their position within the plume. In so doing, the expected patterns of concentration with time must also be understood in order to evaluate the data with respect to the various fate and transport mechanisms described above.

For this purpose, Figure 5.2-1 is a modified version of Kennel's Figure 1.2 which shows four well locations, W-1 to W-4. W-1 is located in the source area; W-3 is located in the mid-plume area; W-2 is located in the plume between W-1 and W-3, and W-4 is located near the downgradient limit of the plume. The pattern of concentrations with time at each of these well locations will be affected by which of them are extraction wells and which are monitoring wells. If W-1 were a properly constructed and effective extraction well in this karst aquifer, concentrations would initially be high due to the effects of DNAPL source material. However, after the well began pumping, the concentrations would decline due to the induced radial flow toward the well from areas beyond the source. Nevertheless, the concentrations would soon "plateau" due to the continuing effect of dissolution from DNAPL source material. If the other three wells were used solely to monitor groundwater quality, concentrations in all three would begin to decline provided the operation of W-1 effectively controlled groundwater chemical flux from the source area. Based on their position in the plume, the pattern of concentration reduction in all three wells would be similar, but their initial concentrations would be progressively lower from W-2 to W-3 to W-4. Concentrations at these wells would decline substantially, but with a tailing effect that would be associated with secondary sourcing from reverse diffusion and desorption within the plume.

On the other hand, if W-3 were an extraction well and the other three were monitoring wells, concentrations in W-1, now a source area monitoring well, would indicate the likely presence of DNAPL source material and would not decline rapidly or to any great extent. Concentrations in W-2 would also display the effects of a continuing DNAPL source, although at a lower concentration than would occur at W-1. At the extraction well, W-3, concentrations would drop rapidly upon startup due to the induced radial flow to the well, but from a lower initial value than at W-1 or W-2. Both W-2 and W-3 might also exhibit concentration patterns indicative of reverse diffusion, provided they were not masked by the effects of induced chemical flux from the source area. Concentrations at W-4 would drop most rapidly and to the lowest values because they would no longer be impacted by chemical flux from the source. Due to the effects of secondary sourcing, this well would likely exhibit a tailing effect, but at levels that are low compared to the other wells.

Figure 5.2-2 is taken from Mackay and Cherry, 1989. It depicts the patterns of concentration with time in extracted groundwater that vary based on the condition of the aquifer where the well is located. Examples (a) and (b) are situations in which there is fairly simple geology and only aqueous phase chemistry with no secondary sourcing. These are conditions that may exist on the fYNOP Site, but if so, they are rare.

Example (c), although labeled as having a clay lens in uniform sand and gravel is comparable to a location in bedrock that is affected by secondary sourcing due primarily to reverse diffusion from the rock matrix or, in the case of the carbonate rock, the residuum or sediments. As shown, a well in this category would exhibit a long tailing effect with concentrations remaining somewhat elevated depending on the magnitude of impacts from secondary sourcing.

Finally, example (d) represents the pattern expected when the concentrations in an extraction well are impacted by a continuing DNAPL source. If the well is located within the source area, the concentrations would be higher, as in the example of extraction well W-1 above, or lower as in the example of extraction well W-3 above. The important distinction is that so long as there is primary DNAPL source material remaining in the source area, an extraction well that captures mass flux from that source area will exhibit a plateau in concentrations at a level that will be determined in large part by its distance from the source and the magnitude of the extraction rate. The same pattern will be seen in a monitoring well located between a flux control well and the source area (i.e., W-2 in the case where W-3 functions as an extraction well).

5.2.1 DNAPL Sources: Occurrence and Persistence

DNAPL has not been directly detected in samples from well drilling or sampling or in the soils during the remedial investigations, but there is sufficient evidence to support the occurrence at a number of locations on Site. During the installation of test groundwater extraction well CW-20 in the southwest corner of the WPL where very high dissolved concentrations of PCE and TCE were found in groundwater, SAIC tested sediments from the solution cavities penetrated by the well using black light and hydrophobic dye to assist in the detection of free product DNAPL. No detections were observed using these methods (SAIC, June 2008). However, the historical use, storage, handling and disposal of chlorinated solvents at this Site support the likely conclusion that releases at the Site were principally in the form of separate phase liquids. The questions to be addressed in this subsection are: 1) What was the likely extent of DNAPL sources prior to remediation (the initiation of groundwater extraction in the WPL); and 2) Where do those sources persist?

5.2.1.1 Data Analysis Methodologies

In the absence of any direct evidence of DNAPLs, the identification of likely DNAPL releases in source areas will have to be based on inferences from four evaluation criteria. The first of these is based on observed concentrations of CVOCs in groundwater. Concentrations of CVOCs dissolved in groundwater at or exceeding 1% of their respective solubilities are often used to indicate likely locations where DNAPL may be present (USEPA, January 1992). Therefore, comparison of pre-remediation concentrations of CVOCs in each apparent source area to the percent of solubility criteria established by USEPA can be applied to identifying the locations of pre-remediation DNAPL source areas and their extent in the subsurface. It is acknowledged that some value less than 1% can be justified in karst aquifers where chemical equilibrium may not be reached due to short residence time of rapidly migrating groundwater and minimal contact in large voids. However, utilization of the additional criteria should effectively consider that variable.

The second criterion applied to identifying DNAPL source areas is the pattern of observed concentrations in groundwater versus time at extraction wells and monitoring wells since remediation began. Evaluation of this criterion will be based on the discussion of time versus concentration patterns provided above and shown on Figure 5.2-2.

The third criterion for identifying DNAPL source zones is focused on the question of where they still occur after nearly 20 years of remediation. This criterion is based on the evaluation of the occurrence of TCA and its transformation product 11DCE and the ratio of the one to the other. Since TCA begins to transform to 11DCE immediately upon dissolving from the pure phase to the aqueous phase, anywhere that TCA occurs in the absence or near absence of 11DCE (i.e., a very low 11DCE to TCA ratio) that TCA could only have dissolved in from its pure phase very recently, proving the continued presence of a DNAPL at that location.

The fourth and final evaluation criterion applied to the identification of DNAPL sourcing is the depth at which comparatively higher concentrations of CVOCs are present beneath the Site. Since DNAPL can follow a fairly discrete vertical flow path, it is often the case that much higher CVOC concentrations are found in a deeper monitoring well of a pair or cluster. This spatial pattern of increasing concentrations with depth suggests discrete DNAPL transport. It may also raise the question of whether or not the current level of characterization has defined the maximum depth to which DNAPL has penetrated.

5.2.1.2 Evidence for DNAPL Sourcing

The following four subsections apply the data analysis methods just described to the groundwater monitoring data for the Site to determine the occurrence and persistence of DNAPL sources for groundwater contamination at the Site.

5.2.1.2.1 Concentrations Exceeding 1% of DNAPL Solubility

Figure 5.2-3 shows locations on Site where pre-remediation PCE concentrations in groundwater equal or exceed 2,400 µg/l, which is 1% of the solubility of PCE (Broholm and Feenstra, 1995). The map frame on the left shows maximum concentrations in wells prior to the inception of the first on-Site pump and treat operations at the Bldg 2 TCA Tank area in November 1991. This frame provides an indication of DNAPL areas prior to interim remediation activities. High concentration areas potentially indicative of DNAPL are shown in the southwest WPL (MW-37S and MW-37D) and near the northwest corner of Building 4 in wells MW-49S, MW-49D, and MW-51S. The map frame on the right shows concentrations equaling or exceeding 2,400 µg/l during the May/June 2008 sampling (Supplemental RI Round 1). This map frame is indicative of present conditions. High dissolved concentrations potentially indicating evidence of continuing DNAPL presence are shown to occur only in two wells, MW-37D and MW-75S, both in the SW WPL. (Data were not available from MW-75S prior to 1992, but more recent data clearly indicate a DNAPL source.)

Figure 5.2-4 shows locations on Site where TCE concentrations in groundwater equal or exceed 14,000 µg/l, which is 1% of the solubility of TCE (Broholm and Feenstra, 1995). The map frame on the left shows maximum concentrations in wells prior to interim remediation activities. High concentrations potentially indicative of DNAPL are shown in three wells near the northwest corner of Building 4 (MW-49S, MW-49D, and MW-51S). The map frame on the right shows concentrations equaling or exceeding 14,000 µg/l during the May/June 2008 sampling round, indicating current conditions. High dissolved concentrations potentially indicative of TCE DNAPL are not shown in any wells. Therefore, based on this criterion alone, there would be no remaining TCE DNAPL sources on the Site.

Figure 5.2-5 shows locations on Site where TCA concentrations in groundwater equal or exceed 12,500 µg/l, which is 1% of the solubility of TCA (Broholm and Feenstra, 1995). The map frame on the left shows maximum concentrations prior to interim remediation activities. High concentration areas potentially indicative of TCA DNAPL are shown near the northwest corner of Building 4 and near the Building 2 TCA Tank. The map frame on the right shows no concentrations equaling or exceeding 12,500 µg/l during the May/June 2008 sampling (Supplemental RI Round 1). Therefore, based on this criterion alone, there would be no remaining TCA DNAPL sources on the Site.

5.2.1.2.2 Other DNAPL Source Identification Criteria

As noted above, there are three additional criteria that can be applied to identifying potential DNAPL sources. These are:

- The pattern of CVOC concentrations over time;
- The ratio of 11DCE to TCA and related timing indicated for TCA dissolution; and
- The vertical pattern of CVOC concentrations with depth.

The first column of Tables 5.2-1a to 5.2-1d lists wells grouped by area of the Site as shown on Plate 4E. The information presented in these tables addresses the first two of these three criteria. In this regard, the second, third and fourth columns assign a time versus concentration pattern for TCE, PCE and TCA based on the patterns (a, b, c, and d) shown on Figure 5.2-2 (Mackay and Cherry, 1989). The pattern of CVOC concentrations with time has been evaluated for each of these primary constituents based on inspection of time versus concentration plots in Appendix C.

For the purposes of this analysis, the following interpretations of these codes are being used to determine what pattern a given well's data matches most closely:

- "a" - Simple geology, only aqueous phase chemistry and no evidence of secondary sourcing; concentrations decline rapidly to levels at or near groundwater standards;
- "b" - More complex geology, only aqueous phase chemistry and no evidence of secondary sourcing; concentrations decline to levels at or near groundwater standards, but over a longer period of time;
- "c" - More complex geology, only aqueous phase chemistry, strong evidence for secondary sourcing creating a protracted tailing effect; concentrations decline, but much more slowly and to levels that rarely achieve groundwater standards, but are not high enough to suggest continuing separate phase sourcing; wells with this pattern are typically located within plume areas down gradient from a DNAPL source where high initial plume concentrations have been present over many years or decades resulting in considerable opportunity for adsorption and matrix diffusion to have occurred; the interception of flux from the source has caused concentrations in flowing groundwater to decline, thus inducing back diffusion; and

- "d" - More complex geology, both DNAPL (primary) and secondary sourcing are present; concentrations decline initially following the start of pump and treat and then level off at concentrations well above groundwater standards; a trend of slowly declining concentrations in spite of these elevated levels could indicate that source depletion is having a significant effect on the impact of the continuing DNAPL source; if true, eventually the pattern will be one that reflects increased impacts from secondary sourcing over those of separate phase sourcing.

In addition to these designations, the "c" code for TCA has been annotated where appropriate to indicate that the evidence for secondary sourcing is related to the predominance of 11DCE back diffusion as described in subsection 5.1.2.4 and shown on Figure 5.1-10. Furthermore, the "d" code has been further annotated with a "DG" to distinguish a well that is down gradient from a source, but still impacted by flux from that source, from a well that is located within the source area, designated as "SA".

The fifth and sixth columns of these tables relate specifically to the identification of TCA source areas based on the extent of TCA transformation to 11DCE. Both of these columns list calendar dates in years that are based on calculations made from molar concentrations of TCA and 11DCE in groundwater samples collected at that location following the method of Gauthier and Murphy, 2003. Since the transformation of TCA to 11DCE begins immediately after the TCA is dissolved in groundwater and no sooner, the dates calculated using this method should provide an approximation of the date on which the TCA detected in a given sample from each of these locations was first dissolved in groundwater. The fifth column in each table provides dates based on data collected before remediation began. These dates indicate the most recent time by which TCA dissolved from DNAPL into groundwater.

The sixth column indicates the date or range of dates calculated from data collected after remediation began. In general, if this date range is long and it extends into the period of time following the beginning of remediation, then it's likely that TCA continues to dissolve from separate phase TCA, thus yielding a concentration of TCA that is a combination of more recently dissolved TCA and TCA that is back diffusing from the rock matrix or residuum/sediments, the latter accompanied by a much higher proportion of 11DCE.

Along with these tables, reference will also be made in this discussion to five figures. Figures 5.2-6 is a map of pie diagrams showing the relative proportions of all seven prominent CVOCs at monitoring and extraction wells within the western portion of the Site. Figure 5.2-7 is a similar map showing relative proportions of just TCA and its degradation products, 11DCE and 11DCA The other two figures, already discussed in section 4, are Figures 4.2-3 and 4.2-4 which display cross sections A-A' and B-B', respectively.

The remainder of this subsection will use these tables and figures to identify the likely source areas, the extraction wells and monitoring wells that are impacted by flux from those sources, the monitoring wells that are more likely impacted by secondary sourcing as opposed to primary (DNAPL) sourcing and some monitoring wells in which groundwater concentrations are at or approaching groundwater standards.

Building 58-66 Area / Central Plant Area / West Parking Lot South

The first areas that will be examined lie in sequence from east to west, which is also from up-gradient to down-gradient with respect to the direction of natural groundwater flow. These are the Building 58-66 Area, the CPA (TCA Tank and TCA Degreaser) and the WPL South.

Beginning with the Building 58-66 Area, Figure 5.2-6 shows that the chemistry of this area is dominated by TCE and cis12DCE, with a sliver of the pies comprised primarily of TCA and its degradation products and a very minor component of PCE. Figure 5.2-7 then shows that the TCA degradation series compounds are represented primarily by 11DCE and then TCA, with one minor occurrence of DCA at MW-57. While TCA is present in nearly all of these wells, it appears that the last date it dissolved in groundwater in this area was in the mid-to-late '80s, before remediation began. There is no indication from Figure 5.2-7 or Table 5.2-1a that TCA has dissolved from the separate phase liquid to any appreciable extent in the last 20 years. Also, in all of the wells where the time versus concentration pattern indicates secondary sourcing (c-code) the primary constituent associated with the TCA degradation series is 11DCE, suggesting the model shown on Figure 5.1-10 probably most accurately describes the process that is generating concentrations of 11DCE greater than TCA in this area.

Table 5.2-1a: Temporal Patterns of Concentrations

Building 58 – 66 Area

Well No.	**Depth Interval**	**Geologic Unit**	**Primary Solvent TCE**	**PCE**	**TCA**	**11DCE:TCA Date Pre-1992**	**Post-1991**
MW-57	25-35’	OB	d-DG	d-DG	c (DCE)	NA	’65-‘68
MW-80	20-40’	OB	d-DG	d-DG	c (DCE)	NA	’83-‘84
MW-87	75-95’	OB/BR-LS	d-DG	d-DG	c (DCE)	NA	’79-‘89
MW-88	30-50’	BR-LS	d-DG	d-DG	b	NA	’78-‘86
MW-113	131-151	BR-LS	d-DG	d-DG	c (DCE)	NA	’81-‘83
CW-18	38-48	BR-LS	d-DG	d-DG	c (DCE)	NA	’76-‘77

OB=overburden; BR=bedrock; LS=limestone; DCE=1,1-dichlorethene

NA=none available; DG=down gradient; SA=source area

[1] Calculation of date strongly affected by transformation of TCA to 11DCA

Other observations that can be made from this table regarding TCE and PCE include:

- All of the wells in this area exhibit a “plateau” with respect to TCE and PCE concentrations, suggesting impacts from a continuing DNAPL source;
- The four of these wells with monitoring intervals above 50 ft. bgs have concentration ranges for the total TCE series that are in the range of 100 to 1,000 µg/L; and
- The two wells with the deepest monitoring intervals (MW-87 and MW-113) exhibit total TCE series concentrations in the range of 1,000 to 5,000 µg/L.

These three observations regarding the pattern of TCE and PCE in this area plus the comparatively high concentrations of TCE in the two deepest wells (MW-87 and MW-113) combined with a locally upward hydraulic gradient (see Figure 4.2-3) suggest the possibility of a potential DNAPL source located deeper than any of the existing monitoring wells.

The next area of concern to the west is the CPA which includes the TCA Tank and the TCA Degreaser. Figure 5.2-6 shows groundwater chemistry in this area to include a strong overlay similar to the TCE and cis12DCE signature that dominates the Building 58-66 Area, but with the addition of TCA degradation series components in a strongly degraded condition at the TCA Degreaser location (MW-54 and MW-55) and a second TCA degradation series component in a less strongly degraded condition at the TCA Tank Area. Figure 5.2-7 shows this variation in the composition of the TCA series compounds, with MW-55 representing the extreme in TCA transformation to 11DCE and MW-32S showing a much higher proportion of TCA than 11DCE.

Table 5.2-1b lists the results of an analysis of temporal patterns in groundwater concentration data for the wells in the CPA. The columns in this table are the same as those described for Table 5.2-1a. The table has been organized into separate section for the TCA tank area and the TCA degreaser. Based on the analysis of relative 11DCE and TCA concentrations, two wells are identified in the TCA tank area as occurring in a continuing DNAPL source zone (extraction well CW-8 and monitoring well MW-32S). Two other wells, MW-32D and MW-33 indicate a pattern of reverse diffusion of 11DCE and the remaining five wells in the tank area show a pattern of declining TCA concentrations to levels at or near groundwater standards, including four wells that are on the down gradient side of the capture zone resulting from the operation of extraction well CW-8. For these wells, PCE concentrations were also lowered to levels comparable to groundwater standards. However, the pattern of their TCE concentrations indicates likely effects of reverse diffusion keeping TCE concentrations above levels comparable to groundwater standards.

Table 5.2-1b: Temporal Patterns of Concentrations							
Central Plan Area-TCA Tank/Vapor Degreaser							
TCA Tank Area							
Well	**Depth**	**Geologic**	**Primary Solvent**			**11DCE:TCA Date**	
No.	**Interval**	**Unit**	**TCE**	**PCE**	**TCA**	**Pre-1992**	**Post-1991**
MW-28	10-55’	OB/BR-LS	c	b	b	’83-‘88	’69-‘89[1]
MW-32D	210-220’	BR-LS	d-DG	d-DG	c (DCE)	’80-‘83	’65-‘81[1]
MW-32S	138-148	BR-LS	d-DG	d-DG	d-SA	’83-‘84	’82-‘00
MW-33	23-43’	OB/BR-LS	c	c	c (DCE)	‘80	’79-‘82
MW-34D	115-125’	BR-LS	c	b	B	’80-‘85	’75-‘81
MW-34S	17-37’	BR-LS	c	b	B	‘84	’82-‘94
MW-35D	114-124	BR-LS	c	b	b	’78-‘81	’76-‘83
MW-35S	9-19’	OB/BR-LS	c	b	b	‘81	NA
CW-08	47-50’	BR-LS	d-DG	d-DG	d-SA	’79-‘86	’78-‘01
TCA Degreaser							
Well	**Depth**	**Geologic**	**Primary Solvent**			**11DCE:TCA Date**	
No.	**Interval**	**Unit**	**TCE**	**PCE**	**TCA**	**Pre-1992**	**Post-1991**
MW-54	20-30’	BR-LS	d-SA	d-SA?	c (DCE)	NA	’50-‘87[1]
MW-55	21-31’	OB/BR-LS	d-SA	d-SA?	c (DCE)	NA	’65-‘74
CW-16	30-50’	BR-LS	d-DG	d-DG	c (DCE)	NA	’76-‘87
OB=overburden; BR=bedrock; LS=limestone; DCE=1,1-dichlorethene							
NA=none available; DG=down gradient; SA=source area							
[1] Calculation of date strongly affected by transformation of TCA to 11DCA							

Finally, the pattern of TCE and PCE concentrations in three wells (MW-32S, MW-32D, and CW-08) indicate that they are influenced by a likely continuing DNAPL source, but they appear to be down gradient from that source. From the concentration contours and flow arrows on Figure 4.2-3, it appears that the likely source is the same potential deeper source that was suggested to be affecting the TCE and PCE concentrations in the two deeper wells at the Building 58-66 Area. The pattern of concentrations in the deepest well in the TCA tank area also shows the greatest extent of TCE degradation to cis12DCE and VC of any of the deeper wells in these two areas. Given the upward vertical gradient at this well, the greater extent of reductive dechlorination could indicate a source deeper in the bedrock where more reducing conditions might reasonably occur.

The second section of Table 5.2-1b addresses temporal patterns in data from the TCA degreaser area. As shown in this table and on Figure 5.2-7, the TCA series chemistry in this area is dominated by reverse diffusion of 11DCE. However, as shown on Figure 4.2-3 and listed in Table 5.2-1b, wells MW-54 and MW-55 appear to monitor a shallow TCE, and to a lesser extent, PCE source zone that is contributing flux to extraction well CW-08. The pattern of chemical concentrations in well CW-16 (an inactive extraction well) appears to reflect impacts of this shallow source at a point between the source area wells and extraction well CW-08.

Further west of the TCA Tank Area, Figure 5.2-6 shows monitoring wells and an extraction well in the southern portion of the WPL. From the pie charts displayed at each well, it is apparent that the principal compound present in groundwater in this area is PCE. TCE and its transformation product, cis12DCE are also present, as is TCA and its transformation products 11DCE and 11DCA, the latter occurring only at well MW-107 (Figure 5.2-7).

Table 5.2-1c: Temporal Patterns of Concentrations

West Parking Lot South

Well	**Depth**	**Geologic**	**Primary Solvent**			**11DCE:TCA Date**	
No.	**Interval**	**Unit**	**TCE**	**PCE**	**TCA**	**Pre-1994**	**Post-1993**
MW-37D	131-141’	BR-LS	d-DG	d-DG	d-DG	‘84	’90-‘08
MW-37S	12-32’	OB/BR-LS	b	c	b	’88-‘89	’90-‘09
MW-75D	205-215’	BR-LS	d-DG	d-DG	d-DG	NA	’91-‘08
MW-75S	168-173’	BR-LS	d-SA	d-SA	d-SA	NA	’94-‘10
MW-93D	135-145’	BR-LS/DS	c	c	b	NA	’89-‘99
MW-93S	26-41’	BR-LS/DS	b	b	NA	NA	NA
CW-09	47-50’	BR-LS	d-DG	d-DG	d-DG	’85-‘90	’86-‘06
CW-20		BR-LS	d-DG	d-DG	d-DG	NA	’96-‘10

OB=overburden; BR=bedrock; LS=limestone; DS=dolostone; DCE=1,1-dichlorethene

NA=none available; DG=down gradient; SA=source area

[1] Calculation of date strongly affected by transformation of TCA to 11DCA

Table 5.2-1c presents the results of an analysis of temporal patterns in concentrations in the WPL South. For the TCA degradation series, column six in the table indicates that every well in this area with TCA series constituents present shows the effects of recent dissolution of TCA from separate phase liquid. For well MW-75S, where the highest concentrations occur, the 2010 sample indicated that dissolution of the TCA had occurred in 2010. Therefore, the pie for this well on Figure 5.2-7 indicates all of the TCA series concentration is comprised of TCA. Therefore, MW-75S has been identified as a source area well. The other wells nearby in the deeper bedrock, including MW-37D, MW-75D and CW-20 (an inactive extraction well) have been determined to exhibit patterns that indicate impact from a continuing source, but that impact is attributed to their location down gradient from the source well MW-75S. TCA series concentrations in two other monitoring wells

(MW-37S and MW-93D) have declined to levels at or near groundwater standards. MW-37S is the shallowest well in the well cluster that includes MW-75S with its screened interval well above the source zone at the depth of MW-75S. As shown on Figure 5.2-7, MW-93D is located side gradient from the source area around MW-75S and it is a deeper bedrock well. Its location relative to CW-09 and the direction of groundwater flow suggests that it is monitoring the quality of groundwater being drawn back toward the plant site from the area west of the railroad but east of the groundwater divide shown on Figures 5.2-6 and 5.2-7. Therefore, at least with respect to the TCA series compounds in the area west of the railroad, the data for MW-93D would indicate that concentrations of these constituents have declined to levels at or near groundwater standards.

Table 5.2-1c also addresses concentration patterns for TCE and DCE. As in the case of TCA series compounds, MW-75S has been identified as monitoring a source zone in the deeper bedrock, while other deeper bedrock wells, including MW-37D, MW-75D, and CW-20, have been identified as monitoring wells impacted by a continuing DNAPL source as a result of being down gradient from MW-75S. The concentration pattern at CW-09 also shows that this well is being impacted by the continuing source at MW-75S as a consequence of its role in intercepting chemical flux from this source area. Finally, concentration patterns at the three remaining monitoring wells indicate that TCE concentrations at MW-37S and MW-93S have been reduced to levels near groundwater standards while concentrations of PCE at MW-37S and TCE and PCE at MW-93D indicate effects of reverse diffusion that are maintaining concentrations of these CVOCs at levels above groundwater standards.

Figure 4.2-3 shows that, as in the case of the first two areas discussed above, there is a spatial pattern of increasing concentrations with depth. However, this cross section also shows that the ratio of the TCE and PCE concentrations in the deeper wells is significantly different from that in the deeper wells at CPA and the Building 58-66 Area. It is therefore likely that there is a deeper source zone in the WPL South area which is distinctly different and separated from the inferred deeper source in the other two areas.

Finally, both the groundwater elevation contours on Figures 5.2-6 and 5.2-7 and the groundwater elevation and TCE concentration contours on Figure 4.2-3 support the following conclusions regarding the capture zones of extraction wells CW-08 (operating at a nominal rate of 100 gpm) and CW-09 (operating at a nominal rate of 70 gpm):

- It appears from these figures that CW-08 controls groundwater chemical flux from the Building 58-66 Area and the CPA (including the TCA degreaser and the TCA tank). Control of these plume areas and sources by CW-08 provides obvious separation between them and the source and plume in the WPL South area.

- These same figures demonstrate that the groundwater chemical flux from the source identified at MW-75S is captured by the operation of CW-09.

WBld2 Corridor/NBldg4/BPA

Table 5.2-1d will be used together with Figures 5.2-6 and 5.2-7 and Figure 4.2-4 (Cross Section B-B') to discuss the criteria for identifying source areas in the three areas identified on Plate 4E as the WBldg2 Corridor, NBldg4 and the BPA. Figure 4.1-2 indicates that the first of these three areas, the WBldg2 Corridor, is located down gradient from a suspected TCE source area. Figure 5.2-6 seems to confirm this observation with TCE being the prominent CVOC in three of the four wells in this area. However, the chemistry of the fourth well (MW-27) is dominated by PCE.

The only detection of a TCA series compound at well MW-114 was 53 ug/L of 11DCE during the sampling round used to construct Figure 5.2-7 (April/May 2008). However, since no other detections of TCA series compounds have occurred in this well, column six in Table 5.2-1d indicates the TCA series is not significant in this well. The same is true at well MW-27 where no detections of TCA series compounds have been confirmed. More detections of TCA series compounds have occurred at MW-81D&S, almost exclusively associated with the degradation products 11DCA and 11DCE at concentrations at or near groundwater standards. This is an indication that the TCA monitored at these locations has been dissolved in groundwater for many years and is likely present due to reverse diffusion.

Table 5.2-1d: Temporal Patterns of Concentrations							
West Building 2 Corridor/North Building 4/Burn Pile Area							
West Building 2 Corridor							
Well	**Depth**	**Geologic**	**Primary Solvent**			**11DCE:TCA Date**	
No.	**Interval**	**Unit**	**TCE**	**PCE**	**TCA**	**Pre-1994**	**Post-1993**
MW-27	10-70’	OB/BR-LS	c, d-DG	c, d-DG	NS	NA	NS
MW-81D	56-65	BR-LS	c, d-DG	c	b	NA	NS
MW-81S	31-41’	OB	c, d-DG	c	b	NA	NS
MW-114	90-144’	BR-LS	c, d-DG	c, d-DG	NS	NA	NS
North Building 4 Area							
Well	**Depth**	**Geologic**	**Primary Solvent**			**11DCE:TCA Date**	
No.	**Interval**	**Unit**	**TCE**	**PCE**	**TCA**	**Pre-1994**	**Post-1993**
MW-7	15-35’	OB/BR-LS/SS	d-DG	d-DG	c (DCE) d-DG	’71-77	’84-87
MW-47	15-35’	OB	c	c	b	‘72	’68-‘83
MW-49D	202-212’	BR-LS	d-SA	d-SA	d-SA	’85-‘87	’98-‘02[1]
MW-49S	135-140’	BR-LS	d-SA	d-SA	d-SA	’85-‘87	’84-‘93[1]
MW-50D	160-170’	BR-LS	d-DG	d-DG	d-DG	‘83	’48-’78[1]
MW-50S	110-120’	BR-LS	c	c	b	‘80	’60-‘78[1]
MW-51D	110-120’	BR-LS	b	b	b	‘74	’58-‘79[1]
MW-51S	34-44’	BR-LS	c	c	c	’76-‘77	’75-‘83
CW-13	60-70’	BR-LS	d-DG	d-DG	c, d-DG	’62-‘65	’83-‘05
CW-15A	18-68’	OB/BR-LS	d-SA	d-SA	d-SA	’83-‘85	’83-‘98
CW-17	32-65’	BR-LS	d-DG	d-DG	d-DG	NA	’76-‘09
Burn Pile Area							
Well	**Depth**	**Geologic**	**Primary Solvent**			**11DCE:TCA Date**	
No.	**Interval**	**Unit**	**TCE**	**PCE**	**TCA**	**Pre-1994**	**Post-1993**
MW-39D	55-65’	BR-LS	c	b	b	’81-‘92	’78-‘05
MW-39S	4-24’	OB/BR-LS	c	b	b	’82-‘90	’81-‘05
MW-74D	225-250’	BR-LS	c	b	b	NA	’77-‘87
MW-74S	183-193’	BR-LS	c	b	b	NA	’84-‘87
MW-95	40-50’	BR-LS	c	b	NS	NA	NA
MW-96D	78-88’	BR-LS	c,d-SA?	c,d-SA?	NA	NA	NA
MW-96S	29-39’	BR-LS	d-SA?	d-SA?	NA	NA	NA
MW-105	12-22’	OB	d-SA	d-SA	d-SA	NA	’08-‘09
CW-17	32-65’	BR-LS	d-DG	d-DG	d-DG	NA	’76-‘09
OB=overburden; BR=bedrock; LS=limestone; SS=sandstone; DCE=1,1-dichlorethene							
NA=none available; DG=down gradient; SA=source area							
[1] Calculation of date strongly affected by transformation of TCA to 11DCA							

As shown on Table 5.2-1d, all four wells in this area exhibit TCE concentration patterns that reflect either reverse diffusion at relatively high concentrations or impacts from an upgradient source. The same is true for PCE at MW-27 and MW-114, which together suggest the existence of a shallow PCE source in the northern portion of this area. However, the pattern for PCE in MW-81D&S suggests reverse diffusion of PCE at lower concentrations that are just above the range of groundwater standards.

Table 5.2-1d shows that examination of temporal patterns for wells in the North Building 4 area confirms that wells MW-49D&S, and CW-15A are located in a common DNAPL source area. This source has been shown by the analysis of data, including examination of relative TCA and DCE concentrations, to include separate phase TCE, PCE and TCA, as is suggested by the pie diagrams for the source area wells on Figures 5.2-6 and 5.2-7 (the latter for TCA). Abandoned well MW-48, which is not included in Table 5.2-1d, exhibited TCE concentrations as high as 280,000 ug/L, TCA at 94,000 ug/L and PCE at 11,600 ug/L. This former well is located immediately adjacent to source area wells MW-49D&S (screened from 202-212' and 135-140' bgs, respectively), but it is screened at a much shallower depth (3-22' bgs).

Together with nearby monitoring wells, these wells support the existence of a discrete vertical DNAPL transport pathway from the overburden monitored in MW-48 to the deep bedrock monitored in MW-49D&S. This observation is further supported by the results reported in Table 5.2-1d for nearby monitoring wells. Three of the four wells in the MW-50D&S and MW-51D&S well pairs are completed at depths of 120' bgs or less. All of them show patterns that suggest they are not impacted by a continuing DNAPL source. Rather they exhibit concentrations that either already meet groundwater standards or exhibit concentration trends that indicate impacts from reverse diffusion. MW-50D, the only one of these four wells completed at a depth interval greater than 120' bgs (160-170' bgs), also exhibits concentrations that suggest strong impact from the DNAPL source present at well locations MW-49D&S.

Figure 4.2-4 shows these relationships in cross section view. As shown, groundwater chemical flux from the comparatively deep DNAPL source apparent in data from wells MW-49D&S is being drawn locally into extraction well CW-15A and more distally into extraction well CW-17. The same may be true for extraction well CW-13, but it's not clear that its influence extends to the North Building 4 area. The important observation to be made from Cross Section B-B' is that control of flux from this apparent DNAPL source zone at depths greater than 200' bgs relies on the operation of two (and maybe three) extraction wells with depths no greater than 70' bgs. Cross Section B-B' also shows that the deepest well in this area (MW-49D) has not defined the vertical limits of this DNAPL source zone. Therefore, although the groundwater elevations in the MW-49D&S well pair show a slight upward vertical gradient, the bottom of the source zone should be found before hydraulic capture can be demonstrated.

Finally, Table 5.2-1d lists conclusions regarding temporal patterns of concentrations in wells in the BPA. As noted in the table, one well, MW-105, has been determined to be impacted by a continuing source based on the pattern of concentrations. Two other wells, MW-96D&S are believed to be impacted by a continuing source containing TCE and PCE, but this conclusion is uncertain.

The first five wells listed for this area in Table 5.2-1d are observation wells. As noted these wells are not believed to be impacted by a continuing source. This is due in part to their position relative to the source area wells and CW-17, which is the extraction well that appears to capture groundwater chemical flux from this area (Figure 4.2-4). Since they are not located within the flow path from the source area to the extraction well and their temporal concentration patterns do not match ones that would indicate impacts from a source, they are shown to exhibit concentrations that are either in the range of groundwater standards for PCE and TCA or suggest impacts from secondary sourcing for TCE. This last observation is consistent with patterns at other sites where TCE has been the most recalcitrant of these three principal CVOCs. This may be the case if TCE was the first of these compounds released to the environment and may have occupied the preferred sorption sites as well as had more time to diffuse into the rock matrix and the residuum/sediments.

Other Site Areas

These same criteria have been applied to other areas of the Site resulting in the following observations regarding locations at which there is evidence for continuing impact of a persistent source:

- In the NPBA East, the temporal pattern of TCE concentrations indicates evidence of a persistent source in three extraction wells (CW-1, CW-2, and CW-7A) and three monitoring well locations (MW-9, MW-10 and MW-12); however, data for RW-1 to RW-4 off-Site to the north indicate that concentrations in this area have been reduced to below groundwater standards.

- In the NPBA West, the temporal pattern of concentrations shows evidence of a persistent source for TCE in one extraction well (CW-4) and two monitoring wells (MW-18D&S), and for PCE in one monitoring well (MW-16S); potential off-Site transport of CVOCs is possible to the west of MW-18D&S.

- In the SPBA at the southeast corner of the property, both the shallow well, MW-64S (35-40’ bgs) and the deep well, MW-64D (70-75’ bgs) indicate potential impact from a persistent source of TCE and PCE; the shallow well is completed in overburden above sandstone/quartzite and the deep well is completed in limestone bedrock; concentrations in the deep well are higher than those in the shallow well indicating a downward vertical concentration gradient potentially associated with DNAPL transport; a single well down gradient just north of Arsenal Road (MW-110) shows a similar pattern of concentrations at lower levels. The horizontal and vertical extent of this plume is not well defined.

- Further west along the southern property line, in the vicinity of the intersection of Arsenal Road with Eden Road, there is evidence of a persistent source of TCE in well MW-43D; this well is completed in the limestone bedrock at a depth interval of 82-92’ bgs; the potential for CVOCs detected in this well to be transported off-Site to the south is uncertain based on incomplete characterization of the groundwater flow direction in this area.

5.2.2 Transformation of CVOCs

From the previous discussion of transformations of the principal CVOCs at this Site, the transformation products known to be derived from these compounds include: cis12DCE, VC, 11DCA and 11DCE. Although TCE can be a transformation product of PCE, as stated previously, this process does not favor TCE, but rather proceeds more readily to cis12DCE. The following is a discussion of the occurrence of these transformation products at the fYNOP Site:

- Cis12DCE: This is the transformation product that occurs most frequently at the Site. The highest concentration was detected at MW-49S (15,000 ug/L) in 2008 and concentrations of this CVOC above 1000 ug/L are most prevalent in the WBldg2 Corridor wells MW-81S and MW-114, in six wells in the NBldg4 area (MW-7, MW-49D&S, MW-50D, and MW-51D&S); concentrations above 1000 ug/L have also been detected in two wells in the BPA (MW-39D&S), in two wells in the NPA (MW-60 and MW-116), in two wells in the NETT area (MW-26 and MW-71S), in one well in the Building 58-66 area (MW-113) and at one well location in the SW-WPL (MW-75D).

- Vinyl Chloride: The presence of vinyl chloride is an indication of strongly reducing conditions. It is typically found together with cis12DCE, from which it is derived by reductive dechlorination. VC was detected above 100 ug/L at only seven monitoring well locations. These include two in the NBldg4 area (MW-50D and MW-51D) (the latter where the highest concentration occurred), two in the NETT area (MW-71S and MW-115), two in the NPA (MW-60 and MW-115) and one in the WPL-Central area (MW-38D).

- 11DCA: 11DCA is derived from TCA by reductive dechlorination. It is one of two degradation products of TCA detected at the Site. The other is 11DCE, discussed below. Figure 5.2-7 depicts the relative proportions of TCA, 11DCA and 11DCE in wells within the western portion of the Site. Neither TCA nor its degradation products are significant contaminants in the eastern portion of the Site. Of the six monitoring wells where 11DCA has been detected above 1000 ug/L, five of them are in the NBldg4 area (MW-48, MW-49D&S, MW-50D, and MW-51D) and they correspond closely to the wells in which high cis12DCE concentrations have been detected. Two of them are also locations at which VC has been detected above 100 ug/L (MW-50D and MW-51D). Altogether, the occurrences of these transformation products of reductive dechlorination together in wells in the NBldg4 area indicates that strong reducing conditions are present in this area. The sixth well at which 11DCA was detected above 1000 ug/L was MW-54 in the CPA-TCA Degreaser area.

- 11DCE: As noted previously, 11DCE occurs as a transformation product of TCA by the abiotic hydrolysis reaction. Since this process begins as soon as the TCA dissolves in groundwater, it will be present at some level wherever TCA is present. The relative distribution of this constituent together with TCA and its other degradation product 11DCA is shown on Figure 5.2-7 based on the May 2008 sampling round. The highest

> concentrations of 11DCE were detected in 1990 and 1991 at well MW-48 (20,400 ug/L and 19,000 ug/L). However, the highest concentration of this CVOC during the May 2008 round was at MW-55 (3,000 ug/L). Other wells in which 11DCE has been detected above 1,000 ug/L in samples collected since remediation began include MW-54, also in the CPA- TCA degreaser area, and MW-49S, MW-50, and MW-51D, all within the NBldg4 area.

With the exception of VC at a maximum concentration of 15 ug/L in MW-10, cis12DCE is the only transformation product that occurs in the eastern portion of the site. The maximum concentration of cis12DCE in this area is 470 ug/L at MW-10, where there is also evidence of an increasing trend with time.

5.3 Groundwater – Surface Water Interface

Prior to the initiation of groundwater extraction in the WPL area, transport of CVOCs in plumes emanating from source areas in the western portion of the plant to the Codorus Creek was impeded only by the attenuation characteristics of the soil and bedrock between them (i.e., their organic carbon partition coefficient, organic carbon content, matrix porosity and diffusion coefficient). It is reasonable to assume, based on pre-remediation concentrations observed in wells along the current Eden Road, that concentrations of CVOCs in the thousands of micrograms per liter were present in groundwater flowing off-Site to the west.

However, since the inception of groundwater extraction, the hydraulic gradient has been reversed and concentrations in those wells have diminished substantially, as will be discussed further in Section 6. However, a groundwater divide has developed between Eden Road and the creek. As shown on Figure 5.2-6, it is believed that this divide lies to the east of four clusters or pairs of wells along the levee boarding the creek. Based on this interpretation of groundwater elevation data, the only remaining groundwater chemical flux to the creek is from the area west of this divide, as shown in Cross Sections A-A' and B-B' (Figures 4.2-3 and 4.2-4, respectively). An analysis of the permanence of this divide under varying hydrologic conditions was discussed in sections 3.4 and 3.5 based on data from a collection well shutdown and restart test performed in late 2008. Based on this test, the divide shown on Figure 5.2-6 was maintained throughout virtually all changes in hydraulic conditions during this long-term test except during the time when the extraction wells were shut down. Therefore it is reasonable to conclude that this divide is maintained so long as the extraction wells are operating.

While this conclusion seems completely justified by the hydraulic data, there is also chemical concentration data that supports the hydraulic separation of the source areas on the fYNOP plant site and the levee wells located between the creek and the groundwater divide. This chemical evidence is presented on Figures 5.2-6 and 5.2-7. Figure 5.2-6 shows the proportions of various CVOCs in wells along the levee and those on the plant site. On both sides of the divide this chemical signature is dominated by ethene compounds PCE, TCE and cis12DCE. Other than to allow a comparison of their relative chemical signatures, comparing the proportions of these compounds on each side of the divide will not permit any conclusions to be made regarding when the most recent transport of groundwater containing these CVOCs crossed the current location of the divide.

However, as shown on Figure 5.2-7, TCA and its transformation product 11DCE occur in wells on both sides of the divide. As discussed previously, the ratio of their molar concentrations can be used to calculate when the TCA was first dissolved in groundwater, after Gauthier and Murphy, 2003. Therefore, if it can be shown that the TCA and 11DCE concentrations on the west side of the divide reflect a pre-pumping date for the dissolution of the TCA and the comparable data on the east side of the divide shows significantly later dating, then it can reasonably be concluded that the chemistry currently observed in the levee wells has not been impacted by flux from the east side of the divide since pumping began in 1994.

Table 5.3-1 shows the calculations for wells east and west of the divide in the WPL-South area. Columns in this table include the well number, sample date, TCA, 11DCA and 11DCE concentrations, the 11DCE:TCA ratio, the calculated years since the TCA dissolved in groundwater and the date (year) in which that occurred. The 11DCA concentrations are provided because degradation of TCA to this compound can affect the calculations based on the 11DCE:TCA ratio. In general the presence of 11DCA did not materially affect the calculations.

From Table 5.3-1 it is possible to see that the calculated years since TCA dissolved in groundwater and the date (year) in which that occurred are strikingly consistent at 22.8 to 26.0 years and 1981-1984, respectively. Importantly, all of these dates are before the inception of pumping in the WPL source areas when migration of TCA into the area west of the divide would have been unimpeded. By contrast, the years since TCA dissolved in groundwater and the dates for the wells east of the divide are both highly variable with all of the wells indicating impacts from TCA that dissolved in groundwater after the pumping began. More importantly all of these wells have dates that are much more recent than those for the wells west of the divide.

The same conclusion is possible for the comparison shown for wells in the BPA on Table 5.3-2. The dates calculated for when TCA dissolved in groundwater are consistent in the range of 1983 to 1989. In this case a few of the wells on the east side of the divide exhibit several early dates comparable to those for the wells on the west side. However, for each of these wells much more recent, post-pumping dates have also been calculated.

From this analysis of chemical concentration data for TCA and 11DCE it is possible to conclude that the chemistry in wells west of the divide has not been influenced by flux across the divide since the 1980s at a time prior to the inception of pumping.

Table 5.3-1: WPL Central and South- TCA to 11DCE Transformation Timing

West of Divide

Well No.	Sample Date	TCA µg/l	11DCA µg/l	11DCE µg/l	11DCE:TCA	Years	Initial Date
MW-100D	05/22/08	6	2.9	8.3	1.38	26.0	1982
MW-100D	09/22/08	8.4	5.3	13	1.55	27.2	1981
MW-100D	07/01/09	4.2	2.3	5.4	1.29	25.3	1984
MW-100I	05/21/08	8	2.7	8.7	1.09	23.6	1984
MW-100I	09/24/08	3.8	0	3.8	1.00	22.8	1985
MW-100I	06/30/09	3.9	1.6	4.2	1.08	23.5	1985
MW-100S	05/22/08	7.5	2.5	8.4	1.12	23.9	1984
MW-100S	05/22/08	7.4	0	8.1	1.09	23.7	1984
MW-100S	07/02/09	3	0	3.6	1.20	24.6	1984

East of Divide

Well No.	Sample Date	TCA µg/l	11DCA µg/l	11DCE µg/l	11DCE:TCA	Years	Initial Date
MW-037D	01/26/90	210	15	21	0.10	5.7	1984
MW-037D	04/03/90	130	10	14	0.11	6.0	1984
MW-037D	01/30/92	110	9	4	0.04	2.4	1990
MW-037D	06/24/93	50	0	0	0.00	0.0	1993
MW-037D	04/28/94	1000	20	10	0.01	0.7	1993
MW-037D	07/12/94	3200	0	0	0.00	0.0	1994
MW-037D	10/27/95	1700	39	200	0.12	6.4	1989
MW-037D	07/15/96	2100	0	230	0.11	6.1	1990
MW-037D	10/20/97	760	28	75	0.10	5.6	1991
MW-037D	12/14/98	460	18	42	0.09	5.3	1993
MW-037D	04/07/00	870	22	96	0.11	6.1	1994
MW-037D	06/26/01	1220	35	136	0.11	6.2	1995
MW-037D	06/19/02	332	15	43	0.13	6.9	1995
MW-037D	06/06/03	262	11	20.7	0.08	4.7	1998
MW-037D	04/15/04	160	7.8	27	0.17	8.4	1996
MW-037D	06/08/04	220	9.2	30	0.14	7.2	1997
MW-037D	06/15/05	400	14	36	0.09	5.2	2000
MW-037D	06/24/06	6	0	0	0.00	0.0	2006
MW-037D	06/29/07	98	0	6.6	0.07	4.1	2003
MW-037D	05/14/08	390	0	31	0.08	4.7	2003
MW-037D	10/01/08	280	0	0	0.00	0.0	2008
MW-037D	07/13/09	710	0	72	0.10	5.7	2003
MW-037S	01/26/90	820	32	18	0.02	1.5	1988
MW-037S	04/03/90	550	33	11	0.02	1.4	1989
MW-037S	01/31/92	880	21	30	0.03	2.3	1990
MW-037S	04/28/94	1200	40	0	0.00	0.0	1994
MW-037S	07/12/94	1800	80	20	0.01	0.8	1993
MW-037S	10/27/95	73	10	6	0.08	4.9	1990
MW-037S	07/15/96	23	3	0	0.00	0.0	1996
MW-037S	10/20/97	74	7	3	0.04	2.7	1994
MW-037S	12/14/98	280	13	8.5	0.03	2.0	1996
MW-037S	09/22/99	140	6	4	0.03	1.9	1997
MW-037S	04/03/00	96	0	0	0.00	0.0	2000
MW-037S	06/25/01	110	5.2	2.5	0.02	1.6	1999
MW-037S	06/12/02	71	4.8	1.2	0.02	1.2	2001
MW-037S	06/03/03	19.9	1.7	0	0.00	0.0	2003
MW-037S	04/15/04	1.9	0	0	0.00	0.0	2004

MW-037S	06/07/04	22	3	1.2	0.05	3.4	2001
MW-037S	06/21/05	30	2.1	0	0.00	0.0	2005
MW-037S	06/23/06	8.7	0	0	0.00	0.0	2006
MW-037S	06/29/07	53	0	0	0.00	0.0	2007
MW-037S	05/14/08	12	0	0	0.00	0.0	2008
MW-037S	05/14/08	12	0	0	0.00	0.0	2008
MW-037S	09/18/08	23	0	0	0.00	0.0	2008
MW-037S	07/01/09	8.3	0	0	0.00	0.0	2009
MW-038D	01/26/90	11	6	2	0.18	8.8	1981
MW-038D	04/03/90	8	4	1	0.13	6.7	1983
MW-038D	01/31/92	22	1	2	0.09	5.3	1987
MW-038D	04/28/94	40	0	0	0.00	0.0	1994
MW-038D	07/11/94	230	20	0	0.00	0.0	1994
MW-038D	10/31/95	220	50		0.00	0.0	1995
MW-038D	07/15/96	49	11	0	0.00	0.0	1996
MW-038D	10/20/97	39	13	0	0.00	0.0	1997
MW-038D	12/14/98	16	13	0	0.00	0.0	1998
MW-038D	03/29/00	3.2	1.7	0	0.00	0.0	2000
MW-038D	06/19/01	4	2.8	1.4	0.35	13.4	1988
MW-038D	06/03/03	1.6	2	0	0.00	0.0	2003
MW-038D	04/15/04	0.8	0.9	0	0.00	0.0	2004
MW-038D	06/09/04	1.8	1.5	0	0.00	0.0	2004
MW-038D	06/14/05	1	1.2	0	0.00	0.0	2005
MW-038D	04/28/08	0.56	1.1	0.49	0.88	21.5	1986
MW-038D	06/18/09	0.64	1.3	0	0.00	0.0	2009
MW-038S	02/07/90	4	2	0	0.00	0.0	1990
MW-038S	04/03/90	5	3	0	0.00	0.0	1990
MW-038S	07/15/96	4	1	0	0.00	0.0	1996
MW-038S	10/20/97	2	1	0	0.00	0.0	1997
MW-038S	12/14/98	2	0	0	0.00	0.0	1998
MW-075D	09/17/99	270	0	0	0.00	0.0	1999
MW-075D	04/07/00	280	0	40	0.14	7.4	1993
MW-075D	06/26/01	95	4.5	21	0.22	10.1	1991
MW-075D	06/18/02	218	20	42	0.19	9.2	1993
MW-075D	06/06/03	240	13.7	50	0.21	9.7	1993
MW-075D	04/16/04	680	0	120	0.18	8.7	1995
MW-075D	06/10/04	1000	0	0	0.00	0.0	2004
MW-075D	06/10/04	930	0	0	0.00	0.0	2004
MW-075D	06/17/05	620	0	0	0.00	0.0	2005
MW-075D	06/24/06	350	0	0	0.00	0.0	2006
MW-075D	06/29/07	190	0	0	0.00	0.0	2007
MW-075D	05/21/08	45	0	13	0.29	12.0	1996
MW-075D	10/02/08	110	0	0	0.00	0.0	2008
MW-075S	09/17/99	1200	0	0	0.00	0.0	1999
MW-075S	04/07/00	1620	21	163	0.10	5.7	1994
MW-075S	06/26/01	1710	0	233	0.14	7.2	1994
MW-075S	06/18/02	778	19	91	0.12	6.4	1996
MW-075S	06/06/03	511	18	70.1	0.14	7.2	1996
MW-075S	04/15/04	300	0	45	0.15	7.7	1996
MW-075S	06/10/04	1100	0	0	0.00	0.0	2004
MW-075S	06/17/05	550	0	0	0.00	0.0	2005
MW-075S	06/23/06	690	0	0	0.00	0.0	2006
MW-075S	05/21/08	1000	0	0	0.00	0.0	2008

MW-075S	10/06/08	680	0	0	0.00	0.0	2008
MW-075S	07/06/10	630	0	0	0.00	0.0	2010
MW-093D	04/16/04	40	0	7.3	0.18	8.9	1995
MW-093D	04/26/04	180	0	28	0.16	7.9	1996
MW-093D	04/26/04	200	0	34	0.17	8.4	1996
MW-093D	06/20/05	4.6	1.6	1.3	0.28	11.8	1993
MW-093D	06/23/06	18	0	4.4	0.24	10.8	1995
MW-093D	06/27/07	37	2.7	6	0.16	8.2	1999
MW-093D	05/13/08	13	0	6.7	0.52	16.6	1991
MW-093D	09/22/08	3.8	2	2.5	0.66	18.8	1989
MW-093D	06/26/09	9.8	4.1	6.6	0.67	19.0	1990
MW-093S	04/16/04	1.9	0	0	0.00	0.0	2004
MW-093S	04/16/04	1.7	0	0	0.00	0.0	2004
MW-093S	04/26/04	5.5	0.9	0.4	0.07	4.4	2000
MW-097	09/19/08	6.8	0	0	0.00	0.0	2008

Table 5.3-2: Burn Pile Area- TCA to 11DCE Transformation Timing

West of Divide

Well No.	Sample Date	TCA µg/l	11DCA µg/l	11DCE µg/l	11DCE:TCA	Years	Initial Date
MW-098I	05/23/08	0.58	0	0.55	0.95	22.3	1986
MW-098I	09/12/08	0.51	0.41	0.57	1.12	23.9	1984
MW-098I	06/18/09	0.39	0.38	0.39	1.00	22.8	1986
MW-098S	05/22/08	0.22	0	0.17	0.77	20.3	1988
MW-099D	05/22/08	5.9	0	5.2	0.88	21.6	1986
MW-099D	06/25/09	2.9	0	3.1	1.07	23.5	1986
MW-099D	06/22/10	3.2	0	3	0.94	22.2	1988
MW-099S	05/22/08	4.1	0	4.3	1.05	23.3	1985
MW-099S	09/24/08	3	0	3.7	1.23	24.9	1983
MW-099S	06/26/09	3.6	0	2.7	0.75	20.0	1989

East of Divide

Well No.	Sample Date	TCA µg/l	11DCA µg/l	11DCE µg/l	11DCE:TCA	Years	Initial Date
MW-038S	12/14/98	2	0	0	0.00	0.0	1998
MW-039D	02/22/90	7	0	1	0.14	7.4	1983
MW-039D	04/03/90	10	1	2	0.20	9.4	1981
MW-039D	01/31/92	4	0	0	0.00	0.0	1992
MW-039D	04/29/94	50	0	25	0.50	16.4	1978
MW-039D	07/12/94	40	0	0	0.00	0.0	1994
MW-039D	07/15/96	9	0	0	0.00	0.0	1996
MW-039D	10/20/97	1	2	0	0.00	0.0	1997
MW-039D	03/30/00	6.2	1.5	2.6	0.42	14.9	1985
MW-039D	06/25/01	5	1.7	2	0.40	14.5	1986
MW-039D	06/12/02	3.2	1.3	1.9	0.59	17.9	1984
MW-039D	06/05/03	1.8	0	0	0.00	0.0	2003
MW-039D	06/10/04	3.2	0	0	0.00	0.0	2004
MW-039D	06/17/05	1.5	0	0	0.00	0.0	2005
MW-039S	02/05/90	5	0	0	0.00	0.0	1990
MW-039S	04/03/90	1	0	0	0.00	0.0	1990
MW-039S	01/31/92	9	2	2	0.22	10.1	1982
MW-039S	04/28/94	15	0	5	0.33	13.1	1981
MW-039S	11/01/95	7			0.00	0.0	1995
MW-039S	06/10/04	1.2	0	0	0.00	0.0	2004
MW-039S	06/15/05	0.6	0	0	0.00	0.0	2005
MW-074D	09/15/99	38	6	15	0.39	14.4	1985
MW-074D	04/06/00	17	3.7	12	0.71	19.5	1981
MW-074D	06/21/01	12	4.5	9.1	0.76	20.1	1981
MW-074D	06/14/02	5	1.8	4.8	0.96	22.4	1980
MW-074D	06/05/03	5.5	2.5	6.1	1.11	23.8	1979
MW-074D	06/09/04	3	2.3	4.7	1.57	27.3	1977
MW-074D	06/21/05	2.7	1.9	4	1.48	26.7	1978
MW-074D	06/25/09	1.6	0	2.3	1.44	26.4	1983
MW-074S	09/15/99	11	1	3	0.27	11.6	1987
MW-074S	04/03/00	4.1	1.3	2	0.49	16.2	1984
MW-074S	06/21/01	3.6	1.3	1.9	0.53	16.9	1984
MW-074S	06/13/02	1.6	1.9	0	0.00	0.0	2002
MW-074S	06/14/05	0.6	1.2	0	0.00	0.0	2005
MW-105	05/05/08	19	0	0	0.00	0.0	2008
MW-105	07/09/09	23	0	0	0.00	0.0	2009

6 INTERIM REMEDIATION PROGRESS

This report section describes the scope and progress of groundwater remediation interim remedial action activities performed at the Site. It begins with a discussion of groundwater extraction and treatment operations that were initiated at the site in 1990, followed by a review of temporal changes in COC concentrations and an analysis of the extent to which groundwater quality has improved and the extent to which additional improvement would need to be achieved in order to meet PADEP State-wide medium-specific concentrations.

6.1 Groundwater Extraction and Treatment

The GWTS has been in operation since November 1990. The follow descriptions are excerpted from SAIC, March 2010:

> The GWTS is designed to accomplish the following:
>
> 1. Prevent off-Site groundwater migration in the NPBA.
> 2. Remove VOC-impacted groundwater in the TCA Tank Area near Building 2.
> 3. Prevent off-Site migration of groundwater in the WPL Area.
> 4. Remove VOC-impacted groundwater at the former degreaser in the NBldg4 Area.
> 5. Collect groundwater from the Building 3 Softail Dewatering Area's groundwater interceptor trench system east of the Softail plant which prevents VOC-impacted groundwater from discharging to the surface or into the building.

The extraction system, illustrated on Figure 6.1-1, consists of fifteen active extraction wells: nine in the NPBA, one in the TCA Tank Area, four in the WPL/NB4 Area, and the Softail Dewatering Area's interceptor trench system including one well CW-19.

Extraction wells within the NPBA, TCA Tank Area, NBldg4 and the WPL groundwater extraction areas remove groundwater by means of electric submersible pumps. A lift station pump removes water from a series of collection trenches in the vicinity of the Softail plant. The pumping water level within each extraction well is maintained by liquid level probes and control circuitry between the "on" and "off" probes. This produces an area of drawdown and groundwater capture. The extracted groundwater is conveyed via underground piping to the treatment system where the dissolved VOCs are removed from the groundwater.

The groundwater treatment system is housed in a 30-foot by 40-foot building attached to the west wall of the IWTP, called Building 41. The process flow diagram for the system is presented in Figure 6.1-2. The treatment system consists of a 2,600-gallon equalization tank; a 5-foot-diameter by 47-foot-high Packed Tower Aerator (PTA) capable of treating 400 gpm of water; and a 10,000-pound vapor-phase Granular Activated Carbon (GAC) unit for PTA off-gas treatment.

Extracted groundwater is pumped from the equalization tank at a maximum flow rate of 400 gpm to the top of the PTA. The water is then distributed evenly over the top of the polypropylene packing and flows down through the 36-foot-high packed section of the PTA. A 4,000 cubic foot per minute (cfm) centrifugal blower draws air through the PTA column. The VOCs are effectively "stripped" from the water and then adsorbed to the GAC. The treated groundwater flows to a groundwater pump station located on the north side of Building 41 where it is pumped to a storm water outlet (Outfall No. 3) and discharged to Codorus Creek.

As of December 31, 2010, a system-wide total of approximately 38,444 pounds of VOCs have been removed by the groundwater treatment system (SAIC, March 2011). On average, prior to start-up of the WPL system in May 1994, approximately 131 gpm of groundwater and 1.2 pounds per day (lbs/day) of total VOCs were being extracted by the system. Since the WPL system became operational, the average groundwater pumping rate from 1995 through December 2010 was approximately 303 gpm with 5.7 lbs/day of total VOCs being removed (calculated from Table 4-1 of SAIC, March 2011). The estimated removal rate for 2010 was reported as 3.8 lbs/day (SAIC, March 2011).

6.1.1 TCA Tank Area

The current groundwater quality conditions and chemistry concentration trends for CVOCs in the vicinity of the TCA Tank extraction system (pumping well CW-8) are discussed in Section 4.2.6.1. TCA has effectively been removed from all but a few wells. Even those wells, however, have recent TCA concentrations below the groundwater MSC.

The ratio of the current concentrations of TCA compared to the maximum concentration prior to 1992 is plotted for wells CW-8 and MW-32S&D. These graphs are included in alphanumeric order in Appendix F, and designated as graphed for $C/Cmax_{1992}$ on Plate 4E. These graphs show that CW-8 and MW-32D quickly dropped below the Act 2 standard (PADEP Generic Statewide Health Residential MSC for used aquifers with total dissolved solids less than 2,500 milligrams per liter). MW-32S has been below the standard since 2006.

Concentrations of TCE, PCE and cis12DCE are considerably above the PADEP MSC. It is obvious from the concentration trends that a plume from an undetermined source area was pulled in as a result of pumping CW-8. The concentrations are stable (not declining).

6.1.2 NPBA

The current groundwater quality conditions and chemistry concentration trends for CVOCs in the NPBA are discussed in Section 4.2.1. The 9-well groundwater extraction system appears to have effectively improved off-Site groundwater quality to below residential MSCs (see trend graphs in Appendix C). Most extraction well concentrations are steadily decreasing; however, western extraction wells (CW-5 and CW-6) have drawn in groundwater with elevated concentrations of TCE (up to 1,800 µg/l) into monitoring wells MW-18S&D. The ratio of the current concentrations of TCE compared to the maximum concentration prior to 1992 is plotted for wells RW-2, MW-10 and MW-18S. These graphs are included in alphanumeric order in Appendix F, and designated as graphed for $C/Cmax_{1992}$ on Plate 4E. These graphs show that RW-2 has remained below the PADEP MSC for TCE since 2003, while MW-10 and MW-18S remain considerably above the MSC for TCE.

Site-related COCs detected in off-Site residential groundwater wells to the north were most likely drawn to the off-Site wells by pumping of those wells as water supplies. Those wells are no longer used as water supplies. Whether groundwater would naturally migrate northward from the NPBA to off-Site properties if the groundwater extraction system were deactivated has not been determined.

6.1.3 Building 3

The groundwater interceptor trench, the toe drain, and groundwater extraction well CW-19 make up the Building 3 groundwater depression system. The system collects minimum amounts of groundwater, which have relatively low concentrations of COCs. The system was not installed to remove mass or clean up the aquifer, but to protect Building 3 from the impacts of contaminated groundwater. Groundwater extraction well CW-19 was constructed as a failsafe mechanism to prevent contaminated groundwater from coming in contact with the sub-slab tank/pit in Building 3. The pump in this well has not activated since installation because the groundwater level has not risen to an elevation that would endanger the tank. Recently, due to various conditions related to the expansion activities being conducted around Building 3, the pumping station has operated intermittently, with some periods of inactivity. There has been no noticeable groundwater seepage into the building or the tank/pit area, however diligent monitoring of water levels has not been conducted. Due to the low concentrations of CVOCs in the groundwater and the potential that water levels may not rise sufficiently to enter the lowest portions of the building if the pumping station were deactivated, operation of the interceptor trench may not be necessary. However, if the pumping station is deactivated, it would be prudent to carefully monitor the recovery of the water table and its potential rise relative to the building facilities, particularly during seasonal high water table/recharge conditions.

6.1.4 West Parking Lot

The current groundwater quality conditions and chemistry concentration trends for CVOCs in the WPL are discussed in Section 4.2.7. The WPL extraction system was designed to prevent off site migration of groundwater, and as discussed and qualified in Section 3.4, that goal was demonstrated to have been met. Although groundwater quality has improved in the WPL and will be discussed in upcoming Section 6.2.5, the suspected DNAPL source areas in the SW-WPL and NBldg4 Area continue to supply high concentrations of dissolved CVOCs, which are pulled to the pumping wells.

6.2 Reduction in Groundwater Concentrations of COCs

The processes described in Section 5 combined with aggressive interim remedial action activities have resulted in a reduction in concentration of the primary COCs in Site groundwater. The purpose of this analysis is to demonstrate the extent to which groundwater quality has improved and the extent to which additional improvement would be need to be achieved in order to meet PADEP State-wide medium-specific concentrations.

Figure 6.2-1 is a map of the Site showing the generalized concentration contours of TCE from samples collected during four recent sampling rounds, and are the same concentration contours repeated from Figure 4.1-4. The sample locations and data supporting those contours are not included on Figure 6.2-1. The seventy-one wells shown on the map are wells that have a long history on site, and have been sampled frequently or from very early in the remedial investigation. The symbols representing the well locations are color coded to identify the percentage of reduction of TCE concentration in groundwater from that well, comparing the maximum concentrations to current concentrations. This was calculated by the following formula:

$$1 - C / Cmax \ X\ 100 \quad \text{where:}$$

C = the TCE concentration in μg/l during Round 1 (April/May 2008), and

Cmax = the maximum concentration of TCE in μg/l over the period of record.

Of the wells shown on Figure 6.2-1, fifty-seven have concentrations of TCE that have reduced by greater than 80% (shown by the dark blue symbols). Forty-nine wells have concentrations that have reduced by 90% or greater, thirty-eight have reduced by 95% or greater, and fifteen have reduced by 99% or greater. Only five wells have reduced from their maximum concentration by 60% or less. They are located in the NPBA (MW-9 and MW-18S&D), in the TCA Tank Area (MW-33) and west of NBldg4 (MW-50D) and in all cases represent high concentrations from primary source areas that have been mobilized by the groundwater extraction wells.

Likewise, as shown on Figure 6.2-2, TCA concentration reduced by greater than 80% in seventy out of seventy-one wells. Sixty-nine wells have concentrations that have reduced by 90% or greater, sixty-four have reduced by 95% or greater, and sixty have reduced by 99% or greater. TCA is only a significant CVOC in the western portion of the site, thus the map shows only the western portion of the site.

PCE concentrations show similar reductions (Figure 6.2-3), with fifty-five of seventy-one wells indicating concentration reductions of greater than 80 %. Thirty-six wells have concentrations that have reduced by 90% or greater, twenty-six have reduced by 95% or greater, and twenty-one have reduced by 99% or greater.

However, this condition can be somewhat misleading, unless compared to the reduction necessary to meet PADEP Groundwater MSCs. One issue is that the reduction of the primary chlorinated solvents used on the plant by dechlorination results in the production of daughter products that are also groundwater contaminants. Figure 6.2-4 shows the percentage reduction of cis12DCE has been significant since maximum values prior to 1992, with thirty-seven of seventy-one wells reduced by 80% or more. Thirty-three wells have concentrations that have reduced by 90% or greater, thirty-one have reduced by 95% or greater, and sixteen have reduced by 99% or greater. More significant is the number of wells that represent groundwater on-Site that have cis12DCE concentration ratios that have minimally reduced. Eight of the sixty-seven wells have shown reductions of 20% or less, while nineteen of sixty-seven have reduced 60% or less. The locations where these minimal reductions of cis12DCE occur are areas where persistent sources of TCE are suspected, namely the NPBA, NBldg4, and the TCA Tank Area. Notably absent in this list is the SW WPL.

The following sections will examine key areas of the Site in detail.

6.2.1 NPBA

Figure 6.2-5 shows the percentage of TCE reduction from the maximum concentration in the NPBA. The percent reduction has exceeded 90% in sixteen of the twenty-two wells in this area. Posted beside the percent reduction is the percentage reduction necessary to meet PADEP MSCs. For instance, the posting next to monitoring well MW-10 in the northeastern corner of the map shows that the concentration of TCE has reduced in this well by 95.2% from the maximum concentration detected (156 µg/l). However, in order to meet the PADEP statewide generic MSC for TCE of 5 µg/l, the percentage reduction would have to be 99.6 %.

This concept is shown graphically on MW-10 graph in Appendix F, which indicates the concentration trend MW-10 has dropped in steps. In the case of the C/Cmax graphs, the Cmax represents the maximum concentration prior to 1992. In this way, the graphs represent the concentration prior to significant change caused by remediation. The ratio of C/Cmax needed to meet the statewide MSC is shown as a horizontal blue line. By showing this trend as a percentage reduction, it is possible to normalize the CVOCs of concern and the various concentrations and MSCs, comparing them to the statewide groundwater standard for residential used aquifers. This graph shows a significant increase in concentration from the pre-pumping condition, most likely a result of the pumping system mobilizing groundwater with higher concentrations of TCE from south of MW-10. Although the overall trend shows a decrease in concentration, the progress over the 25 years does not suggest the current activity will result in TCE concentrations below the MSC in the next few years.

RW-2, a residential well located north of the Site property line, shows a much different trend. As shown on the graph of the ratio of C/Cmax over time (Appendix F), a continuous steady declining trend is revealed, showing that the PADEP MSC was achieved, and has been maintained since 2004. This is the expected results if no source exists beyond (in this case, to the north of) the monitoring well. The successful clean up of this well from an original maximum concentration of greater than 2,000 µg/l is an indication that the CVOC was drawn into the residential water supply by pumping and not as a result of natural migration from the Site to the north. Had natural migration caused the CVOC to reach RW-2, the 30+/- years of migration prior to reversal by the groundwater extraction system would likely have carried the high concentrations well beyond the well, and clean-up would have been slower and less complete.

Monitoring well MW-9 shows a reduced concentration ratio of only 52.4%. Referencing the concentration vs. time graphs in Appendix C (NPBA-E), a near well source is suggested by the 2X increase from the first to the second sample, a result of pulling in higher concentrated groundwater as a result of the sampling effort. The steady but slow decline is an indication that the source has been minimally depleted over the 20+ years of operation of the groundwater extraction system.

Monitoring Well MW-18D shows only 22% reduction, which is a flag that indicates a source of TCE has migrated into the well since the initial sampling in 1988 that detected no CVOCs. This well had not been sampled until the supplemental RI sampling in April 2008, when the concentration of TCE was 1,400 µg/l (reference Appendix C [NPBA-W]).

6.2.2 NETT

Active remediation has not been carried out in the NETT area. Figure 6.2-6 shows the generalized plume of TCE concentrations from Figure 4.1-4. Two wells are included on this map, with the upgradient monitoring well MW-19 showing a 64% reduction in TCE concentrations compared to the maximum detected. MW-26, which monitors the groundwater quality down gradient of the NETT experienced a 94% reduction in concentration from the maximum. However, in order to meet PADEP MSCs, the concentration percentage reduction would need to meet 99.1 and 99.9% in groundwater samples from MW-19 and MW-26, respectively. This is shown graphically for these wells in Appendix F, where the trend for TCE is shown as a steady decline, and the PADEP MSC for TCE is shown as a horizontal blue line. In both cases, the intersection of the PADEP MSC by the declining ratio appears to be in the distant future.

The ratio for PCE is also shown on the graph for MW-19, and indicates that natural attenuation processes have brought the PCE concentration below the PADEP MSC. This is due to the original low maximum concentration of PCE (21 µg/l in 1987). The ratio for PCE in monitoring well MW-26 does not appear on the Appendix F graph because the current concentration is not detected (no ratio possible). The 1991 concentration of PCE was 84 µg/l, so natural attenuation as a result of reductive dechlorination was complete and effective. The expected reduction of PCE is dechlorination, which would produce TCE, which probably contributres to the persistence of TCE at this location. For MW-26, the ratio of C/Cmax for TCA has shown a steady decline, with TCA dropping below the PADEP MSC.

6.2.3 TCA Tank Area

Figure 6.2-7 shows the percent reduction of TCE in groundwater in the TCA Tank Area. As recorded in Section 4.4.6.1, pumping well CW-8 was initiated in November 1990 to address a high concentration of TCA, which was reduced in a number of years. However, a plume of TCE was drawn into the area in 1994 by the continued pumping. Reductions of TCA (Figure 6.2-2) in this area ranged from 90 to 100%, comparing the Cmax value with the April 2008 value in the nine wells in this area. No wells exceed the PADEP MSC for TCA.

As posted on Figure 6.2-7, the percent reduction of TCE ranges from 36% to 91%, however the percentage required to meet PADEP MSCs is much higher in all cases. Graphs of the ratio of the concentrations TCE, PCE and TCA for well CW-8 from 1992 Cmax values are graphed and included in Appendix F. The graph shows that TCA concentrations continue to steadily decline, having met the PADEP MSC four years after the initiation of pumping. This is primarily because of the relatively high MSC of 200 µg/l for TCA, compared to 5 µg/l for TCE and PCE. Both TCE and PCE trends have flattened and show no discernable reducing trend over the last several years, with no progress being made to reach the PADEP MSCs for those compounds. Appendix F graphs show similar C/Cmax ratio plots for well couplet MW-32S&D, located 14 feet southwest of CW-8. The trend is somewhat more erratic than the CW-8 trend, but also shows minimal progress being made toward reducing the concentrations of TCE and PCE to PADEP standards.

The TCA Tank Area is an example of groundwater being impacted by a source area of undetermined location, with the COC transported into the area by migration of groundwater, in this case as a result of induced flow from pumping. Minimal progress is being made by pumping of CW-8, although pumping of the well contributes to prevention of off-Site migration by removing a considerable portion of the groundwater flowing through the Site.

6.2.4 North Building 4 Vapor Degreaser Area

The NBldg4 area is shown on Figure 6.2-7. Based on the maximum concentrations of CVOCs exceeding 1% of the solubilities, this is an area of likely DNAPL presence in the past, and continuing to the present to a lesser degree (see Figures 5.2-3 through 5.2-5). Reductions of the percent TCE range from 72 to 99% in the nine wells in the immediate vicinity. However, to meet PADEP MSCs the percent reduction will need to exceed 99.9% in five of the nine wells, and 99.99% in two of the wells, as posted on Figure 6.2-7.

Appendix F includes a graph of the ratio of the maximum concentrations of TCE and PCE in MW-27 prior to 1992, upgradient of the NBldg4. The trend indicates no decline in the ratios of these compounds. Graphs of the ratios of well couplet MW-49S&D (Appendix F), located 50 feet southwest of the degreaser operation, show a reasonable declining trend. However, the level needed to meet the PADEP MSC for TCE does not even plot on the graph, and therefore attainment under the current remedial action is questionable.

Graphs of well couplet MW50S&D (Appendix F) located 180 feet west of the degreaser operation show the evidence of a CVOC plume being drawn into the wells after the year 2000, nearly 6 years after groundwater pumping was initiated in the WPL. While MW-50S, screened in bedrock from 110 to 120 feet bgs, shows TCA and PCE below or approaching the PADEP MSC, the TCE concentration shows minimal progress toward attainment.

6.2.5 West Parking Lot

As shown on Figure 6.2-7, TCE concentrations in samples from well couplet MW-37S&D in the SW-WPL have reduced by 98% and 87%, respectively. Attainment of the PADEP MSC for TCE requires 99.2% and 99.9% reductions, respectively. The graph of the C/Cmax ratios of PCE, TCE and TCA, with the Cmax being the highest value prior to the initiation of pumping in the WPL, shows a stepwise decreasing trend in MW-37S (Appendix F). This well is screened across the residuum/bedrock interface at a depth of 12 to 32 ft. bgs. In contrast, the graph showing the ratio of the April 2008 concentration to the maximum concentration prior to pumping in the WPL, presents an erratic pattern, which has been steadily increasing since 2006. MW-37 is in the location of suspected DNAPL and stacked solution caverns, the combination of which is believed to explain the erratic pattern in MW-37D.

The ratios of two additional wells in the WPL were graphed to compare ratios of concentration in 2008 versus the maximum concentration prior to 1992. MW-8 is located in the southern half of the WPL, and is 165 feet northeast of extraction well CW-9. That graph in Appendix F shows the plot of the ratios for PCE, TCE and TCA. Similarly, the Appendix F graph for MW-7, located in the central portion of the WPL shows similar ratios. These graphs show trends that clearly suggest minimal progress toward the PADEP MSCs, despite the considerable reductions experienced in both of these wells.

6.2.6 Remainder of Site

Groundwater in the vicinity of the eastern and southern perimeter road areas has not undergone active remediation. TCE concentrations have reduced by 98 to 99% in the EPRA in wells MW-14, MW-15, MW-2 and MW-22 (see Figure 6.2-1). As discussed in Section 5.1.4.3, reductive dechlorination is not the likely process of TCE concentration reductions in this area, due to the lack of cis12DCE concentrations. This leaves advection, sorption and volatilization as processes that may have contributed to the reduction. C/Cmax graphs for wells MW-14, MW-2 and MW-22 (Appendix F) show plots of the ratio of current concentrations to maximum concentrations of TCE and PCE in wells in the EPRA. The graphs indicate TCE and PCE concentrations have fallen steadily since the initial sampling in 1986 or 1987 and are approaching the PADEP MSC, or in the case of MW-14, have dropped below the PADEP MSC. The ratio of C/Cmax in well couplet MW-43S&D, along the south property boundary, shows the concentration of TCE in MW-43D has been steady for the last 6 years (see Appendix F).

6.2.7 Summary of Reduction in Groundwater Concentrations of COCs

The reduction in CVOC concentrations in the groundwater across the Site, with a few exceptions, has been significant, with 90 to 99.9% reductions in TCE concentrations in many wells. However, the reduction required to meet PADEP MSCs has not been met in most wells. Figure 6.2-8 is a plot of the Site showing the wells that exceed one or more MSCs for CVOCs, specifically PCE, TCE or TCA and their daughter products. 117 of 133 groundwater sample points on the fYNOP property exceeded MSCs for CVOCs in the round one Supplemental RI sampling of April/May 2008. The fact that chlorinated solvents have not been used on-Site since 1994, or 17 years from this writing (REWEI, January 1995), there has been no known release of chlorinated solvents in over 25 years, and the groundwater pump and treat systems have been operating for over 20 years is an indication of the persistence of the COCs in groundwater.

6.3 Calculation of Mass of CVOCs in the Aquifer

The mass of the CVOCs occurs in the aquifer 1) as mass dissolved in the groundwater, 2) as mass adsorbed on to and diffused into the matrix (granular and solid portions of the aquifer materials) and as 3) as DNAPL, as illustrated on Figures 5.1-1 and 5.1-2. The source of the dissolved mass is desorption and reverse diffusion from the aquifer matrix and dissolution of DNAPL. When groundwater wells are sampled and analyzed for CVOCs, the dissolved portion of the mass is measured. Plume concentration maps represent the general distribution of the dissolved component.

Adsorbed and diffused mass has not been measured on site, but has been extensively discussed in Sections 5.1.2.2 and 5.1.4.2. Likewise, the presence and location of DNAPL in the aquifer has been discussed and inferred throughout Section 5.2.1, but not directly measured. Methods to calculate mass in place of DNAPLs at other sites have not proven to be accurate for many reasons, even in simple hydrogeologic conditions. At the fYNOP site the calculation is complicated by the potential for CVOCs to have been disposed of anywhere on site and the poor record of historical operations where CVOCs were used. In addition, the karst portion of the aquifer is riddled with solution channels that make the migration of DNAPL unpredictable, and raise the potential for pools and residual free-phase liquids to occur in the water-filled voids and within the sediment in the solution channels.

The following approach was used to bracket the estimate of mass in place:

- The dissolved component of the mass was calculated using the concentrations of PCE, TCE, TCA and cis12DCE in groundwater, from the plume maps in Section 4 (Figures 4.1-4 through 4.1-7).

- The volume of groundwater treated by the groundwater extraction system and the concentration of the influent to the treatment plant was used to calculate the quarterly and annual mass removed. The mass removed over time was graphed and the trends were projected for 100 years into the future. The mass projected was compared to the mass removed annually and to the total mass removed since the beginning of extraction system operation.

Appendix G includes electronic spreadsheets that contain the calculations of mass and procedures followed.

6.3.1 Dissolved Mass in the Groundwater

The dissolved mass was calculated by taking the concentration of the four main CVOC COCs in the groundwater multiplying by the volume of the aquifer and taking that volume times the effective porosity of the aquifer. This work was done on spreadsheets that are included in Appendix G. The porosities of the various components of the quartzitic sandstone and carbonate aquifers, as reported in Chapter 3, were calculated or estimated. For the quartzitic sandstone aquifer, a porosity of 0.5% was used. For the carbonate aquifer, the saturated overburden porosity was estimated at 20%. The percentage of solution cavities was estimated from the drilling logs by calculating the ratio of void space drilled versus the total footage drilled in the carbonate bedrock (i.e., excluding the footage drilled in the overburden and excluding wells not drilled in the carbonate). Solution cavities comprise 16% of total drilled footage in the carbonate. Sixty-three percent of these solution cavities were noted on the well logs as being filled with sediment, which was estimated to have a porosity of 25%. Thus the weighted average of channel porosity in the bedrock was 8.5%. The fracture porosity was estimated to be 1% based on Table 3.3-1. Matrix porosity, which is effective at storing diffused mass, and is discussed in Section 3.3 as having a value of 7% was considered to be minimally connected with respect to groundwater in the aquifer, and so a porosity of 0% was used. Thus the total effective porosity for the carbonate rock was estimated to be 9%

The area of each plume concentration contour interval was determined using ArcGIS. Concentrations for discrete depth intervals 0 to 50’, 51-100’, 101-150’, and 151-200’ were estimated by reviewing the monitoring well concentrations and depths of open interval. From 0 to 50’, the footage of the interval below the water table and the footage composed of overburden were estimated. The effective porosity values for overburden, carbonate bedrock or non-carbonate bedrock were assigned to each interval, and the volume of groundwater calculated. Lastly the mass of CVOCs was calculated for each fifty foot interval by multiplying the volume of groundwater times the concentration. The results by chemical species are:

PCE	300 pounds
TCE	1,000 pounds
Cis12DCE	600 pounds

TCA	60 pounds
Total	1,960 pounds

6.3.2 Projected Mass Removed by the Extraction System

The system has removed in excess of 38,000 pounds of total VOCs since the start-up of the system in 1991. Projecting the mass removed by the pumping system over the next 100 years may provide an indication of mass in the aquifer. Assuming the pumping has continued long enough to bring all sources into equilibrium, the calculation may provide a reasonable estimate of mass in place. One hundred years was selected as a convenient number, and the length of the projection will be considered as a variable at the end of this discussion.

Total VOC mass as the sum of the individual masses of six chlorinated compounds monitored quarterly for most of the pumping period through 2009, is shown on Figure 6.3-1. Analytical chemistry data, together with the spreadsheet compiled by SAIC for the 2009 annual operations report (SAIC, 2010) were used as a basis for the mass calculation spreadsheet, which is included in Appendix G.

Projections of total VOCs were graphed with the mass removed represented on both arithmetic and log scales (Figure 6.3-2) versus time on the arithmetic scale. Projections were done starting in 1995, the year that the WPL wells were added to the system. From 1995 to 2000, the rate of mass removal decreases rapidly. By year 2000, the mass removal rate appears to level off. A trend line was matched to the Total VOC mass removed from 1995-2009, and projected to 2099 using an exponential trend line function. Based on that projection, annual mass removals start at 3400 pounds in 1995 and steadily decrease to 2 pounds in 2095. Total removed and projected removed through 2099 is rounded to 53,000 pounds. Subtracting the mass removed from 1995 through 2009, the mass remaining in the aquifer at the end of 2009 is projected to be over 14,000 pounds using this method.

Because the trend from 2000 through 2009 appears to be so flat, there was a concern that there is a steady release from DNAPL pools or other rate-release controlled sources that would not diminish as significantly with time as was experienced from 1995 -2000. Using a baseline of 2000, the mass of total VOCs removed was projected from 2000-2099, as shown on Figure 6.3-3. The exponential trend is much flatter, resulting in mass removals starting at 1770 pounds in 2000 and decreasing to 260 pounds by the year 2099. The total mass removed and projected to be removed through 2099 is rounded to 100,000 pounds. Total VOC mass remaining in the aquifer at the end of 2009 is projected to be over 60,000 pounds using this method. Significant mass remains in the aquifer even after 100 years, using this projection.

Although the projection was done for total VOCs, the properties and the derivation of individual chlorinated compounds vary significantly. For that reason individual plots of mass removed for PCE, TCE, cis12DCE and TCA were constructed:

- Figure 6.3-4 shows arithmetic projections for PCE starting in base years 1995 and 2000. PCE is considerably less soluble in water than TCE and TCA, which could result in PCE's rate of removal differing from the rate for total VOCs. The trend projected from 1995 shows the mass removed of PCE declining to only a few pounds per year in 100 years, while the trend starting with base year 2000 shows a steady rate removed exceeding 400 pounds per day. This latter trend may suggest a sustaining release from DNAPL accumulations, rather than from reverse diffusion.

- Figure 6.3-5 shows arithmetic projections for TCE starting in base years 1995 and 2000. Projections from both base line years show strong decreasing trends, with the trend starting in 1995 showing pounds extracted approaching 0 by the year 2060, while the trend projection starting in 2000 approaches zero around the year 2090.

- Figure 6.3-6 shows arithmetic projections for cis12DCE starting in base years 1995 and 2000. cis12DCE is a product of anaerobic degradation of TCE. TCE must be dissolved (not a DNAPL) in order to be transformed to cis12DCE. Thus the observed removal of TCE from the aquifer is partly a result of degradation. The trend line for cis12DCE mass removed starting in 1995 is slightly downward, from over 300 pounds in 1995 to less than 200 pounds in 100 years. If the trend is projected from year 2000, the mass removed starts at over 200 pounds per year and accelerates to over 1,000 pounds per year before 2030.

Since that exceeds the mass removed of TCE even today, it is presumed that the projection is not accurate for this compound, possibly because it is a degradation product.

- Figure 6.3-7 shows arithmetic projections for TCA starting in base years 1995 and 2000. Annual mass removal trends for TCA starting in 1995 and 2000 are strongly downward, with the mass removed approaching zero by the years 2035 and 2100 respectively.

6.3.3 Discussion of Mass in the Aquifer Projections

Very large reductions in concentrations have occurred in the aquifer since 1995. The processes that resulted in those reductions, as related in Section 5 of this report are: 1) removal by the groundwater extraction system, 2) natural degradation, and 3) adsorption and diffusion onto and into the matrix of the aquifer. The reduction as a result of natural degradation either removes the CVOC from the system or converts it to another CVOC. Adsorption and diffusion take the CVOC mass out of the migrating groundwater, but as concentrations in the groundwater drop, reverse diffusion releases the mass back to the groundwater, buffering the rate of concentration and mass reduction in the aquifer.

As a result of this exercise the following observations are made:

1. The calculated mass dissolved in the groundwater in the plumes on site (approximately 2,000 pounds) is roughly 1.3 times the mass recovered by the groundwater extraction system annually (2,000 pounds/1,500 pounds removed annually = 1.3). The groundwater extraction system pumps approximately 1.4 times the average annual flow through the site, possibly suggesting the mass removed is related to the volume of water passing through the aquifer. Likewise, the volume of groundwater in the calculated plume areas on Site down to 200 feet (390 million gallons) is 2.7 times the average annual pumping rate (145 million gallons), suggesting that much of the water in the aquifer and even in the plumes is not replaced annually. This could be consistent with water moving to pumping wells through preferential flow paths, while leaving large volumes in the aquifer relatively stagnant.

2. The projection of mass removal starting in year 1995 and the resulting calculation of mass remaining in the aquifer raises concern about the usefulness of the projected trend line in calculating mass remaining in the aquifer because of the observed flattening of the rate of

annual mass removed after year 2000. The mass calculation of total VOCs remaining in the aquifer from this projection appears to be unreasonably low.

3. The flattening of the rate of mass removed annually by the groundwater extraction system from year 2000 forward may indicate that sources of CVOCs controlling this trend are in the form of DNAPL, rather than secondary sourcing from reverse diffusion. Dissolution from DNAPL sources tend to be constant, since dissolution of DNAPL occurs only at the interface between the surface of the DNAPL pool and the groundwater in contact with it.

4. In summary, the mass of CVOCs dissolved in groundwater on Site is estimated to be on the order of 2,000 pounds. The rate of CVOC mass removal by the groundwater extraction system projected for the next one hundred years indicates 14,000 to more than 60,000 pounds remain in the aquifer as of the end of 2009. Projecting for an additional 100 years would add an additional 10,000 pounds to the upper limit of the range. This method may not accurately represent the mass remaining in the aquifer as DNAPL. DNAPL is expected to be a substantial component of the mass in the aquifer as a result of the analysis conducted in Section 5.2, and as a result of the observed trend of CVOC mass removed as calculated for this exercise.

5. Better definition of the vertical extent of the karst aquifer, the vertical extent of CVOCs in the aquifer and will result in a somewhat better calculation of the mass of CVOCs in the aquifer.

7 EXPOSURE PATHWAY ANALYSIS

This report section presents an exposure pathway analysis identifying complete exposure pathways between groundwater contaminant sources and receptors. A groundwater risk assessment will be completed at a later date, when more answers regarding the extent of transport of COCs are resolved. This analysis is based on information provided in preceding report sections, including in particular, the discussion of fate and transport in Section 5. A complete exposure pathway consists of the following components: a source, a transport medium (*e.g.*, groundwater), a point of contact (receptor), and an exposure route (*e.g.*, ingestion, dermal, or inhalation). If any of these elements is missing, an exposure pathway is deemed incomplete and can be excluded from the quantitative evaluation of risk (USEPA, 1989). Those exposure pathways determined to be complete under current or future land use scenarios may be evaluated in the quantitative assessment of risk.

Considerable attention has been paid in Section 5.1 of this report to the contaminant hydrogeology of DNAPL releases to both the carbonate and quartzite/sandstone bedrock that underlies the fYNOP Site. Figures 5.1-1 and 5.1-2 describe the discrete vertical DNAPL transport pathways that are strongly controlled by fracture orientation and aperture and, in the carbonate rock, the potential for pooling of DNAPL to occur in solution cavities. Evidence at the Site that supports this contaminant transport mechanism includes:

- The likely release of CVOCs in the form of separate phase liquids based on the use and disposal activities documented for the Site;
- The magnitude of initial CVOC concentrations in groundwater;
- The pattern in several source areas of increasing CVOC concentrations in groundwater with depth below ground surface; and
- The pattern of groundwater concentrations with time that may indicate impacts from a continuing DNAPL source.

Prior to the startup of the groundwater extraction and treatment system, groundwater chemical flux from these sources was uncontrolled. This combination of DNAPL sourcing and uncontrolled groundwater flow, especially in the carbonate aquifer, would have resulted in off-Site transport to the west across the western property boundary with discharge to Codorus Creek, to the north across the northern property boundary to residential supply wells, potentially to the west-northwest across the northern property line and to the south and southwest across the southern property line.

Analyses described in this report regarding the performance of the groundwater extraction and treatment system suggest that groundwater chemical flux across the western property line to Codorus Creek has been intercepted by groundwater extraction in the western half of the Site. The remaining flux to the creek may be from comparatively low concentration groundwater located between the creek and the groundwater divide created by the operation of the on-Site extraction wells in the WPL and CPA. The same is true for groundwater chemical flux formerly crossing the northern property boundary in the northeastern corner of the Site. Therefore, continued groundwater chemical flux leaving the Site includes off-Site transport along the southern property boundary from the southeast corner and the south-central portion of the property; potential off-Site migration in the north-central portion of the property; and migration to Codorus Creek from that limited area underlying the levee that remains uncontrolled by groundwater extraction. Therefore, exposure pathways to off-Site receptors will be limited to those associated with these areas of continuing groundwater flux beyond the property boundaries.

There is a potential that there is an undiscovered deep pathway that could be uncontrolled by the groundwater extraction system. This potential exists because the vertical extent of chlorinated solvents and karst development in the aquifer is not determined. This potential will be addressed by recommended additional investigations (see Section 8.7). It is not included in this analysis, but would be added if the pathway is discovered.

Table 7.1 presents the Conceptual Site Model-Pathway Analysis (PA) for this Site. This table is comprised of a matrix of primary sources, elements of the pathways from those sources, and the receptors exposed to chemical flux from each primary source. The primary sources have been grouped into geographically contiguous source areas that exhibit not only a similar location, but also source chemistry. All of these groupings should be relatively self-explanatory and correspond to source areas described earlier in this report. However, the last primary source listed in this table requires some explanation.

The "Levee Area Adjacent to Codorus Creek" is not a primary source in the typical sense. There were no known or suspected releases that occurred in this area and, in fact, this area is off-Site beyond the western property boundary. Due to the development of the groundwater divide between this area and the source areas on the property, the levee area is believed to have been hydraulically separated from these sources and the plant site since the early 1990s. Consistent with this fact, the primary source mechanism for this area is listed as "pre-pumping groundwater chemical flux". However, groundwater flow through this area over a period of nearly 20 years would have readily removed dissolved CVOCs if the only remaining source of these substances was mass dissolved in groundwater in this area just before the pumping began. The absence of dissolution from primary sources associated with DNAPL in soil and bedrock for more than 20 years has been supported by the analysis of 11DCE:TCA ratios in the levee area (Section 5.3, Table 5.3-1). Nevertheless, data from the levee wells indicate persistent levels in the low hundreds of micrograms per liter for total CVOCs. This is a strong indication of secondary sourcing associated with reverse diffusion and desorption of CVOCs. These two mechanisms are therefore listed in Table 7.1 as the secondary release mechanisms associated with this pathway.

One further reason to separate out the Levee Area as a primary source is that before the remedial pumping began, many of the other primary sources would have been hydraulically uncontrolled. The likely result would have been uncontrolled groundwater chemical flux from virtually all of the primary source areas in the western portion of the property and possibly also some sourcing from the eastern area underlain by quartzite/sandstone. The pre-pumping groundwater chemical flux listed as the primary source for the Levee Area is, therefore, likely to have originated from many of the other primary sources listed in the table, making it difficult to assign any one of them as the primary source of this CVOC mass, and necessary to list a substantial number of them as primary sources. Separating out the Levee Area as a primary source avoids confusion and duplication of pathways in the table and also acknowledges the likely hydraulic separation of this area from on-Site sources for nearly 20 years.

The remainder of this section will discuss the pathway analysis shown in Table 7.1 by receptor beginning with the human receptors and ending with the ecological receptors.

7.1 Human Receptors

There are four categories of human receptors, including: off-Site residents, off-Site recreators, on-Site workers, and on-Site construction workers. This subsection discusses the pathway analysis for each of these receptors individually for the purpose of identifying risk drivers. A complete pathway does not indicate risk, only the potential for risk.

Off-Site Residents: In addition to groundwater flux from the Levee Area to Codorus Creek, there are three areas where contaminated groundwater is or may be leaving the property, two along the southern property boundary and one along the northern property boundary. In the southeast corner of the property, off-Site transport of COCs has been confirmed by detected concentrations in groundwater sampled from off-Site downgradient monitoring wells. In the other two areas (the western portion of the NPBA and the central portion of the SPBA), off-Site transport has not been confirmed by off-Site downgradient monitoring. Although there are no drinking water supply wells known to remain in these areas, in the absence of institutional controls to prevent the use of groundwater as a drinking water supply, the use of groundwater as a water supply must remain a potential future exposure pathway. Therefore, as shown on Table 7.1, exposure routes associated with the future use of groundwater as a drinking water source have been indicated as complete for these areas associated with the Perimeter Road: NPBA and SPBA primary source. Furthermore, the vapor intrusion pathway and associated inhalation exposure route have been indicated as complete for these two areas. A vapor intrusion study has been completed for these areas, and concluded no risk from vapor intrusion (Langan, 2008).

Off-Site Recreators: Off-Site recreators may be human receptors using Codorus Creek for recreational purposes. The primary source for exposure of these receptors to CVOCs would be the Levee Area and the pathway would be groundwater discharge to surface water, resulting in dilute surface water concentrations in the stream. Since such recreational activities would occur in an open air environment, inhalation is not listed as an exposure route in Table 7.1. However, both dermal contact and incidental ingestion of Codorus Creek surface water were associated with a complete exposure pathway for off-Site recreators. Consumption of locally caught fish may occur on rare occasions, but is very uncommon, and therefore the pathway is not being considered complete for the purpose of identifying risk drivers.

On-Site Workers: Since groundwater is not used for drinking water on the Site, the only complete exposure pathway for on-Site workers is vapor intrusion (VI). With the exception of the Levee Area, this complete pathway is shown for all primary sources in Table 7.1 due to the presence of existing occupied structures or the potential for such structures to be constructed in the future.

On-Site Construction Workers: Construction workers at the Site are assumed to be exposed to contaminated environmental media during excavation to a nominal depth of 15 feet bgs. Exposure to contaminated soil to this depth has already been considered in the soil risk assessment (Groundwater Sciences, 2011). A complete exposure pathway to groundwater is considered if the water table is within 15 feet of the surface. Depth-to-the-water table data, as measured in shallow wells (Table 2.4-1), indicate infrequent occurrences of the water table being less than 15 feet from ground surface. Based on the data presented in this table, it is expected that, under pumping conditions, the water table in the western portion of the property will be greater than 15 feet bgs, with the exception of the NPA where water levels even under pumping conditions are only 8 to 10 feet bgs (MW-52,-53). Also, in the area along the base of the hill (spring line, MW-17, MW-18, MW-67, MW-68) the water table is less than 10 feet bgs as well. However, under non-pumping conditions it is anticipated that during the spring, the water table would frequently be less than 15 feet bgs. Due to some obvious uncertainty regarding the depth to the water table across the Site, exposure routes associated with the groundwater pathway have been indicated as complete for the primary source areas for on-Site construction worker receptors. If, during the performance of the groundwater RA, this exposure pathway is deemed to be complete, the excess cancer risk and human health hazard index associated with exposure to contaminated groundwater may have to be combined with the risk and hazard index calculated in the soil RA for construction workers in order to properly assess the total cumulative risk to these receptors.

7.2 Ecological Receptors

Table 7.1 shows only one complete pathway for ecological receptors. This pathway is associated with the Levee Area primary source and the associated groundwater chemical flux to surface water. The related ecological receptors are aquatic species in Codorus Creek and the exposure route is limited to surface water ingestion.

8 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This Supplemental Remedial Investigation Groundwater Report (SRI Report) presents the detailed results of a groundwater Supplemental Site-Wide Remedial Investigation (SRI) completed during the period 2007-2008 at the former York Naval Ordnance Plant (fYNOP) located in York, Pennsylvania (Site) and includes recent groundwater chemistry and remedial operations data through December 2010. This report summarizes the environmental investigations completed on-Site from 1984 through 2006, and draws conclusions from analysis of the entire body of information from 1984 to 2010. Data gaps have been identified that should be addressed prior to the completion of a feasibility study, and recommendations are included to address those data gaps.

8.1 Background

The 230 acre Harley-Davidson Motor Company Operations, Inc. facility in Springettsbury Township, York County, Pennsylvania was initially developed in 1941 by the York Safe and Lock Company, a United States Navy contractor, for the manufacture, assembly, and testing of 40 millimeter (mm) twin and quadruple gun mounts, complete with guns. In 1944, the Navy took possession of the York Safe and Lock Company facility. The Navy owned and operated the facility as the York Naval Ordnance Plant (YNOP) until 1964, switching operations after World War II to overhaul war service weapons and to manufacture rocket launchers, 3-inch/50-caliber guns, 20-mm aircraft guns, and power drive units for 5-inch/54-caliber guns. In 1964, the Navy sold the YNOP to American Machine and Foundry Company (AMF), who continued similar manufacturing. In 1969, AMF merged with Harley-Davidson. In 1973, Harley-Davidson moved its motorcycle assembly operations to the AMF York facility. In 1981, AMF sold the York facility to Harley-Davidson. Harley-Davidson has continued motorcycle assembly operations at the York facility since 1981.

Spills, leaks and disposal practices resulted in the distribution of chlorinated solvents from metal degreasing operations and metals from plating operations in the subsurface and groundwater across the majority of the Site. Chlorinated solvents trichloroethene (TCE), tetrachloroethene (PCE), 1,1,1-trichloroethane (TCA), and their degradation products are the primary Site-related chemicals of concern (COCs), along with plating related substances chromium, nickel and cyanide.

Concentrations of COCs in the groundwater exceed PADEP medium specific concentrations (MSCs).

The groundwater SRI is part of an overall Site-wide remedial investigation and feasibility study (Site-wide RI/FS) being performed at the Site under the auspices of the One Cleanup Program jointly administered by the United States Environmental Protection Agency (USEPA) and the Pennsylvania Department of Environmental Protection (PADEP). For scheduling purposes, and because groundwater investigation activities continued well beyond the completion of soil investigations, the Supplemental Site-Wide RI reporting was divided into a soil investigation report and a groundwater investigation report. The draft soils Supplemental Site-Wide RI report was submitted to regulators on December 2, 2009 (SAIC, December 2009b) and was approved as the final version of that report in a joint letter from PADEP and USEPA dated March 17, 2010.

The groundwater SRI investigation included the installation of thirty-three additional wells on and off of the Site. Ten of those wells were located to characterize karst features along the flood levee of the Codorus Creek, west of the site. Four rounds of groundwater chemistry and water levels collected since the initiation of the SRI are included in this report. Water level recorders were installed in numerous wells on and off site to monitor groundwater responses to seasonal influences and precipitation events. A shut-down and start-up test of the groundwater extraction system in the carbonate aquifer was conducted.

8.2 Physical Characteristics

The Site is located in central York County, north of the City of York, PA (Figure 1.0-1). This area is drained by the Codorus Creek, a tributary to the Susquehanna River with a 237 square mile drainage area above the point where it enters the Site. Hills rim the fYNOP Site on the north and east, forming somewhat of a bowl-like configuration. The eastern one third of the Site is fairly steeply sloping to the west (4 to 20%), forming an upland area to the east of the flat-lying Central Plant Area (CPA). From the base of the hills to the Codorus Creek, the land surface underlying the CPA slopes very gently (0.5%) to the west.

8.2.1 Geology

Unconsolidated overburden materials have developed from the underlying bedrock throughout the Site. These overburden materials range in thicknesses from 15 feet to greater than 60 feet. Portions of the Site also have alluvial deposits, which include more coarse-grained sediments interspersed among the predominantly fine-grained residual soils.

Two bedrock formations underlie the site (Plate 3A):

1. Quartzitic sandstone and phyllite underlie the more steeply sloping hills present on the eastern part of the site. A thin mantle of residual material derived from the weathering of parent material overlies the bedrock.

2. Solution-prone (karst) limestone and dolomite (carbonate) underlie the western flat-lying CPA of the site. Weathering, more specifically called karst development, has taken place within the carbonate bedrock. The high degree of variability in the elevation of the top of bedrock, called a “cutter and pinnacle” bedrock surface (Figure 3.2-1), and the occurrence of numerous caverns and solution channels within the bedrock at the Site indicate processes that are described as karst development. Karst development was evidenced by numerous voids encountered during the drilling of borings and monitoring wells within the carbonate bedrock. The natural (non-fill) overburden materials in the carbonate terrain range in thickness from 15 feet to 60 feet, and are comprised of silt and clay, some or all of which had formed as the residual material from carbonate bedrock weathering, and transported alluvial sediment. In addition, several sinkholes have occurred on the fYNOP property, which are a typical occurrence within areas of soluble carbonate rocks. The solution cavities and fractures often contain mud, silt, and rounded 0.5 to 2-inch quartz and limestone gravels and cobbles, as recorded in numerous boring logs from wells drilled on-Site.

The top of the carbonate bedrock surface was examined by contouring (Figure 3.2-11), 3-D modeling and by examining well logs. A deep broad cutter follows the contact between the quartzitic sandstone and the carbonate, underlying the Central Plant Area. The broad depression, shown as 200 to 800 feet in width, has a general north to south orientation, curving to the west at its northern extent, as the geologic contact curves to the west. The depression contains some of the localized bedrock depressions or sinking points (Figure 3.2-12) into which concentrated groundwater recharge has formed the deeply penetrating solution conduits which pervade the bedrock. The substantial dissolution of the bedrock surface in this area, up to a depth of 76 feet, has likely been created by corrosive groundwater recharge and storm water runoff from the Antietam Formation quartzitic sandstone and Harpers phyllite upland area in the eastern portion of the Site, flowing onto the lower-elevation carbonate bedrock area beneath the western portion of the Site.

Other depressions in the karst bedrock surface were delineated underlying the North End of Building 4 and the West Parking Lot (WPL) (Figures 3.2-11). The lower elevation of the karst bedrock surface and solution cavities associated with these features also generally correlate with concentrated fracture trace patterns. Well locations exhibiting karst features (open or sediment-filled solution cavities) are frequent and well-distributed across the Site (Figure 3.2-11). For sixty-five wells examined, only thirteen had total void thickness less than 1.0 foot. Well locations with no void thickness greater than 1.0 feet appeared to be more prevalent in the southwestern corner of the fYNOP property. Of 5,702 feet of borehole penetration through carbonate rock, 888 feet penetrated voids, constituting 16% of the total volume of the aquifer. Sixty-three percent of the voids were sediment-filled, while the remainder was open (filled with water).

The depth of karst solutioning is evident from solution channels and caverns encountered in carbonate bedrock to a depth of 217 feet. The bottom of the karst solutioning of the carbonate is not known at this time. Experience with the depth of penetration of karst weathering in the mid-Atlantic area carbonate bedrock is approximately 250 feet, although exceptions are found. This would put the estimated base of the karst somewhat below the locations of the deepest known karst beneath the Site.

8.2.2 Hydrogeology

Groundwater generally migrates from east to west, from the high topographic areas underlain by quartzitic sandstone to the carbonate aquifer that underlies the western half of the site. Aquifer transmissivity, the property of the aquifer that describes the ease with which groundwater moves through the saturated subsurface materials, is very different between these two geologic materials. The quartzitic sandstone transmissivity is lower due to the groundwater migrating through minor partings associated with bedding planes, joints and fractures with relative higher resistance compared to the carbonate aquifer because the openings are not solution-enhanced. Because the materials of the carbonate aquifer are prone to dissolution by migrating groundwater, transmissivity in this aquifer is greatly enhanced, and groundwater moves with relative ease through the aquifer.

Water table gradients are steep (6 to 10%) in the upland regions underlain by quartzitic sandstone and diminish to a relatively flat gradient (1% or less) once the groundwater flows into the area underlain by carbonate rocks (Plates 3B and 3C). Groundwater in the upland area flows mainly through the interconnected network of fractures, joints, and bedding planes. Once the groundwater encounters the carbonate rocks, groundwater flow is directed along fractures, dissolution cavities, interconnected conduits, and weathered zones in the rock. The regional groundwater flow through the property follows a general west-southwesterly direction. Locally, the groundwater flow through the karst bedrock is widely variable following the pathways of the karstic conduits. However, responses to pumping tests and migration pathways traced by groundwater chemistry indicate a well-connected aquifer as a result of numerous highly interconnected conduits, suggesting that, on the scale of the entire Site, the carbonate aquifer may be an equivalent porous medium. However, confirmation of this characteristic of the carbonate aquifer would require further investigation and analysis.

The extent of the karst aquifer is limited to the north and east by phyllite, quartzite and quartzitic sandstone. These noncarbonate formations underlie the carbonate formation, dipping at angles of approximately 15 to 20 degrees toward the carbonate, and form the lower limit of the karstified aquifer in the northern and eastern portions of the industrialized area. To the south, the carbonate aquifer is laterally extensive, and the depth of karst aquifer is undetermined. Under the southern portion of the Central Plant Area (CPA) and the WPL, the depth to the bottom of the carbonate aquifer is undetermined.

8.2.2.1 Groundwater Extraction Systems

In the North Property Boundary Area (NPBA), flow directions are locally modified by active groundwater extraction wells; however, groundwater appears to flow off the Site to the west of MW-18. Groundwater flow is redirected locally by the system of capture wells in the WPL. The operation of groundwater extraction wells appears to prevent groundwater flow from the WPL toward Codorus Creek. The combination of pumping from the extraction wells and the discharge of Site storm water to a wetland area between the western property line and the Codorus Creek may have created a divide between the creek and the Site. Groundwater on the east side of the divide migrates toward the Site, and groundwater on the west side of the divide migrates westward toward the Codorus Creek. Capture of Site groundwater and prevention of off-site migration was evaluated:

1. Comparison of extraction well pumping rates to the estimates of groundwater flowing through the aquifer that show, on average, the pumping rate equals 140% of the estimated groundwater flow through the aquifer.
2. Evaluation of hydrographs (Figures 3.3-3A, B, C, D, E and F) of wells indicates persistent influence from the pumping wells on water levels, with piezometric levels in the creek and in wells near the creek that are consistently higher than wells onsite.
3. Groundwater piezometric levels in observation wells (Figures 3.4-1 and 3.4-4) during operation of the groundwater extraction system indicate sufficient influence to maintain capture in the monitored portion of the carbonate aquifer (down to approximately 200 ft. bgs).

However, because extraction wells are relatively shallow, without knowing the full depth to which groundwater flow in the karst aquifer occurs, there is no assurance that capture of all groundwater flow in the carbonate aquifer is complete.

A second concern is the loss of capture during storm events due to a condition called karst loss. A karst aquifer can experience very large and rapid influxes of storm water to the aquifer, directed to the epikarst through swallets, sinkholes, exposed karst openings in bedrock and epikarstic openings in the bedrock surface beneath the overburden. This situation could result in much larger volumes of water flowing through the aquifer for a period of hours or days following high recharge events (rainfall and snow melt) than can be extracted by the pumping system. No evidence that this occurs was observed in hydrographs of observation wells (Figure 3.3-3A). However, the duration of these hydrographs is limited and additional monitoring for a longer duration would be necessary to properly respond to this concern.

The third and final concern is that there are concentrations of Site COCs above PADEP MSCs present in the wells installed along the east side of Codorus Creek. However, the age of the COCs was calculated to predate the start-up of the extraction system (see Section 5.3). The results of this calculation suggest that these compounds may be from residual secondary sourcing, a result of slow releases from the matrix of the aquifer which adsorbed COCs travelling with groundwater toward Codorus Creek prior to the start of pumping of the WPL wells.

8.2.2.2 Role of Codorus Creek as a Discharge Boundary

Under natural conditions (without the operation of the groundwater pump and treat system), groundwater flowing through the Site flows westward toward and discharges to the Codorus Creek. The operation of the groundwater extraction system on the Site has likely intercepted virtually all groundwater flowing within the carbonate aquifer above a depth of 200 feet bgs. For Site related groundwater to pass under Codorus Creek to the north or west would require the existence of a large pumping center or a deep conduit isolated from the shallow aquifer (down to 200 feet). Noncarbonate rocks to the north eliminate northerly migration (Figure 3.5-4). The Roosevelt quarry, 12,000 feet to the west (Figure 3.5-5) could potentially represent a large pumping center caused by dewatering, however the occurrence of the Kinzers Shale between the creek and the quarry (Figure 3.5-6) would tend to prevent the influence of dewatering from reaching the Cordorus Creek at the fYNOP Site. Additional verification of this conceptual model may be necessary through determination of the extent of pumping from the Roosevelt Quarry, field verification of the mapping and effectiveness of the Kinzers Shale to serve as a barrier to northerly and westerly groundwater flow and/or monitoring of groundwater levels in karst conduits at various depths adjacent to the creek.

8.3 Nature and Extent of Groundwater Contamination

Chlorinated solvents PCE, TCE, TCA and degradation products of these compounds, as a group called chlorinated volatile organic compounds (CVOCs) are widely distributed in the groundwater across the Site. The solvents were released in the form of Dense Nonaqueous Phase Liquids (DNAPLs) which are, by definition, immiscible in water and exhibit a higher specific gravity than water. In addition, metal plating-related compounds, gasoline components and semi-volatiles were detected at concentrations that exceed PADEP groundwater Medium Specific Compounds (MSCs), were delineated on Site, but the chlorinated solvents pose the majority of the concern and are the primary COCs. Site activities that resulted in the distribution were described and summarized on Figure 4.0-1.

Primary source areas and migration pathways were distinguished by examining normalized chemical ratios of the parent solvents and their daughter products (Figures 4.1-2 and 4.1-3). Chemical concentration vs. time graphs were examined (Appendix C), and the current conditions of the groundwater quality beneath the Site were characterized. The distribution of chlorinated solvents in the groundwater was depicted on isoconcentration contour maps (Figures 4.1-4, 4.1-5, 4.1-6 and 4.1-7).

- In the higher elevation areas of the site underlain by the noncarbonate rocks, PCE and TCE are distributed in the groundwater near the northeast, east and southeast property lines. These chemicals dissolved in groundwater were pulled off site in the NPBA by former residential water supply wells. TCE and PCE also migrated offsite to the south from the southeast corner of the site.

- Source areas and high concentrations are distributed throughout areas of the carbonate aquifer known as the North End of the Test Track (NETT), CPA and the WPL.

- Concentrations of CVOCs were detected in groundwater in the wells installed off-Site on the east side of Codorus Creek.

8.4 Contaminant Fate and Transport

CVOCs in the form of DNAPLs were discharged on the ground surface and traveled vertically through the subsurface materials, leaving a trail of residual material or forming pools or accumulation zones. At the fYNOP Site, the factors affecting the transport of a DNAPL release are highly dependent on the geologic characteristics at the location of the release (Figures 5.1-1 and 5.1-2). In the karst aquifer, DNAPL is directed along the pinnacled bedrock surface through vertical and lateral solution channels that are open (filled with water) or filled with water-saturated residuum and sediment (sand, silt, clay, gravels and rock fragments). DNAPL is believed to have migrated vertically as deep as 200 feet in four or more areas of the site.

In the aquifer, some of the DNAPL slowly dissolved in the groundwater, undergoing a number of processes. Dissolved (aqueous) phase chlorinated solvents migrated through the aquifer transported by groundwater flow and generated a plume of dissolved CVOCs extending from the source area to the point of discharge to surface water or an extraction well. Prior to operation of the pump and treat system, groundwater in the CPA/NPA/WPL migrated generally westward toward the Codorus Creek through residuum and solution-enhanced pathways in the carbonate bedrock.

The aqueous phase chemicals diffused into the rock matrix, and adsorbed onto organic carbon or mineral surfaces. In the aqueous phase, anaerobic bacteria break down PCE and TCE to cis-1,2-dichloroethene (cis12DCE) and vinyl chloride (VC) and the TCA to 1,1-dichloroethane (11DCA) and chloroethane. TCA also abiotically transforms to 1,1-dichloroethene (11DCE).

DNAPL has likely been present in the fYNOP aquifer for 60 or more years, since vapor degreasing operations began prior to 1948 (Key Reporters, 1991). During that time, the various processes described above, enhanced by interim remedial actions, have resulted in the reduction of the DNAPL mass (Figure 5.1-7). Even so, a number of areas remain as probable DNAPL sources. In addition, diffusion and sorption processes have stored CVOC mass in the aquifer, which is released slowly, resulting in a tailing effect for CVOC concentrations in groundwater. Primary source areas are the Building 58-66 Area, the TCA degreaser in Building 2, the North Building 2 (NBldg2) Corridor, the North Building 4 (NBldg4) Area and the southwest corner of the WPL. In these areas, concentrations increase with depth to the extent investigated (to approximately 200 feet).

8.5 Interim Remediation Progress

Over the last 20 years, CVOC concentrations in the groundwater have reduced 90 to 99% over most of the Site (Figures 6.2-1, 6.2-2, and 6.2-3). The reduction is primarily a result of removal by dissolution into the groundwater that migrates from the source or is captured and removed by the pump and treat systems, natural degradation of the chlorinated solvents by bacteria and abiotically, and by sorption onto and diffusion of the dissolved phase into the matrix of the aquifer. Although greatly reduced, concentrations of chlorinated solvents nonetheless exceed PADEP groundwater

MSCs across most of the Site (Figure 6.2-8). Several facts (i.e., chlorinated solvents have not been used on-Site since 1994, there has been no known release of chlorinated solvents in over 25 years, and the groundwater pump and treat systems have been operating for over 20 years) provide an indication of the persistence of the COCs in groundwater at fYNOP.

Estimates of the mass remaining in the aquifer on Site using trend analysis exceed 60,000 pounds, and may be substantially underestimated because DNAPL pools appear to be present. On the order of 2,000 pounds of this mass occurs as dissolved in groundwater. The remaining mass is adsorbed onto and diffused into the matrix of the aquifer or is in the form of suspected DNAPL pools. These undissolved sources of mass are very slowly released to the groundwater passing through the site.

8.6 Exposure Pathway Analysis

An exposure pathway analysis identifying complete exposure pathways between groundwater contaminant sources and receptors or future receptors was evaluated for four categories of human receptors, including: off-Site residents, off-Site recreators, on-Site workers, and on-Site construction workers. A complete exposure pathway consists of the following components: a source, a transport medium (*e.g.*, groundwater), a point of contact (receptor), and an exposure route (*e.g.*, ingestion, dermal, or inhalation). Source areas were examined, and potential complete pathways identified (Table 7.1).

- Although there are no drinking water supply wells known to remain in the area, the use of groundwater as a water supply is a potential future exposure pathway for off-site residents. Vapor intrusion for off-site residents was evaluated and determined that there is no unacceptable risk.

- Off-site recreators using Codorus Creek for recreational purposes may come in contact with site COCs through dermal contact and incidental ingestion.

- On-Site workers could potentially be exposed to Site-related COCs through inhalation as a result of vapor intrusion into existing or future buildings.

- On-Site construction workers exposure to groundwater (exposure to soil was considered in the soil risk assessment) is potentially complete because excavations may reach the water table at some locations or under seasonally high conditions.

8.7 Recommendations

Questions regarding the Site characterization and the path forward for the eventual closure of the fYNOP site under the PADEP/USEPA One Cleanup program for groundwater are divided into four interrelated categories, which are described in the section.

8.7.1 Nature and Extent

1. The depth of high concentrations of chlorinated solvents in the groundwater is undetermined in the SW-WPL, the TCA Tank/Bldg 2 Degreaser area, the Bldg 58 area, the West Building 2 (WBldg2) Corridor, the South East corner of the Site, and the NBldg4 area. The vertical extent of the carbonate aquifer and the depth of solution-enhanced permeability in the carbonate aquifer are not determined, and may control the depth of DNAPL penetration in the aquifer or the migration of dissolved CVOCs by groundwater advection. Deep wells at these specific locations should be considered to better define the vertical extent.

2. The lateral extent of high concentrations of CVOCs in the groundwater surrounding monitoring well MW-18D in the NPBA is undetermined. High concentrations of TCE were drawn into MW-18D, and to a lesser extent, MW-18S, after activation of the groundwater extraction system, indicating the source is most likely to the west of MW-18. The location of the Site property boundary to the west and the potential for offsite migration of groundwater from this source area increases the concern about this location. Resolution may require installation of one or more monitoring wells to the west of MW-18.

3. Groundwater with CVOCs in the southeast corner of the Site (at well couplet MW-64S&D) migrates offsite to the south. Site-related chlorinated solvents have been traced to off-site monitoring wells. The pathway and persistence of the elevated concentrations in the groundwater is incomplete. Additional off-site wells should be considered to bound the lateral extent of the plume. The occurrence of existing monitoring wells on the Former Cole

Steel property and adjacent properties to the west and south should be investigated. Water levels in existing wells should be monitored and groundwater chemistry analyzed. The potential that dye injected into MW-64D during the RI could be used as a tracer in these off-site wells should be considered. The first paragraph (1.) in this section discusses the need for vertical delineation in this area.

4. The groundwater flow, transport direction and magnitude west of the WPL requires further data analysis and observation, and possibly additional data collection. The potential for migration of Site groundwater beneath Codorus Creek may require additional analysis and investigation. The dewatering operations at the Roosevelt Quarry should be investigated and the effectiveness of the Kinzers Shale on the west side of Codorus Creek as a barrier to groundwater migration should be evaluated. Components of the investigation may include field verifying the Kinzers Shale, wells between the WPL and the Codorus Creek; one or more deep wells on the levee, wells on the west side of Codorus Creek. Work should be staged, with the information learned in initial steps determining the need and refining the approach for following steps.

8.7.2 Hydraulic Characteristics of the Karst Aquifer

1. Evaluate runoff to Johnsons Run and to the wetland to determine the extent to which karst loss may impact the groundwater flow through the Site and the capture system. Determine whether Johnsons Run is a gaining or losing stream, and its relationship to the groundwater. Determine the interconnection of the wetlands to the water table.

2. If karst loss is determined to have a significant impact on the flow through the Site, evaluate the impact of storm events on the capture of the WPL groundwater extraction system. The current capture analysis indicates a high degree of capture, but there is a potential that surges of flow through the karst aquifer during periods of high recharge may overwhelm the capture system. Continuous water level and temperature recorders would be placed in wells and operated through a few sizable rainfall events. Data would be analyzed for hydraulic capture using gradients. Combined with the water budget study and potentially additional

investigations west of the SW WPL, a better understanding of the capture of the groundwater extraction system would be gained.

3. Analyze groundwater for calcite and dolomite mineral saturation. The data should be examined for evidence of undersaturation of groundwater in calcite within boreholes which encountered voids and caverns in the bedrock. Undersaturated groundwater in karst conduits can be evidence of rapid migration / short residence time in the aquifer, resulting in the groundwater not reaching mineral saturation. Also, examine whether mineral saturation increases with distance from east to west through the carbonate bedrock terrain. The purpose of the task is to further understanding of conduit-flow type groundwater movement, and the possible locations and interconnectivity of conduit flow pathways beneath the site. This task would be conducted after the installation of the proposed deep wells.

4. The unusual responses to pumping and recharge events in well couplets MW-50S&D and MW-51S&D may indicate important anomalies in the aquifer. The close proximity to the high CVOC concentrations at NBldg4 Area makes these wells potentially important to the remedial options assessment in this area. Manual and continuous monitoring of temperature and water level responses to recharge events in these wells and manipulation of pumping wells while monitoring are suggested.

5. Drill a stratigraphic boring to approximately 500 feet of depth. The vertical extent of the carbonate aquifer and the depth of solution-enhanced permeability in the carbonate aquifer have not been determined, and may control the depth of DNAPL penetration in the aquifer or the migration of dissolved CVOCs by groundwater advection. The installation and testing of deep wells strategically located across the site would be required. A detailed borehole log analysis of existing data to better define the nature of the contact between the Antietam and the Vintage would be conducted to define one factor in the vertical limit of the carbonate aquifer. Structural orientation of the fault contact between the Chickies/Harpers formations to the north with the carbonate Vintage formation will be another consideration.

6. Install deep wells on the levee near the creek and shallow wells in the saturated residuum. The wells would be used to establish chemical and hydraulic gradients. The information

will assist in determining the potential for deep groundwater migration westward beneath the creek, measure the water level differentials between the creek and the shallow saturated residuum, and also to confirm the source of CVOCs in the levee wells.

7. Conduct tracer testing in the deeper karst system. This work would be conducted after the installation of deep wells. This testing would be designed to evaluate the potential interconnection of karst features, and better understand the capture of water by the extraction wells, and evaluate the potential for discharge to the creek and underflow beneath the creek through a deep conduit system not readily connected to the shallow system.

8. Analyze pumping test data by curve matching to evaluate the carbonate aquifer to determine what type of aquifer best fits the results. Existing pumping test data would be plotted and compared to type curves.

8.7.3 Fate and Transport

1. In order to understand where on the Site transformation of primary CVOCs to daughter products is occurring by reductive dechlorination, analyses of groundwater for monitored natural attenuation parameters should be performed in selected wells.

2. Samples of the residuum and sediments in karst voids should be analyzed for fraction organic carbon to aid in assessing the significance of sorption as a retardation mechanism and desorption as a component of secondary sourcing.

8.7.4 Source Area Investigations

1. A source area investigation is recommended near Building 58, which was identified as a former press area, and may have included activities that used chlorinated solvents.

2. A source area investigation is recommended near a former maintenance area in the WBldg2 Corridor.

8.7.5 Interim Groundwater Extraction System

1. Site-related COCs detected in offsite residential groundwater wells to the north of the NPBA were most likely drawn to the off-site wells by pumping of those wells for domestic water supply. Whether groundwater would naturally migrate northward from the NPBA to off-site properties if the groundwater extraction system were deactivated has not been determined. Therefore, a monitored shutdown of the NPBA groundwater extraction system should be conducted to evaluate the need for continued operation of this extraction system. This shutdown test should be performed and monitored to determine the direction of groundwater flow under non-pumping conditions. During this same shutdown period, monitoring of water quality should be performed in selected wells to observe any occurrence of chemical concentration rebound in the NPBA and off site to the north. The results of this test should be evaluated to demonstrate, if possible, that migration through the property will have no impact on the environment. This investigation will be coordinated with the concerns regarding the source of TCE in MW-18D.

2. Due to the low concentrations of CVOCs in the groundwater and the potential that water levels may not rise sufficiently to damage Building 3 or equipment if the pumping station were deactivated, operation of the interceptor trench may no longer be necessary. Therefore a plan should be developed and implemented to shut this system down and to carefully monitor the recovery of the water table and its potential impact on the building facilities, particularly during seasonal high water table/recharge conditions.

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