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May 22, 2017

Joseph Gowers
Remedial Project Manager (RPM)
Environmental Protection Agency– Region 2,
290 Broadway, 19th Fl.,
New York, N.Y. 10007-1866

RE: Ringwood Mines Superfund Site
Ringwood, New Jersey

Dear Mr. Gowers:

The North Jersey District Water Supply Commission (the "Commission") owns and operates the Wanaque Reservoir, an approximately 29 billion gallon water supply that serves the needs of millions of New Jersey residents and businesses. The Commission's Wanaque Reservoir is located approximately 7.5 miles downgradient of the Ringwood Mines Superfund Site located in Ringwood, New Jersey, the remediation of which is under the direct authority, oversight and supervision of the United States Environmental Protection Agency ("EPA").

In response to the EPA's recent investigative activities with respect to soil and groundwater contamination associated with the Ringwood Mines Superfund Site, and more particularly the recent detection of 1,4-dioxane, the Commission retained Jacobs Engineering Group, Inc. ("Jacobs") to assess the effectiveness of the proposed remedial plans for the Superfund Site and the risk of contaminants, including 1,4-dioxane, impacting the Wanaque Reservoir and finished water quality. On behalf of the Commission, enclosed herewith please find a copy of the "Final Report of the Potential Fate and Transport of Benzene, 1,4-Dioxane, Lead and Arsenic at the Ringwood Mines Superfund Site Relative to the Wanaque Reservoir," prepared by Jacobs.

It is our understanding that the a Remedial Investigation ("RI") addendum report and Feasibility Study ("FS") for soil and groundwater is expected to be completed within the next two to three months that will serve as the basis for the

selection of a remedy(s) to address both soil and groundwater contamination. We request that the EPA review the Jacobs report and recommendations contained therein in the context of the preparation of the RI/FS and the ultimate recommended remedial action(s). The Commission further requests that the RI/FS and recommended remedial action(s) be provided directly to the Commission for review and comment.

Thank you very much for your consideration in this regard.

Very truly yours,

Todd Caliguire, Executive Director

cc: Kenneth J. Petrone, Section Chief – NJDEP

JACOBS

Final Report of the Potential Fate and Transport of Benzene, 1,4-Dioxane, Lead and Arsenic at the Ringwood Mines Superfund Site Relative to the Wanaque Reservoir

North Jersey District Water Supply Commission

Ringwood Mines Superfund Site

Ringwood, New Jersey

May 2017

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Acronyms

CMP – Cannon Mine Pit

EPA – United States Environmental Protection Agency

ft bgs – feet below ground surface

FS – feasibility study

J – estimated value

LBG – Leggette, Brashears & Graham

MCL – Maximum Contaminant Level

msl – mean sea level

ND – nondetect

NJDEP – New Jersey Department of Environmental Protection

OCDA – O'Connor Disposal Area

OU – Operable Unit

PMP – Peters Mine Pit

PRP – Potentially Responsible Party

RI – remedial investigation

ROD – Record of Decision

µg/L – micrograms per liter

VOC – volatile organic compounds

WTP – Water Treatment Plant

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Executive Summary

Background/History. The Ringwood Mines Superfund Site (hereinafter "Site") in the Borough of Ringwood, County of Passaic, State of New Jersey (hereinafter the "Borough") is a United States Environmental Protection Agency (EPA) Superfund Site due to historical dumping of wastes on the property and the resulting soil, surface water and groundwater contamination. The source of the waste is attributed to both the Ford Motor Company and the Borough dating to the 60s and 70s. Ford dumped paint sludge, high temperature salt bath sludge and standard refuse directly on the ground and in the mines. Municipal waste, including cars, was also dumped at the property by the Borough. In 1988 EPA found Ford Motor Company to be "a potentially responsible party at the Site under Section 107(a) of CERCLA 42 U.S.C. 9607(a)". The Borough has a cost sharing agreement with Ford to pay for part of the cleanup. The Wanaque Reservoir, a 29-billion gallon water supply for millions of New Jersey residents and businesses, and the associated water treatment plant (WTP) owned and operated by North Jersey District Water Supply Commission (hereinafter the "Commission"), are downgradient of the contamination.

Present Conditions at the Site. EPA's investigative reports, through February 2017, described three areas of concern at the Ringwood Mines Superfund Site: Peters Mine Pit (PMP) Area, Cannon Mine Pit (CMP) Area, and O'Connor Disposal Area (OCDA). The land area and soil in these areas are defined by EPA as Operable Unit 2 (OU2). Soil contaminants include lead, arsenic and chromium. The primary water contaminants which exceed groundwater water quality standards are benzene and 1,4-dioxane. The observed concentrations of 1,4-dioxane include: the PMP air shaft (146 micrograms per liter (µg/L)), local groundwater (0.156-152 µg/L) and surface water (0.125-2.32 µg/L). The groundwater detection of 152 µg/L was observed in Monitoring Well RW-3DD and is discussed in the Ringwood Mines/Landfill Superfund Site Annual Groundwater, Mine Water, and Surface Water Sampling – 2016 Report (Cornerstone Environmental, 2016d). Cornerstone Environmental concluded that while no specific reason was found to invalidate the reported value of 152 µg/L, the collective data suggest that this value is not representative (Cornerstone Environmental, 2016d). The next highest 1,4-dioxane concentration detected in groundwater was 86.6 µg/L in February 2017 from Monitoring Well RW-11D (Cornerstone Environmental, 2017). The highest concentration of benzene (344 µg/L) was observed in a monitoring well just downgradient of Peters Pond. Benzene in groundwater was detected at the PMP Area in the air shaft, overburden monitoring wells, and shallow bedrock wells nearest the PMP. EPA has a health screening guideline of 0.35 µg/L for 1,4-dioxane. The New Jersey Department of Environmental Protection (NJDEP) has interim Ground Water Quality Standards of 0.4 µg/L for 1,4-dioxane and 1 µg/L for benzene. Lead and arsenic have also been detected in groundwater samples from these areas at levels exceeding the NJDEP Ground Water Quality Standards. The highest reported groundwater concentrations of lead (980 µg/L) and arsenic (26.6 µg/L) were detected in the Peters Mine air shaft and southeast of the PMP Area, respectively.

EPA has proposed capping PMP and CMP and has proposed two soil clean-up options for OCDA: soil excavation and a cap. The Borough is reviewing whether to build a recycling center on top of the cap in OCDA. EPA has not yet proposed a solution for the groundwater contamination in any of the areas of concern. Groundwater in the area is defined as Operable Unit 3 (OU3).

Jacobs' Scope of Services. As part of the General Engineering Services work for the Commission, Jacobs reviewed data from a variety of sources through February 2017, including the EPA's investigation report, and summarized the nature and extent of ground and surface water contamination and the hydrogeological conditions in the aquifer. The primary objective of the work was to assess the risk of the contamination to affect the Commission's finished water quality. To that end, Jacobs assessed the likelihood of benzene, arsenic, lead and 1,4-dioxane reaching the Commission's Wanaque Reservoir intake as well as the ability of the current treatment scheme to remove those contaminants. The risk assessment utilized EPA's risk approach of assessing both the likelihood and the impact of event. Scores were allocated to both the likelihood and the impact of each contaminant affecting the finished water, and a risk score was determined.

Conclusions

Groundwater/Surface Water Monitoring at the Ringwood Mines Superfund Site. Additional groundwater, surface water and reservoir sampling is needed. While groundwater monitoring wells are well distributed across the Site for characterizing groundwater quality, additional monitoring wells are needed to address data gaps and provide a more complete understanding of potential source areas, contaminant distributions, and zones of discharge to local streams and surface water bodies. Similarly, additional surface water monitoring of these discharge areas would provide verification of these discharge areas and additional information on the magnitude of concentrations along stream paths. In addition, since both major surface water pathways to the reservoir from the mine areas converge prior to discharging, monitoring at the confluence of Ringwood Creek and the reservoir would identify mass loading to the reservoir by stream pathways.

Benzene, Arsenic and Lead. There is a low probability of benzene at non-compliance levels (above 1 µg/L) reaching the finished water. The levels at the Ringwood Mines Superfund Site and the hydrogeological conditions along with benzene's volatility and the planned addition of powdered activated carbon feed to the WTP indicate that it will likely be removed in treatment to regulatory levels. While the impact of benzene exceeding standards would be significant, the overall risk of benzene impacting water treatment operations has been designated as low since the likelihood of non-compliance is very low. Arsenic is naturally occurring and prevalent within the bedrock formations and mine tailings at the Site and poses low risk of reaching the finished water. Arsenic can be oxidized with the addition of chlorine or potassium permanganate and removed from source water in conventional treatment. Adjustment of pH may be needed for arsenic removal. There is a low-moderate risk of lead reaching the finished water. Lead in source water can be removed through chemical precipitation, ion exchange or adsorption.

1,4-Dioxane. Based on preliminary analysis of current conditions at the Site, there is a low probability of 1,4-dioxane threatening the Wanaque Reservoir intake or resulting in non-compliance with the Maximum Contaminant Level (MCL) of 0.35 µg/L in the finished water. However, since the existing plant cannot remove 1,4-dioxane, if the contaminant reaches the intake it will impact the finished water quality. Hence, the likelihood of non-compliance is higher than benzene. The impact of exceeding the regulatory standard is significant. The overall risk is designated as low-moderate.

Seismic Activity. There is a low risk of seismic activity affecting contaminant transport.

Recommendations

Short-Term

Remedial Action. Given the severity of the impact to the water supply if the contaminants, in particular 1,4-dioxane, reach the intake, Jacobs recommends that an active treatment approach be implemented for groundwater remediation particularly in the Peters Mine air shaft where some of the highest 1,4-dioxane concentrations have been detected. A pump and treat approach to contain the contaminant plume is one possible active treatment approach. This could include a well pump and treatment (e.g., advanced oxidation using hydrogen peroxide with ultraviolet light (UV) or ozone). The active treatment approach should ensure that contaminants do not migrate downgradient and impact the water supply. System redundancy and proper controls would be needed to prevent any untreated groundwater from being discharged to surface water.

Both a remedial investigation (RI) addendum report and feasibility study (FS) for OU3 are expected to be completed in the summer of 2017 and will serve as the basis for the selection of a remedy for Site wide groundwater. Typically, FS reports evaluate a variety of options to address contaminants in groundwater, such as active or passive treatment, monitored natural attenuation or no action with ongoing monitoring. The Commission should review the recommended option once EPA completes its work and solicits public comments on the plan.

Modeling. Models of the reservoir and local and/or regional groundwater are recommended to better determine the levels of 1,4-dioxane and lead on Site which may threaten the water supply. The modeling would use information from the enhanced monitoring program described below. Challenges in developing a representative groundwater flow and transport model include the fractured nature of the bedrock beneath the Site, and the fact that contaminants are known to migrate through these zones. In these cases, simplifying assumptions may be required to address flow and transport in the fractured zone, with the model primarily simulating behavior in the saturated overburden, and discharge to local streams and other surface water bodies (ponds and the reservoir). A surface water model may be useful to evaluate the degree of mixing and any channelization through the Wanaque Reservoir and the effects of these factors on potential influent concentrations at the intake.

Long-Term

Monitoring. The currently monitored groundwater and surface water locations should continue to be monitored. Some of the sources of known groundwater contamination have not been identified. Jacobs recommends the addition of groundwater monitoring wells and surface water sample locations, upgradient of the reservoir. This would help better define groundwater flow directions and magnitudes, and provide a better understanding of contaminant distributions to help identify likely active sources. It would also allow better characterization of any changes in the source(s) at the Site, serve as an "early warning" of likely downgradient contaminant transport, and, along with data from more downgradient locations, provide perspective on any reductions in contaminant levels along the streams due to dilution, volatilization or other transport processes.

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New wells placed upgradient and at vertically separated intervals along the flowpaths associated with historic 1,4-dioxane detections can be used to better characterize the extent of contamination and thus, the likelihood of 1,4-dioxane discharge to the reservoir. Applicable locations include: 1) downgradient of suspected Peters Mine and Cannon Mine source areas; 2) near the intersection of Cannon Mine Road and Peters Mine Road; and 3) near the intersection of Peters Mine Road and Margaret King Avenue.

Additional surface water monitoring locations should be identified along local streams such as Park Brook, Peters Mine Brook (also named the Ringwood Creek Tributary), and Ringwood Creek. Based on the conceptual model of groundwater flow and discharge at the Site, these streams serve as some of the primary potential contaminant migration pathways to the reservoir. Park Brook is an indirect tributary to Ringwood Creek, initially discharging to Sally's Pond. Additional monitoring locations along it, and the upper reaches of Peters Mine Brook, could help identify initial groundwater contaminant discharge locations. To help characterize potential contaminant discharge to the reservoir, additional surface water monitoring is also recommended for the confluence of Ringwood Creek and the reservoir.

As a precaution, monitoring of the water intake at the Wanaque Reservoir for 1,4-dioxane should be implemented. In addition, a review of 1,4-dioxane results from any public water sources in the vicinity of Ringwood Mines is recommended, along with a determination of the need for additional sampling at these locations.

Treatment at the Wanaque WTP. If, at any point during the span of the remediation, monitoring results show evidence of increased levels of contamination in surface water or groundwater that would threaten the reservoir water quality, EPA would also be tasked with adding upgrades at the Wanaque WTP. In anticipation of that possibility, the Commission may wish to assess alternative treatment technologies to address these contaminants at the plant as detailed in the preliminary recommendations below:

Preliminary Recommendations for Alternative Treatment Technology

Contaminant	Preliminary Recommendation
1,4-Dioxane	Assessment of advanced oxidation process systems
Benzene	Assessment of activated carbon and/or packed tower aerator systems
Lead	Evaluation of removal options including chemical precipitation, ion exchange, adsorption and a coagulation-flocculation-solids separation process
Arsenic	Assessment of oxidation via addition of chlorine or potassium permanganate and the need for pH adjustment

This evaluation would provide a preliminary plan in the event contaminant levels continue to rise. The plan would include treatment options, a recommended treatment, cost, and a timeframe for implementation. The Commission could begin implementation if and when levels rise in the flowpaths.

Summary of Recommendations

Recommendation	Short/Long Term	Responsibility
Active remediation of groundwater to control the source particularly at Peters Mine Shaft	Short	EPA
Modeling of groundwater contamination	Short	EPA
Additional surface and groundwater monitoring	Long	EPA
Additional monitoring at Wanaque Reservoir and Intake	Long	Commission
Treatment evaluation at Wanaque WTP	Long term – if levels rise	EPA

Introduction

The Ringwood Mines Superfund Site in Ringwood, New Jersey is an EPA Superfund Site due to historical dumping on the property and the resulting soil, surface water and groundwater contamination. The source of the waste is attributed to both the Ford Motor Company and the Borough. Ford dumped paint sludge, high temperature salt bath sludge and standard refuse directly on the ground and in the mines. Municipal waste was also dumped at the property by the Borough. In 1988 EPA found Ford Motor Company to be "a potentially responsible party at the Site under Section 107(a) of CERCLA 42 U.S.C. 9607(a)." The Borough has a cost sharing agreement with Ford to pay for part of the cleanup. The Wanaque Reservoir, a 29 billon gallon water supply for millions of New Jersey residents and businesses, and the associated WTP owned and operated by the Commission, are downgradient of the contamination.

Following recent detections of 1,4-dioxane on the Superfund Site, Jacobs has been requested by the Commission to assess the effectiveness of the proposed remedial plan (capping) and the risk of the contaminants, particularly 1,4-dioxane, impacting the Wanaque Reservoir and finished water quality. The water intake for the Commission is located near Raymond Dam at the southern extent of the Wanaque Reservoir, approximately 7.5 miles south-southwest of the Ringwood Mines Superfund Site.

Jacobs met with Joseph Gowers, EPA; Kenneth Petrone, NJDEP; and a representative from Ford on June 16, 2016, to tour the Site and better understand the remediation plan. A subsequent meeting with NJDEP, EPA and the Commission was held on April 12, 2017. A conference call with the Borough's consultant, Excel Environmental Resources, was held on April 24, 2017. Relevant and historical documentation available through the EPA website, including the remediation plan prepared by Cornerstone Environmental, dated March 25, 2016, sampling data results through February 2017, and several investigative reports by Arcadis, have been reviewed by Jacobs. Several environmental studies and sampling events have been conducted at the Site, and many of the more recent reports are available from the EPA website for review. This report summarizes much of the Site and contaminant analysis described in some of the more recent reports by Cornerstone Environmental and Arcadis, which were hired by Ford to conduct site investigations. In particular, the Ringwood Mines Site-Related Groundwater Remedial Investigation Report (Arcadis 2015a) is frequently referenced. Jacobs has not

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conducted any testing or participated in the preparation of any of the reports provided for the Ringwood Mines Superfund Site or the remediation plan. This report is limited to a review of the available documents on the EPA website, which are referenced herein and listed in the References Section.

This report has several objectives:

- Provide a brief description of the Site and an overview of known 1,4-dioxane, benzene, arsenic and lead contaminant distributions onsite
- Provide a qualitative evaluation of the monitoring well and surface water monitoring network onsite
- Assess the remedial plan in the context of groundwater and surface water contamination
- Identify locations for additional monitoring to address possible data gaps
- Describe the status of the regulatory process for the operable units onsite
- Assess the short-term and long-term risks of the contaminants reaching the Wanaque Reservoir intake
- Conduct a qualitative evaluation of the risk of contamination in the Wanaque Reservoir and at the water intake based on recent and historical benzene, lead, arsenic and 1,4-dioxane detections at the Site in groundwater and surface water samples

It is noted that the report is not intended to be a comprehensive summary of all of the studies that have been conducted at the Site, or to provide an independent assessment of any reports, studies or their results/conclusions.

Site Description

There is an extensive record of data collection characterizing the Site geologic, hydrogeologic, and other site features related to the previous mining and waste disposal activities. Historical data on 1,4-dioxane at the Site is more limited with the record of sampling dating from August 2015 to February 2017. There are three Areas of Concern: the PMP Area, the CMP Area, and the OCDA. EPA has defined these land areas as Operable Unit 2 (OU2). In addition, there is Site-Related Groundwater, defined as Operable Unit 3 (OU3). Benzene and 1,4-dioxane are two of the primary contaminants, for which the groundwater concentrations exceed NJDEP Ground Water Quality Standards. The highest reported groundwater concentration of 1,4-dioxane (152 µg/L) was from monitoring well RW-3DD, located near the PMP and the flooded Peters Mine air shaft; the highest groundwater concentration of benzene (344 µg/L) was found in RW-6, a monitoring well just downgradient of Peters Pond. Soil contaminants include lead, arsenic and chromium. Lead and arsenic have also been detected in groundwater samples from these areas at levels exceeding the NJDEP Ground Water Quality Standards. The highest reported groundwater concentrations of lead (980 µg/L) and arsenic (26.6 µg/L) were detected in the Peters Mine air shaft and southeast of the PMP Area, respectively.

Geology

The Site is located in the southeastern extension of the New England Highlands Physiographic Province, which is characterized by a series of north-northeast/south-southwest trending valleys interrupted by

east-west trending valleys associated with past glacial ice erosion and deposition which occurred in the region about 12,000 years ago (Leggette, Brashears & Graham, Incorporated 2016 (LBG)). Bedrock is encountered at approximately 25 to 50 feet below ground surface (ft bgs). In general, the Site is primarily underlain by Precambrian-age gneiss, a foliated rock formed by regional metamorphism. There are occurrences of pegmatite, pyroxene-amphibolites, biotite-quartz feldspar gneiss, and magnetite iron ore (Arcadis 2015a). Granite gneiss and pegmatite form sharp ridges separated by narrow troughs underlain by less resistant gneiss (Arcadis 2015a). The gneisses are moderately to well foliated, have mineral lineation, and display evidence of three distinct folding events. Geologic structural features of the New Jersey Highlands, which are regionally related either spatially or tectonically, include folds, faults, lineation trends, and jointing (Arcadis 2015a). Major cross faults are visible as trench-like features that interrupt minor drainage lines, and offset small valleys and ridges. These faults generally strike approximately east-west across the predominant northeast strike of the major ridges and valleys (Hotz 1953). Joints are prevalent in the bedrock and are moderately to steeply dipping with spacing from one foot to several tens of feet (Volkert 2008). Several sets of vertical or steeply dipping joints occur in the Precambrian rocks. One set is parallel to the regional structure. A second set is transverse to it, and a third set is oblique to the regional structure. The transverse joints are the most abundant and the most prominent set (Carswell and Rooney 1976).

Unconsolidated soil and sediment deposits are primarily confined to the stream valleys and corridors. Based on the findings of a RI conducted by Arcadis, the unconsolidated deposits range from approximately 25 to 50 feet thick and are thickest in the eastern and southern parts of the Site (Arcadis 2015a). The overburden consists of the Rahway Till dating from the Pleistocene age and is reddish-brown, light reddish-brown, reddish-yellow silty sand to sandy silt containing some to many sub-round and sub-angular pebbles and few sub-rounded boulders (Arcadis 2015a). The 'Faulting and Seismic Activity Considerations' section below contains additional information on the geologic setting for the Site and groundwater occurrence as it relates to faulting and seismic activity.

Hydrogeology

The geological characteristics of the area not only significantly affect the expression of surficial features in the area, but the characteristics of groundwater flow beneath the Site. In unconsolidated deposits and in friable consolidated rocks, groundwater is stored in and moves through the intergranular openings. Groundwater in the consolidated rocks occurs in and moves through cleavage planes, joints, fractures, and faults. These openings become fewer and tighter with increasing depth below the land surface but tend to be distributed in an orderly geometric attitude within rock units of homogeneous composition. The openings are better developed and enlarged in some rocks than others; however, the openings form a comparatively small volume in comparison to the volume of the rock as a whole (Carswell and Rooney 1976). The movement of groundwater in the Precambrian igneous and metamorphic rocks is probably largely in a direction transverse to the regional structure of the beds (southeasterly and not directly toward Wanaque Reservoir). Openings along the joint set transverse to the regional structure have probably been selectively enlarged by weathering more than those openings along joints parallel and oblique to the regional structure. The greater weathering of transverse joints is indicated by their greater abundance and prominence and by the dominant east-west alignment

(parallel to the direction of dominant jointing) of streams cutting the Precambrian rocks (Carswell and Rooney 1976).

In Passaic County the groundwater reservoir is a few hundred feet thick and can be visualized as a number of small basins separated by divides, which at land surface coincide with surface water drainage divides. In the subsurface these groundwater divides do not necessarily descend vertically through the zone of fresh water circulation but may in places become essentially horizontal where they form divides between shallow local flow systems and deeper and larger flow systems. Groundwater flow systems in the county are generally small; the largest underlie probably only a few square miles. No regional groundwater flow system underlies the entire area (Carswell and Rooney 1976).

On hilltops or divides a comparatively small volume of water enters and moves through the secondary openings, limiting the amount of weathering. Water-bearing fractures at different depths below land surface contain water under different hydraulic heads. On stream drainage divides, hydraulic heads decrease with increasing depth, and in major valleys they increase with increasing depth below land surface (Carswell and Rooney 1976). This is an important factor to note with respect to contaminant migration, as it results in upward gradients in valley areas, which tend to drive water (contaminated and uncontaminated) from fractured bedrock zones to local surface water features.

Peters Mine Pit Area (PMP)

The PMP Area is located near the northern portion of the Site (Figure 1). The Peters Mine was one of the most productive magnetite iron ore mines on the Site and was in operation from the mid-1700s until the 1930s. Ownership of the PMP Area is currently divided between the Borough of Ringwood and the NJDEP, which owns Ringwood State Park (Arcadis 2015a).

A flooded air shaft is located adjacent to the pit. The volume of water in the Peters Mine air shaft is approximately 213 million gallons when flooded (Arcadis 2015a). By comparison, the capacity of Wanaque Reservoir is approximately 29.63 billion gallons (approximately 140 times the volume of the Peters Mine air shaft). The ground surface opening to the air shaft is approximately 15 feet by 15 feet. Based on downhole logging, the shaft extends approximately 232 ft bgs. Within the air shaft, there is a thermal and geochemical stratification of the water at approximately 170-180 ft bgs that limits the physical mixing of water at the deeper zones, where there are elevated concentrations of benzene and 1,4-dioxane, and the more shallow zones (Arcadis 2015a). Historical dewatering rates for the mine shaft were very low, which suggests the hydraulic conductivity of the surrounding bedrock is limited (Arcadis 2015b).

Groundwater in the unconsolidated overburden fill and sediments in the PMP Area occurs under unconfined conditions at depths of approximately 15 ft bgs. Data generated during the RI indicates that the pond water surface within the former PMP is a surface expression of the unconfined overburden water table. Based on topography and measurements from groundwater monitoring wells within the PMP Area, the unconfined overburden groundwater flows in a southeasterly direction across the PMP Area (Arcadis 2015a).

In the PMP Area, groundwater in bedrock has an upward vertical potentiometric gradient, which indicates possible hydraulic communication between shallow and deep bedrock and also with groundwater in the overlying overburden. The overburden groundwater mixed with the bedrock groundwater is discharging to Park Brook and through seeps in the vicinity of State Road 3. Excess water from storms that enters the PMP over land also discharges through overburden to surface water. Surface water within Park Brook ultimately discharges into Sally's Pond (also known as Furnace Dam Pond or Ringwood Mill Pond), which ultimately discharges to Ringwood Creek approximately 1 mile upstream of its confluence with Wanaque Reservoir. The reservoir is located approximately 1.5 miles downstream of the PMP Area (Arcadis 2015a).

A more complete description of the PMP Area, including known history of mining and waste disposal activities, is available in the Site-Related Groundwater Remedial Investigation Report (Arcadis 2015a).

Cannon Mine Pit Area (CMP)

The CMP Area is located in the southwestern-most portion of the Site near the cul-de-sac at the end of Van Dunk Lane on a bedrock ridge that slopes steeply to the west and gently to the south and east (Figure 2). Because this area of concern is located on a bedrock ridge, the overburden is thin to non-existent and, where present, is draped over shallow bedrock encountered at depths of less than 10 ft bgs. The pit at Cannon Mine is approximately 150 feet wide by 300 feet long and between 140 and 180 feet deep. The pit was not filled to ground surface after it was closed, and was subsequently used as a landfill where industrial and municipal-type wastes were deposited above the blast rock. There is a vertical mine shaft, located approximately 500 feet east of the pit at the intersection of Van Dunk Lane and Milligan Lane. The vertical shaft is approximately 500 feet deep and currently sealed with railroad ties and a 6-inch-thick concrete slab, which is located at approximately 3 ft bgs. A review of historical records by Arcadis indicated that the pit at Cannon Mine was backfilled to grade with a combination of rock blasted from the sides of the pit wall, municipal-type and industrial solid waste, and imported fill soil (Arcadis 2015a).

Groundwater occurs in the shallow and deeper bedrock and within the mine pit, but the overburden, where it occurs, is too thin to sustain a water-bearing zone and is unsaturated. Because the overburden in the CMP Area is thin to non-existent, heavy precipitation tends to run off as storm water to surface water rather than infiltrate into bedrock, although recharge directly into the pit will occur. Groundwater flow may be variable near the bedrock ridge, as there is a groundwater flow divide present, and is also somewhat complicated by the hydraulic influence of the mine pit. Groundwater flows radially away from the crown of the bedrock ridge (higher elevations to lower elevations) toward Mine Brook in a manner similar to storm water runoff (Arcadis 2015a).

A sinkhole was discovered and reported near Van Dunk Lane on November 23, 2016. Since Jacobs' scope involves groundwater transport, this development was determined to be irrelevant to the analysis.

A more complete description of the CMP Area, including the known history of mining and waste disposal activities, is available in the Site-Related Groundwater Remedial Investigation Report (Arcadis 2015a).

O'Connor Disposal Area (OCDA)

The OCDA is located south of the PMP Area, just west of Park Brook, a small stream that flows southeast from the PMP Area to Sally's Pond (Figure 1). The OCDA was used during active mine operations as a "slime pond" for the settlement of waste mine tailings from the wet ore processing operations. "Slime" is a mining industry term that refers to silt size and finer mine tailings. Based on visual inspection of the OCDA, the slime pond berm is still present along the eastern perimeter of the OCDA adjacent to Park Brook (Arcadis 2015a). As detailed in the Remedial Investigation Report for OCDA (Arcadis 2013), test trenching and test pitting events conducted as part of the RI within the OCDA showed that, at many locations within OCDA, fill material contained a varied abundance of debris (including refuse and rubbish) that was intermixed with mine tailings and reworked soil (Arcadis 2015a).

Shallow groundwater flows through the native overburden soil upgradient of the OCDA and then through OCDA fill materials and mine process waste prior to discharging to Park Brook and wetlands on the eastern, downgradient OCDA boundary. Groundwater elevations confirm groundwater discharge into Park Brook (Arcadis 2015a). As expected, the depth to groundwater fluctuates seasonally and is typically deeper during drier summer months, with some wells being dry, or nearly dry, during drought conditions. As a result, groundwater discharge volumes to Park Brook vary seasonally. Low-level detections of 1,4-dioxane have been observed in overburden monitoring well OB-14B, screened from 25-35 ft bgs. Higher concentrations have been reported in downgradient Monitoring Well OB-17. No bedrock monitoring wells are present in or downgradient of the OCDA.

A more complete description of the OCDA, including known history of mining and waste disposal activities, is available in the Site-Related Groundwater Remedial Investigation Report (Arcadis, 2015a).

This report primarily focuses on contamination associated with the PMP Area, as the number of detection and the concentration values at the PMP Area are significantly greater than observed at the CMP or OCD Areas.

1,4-Dioxane

Properties

1,4-dioxane is a clear liquid used as a solvent in the manufacture of chemicals. It has also been used as a stabilizer in chlorinated solvents. It can be found in paint, adhesives, pesticides and some consumer products such as household cleaners, detergents, shampoos, deodorants and cosmetics. Its main industrial use is in degreasing solvents where it is present in combination with other chemicals (EPA 2006).

1,4-dioxane is among the most mobile organic contaminants in the saturated zone. As a result, it may be found far in advance of any solvents with which it might have entered the subsurface originally (EPA Clu-In Technical Overview, 2017). 1,4-dioxane is hydrophilic, is only minimally retarded in groundwater, and is not prone to sorption to soil. These properties generally make it a good candidate for pump-and-treat remediation (EPA 2006), although other technologies may be equally effective depending on site conditions.

Treatment

A Remedial Investigation Addendum Report and a Candidate Technologies Memorandum (CTM) should be provided to the EPA in May 2017. Both of the reports will be developed for Ford by Cornerstone Environmental. The CTM will include an evaluation of potential treatment technologies for addressing onsite groundwater contaminants, including 1,4-dioxane. Those technologies will be screened, usually based on the effectiveness of the technology to meet site objectives, and those passing will be further evaluated and described in an FS due to EPA in June 2017.

Some treatment technologies that may be considered in the development of the CTM and/or FS would include in situ biological treatment, in situ chemical oxidation treatment, groundwater extraction treatment (pump and treat), and subsurface injection technologies. In situ biological treatment technologies include:

- Bioremediation - enhances introduced or existing microbes which are capable of degrading a contaminant
- Bioaugmentation introduces microorganisms specifically adapted for degradation of a contaminant (AMEC Environment & Infrastructure, Inc. 2015)
- Monitored natural attenuation - relies on the attenuation of a contaminant by natural processes including biodegradation, abiotic degradation, adsorption, and dilution (AMEC Environment & Infrastructure, Inc. 2015)
- Phytoremediation - uses plants to destroy or remove a contaminant

In situ chemical oxidation introduces an oxidant such as persulfate to degrade/destroy a contaminant such as 1,4-dioxane. Pump and treat involves ex situ treatment of water prior to discharge. Subsurface injection treatment technologies may include push probe injection, recirculation wells, and hydraulic fracturing, all designed to improve the effectiveness of any agent injected into the subsurface (AMEC Environment & Infrastructure, Inc. 2015).

As a hydrophilic contaminant, 1,4-dioxane is not amenable to the conventional ex situ treatment technologies typically used for chlorinated solvents. Successful remedial technologies must take into account its challenging chemical and physical properties. Conventional water treatment practices (e.g., coagulation, sedimentation, and filtration), aeration, GAC adsorption, ozone, ultraviolet light (UV), and biofiltration have proven to be ineffective at removing 1,4-dioxane from water (Water Research Foundation, 2014). However, advanced oxidation techniques involving hydrogen peroxide and UV or ozone have been applied successfully to destroy it (EPA 2006). Other processes shown to be effective for removing 1,4-dioxane include photocatalysis using titanium dioxide, sonication with or without UV irradiation, zero-valent iron, distillation, and electrolysis. However, these techniques have very limited drinking water application and/or can be prohibitively expensive.

1,4-Dioxane Concentrations and Distribution

EPA has not established a Federal drinking water standard or MCL for 1,4-dioxane. NJDEP recently lowered its Interim Ground Water Quality Standard for 1,4-dioxane to 0.4 µg/L. There is no current NJDEP surface water standard or drinking water limit for the contaminant. A Technical Fact Sheet issued

by the EPA outlines the environmental and health related risks of 1,4-dioxane, guidelines, detection and characterization methods, and treatment methods (Appendix A). The following table summarizes Federal and State guidelines for 1,4-dioxane from the fact sheet.

Summary of Regulations for 1,4-Dioxane

Organization/Authority	Type of Guideline	Guideline Value
EPA	Drinking water concentration representing a 1×10^{-6} cancer risk level *	0.35 µg/L
EPA	Federal MCL	None
EPA	1-day health advisory in drinking water for a 10-kg child	4.0 mg/L
EPA	10-day health advisory in drinking water for a 10-kg child	0.4 mg/L
California Department of Public Health	Notification level for drinking water	1 µg/L
New Hampshire Department of Environmental Services	Reporting limit for all public water supplies	0.25 µg/L
Massachusetts Department of Environmental Protection	Drinking water guideline level	0.3 µg/L
NJDEP	Interim specific ground water quality criterion	0.4 µg/L

**Risk level assumes an exposure through water consumption of 2L/day by a 70 kg human at 0.35 µg/L of 1,4-dioxane over 70 years. The cancer risk level means there is a risk of one additional occurrence of cancer, in one million people, at the given exposure assumptions.*

Based on the sample results available in reports on the EPA website, sampling for 1,4-dioxane at the Site began in August 2015. The highest concentrations in groundwater have generally been in wells located within or downgradient of the PMP Area (Figure 1). Concentrations in these wells range from nondetect (ND) to 152 µg/L. A snapshot of 1,4-dioxane levels from the August 2015 sampling event is shown in Figure 3. The cross-section suggests that 1,4-dioxane is migrating from the PMP Area through saturated, fractured bedrock and overburden. The vertical distribution of this compound varies and is most likely reflective of the depth of occurrence of the contributory discontinuities (e.g., fractures, and faults) (LBG). It is uncertain whether concentrations have reached a steady-state condition or will decrease or increase significantly in the future. A longer record of monitoring at the Site will be required to more definitively determine contaminant trends.

Summary of Water Quality Data

Well	Sample Source	Distance to Reservoir	Date	Concentration of 1,4-Dioxane
PMP Air Shaft (230)	Groundwater	2 ½ miles	August 2015	140 µg/L
PMP Air Shaft (230)	Groundwater	2 ½ miles	December 2015	31.1 µg/L
PMP Air Shaft (230)	Groundwater	2 ½ miles	June 2016	144 µg/L
PMP Air Shaft (230)	Groundwater	2 ½ miles	August 2016	146 µg/L
PMP Air Shaft (230)	Groundwater	2 ½ miles	February 2017	129 µg/L
PMP Air Shaft (180)	Groundwater	2 ½ miles	August 2015	12 µg/L
PMP Air Shaft (180)	Groundwater	2 ½ miles	December 2015	5.76J µg/L

Well	Sample Source	Distance to Reservoir	Date	Concentration of 1,4-Dioxane
PMP Air Shaft (180)	Groundwater	2 ½ miles	June 2016	18.2 µg/L
PMP Air Shaft (180)	Groundwater	2 ½ miles	August 2016	20.3 µg/L
PMP Air Shaft (180)	Groundwater	2 ½ miles	February 2017	15.2 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	August 2015	17 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	May 2016	2.9 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	August 2016	17.5 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	February 2017	16 µg/L
RW-2 (279-289)	Groundwater	$^{2}/_{3}$ miles	August 2015	10 µg/L
RW-2 (279-289)	Groundwater	$^{2}/_{3}$ miles	August 2016	11.9 µg/L
RW-2 (279-289)	Groundwater	$^{2}/_{3}$ miles	February 2017	10.6 µg/L
RW-2 (441-472)	Groundwater	$^{2}/_{3}$ miles	August 2015	4.7J µg/L
RW-2 (441-472)	Groundwater	$^{2}/_{3}$ miles	August 2016	0.901 µg/L
RW-2 (441-472)	Groundwater	$^{2}/_{3}$ miles	February 2017	1.18 µg/L
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	August 2015	20 µg/L
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	December 2015	8.95 µg/L
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	May 2016	4.9/28.1 µg/L
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	August 2016	152/29.2J/20.9* µg/L
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	February 2017	27.7/23 µg/L
RGMW1	Groundwater	1 ½ miles	September 2016	0.1 µg/L
RGMW1	Groundwater	1 ½ miles	September 2016	ND
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	August 2015	0.27U µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	March 2016	0.157 µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	May 2016	0.8 µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	August 2016	0.34 µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	February 2017	0.678 µg/L
SW-PAB-03	Surface Water	2 $^{1}/_{3}$ miles	August 2015	0.29J µg/L
SW-PAB-03	Surface Water	2 ½ miles	March 2016	0.125 µg/L
SW-PAB-03	Surface Water	2 ½ miles	May 2016	0.902 µg/L
SW-PAB-03	Surface Water	2 ½ miles	August 2016	0.442 µg/L
SW-PAB-03	Surface Water	2 ½ miles	February 2017	0.766 µg/L
SW-PMB-02	Surface Water	2 ½ miles	August 2015	2.3J µg/L
SW-PMB-02	Surface Water	2 ½ miles	May 2016	<0.0735 µg/L
SW-PMB-02	Surface Water	2 ½ miles	August 2016	<0.0735 µg/L

U - Indicates that the analyte / compound was analyzed for, but not detected.

J - Indicates an estimated value. This flag is used either when estimating a concentration for a tentatively identified compound or when the data indicates the presence of an analyte / compound but the result is less than the sample Quantitation limit, but greater than zero. The flag is also used in data validation to indicate a reported value should be considered estimated due to associated quality assurance deficiencies.

Note – numbers in parentheses following Well/Location IDs represent ft bgs, either of the sample elevation for mine shaft samples, or the screened interval of wells.

* - First two results via 8270 SIM-ID, second result outside of hold time, third result is via Method 522 from Pace Analytical as part of isotope study (Cornerstone Environmental 2017).

The maximum 1,4-dioxane detection in the Peters Mine air shaft was 146 µg/L in August 2016, observed at approximately 230 ft bgs. The maximum concentration in a shallower zone (180 ft bgs) of the air shaft, also observed in August 2016, was 20.3 µg/L. However, as noted previously, deeper water in the Peters Mine air shaft has been found to have very limited or no hydraulic connectivity with overburden and bedrock, resulting in negligible mixing of mine pool water and downgradient groundwater.

Outlying detections have been observed in Monitoring Well OB-17, located just east of the OCDA (Figure 1), with concentrations ranging from 2.9 to 17.5 µg/L. Groundwater flow directions in this area are eastward toward Park Brook, suggesting a local source in or near the OCDA. More recent sample results from the OB-17 in February 2017 show concentrations of 16 and 13 µg/L. The isolated nature of the detections suggests that this is likely indicative of a relatively small zone of contamination, and although some discharge of 1,4-dioxane to Park Brook from this area is likely already occurring, a more widespread zone that would result in elevated concentrations across a larger area downgradient is unlikely. This is supported by the non-detections of 1,4-dioxane in monitoring wells located near OB-17, such as OB-16, OB-18, and OB-28.

Another outlier in the data given the values of nearby monitoring wells is well RW-2, which is located approximately 800 feet east of the CMP area, and within 75 feet of the Cannon Mine air shaft. RW-2 has been sampled three times for 1,4-dioxane, with results ranging from 10 to 11.9 µg/L. It represents the highest groundwater concentration of 1,4-dioxane in the southern portions of the monitoring area. The straight-line distance from RW-2 to the uppermost extent of the Wanaque Reservoir is approximately 2/3 of a mile. The screened interval in which the detection occurred was from 279 to 289 ft bgs. At a deeper interval (452 to 462 ft bgs), the reported high concentration was 4.7J µg/L. Overburden well OB-4 was ND for 1,4-dioxane during sampling for the contaminant at the well in August 2015, and in August 2016 the reported concentration was 0.079J µg/L.

The most recent publicly available monitoring data for the Site is from sampling events conducted in February 2017. In general, sample analyses of mine water and groundwater indicate that concentrations of volatile organic compounds (VOCs) were at levels consistent with historical concentrations.

Six relatively recent 1,4-dioxane samples were collected at monitoring wells at the Shooting Range (Figure 2), the intake at Raymond Dam and the headwater of Ringwood Creek on 09/21/2016 (see additional Figures 8-10). All of these were ND, with the exception of a value of 0.1 µg/L in Monitoring Well RGMW1, located at the Shooting Range. The method detection limit for the laboratory analysis was reported as 0.07 µg/L. A re-sampling of the well was ND for 1,4-dioxane. No information on the depth, screen interval or water level(s) in Monitoring Well RGMW1 was available at the time of this report.

With regards to surface water in the PMP Area, 1,4-dioxane concentrations appear to be discharging in low levels to Park Brook and Peters Mine Brook, which flows from the OCDA to a tributary of Ringwood Creek (Figures 1 and 4). The most downgradient surface water detection of 1,4-dioxane along the Park Brook stream path is at SW-PAB-04, located at Sally's Pond, near the Park Brook discharge point into the

pond. Observed detections range from 0.157 to 0.8 µg/L. Detections at surface water sample location SW-PAB-03, located farther upstream, range from 0.125 to 0.902 µg/L. Along Peters Mine Brook, the southernmost detection of 1,4-dioxane was in August 2015 at SW-PMB-02 (2.3J µg/L) (Figure 5). This was an estimated value, and more recent sample results at the same location in March, May/June, and August 2016 were ND for 1,4-dioxane (Cornerstone Environmental 2016b and 2016c).

Regarding the collection analysis of the 1,4-dioxane samples, it is noted that Cornerstone shared samples with Excel, an independent environmental consulting firm retained by the Borough to independently analyze groundwater data collected by Ford's remediation agent, Arcadis, and the EPA. Cornerstone submitted their samples to Test America Laboratories and SGS Accutest, and Excel submitted their samples to Alpha Analytical. As noted in the May/June 2016 report (Cornerstone Environmental 2016b), the 1,4-dioxane results reported by Alpha Analytical were consistently higher (by a factor of 3.9 on average) than those reported by Test America and SGS Accutest, which is another lab used by Cornerstone. While the labs used the same method for analyzing 1,4-dioxane, the difference in results may be attributable to a variation in the analysis protocol for 1,4-dioxane as described in the May/June 2016 report by Cornerstone. The variation allows for the concentration of 1,4-dioxane to be calculated as a percentage of the surrogate recoveries of 1,4-dioxane. Perhaps the most dramatic difference in the analytical results occurred in the split sample from the Peters Mine air shaft at the 230 ft bgs interval, where the reported concentration from either Test America or SGS Accutest (the testing lab was not readily identifiable from the report) was 15 µg/L and the result from Alpha Analytical was 144 µg/L. Figures in this report showing historical high concentrations of 1,4-dioxane are based on Test America/SGS Accutest reported values. It is noted that concentrations of other VOCs tested by the various labs from split samples were generally consistent, suggesting no large discrepancy for those VOCs based on individual lab methods or protocols. As a result of the discrepancy in the 1,4-dioxane results, Ford will direct laboratories analyzing future samples of 1,4-dioxane to use the Alpha Analytical method for analysis (Cornerstone Environmental 2016c). The recent 1,4-dioxane samples collected at monitoring wells, the intake at Raymond Dam and the headwater of Ringwood Creek were analyzed by ALS Environmental located in Middletown, PA. The method of analysis was EPA Method 522, which is similar to EPA Method 8270. It is unknown if ALS used surrogate recoveries in determining the concentrations of 1,4-dioxane.

The majority of the mass of 1,4-dioxane appears to be located approximately 230 ft bgs in the Peters Mine air shaft and is somewhat isolated hydrologically due to the relatively limited capacity of the surrounding bedrock to transmit groundwater. Studies indicate that the bedrock groundwater in the locations of the underground mine workings has an upward vertical gradient, resulting in possible hydraulic communication between the deeper bedrock groundwater and the groundwater in the overburden and shallow bedrock (Arcadis 2016a). Therefore, it is likely that the bulk of any contaminant contribution to the Wanaque Reservoir from the PMP Area will occur through shallow groundwater and surface water flowpaths. In the PMP Area, the primary groundwater flowpath to the reservoir is through shallow bedrock and overburden to the southeast, with much of it discharging to Park Brook. Surface water then flows to Sally's Pond, which flows into Ringwood Creek, which discharges to the reservoir. Another flowpath from the PMP Area is south along Peters Mine Brook.

Benzene, Arsenic and Lead

Benzene Concentrations and Distribution

Benzene in groundwater at the PMP Area has been detected in the air shaft, overburden monitoring wells, and shallow bedrock wells nearest the PMP. It has been detected predominantly downgradient of the PMP with higher, but still slight, concentrations reported either in wells immediately downgradient of the PMP or at the base of the Peters Mine air shaft (Arcadis 2015a). The maximum historical benzene concentration was 344 µg/L in Monitoring Well RW-6 in March 2015. RW-6 is screened at approximately 110 ft bgs and is located downgradient of Peters Pond (Figure 1). This concentration is significantly higher than any previously reported in any PMP Area bedrock or overburden monitoring well. The detection appears to have been related to a "hot spot" of contamination, as benzene concentrations observed in the well in the five sampling events conducted subsequent to the March 2015 detection have all been equal to or less than 2.2 µg/L.

There have been sporadic low-level detections of benzene in the CMP Area, one of which was attributed to sample equipment cross-contamination (Arcadis 2015b).

With respect to surface water, although trace concentrations of benzene have been reported in one of the two groundwater seeps in the vicinity of the SR-3 Area located downgradient of the PMP, benzene has never been detected in groundwater in the OCDA located immediately downgradient of this seep or in the adjacent Park Brook surface water or sediment.

Arsenic and Lead

Total arsenic and total lead were detected in groundwater and mine water samples from all three target areas. The highest reported groundwater concentration of arsenic (26.6 µg/L) was detected southeast of the PMP Area at OB-11R in September 2014. High levels of arsenic were also detected at OB-27, OB-25 and RW-3DD. Arsenic is naturally occurring and prevalent within the bedrock formations and mine tailings at the Site. Arsenic can be removed from source water via oxidation in the reservoir if enough dissolved oxygen is present in the water.

The highest reported groundwater concentration of lead (980 µg/L) was detected at the Peters Mine air shaft in August 2015. High concentrations of lead were also detected in the Cannon Mine air shaft and directly outside the Cannon Mine Pit Area at RW-2 and RW-5. In samples for which total lead concentrations exceeded water quality standards, dissolved lead concentrations were not above standards. This indicates that the lead detections reported were primarily associated with particulates in the groundwater samples. Dissolved lead can be removed via chemical precipitation, ion exchange or adsorption.

Remedial Plan for Operable Unit Two

The Preliminary Remedial Design Report (Cornerstone Environmental 2016a) describes requirements of the Record of Decision (ROD) and preliminary remedial options for OU2. The ROD was issued by the EPA in June 2014 and is intended to address waste contained in the three disposal areas comprising OU2,

which are the PMP Area, the OCDA, and the CMP Area (Cornerstone Environmental 2016a). The response action described in the ROD represents the second of three planned remedial phases, or operable units, for the Site. The third phase (OU3) addresses the groundwater across the Site. The RI Addendum and FS for OU3 is ongoing and will serve as the basis for the selection of a remedy for Site-wide groundwater. A remedy for OU1, presumed to encompass the entire Site, was originally intended to comprehensively address contamination at the Site. However, subsequent to the completion of the OU1 remedy and deletion of the Site from the National Priorities List, additional contamination was found at the Site that resulted in the need for further evaluation of conditions at the Site and implementation of OU2 and OU3 (EPA 2014). EPA has been designated as the lead agency for cleanup of the Site, with NJDEP functioning in a support role. Investigations and cleanup actions conducted at the Site have been primarily funded by Ford, which has been identified as a Potentially Responsible Party (PRP) (EPA 2014). There is a cost sharing agreement in place between Ford and the Borough.

The current remedial plan for OU2 was designed by Cornerstone Environmental and includes capping the contaminated zones within the three areas with clean, permeable soil. The cap is designed to prevent physical contact with the soil. EPA estimated 70,000 tons of material in the Peters Mine Pit area, more than 100,000 tons in OCDA and 40,000 tons in the Cannon Mine Pit area. These weights include contaminated and uncontaminated material. In addition to capping contaminated zones, areas of contaminated soil will be excavated and the soil removed, along with drums and paint waste.

It is unknown if the removal of these soil and waste areas and the associated capping will address any continuing or potential sources of contamination, or result in a decline in groundwater concentrations of benzene or 1,4-dioxane. Determination of specific source areas for groundwater samples collected in monitoring wells is often complicated by several factors, including a lack of detailed history of the location, quantity, characteristics and timing of the placement of waste. Waste disposal activities at the Site have been extensive, and although many are fairly well documented, the historical record is generally not detailed enough to identify individual sources or source areas. In addition, natural variability in the direction of groundwater flow and groundwater level magnitudes may be significant, making determination of specific sources difficult.

Three-dimensional groundwater flow models may be used with reverse particle tracking to help identify these locations, but these are often steady-state models that do not reflect the natural variability of rainfall and hydraulic gradient direction and magnitude that may affect the ultimate downgradient location of contaminants. In addition, well-calibrated groundwater models require significant time and effort to develop.

As part of the ROD for OU2, groundwater monitoring at the Site will continue until a groundwater remedy is selected, which may or may not involve a pump and treat option. The cap is estimated to be built by 2018 and, if selected as a remedy, any groundwater treatment may be installed by 2019.

Faulting and Seismic Activity Considerations

The bedrock units underlying the Site are reportedly penetrated by naturally occurring brittle structural features, such as fractures and faults (large scale fractures which are the result of breakage and movement of the comprising rock mass) (LBG). These brittle features in bedrock can influence groundwater movement and storage, as well as contaminants that may occur in the groundwater (LBG). The available information indicates that a major fault (oriented northeast-southwest and connected to shorter northwest-southeast oriented faults) exists in the study area (although removed from source areas), paralleling the main stem of Ringwood Creek and through the Wanaque Reservoir (Figure 6). This fault and the shorter connected faults are "active" faults and are classified as "normal" faults (with a relative steep angle or dip) (LBG). They are sometimes identifiable by way of topographic and bedrock exposure features.

Besides these surficially recognizable faults, faults have also been documented occurring within the PMP and CMP. In the PMP, a few small faults along which there has been very slight displacement have been observed (Hotz 1953). It is unlikely these extend significant distances from the mine. A larger fault is present in the Cannon Mine, identifiable across four levels of the mine with a northeast strike. Based on the reported orientation of this fault, it is conceivable that it may intercept the Wanaque Reservoir at depth. While the extent of this fault is unknown, the nature of contaminants in the CMP and Cannon Mine air shaft, and the fact that the fault has not been shown to be a conduit of significant groundwater flow, currently make it of lower concern. Based on investigations completed by others, the bedrock units underlying the PMP and CMP are of very low groundwater bearing potential. As such, the ability for contaminated groundwater in these units to potentially impact local surface water bodies is reportedly minimal (LBG). In the event of significant future seismic activity associated with known and unknown faults, additional breakage and fracturing may occur, which may change the potential for future contributions to local surface-water bodies. The possibility of impact would rely in part on the concentration of the contaminant, and the volume of water in the receiving surface water body (LBG).

Besides identifying the location, type, and extent of faults, information regarding their local seismic activity is also of importance when trying to assess potential for related future changes in groundwater conditions (and possible contaminant impacts) (LBG). To this end, information available from the New Jersey Geological Survey and the United States Geologic Survey was used to identify the locations of past seismic activity (e.g., earthquake) in the study area. Based on this information, a minor intensity earthquake occurred along the fault underlying the Wanaque Reservoir as recently as January 2016 (Figure 6) (LBG). Historically, numerous minor earthquakes along this and nearby structurally related faults have occurred going back at least to 1978, and possibly as far back as the 1800s and earlier (LBG). This indicates the faults in the study area are active, and will most likely experience future seismic activity (LBG). The intraplate setting of the area, which limits potential seismic stresses, combined with the relatively numerous faults in the region which serve to alleviate the stresses that do occur, renders the chances of a very strong earthquake in the region low. In addition, the long history of seismic activity in the region and the fact that the bedrock units underlying the PMP and CMP have not been extensively fractured by this activity suggest that the chances of new faults/fractures large enough to serve as conduits to the reservoir are minor.

Risk Analysis

The EPA's risk analysis approach was utilized to assess the risks of benzene and 1,4-dioxane reaching the Commission's finished water. This approach involves assigning ratings for both the likelihood and the severity of each scenario. The bases for ratings in each of these categories are defined below:

Likelihood Rating

1 – Scenario has little to no chance of occurrence
2 – Scenario has a 25% chance of occurrence
3 – Scenario has a 50% chance of occurrence
4 – Scenario has a 75% chance of occurrence
5 – Scenario is assumed to occur

Severity Rating

1 – Scenario will likely not have any health impacts
2 – Scenario will impact fewer than 10% of customers and/or have minimal health impacts
3 – Scenario will impact 10%-25% of customers and/or have moderate impacts to health
4 – Scenario will impact 25%-50% of customers and/or have long term impacts to health
5 – Scenario will have a widespread impact (>50% of customers) and/or cause danger to life and health

Risk Score. Multiplying the likelihood and severity ratings results in a final risk score for each scenario. The risk scores are categorized below:

1:4 – Low	5:9 – Low-Moderate	10:16 – Moderate-High	17:25 – High

Risk Analysis for Groundwater Contaminants Reaching Finished Water

Scenario (Contaminant)	Likelihood Rating	Severity Rating	Risk Score (Likelihood x Severity)
Benzene	1	4	4 – Low
Arsenic	1	4	4 – Low
Lead	2	4	8 – Low-Moderate
1,4-dioxane	2	4	8 – Low-Moderate

Summary of Results, Conclusions and Recommendations

Summary of Results

Summary of Water Quality Data

Well	Sample Source	Distance to Reservoir	Date	Concentration of 1,4-Dioxane
Peters Mine Air Shaft 230	Groundwater	2 ½ miles	August 2015	140 µg/L
Peters Mine Air Shaft 230	Groundwater	2 ½ miles	December 2015	31.1 µg/L
Peters Mine Air Shaft 230	Groundwater	2 ½ miles	June 2016	144 µg/L
Peters Mine Air Shaft 230	Groundwater	2 ½ miles	August 2016	146 µg/L
Peters Mine Air Shaft 230	Groundwater	2 ½ miles	February 2017	129 µg/L

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Well	Sample Source	Distance to Reservoir	Date	Concentration of 1,4-Dioxane
Peters Mine Air Shaft 180	Groundwater	2 ½ miles	August 2015	12 µg/L
Peters Mine Air Shaft 180	Groundwater	2 ½ miles	December 2015	5.76J µg/L
Peters Mine Air Shaft 180	Groundwater	2 ½ miles	June 2016	18.2 µg/L
Peters Mine Air Shaft 180	Groundwater	2 ½ miles	August 2016	20.3 µg/L
Peters Mine Air Shaft 180	Groundwater	2 ½ miles	February 2017	15.2 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	August 2015	17 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	May 2016	2.9 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	August 2016	17.5 µg/L
OB-17	Groundwater	2 $^{1}/_{3}$ miles	February 2017	16 µg/L
RW-2 (279-289)	Groundwater	$^{2}/_{3}$ miles	August 2015	10 µg/L
RW-2 (279-289)	Groundwater	$^{2}/_{3}$ miles	August 2016	11.9 µg/L
RW-2 (279-289)	Groundwater	$^{2}/_{3}$ miles	February 2017	10.6 µg/L
RW-2 (441-472)	Groundwater	$^{2}/_{3}$ miles	August 2015	4.7J
RW-2 (441-472)	Groundwater	$^{2}/_{3}$ miles	August 2016	0.901
RW-2 (441-472)	Groundwater	$^{2}/_{3}$ miles	February 2017	1.18
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	August 2015	20
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	December 2015	8.95
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	May 2016	4.9/28.1
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	August 2016	152/29.2J/20.9*
RW-3DD (175-180)	Groundwater	2 $^{1}/_{3}$ miles	February 2017	27.7/23
RGMW1	Groundwater	1 ½ miles	September 2016	0.1 µg/L
RGMW1	Groundwater	1 ½ miles	September 2016	ND
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	August 2015	0.27U µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	March 2016	0.157 µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	May 2016	0.8 µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	August 2016	0.34 µg/L
SW-PAB-04	Surface Water	2 $^{1}/_{3}$ miles	February 2017	0.678 µg/L
SW-PAB-03	Surface Water	2 $^{1}/_{3}$ miles	August 2015	0.29J µg/L
SW-PAB-03	Surface Water	2 ½ miles	March 2016	0.125 µg/L
SW-PAB-03	Surface Water	2 ½ miles	May 2016	0.902 µg/L
SW-PAB-03	Surface Water	2 ½ miles	August 2016	0.442 µg/L
SW-PAB-03	Surface Water	2 ½ miles	February 2017	0.766 µg/L
SW-PMB-02	Surface Water	2 ½ miles	August 2015	2.3J µg/L
SW-PMB-02	Surface Water	2 ½ miles	May 2016	<0.0735 µg/L
SW-PMB-02	Surface Water	2 ½ miles	August 2016	<0.0735 µg/L

U - Indicates that the analyte / compound was analyzed for, but not detected.

J - Indicates an estimated value. This flag is used either when estimating a concentration for a tentatively identified compound or when the data indicates the presence of an analyte / compound but the result is less than the sample Quantitation limit, but greater than zero. The flag is also used in data validation to indicate a reported value should be considered estimated due to associated quality assurance deficiencies.

Note – numbers in parentheses following Well/Location IDs represent ft bgs, either of the sample elevation for mine shaft samples, or the screened interval of wells.

* - First two results via 8270 SIM-ID, second result outside of hold time, third result is via Method 522 from Pace Analytical as part of isotope study (Cornerstone Environmental 2017).

1,4-Dioxane in the Shooting Range. The most recent sample results from monitoring wells near the Shooting Range included a low-level detection of 1,4-dioxane (0.1 µg/L). A resampling of the well resulted in a ND value. It has also been detected in relatively high concentrations (10 µg/L in Monitoring Well RW-2) in groundwater approximately 2/3 of a mile from those areas.

Summary of Regulations for 1,4-Dioxane

Organization/Authority	Type of Guideline	Guideline Value
EPA	Drinking water concentration representing a 1×10^{-6} cancer risk level *	0.35 µg/L
EPA	Federal MCL	None
EPA	1-day health advisory in drinking water for a 10-kg child	4.0 mg/L
EPA	10-day health advisory in drinking water for a 10-kg child	0.4 mg/L
California Department of Public Health	Notification level for drinking water	1 µg/L
New Hampshire Department of Environmental Services	Reporting limit for all public water supplies	0.25 µg/L
Massachusetts Department of Environmental Protection	Drinking water guideline level	0.3 µg/L
NJDEP	Interim specific ground water quality criterion	0.4 µg/L

**Risk level assumes an exposure through water consumption of 2L/day by a 70 kg human at 0.35 µg/L of 1,4-dioxane over 70 years. The cancer risk level means there is a risk of one additional occurrence of cancer, in one million people, at the given exposure assumptions.*

Conclusions

Groundwater/Surface Water Monitoring at the Ringwood Mines Superfund Site. While groundwater monitoring wells are well distributed at the Site for characterizing groundwater quality, additional monitoring wells would address data gaps and provide a more complete understanding of potential source areas, contaminant distributions, and zones of discharge to local streams and surface water bodies. Similarly, additional surface water monitoring of these discharge areas would provide verification of these discharge areas and additional information on the magnitude of concentrations along stream paths. In addition, since both major surface water pathways to the reservoir from the mine areas converge prior to discharging, monitoring at the confluence of Ringwood Creek and the reservoir would identify mass loading to the reservoir by stream pathways.

Benzene, Arsenic and Lead. The higher benzene concentrations are generally restricted to the groundwater and surface water areas near the PMP. These relatively low levels suggest that there is not a high-mass source of benzene that could generate concentrations far enough downgradient to be a threat to the headwaters of the Wanaque Reservoir, and certainly not as far as the water intake, which is located approximately 7.75 miles from the PMP Area. Benzene is less persistent in the environment than 1,4-dioxane, being more susceptible to natural attenuation processes such as volatilization and degradation. Previous studies also indicate that degradation of benzene is occurring at the Site, including volatilization of benzene that does enter Park Brook (Arcadis 2015b). Arsenic is naturally

occurring and prevalent within the bedrock formations and mine tailings at the Site, and poses low risk of reaching the finished water. Arsenic can be oxidized with the addition of chlorine or potassium permanganate and removed from source water in conventional treatment. Adjustment of pH may be needed to remove arsenic. There is a low-moderate risk of lead reaching the finished water. Lead in source water can be removed through chemical precipitation, ion exchange or adsorption. It is possible for some removal of lead to be accomplished with coagulation as floc has some precipitative properties; however, this would need to be verified at bench scale.

1,4-Dioxane. Primary flowpaths from the PMP Area to the reservoir appear to be through shallow bedrock and overburden groundwater, mostly discharging to local surface water ponds and streams, which then discharge to the reservoir. Direct groundwater transport of 1,4-dioxane from bedrock fractures to the reservoir in large volumes appears unlikely. Seismic activity of a magnitude that could change this is also unlikely. Based on the observed concentrations of 1,4-dioxane in the Peters Mine air shaft (146 µg/L), local groundwater (0.156-152 µg/L) and surface water (0.125-2.32 µg/L), it was inferred that levels at the intake are unlikely to exceed the EPA action level (0.35 µg/L). The consequence of elevated 1,4-dioxane at the intake is significant. The current water treatment plant cannot treat for 1,4-dioxane. A capital-intensive upgrade of the plant involving an advanced oxidation process would likely be required. .

Risk of Seismic Activity Affecting Contamination Transport. Based on the known seismic history of the area, the limited potential for large-magnitude seismic events, and the observed nature of bedrock underlying the PMP and CMP Areas, it is unlikely that future seismic activity will significantly alter contaminant flowpaths or change the conceptual model of flow and transport at the Site.

Variability in Lab Results for 1,4-Dioxane. It is noted that the most recent quarterly monitoring report (Cornerstone Environmental 2016c) from May/June 2016 describes variability in analytical results for 1,4-dioxane in samples collected by Cornerstone and split with Excel Environmental. Alpha Analytical results are consistently higher. This may result in higher acknowledged concentrations of 1,4-dioxane across the Site and increase the concern that 1,4-dioxane may leave the Site in concentrations greater than the NJDEP interim Ground Water Quality Standard of 0.4 µg/L.

Summary of Conclusions

The following table summarizes the conclusions of this report and the basis upon which they were made.

Conclusion	Basis for Conclusion
1. Additional groundwater, surface water and reservoir sampling is needed	Data analysis
2. Low risk of benzene and arsenic threatening the finished water	Water quality analysis, groundwater and surface water transport analysis
3. Low-moderate risk of 1,4-dioxane and lead threatening the finished water	Water quality analysis, groundwater and surface water transport analysis
4. Low risk of seismic activity affecting contamination transport	Seismic hydrogeological analysis
5. Variability in 1,4-dioxane results	Data analysis

Recommendations

Short-Term

Remedial Action. Given the severity of the impact to the water supply if the contaminants, in particular 1,4-dioxane, reach the intake, Jacobs recommends that an active treatment approach be implemented for groundwater remediation particularly in the Peters Mine air shaft where the highest 1,4-dioxane concentrations have been detected. A pump and treat approach to contain the contaminant plume is one possible active treatment approach. This could include a well pump and treatment (e.g., advanced oxidation using hydrogen peroxide and UV or ozone). The active treatment method should ensure that contaminants do not migrate downgradient and impact the water supply. System redundancy and proper controls would be needed to prevent any untreated groundwater from being discharged to surface water.

An RI addendum report and FS for OU3 is expected to be provided to EPA in May 2017 and will serve as the basis for the selection of a remedy for Site-wide groundwater. Typically, feasibility studies will evaluate a variety of options to address contaminants in groundwater, such as active or passive treatment, monitored natural attenuation or no action with ongoing monitoring. The Commission should review the recommended option once EPA completes its work and solicits public comments on the plan.

Modeling. Models of the reservoir and local and/or regional groundwater are recommended to better determine the levels of 1,4-dioxane and lead onsite which may threaten the water supply. This modeling would utilize information from the enhanced monitoring program described below. The fractured nature of the bedrock beneath the Site, and the fact that contaminants are known to migrate through these zones, pose a challenge in the development of a representative groundwater flow and transport model. In these cases, simplifying assumptions may be required to address flow and transport in the fractured zone, with the model primarily simulating behavior in the saturated overburden and discharge to local streams and other surface water bodies (ponds and the reservoir). A surface water model may be useful to evaluate the degree of mixing and any channelization through the Wanaque Reservoir and the effects of these factors on potential influent concentrations at the intake.

Long-Term

Monitoring. The currently monitored groundwater and surface water locations should continue to be monitored. Some of the sources of known groundwater contamination have not been identified. We recommend the addition of groundwater monitoring wells and surface water sample locations, upgradient of the reservoir. This would help better define groundwater flow directions and magnitudes, and provide a better understanding of contaminant distributions to help identify likely active sources. It would allow better characterization of any changes in the source(s) at the Site, serve as an "early warning" of likely downgradient contaminant transport, and along with data from more downgradient locations, provide perspective on any reductions in contaminant levels along the streams due to dilution, volatilization or other transport processes.

New wells placed upgradient and at vertically separated intervals along the flowpaths associated with historic 1,4-dioxane detections can be used to better characterize the extent of contamination and, thus, the likelihood of 1,4-dioxane discharge to the reservoir. Applicable locations include: 1) downgradient of suspected Peters Mine and Cannon Mine source areas; 2) proximal to the intersection of Cannon Mine Road and Peters Mine Road; and 3) near the intersection of Peters Mine Road and Margaret King Avenue.

Additional surface water monitoring locations should be identified along local streams such as Park Brook, Peters Mine Brook (also named the Ringwood Creek Tributary), and Ringwood Creek. Based on the conceptual model of groundwater flow and discharge at the Site, these streams serve as some of the primary potential contaminant migration pathways to the reservoir. Park Brook is an indirect tributary to Ringwood Creek, initially discharging to Sally's Pond. Additional monitoring locations along it, and the upper reaches of Peters Mine Brook, could help identify initial groundwater contaminant discharge locations. To help characterize potential contaminant discharge to the reservoir, additional surface water monitoring is also recommended for the confluence of Ringwood Creek and the reservoir.

As a precaution, monitoring of the water intake at the Wanaque Reservoir for 1,4-dioxane should be implemented. In addition, a review of 1,4-dioxane results from any public water sources in the vicinity of Ringwood Mines is recommended, along with a determination of the need for additional sampling at these locations.

Treatment at the Wanaque WTP. If at any point during the span of the remediation, monitoring results show evidence of increased levels of contamination in surface water or groundwater that would threaten the reservoir water quality, EPA would also be tasked with adding upgrades at the Wanaque WTP. In anticipation of that possibility, the Commission may wish to assess alternative treatment technologies to address these contaminants at the plant. Preliminary recommendations to address each contaminant are listed in the table below:

Preliminary Recommendations for Alternative Treatment Technologies

Contaminant	Preliminary Recommendation
1,4-Dioxane	Assessment of advanced oxidation process systems
Benzene	Assessment of activated carbon and/or packed tower aerator systems
Lead	Evaluation of removal options including chemical precipitation, ion exchange, adsorption and a coagulation-flocculation-solids separation process
Arsenic	Assessment of oxidation via addition of chlorine or potassium permanganate and the need for pH adjustment

This evaluation would provide a preliminary plan in the event levels continue to rise. The plan would include treatment options, a recommended treatment, cost, and timeframe for implementation. The Commission could begin implementation if and when contaminant levels rise in the flowpaths.

Summary of Recommendations

Recommendation	Short/Long Term	Responsible Party
Active remediation of groundwater to control the source, particularly at Peters Mine air shaft	Short	EPA
Modeling of groundwater contamination	Short	EPA
Additional surface and groundwater monitoring	Long	EPA
Additional monitoring at Wanaque Reservoir and Intake	Long	Commission
Treatment evaluation at Wanaque WTP	Long – if levels rise	EPA

References

Adamson, David T., R. Hunter Anderson, Shaily Mahendra, and Charles J. Newell. 2015. Evidence of 1,4-Dioxane Attenuation at Groundwater Sites Contaminated with Chlorinated Solvents and 1,4-Dioxane. Environ. Sci. Technol., 2015, 49 (11), pp 6510–6518.

AMEC Environment & Infrastructure, Inc. 2015. 1,4-Dioxane Remediation Approach Focused Feasibility Study. January 2015.

ARCADIS. 2013. Remedial Investigation Report for O'Connor Disposal Area. Ringwood Mines/Landfill Site, Ringwood, New Jersey. June 2013.

ARCADIS. 2015a. Site-Related Groundwater Remedial Investigation Report. Ringwood Mines/Landfill Site, Ringwood, New Jersey. January 2015.

ARCADIS. 2015b. Draft Baseline Human Health Risk Assessment for Site-Related Groundwater, Ringwood, New Jersey. May 2015.

Carswell, L.D. and J.G. Rooney. 1976. Summary of geology and ground-water resources of Passaic County, New Jersey, 1976. United States Geological Survey Water-Resources Investigations Report 76-75.

Cornerstone Environmental Incorporated. 2015. Ringwood Mines/Landfill Superfund Site Annual Groundwater and Surface Water Sampling. November 2015.

Cornerstone Environmental Incorporated. 2016a. Preliminary Remedial Design Report, Ringwood Mines/Landfill Superfund Site, Operable Unit Two, Ringwood, New Jersey, EPA ID# NJD980529739. March 2016.

Cornerstone Environmental Incorporated. 2016b. Ringwood Mines/Landfill Superfund Site March 2016 Surface Water Sampling 1,4-dioxane Results (Letter Report). April 2016.

ED_001829_00000825-00030

Cornerstone Environmental Incorporated. 2016c. Ringwood Mines/Landfill Superfund Site May/June 2016 Groundwater, Mine Water, and Surface Water Sampling. August 2016.

Cornerstone Environmental Incorporated. 2016d. Ringwood Mines/Landfill Superfund Site Annual Groundwater, Mine Water, and Surface Water Sampling – 2016. October 2016.

Cornerstone Environmental Incorporated. 2017. Ringwood Mines/Landfill Superfund Site February 2017 Groundwater, Mine Water, and Surface Water Sampling. March 2017.

EPA Clu-In 1,4-Dioxane Technical Overview. 2017. Retrieved from https://clu-in.org/contaminantfocus/default.focus/sec/1,4-Dioxane/cat/Overview/

Hotz, P.E. 1953. Magnetite Deposits of the Sterling Lake, N.Y. – Ringwood, N.J. Area. Contributions to Economic Geology, 1952. Geological Survey Bulletin 982-F. U.S. Government Printing Office, Washington. 1953.

Leggette, Brashears & Graham, Incorporated. 2016. Potential for Faulting and Seismic Activity to Affect Contaminant Transport in Groundwater from the Ringwood Mines Complex - Ringwood, New Jersey [Memorandum]. October 2016.

Mohr, Thomas K. G., Julie A. Stickney, and William H. DiGuiseppi. 2010. Environmental Investigation and Remediation 1,4-Dioxane and other Solvent Stabilizers. CRC Press. 2010.

United States Environmental Protection Agency (EPA) 2006. Treatment Technologies for 1,4-Dioxane: Fundamentals and Field Applications. EPA-542-R-06-009. December 2006.

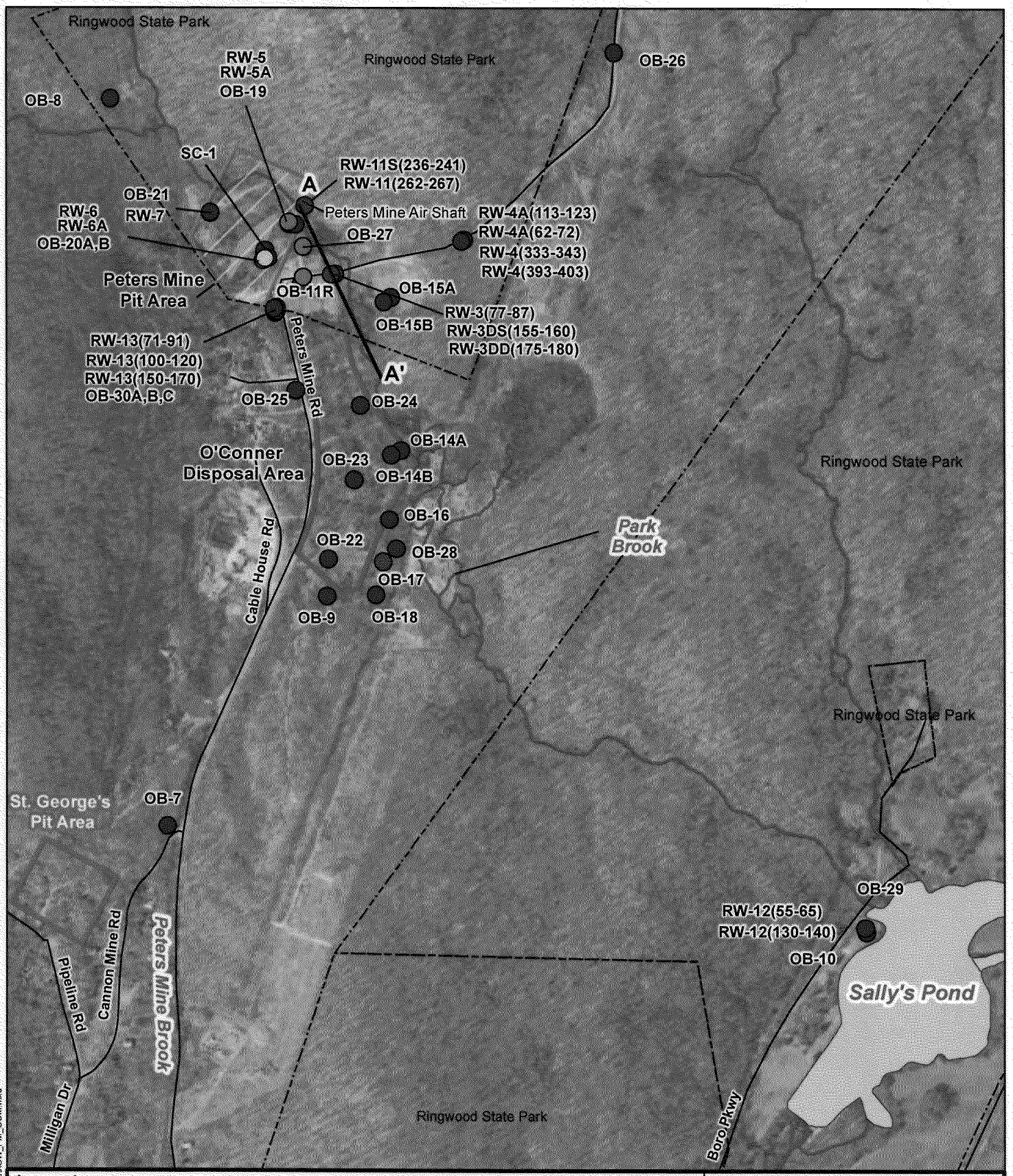
EPA 2014. Record of Decision Ringwood Mines/Landfill Superfund Site Operable Unit Two. June 2014.

Volkert, R. 2008. Bedrock Geologic Map of the Greenwood Lake Quadrangle, Passaic and Sussex Counties, New Jersey. New Jersey Geological Survey Open-File Map (unpublished).

Water Research Foundation 2014. 1,4-Dioxane White Paper (White Paper). Water Research Foundation, Denver, CO.

Zimmer, David M. Ringwood residents urge EPA to scrap Superfund cap. NorthJersey.com, December 2016

FIGURES



Legend

1,4-Dioxane Groundwater Concentrations (µg/L)

- 0.00 - 0.40
- 0.41 - 2.50
- 2.51 - 15.00
- 15.10 - 40.00

0 375 750 Feet

1:7,000

N

Source: GIS data provided by New Jersey Geographic Information Network
Data Projection: NAD_1983_SP_New_Jersey_FIPS_2900_Feet

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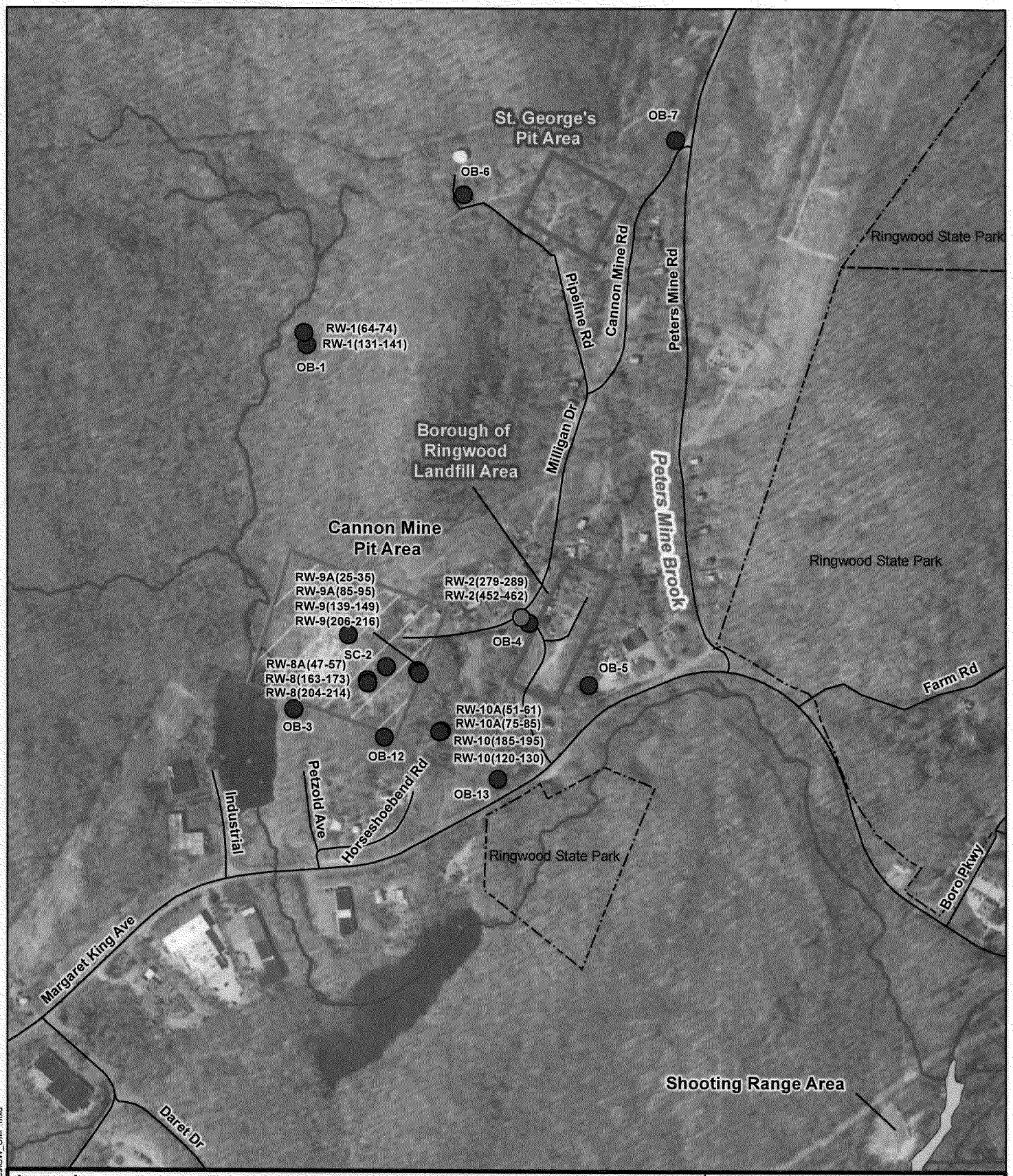
JACOBS

Ringwood Mines, New Jersey
Peters Mine and O'Connor Disposal Area
1,4-Dioxane Groundwater
Highest Historical Concentrations
Ringwood, NJ

NAME: jdefenderfer Date: 5/9/2017

Figure 1



Legend

1,4-Dioxane Groundwater Concentrations (µg/L)

- 0.00 - 0.40
- 0.41 - 2.50
- 2.51 - 15.00
- 15.10 - 40.00

0 375 750 Feet

1:7,000

N

Source: GIS data provided by New Jersey Geographic Information Network
Data Projection: NAD_1983_SP_New_Jersey_FIPS_2900_Feet

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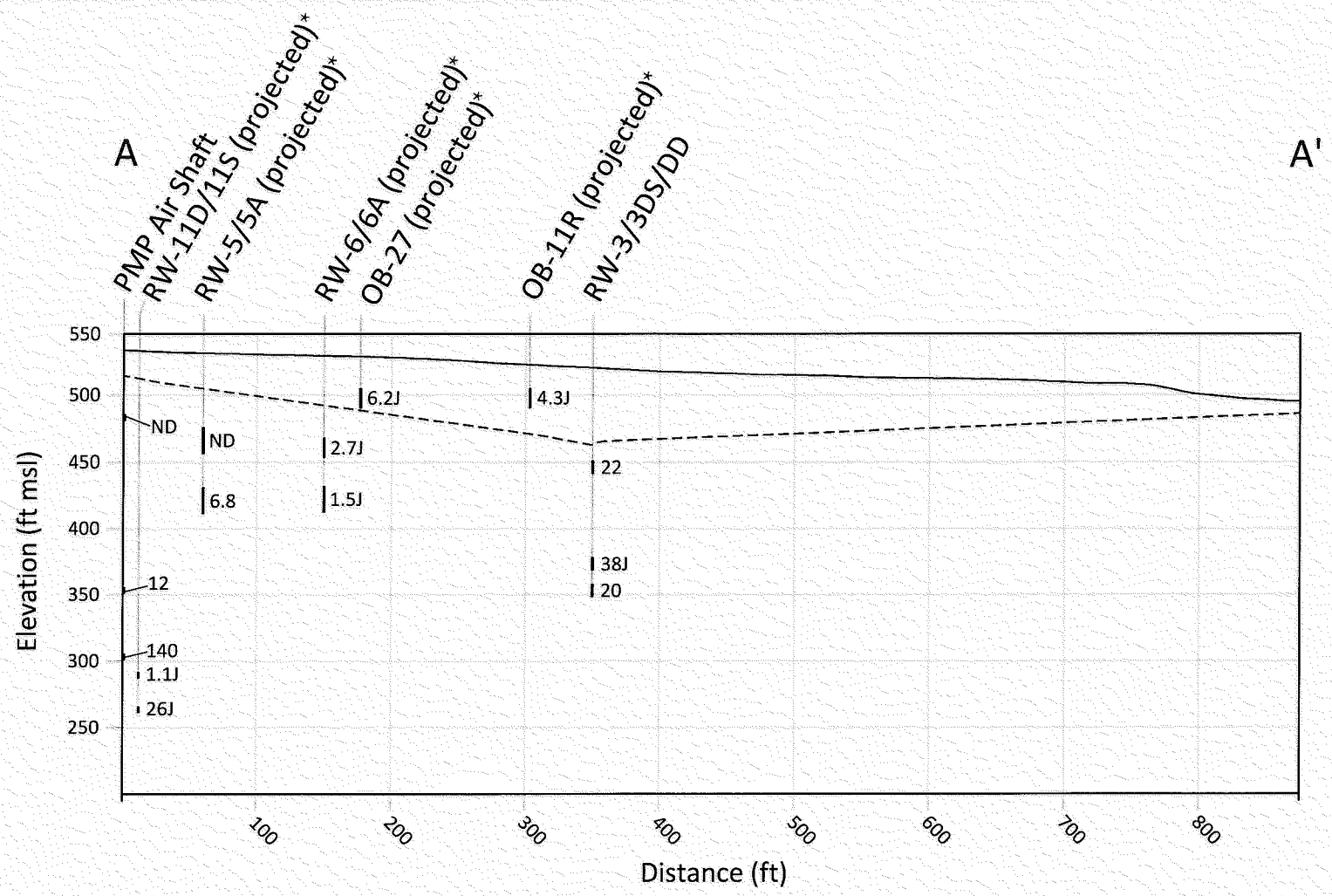
JACOBS

Ringwood Mines, New Jersey
Cannon Mine Area
1,4-Dioxane Groundwater
Highest Historical Concentrations

Ringwood, NJ

NAME: jdefenderfer Date: 10/30/2016

Figure 2



Legend

Monitoring Well Screened Interval with 1,4-Dioxane Concentration (µg/L)

6.8

Topography

Bedrock Surface

* Projected: wells are not directly on the A-A' section and their location is projected to that line.

0 120

Scale in Feet

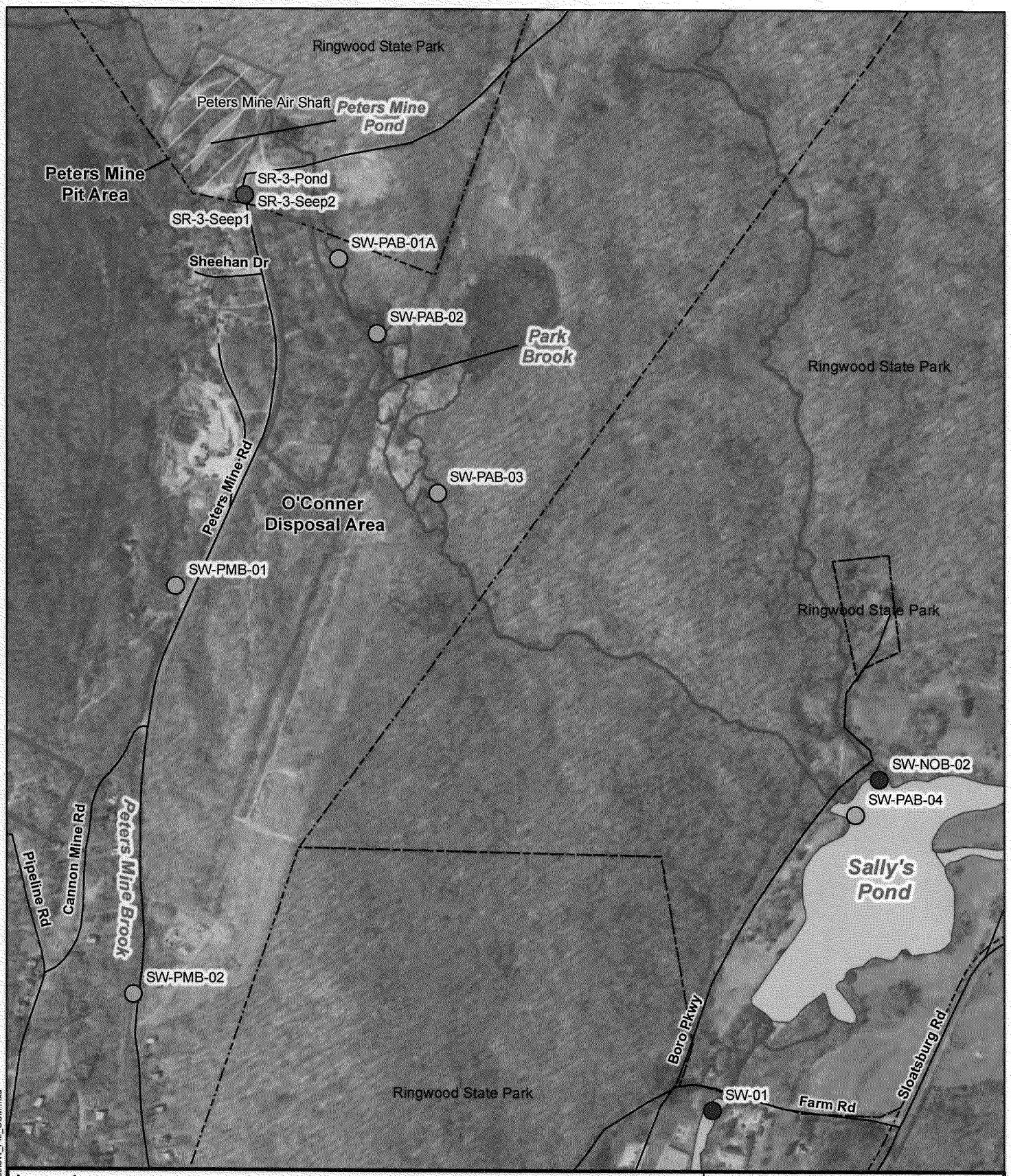
JACOBS

Peters Mine Pit Area
Section A-A'
1,4-Dioxane Concentrations 08/2015
Ringwood Mines, Ringwood, New Jersey

05/09/17 JD 1_4_Dioxane Section.dwg

Figure 3

last modified: 05/09/17 printed: 05/09/17 by JD



Legend

1,4-Dioxane Surface Water Concentrations (µg/L)

- 0.06 - 0.40
- 0.40 - 2.50
- 2.51 - 15.00
- 15.01 - 40.00

0 375 750 Feet

1:7,000

N

Source: GIS data provided by New Jersey Geographic Information Network
Data Projection: NAD_1983_SP_New_Jersey_FIPS_2900_Feet

JACOBS

Ringwood Mines, New Jersey
Peters Mine and O'Connor Disposal Area
1,4-Dioxane Surface Water
Highest Historical Concentrations
Ringwood, NJ

NAME: jdefenderfer Date: 11/15/2016 **Figure 4**

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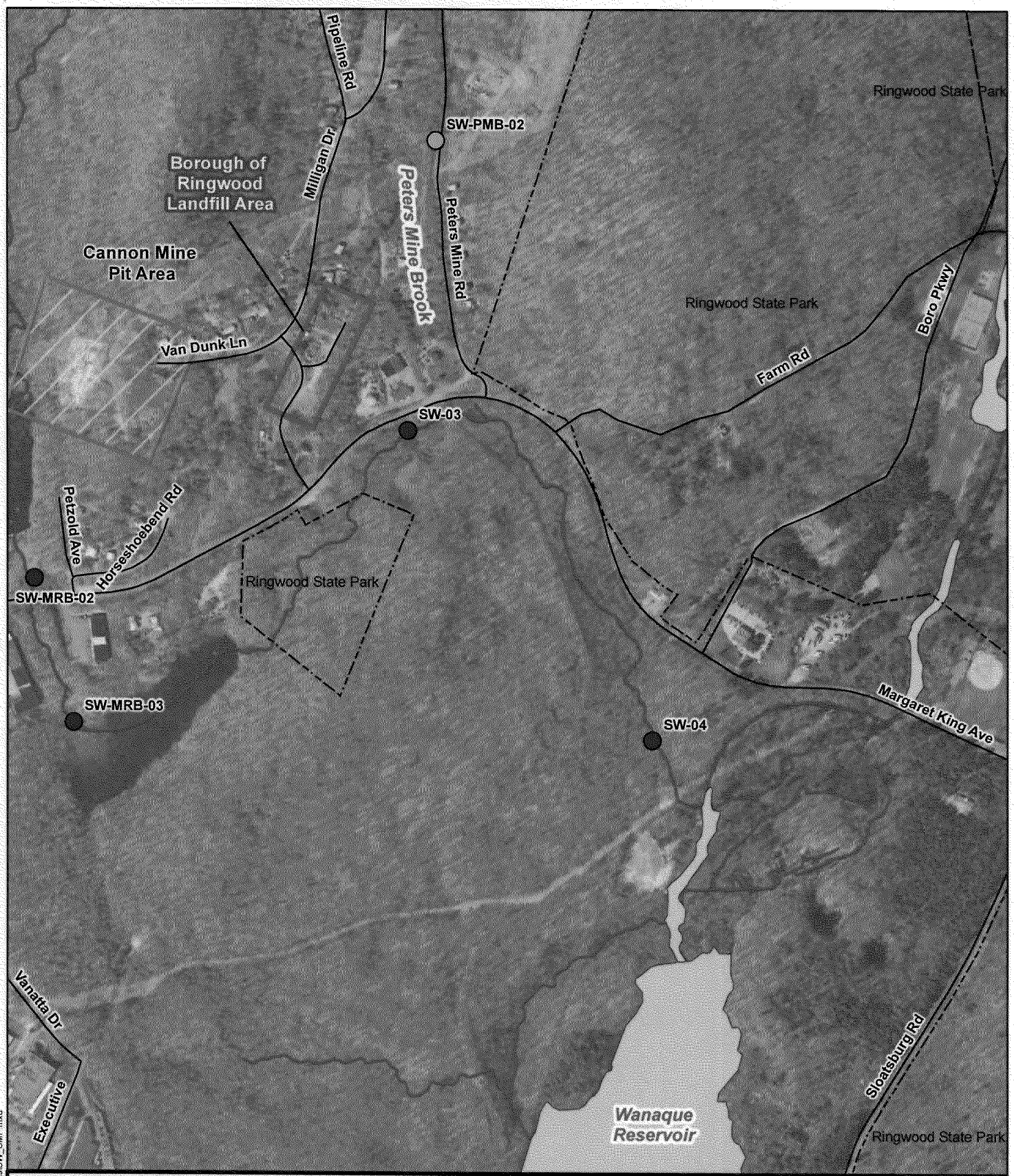

Legend

1,4-Dioxane Surface Water Concentrations (µg/L)

- 0.00 - 0.40
- 0.41 - 2.50
- 2.51 - 15.00
- 15.10 - 40.00

0 375 750 Feet

1:7,000

N

Source: GIS data provided by New Jersey Geographic Information Network
Data Projection: NAD_1983_SP_New_Jersey_FIPS_2900_Feet

JACOBS

Ringwood Mines, New Jersey
Cannon Mine Area
1,4-Dioxane Surface Water
Highest Historical Concentrations
Ringwood, NJ

NAME: jdefenderfer Date: 9/12/2016 **Figure 5**

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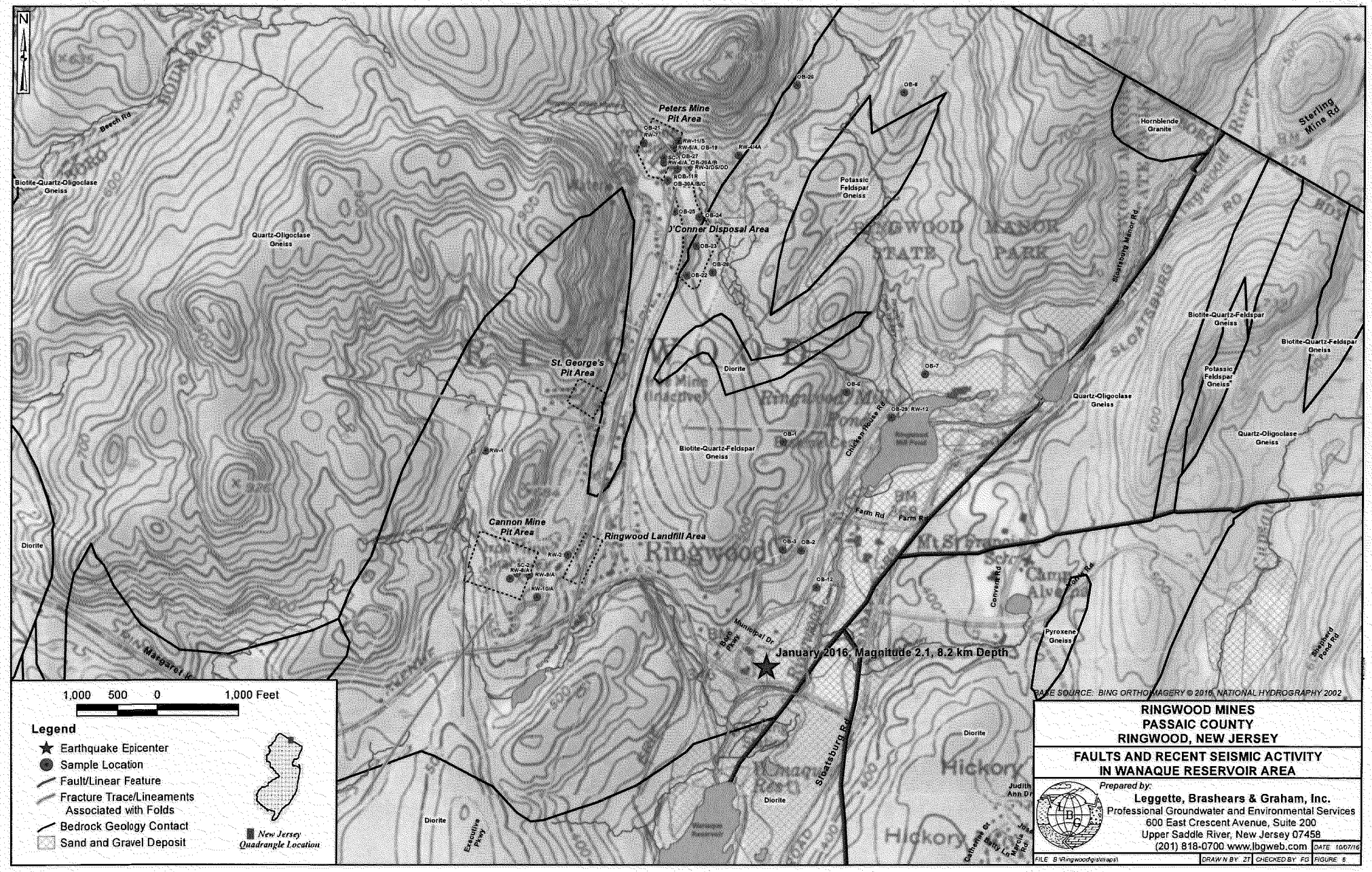

N
Peters Mine Pit Area
O'Conner Disposal Area
St. George's Pit Area
Cannon Mine Pit Area
Ringwood Landfill Area
Biotite-Quartz-Oligoclase Gneiss
Quartz-Oligoclase Gneiss
Potassic Feldspar Gneiss
Hornblende Granite
Sterling Mine Rd
Biotite-Quartz-Feldspar Gneiss
Diorite
Chicken House Rd
Farm Rd
Municipal Dr
Sloatsburg Rd
Convent Rd
Pyroxene Gneiss
Shepherd Pond Rd
Beech Rd
Margaret Rd
Executive Pkwy
Judith Ann Dr
January 2016, Magnitude 2.1, 8.2 km Depth
1,000 500 0 1,000 Feet
Legend
Earthquake Epicenter
Sample Location
Fault/Linear Feature
Fracture Trace/Lineaments Associated with Folds
Bedrock Geology Contact
Sand and Gravel Deposit
New Jersey Quadrangle Location
BASE SOURCE: BING ORTHOIMAGERY © 2016, NATIONAL HYDROGRAPHY 2002
RINGWOOD MINES
PASSAIC COUNTY
RINGWOOD, NEW JERSEY
FAULTS AND RECENT SEISMIC ACTIVITY
IN WANAQUE RESERVOIR AREA
Prepared by:
Leggette, Brashears & Graham, Inc.
Professional Groundwater and Environmental Services
600 East Crescent Avenue, Suite 200
Upper Saddle River, New Jersey 07458
(201) 818-0700 www.lbgweb.com
DATE 10/07/16
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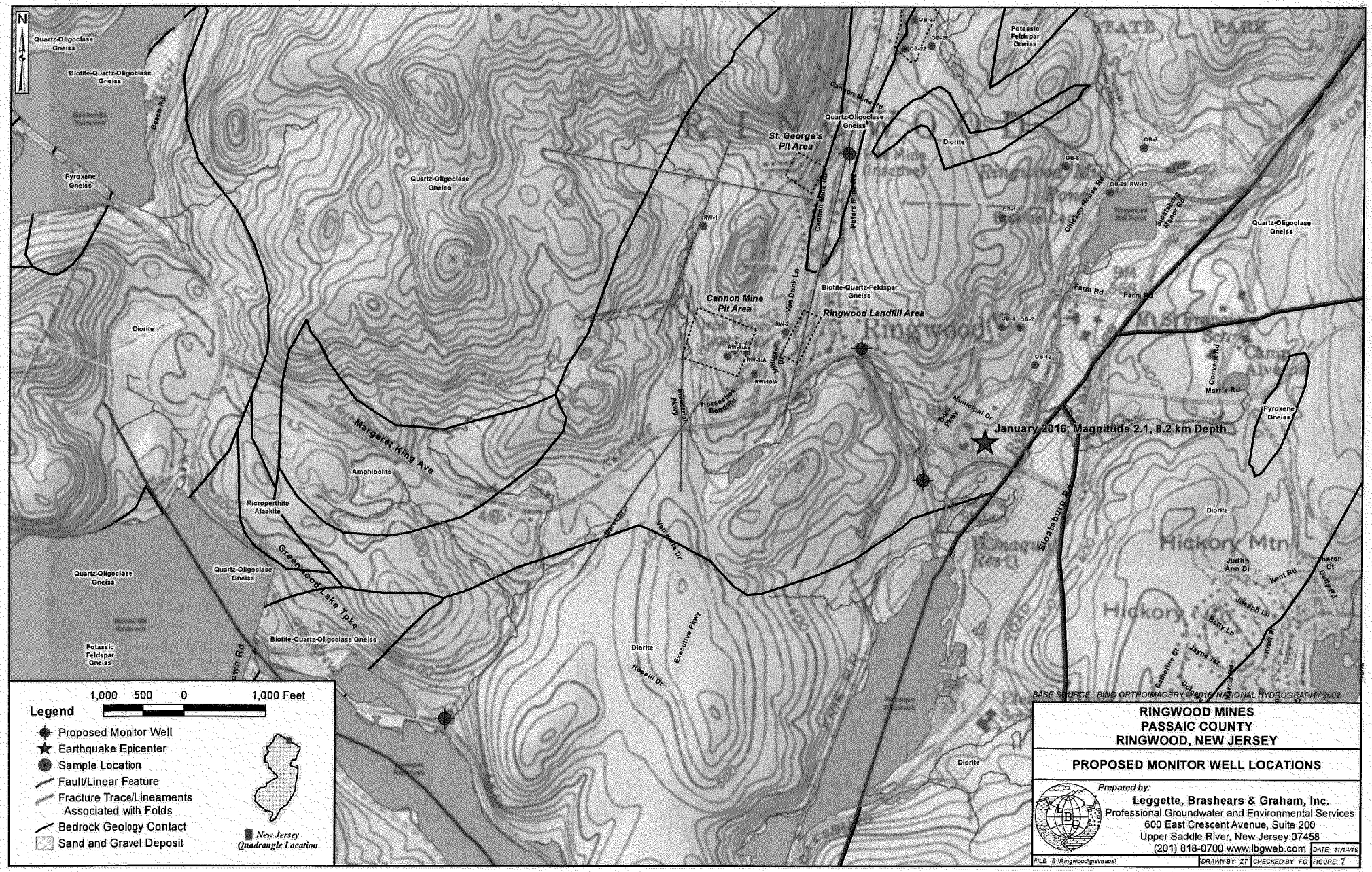
CHECKED BY FG
FIGURE 5


N
Quartz-Oligoclase Gneiss
Biotite-Quartz-Oligoclase Gneiss
Pyroxene Gneiss
Quartz-Oligoclase Gneiss
Diorite
Amphibolite
Microperthite Alaskite
Quartz-Oligoclase Gneiss
Potassic Feldspar Gneiss
Biotite-Quartz-Oligoclase Gneiss
Margaret King Ave
Greenwood Lake Tpke
Beech Rd
Cannon Mine Rd
St. George's Pit Area
Cannon Mine Pit Area
Ringwood Landfill Area
Biotite-Quartz-Feldspar Gneiss
Van Dunk Ln
Hillside Dr
Horseshoe Bend Rd
Interstate Pkwy
Executive Pkwy
Roselli Dr
Vanderbilt Dr
Municipal Dr
Bow Pkwy
Sloatsburg Rd
Chickens House Rd
Sloatsburg Manor Rd
Farm Rd
Convent Rd
Morris Rd
Hickory Mtn
Judith Ann Dr
Kent Rd
Joseph Ln
Sally Ln
Jayne Ter
Catherine Ct
Sharon Ct
Sally Rd
January 2016, Magnitude 2.1, 8.2 km Depth
STATE PARK
Ringwood
Hickory
1,000 500 0 1,000 Feet
Legend
Proposed Monitor Well
Earthquake Epicenter
Sample Location
Fault/Linear Feature
Fracture Trace/Lineaments Associated with Folds
Bedrock Geology Contact
Sand and Gravel Deposit
New Jersey Quadrangle Location
BASE SOURCE: BING ORTHOIMAGERY CP2015; NATIONAL HYDROGRAPHY 2002
RINGWOOD MINES
PASSAIC COUNTY
RINGWOOD, NEW JERSEY
PROPOSED MONITOR WELL LOCATIONS
Prepared by:
Leggette, Brashears & Graham, Inc.
Professional Groundwater and Environmental Services
600 East Crescent Avenue, Suite 200
Upper Saddle River, New Jersey 07458
(201) 818-0700 www.lbgweb.com
DATE 11/14/16
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DRAWN BY: ZF
CHECKED BY: FG
FIGURE 7

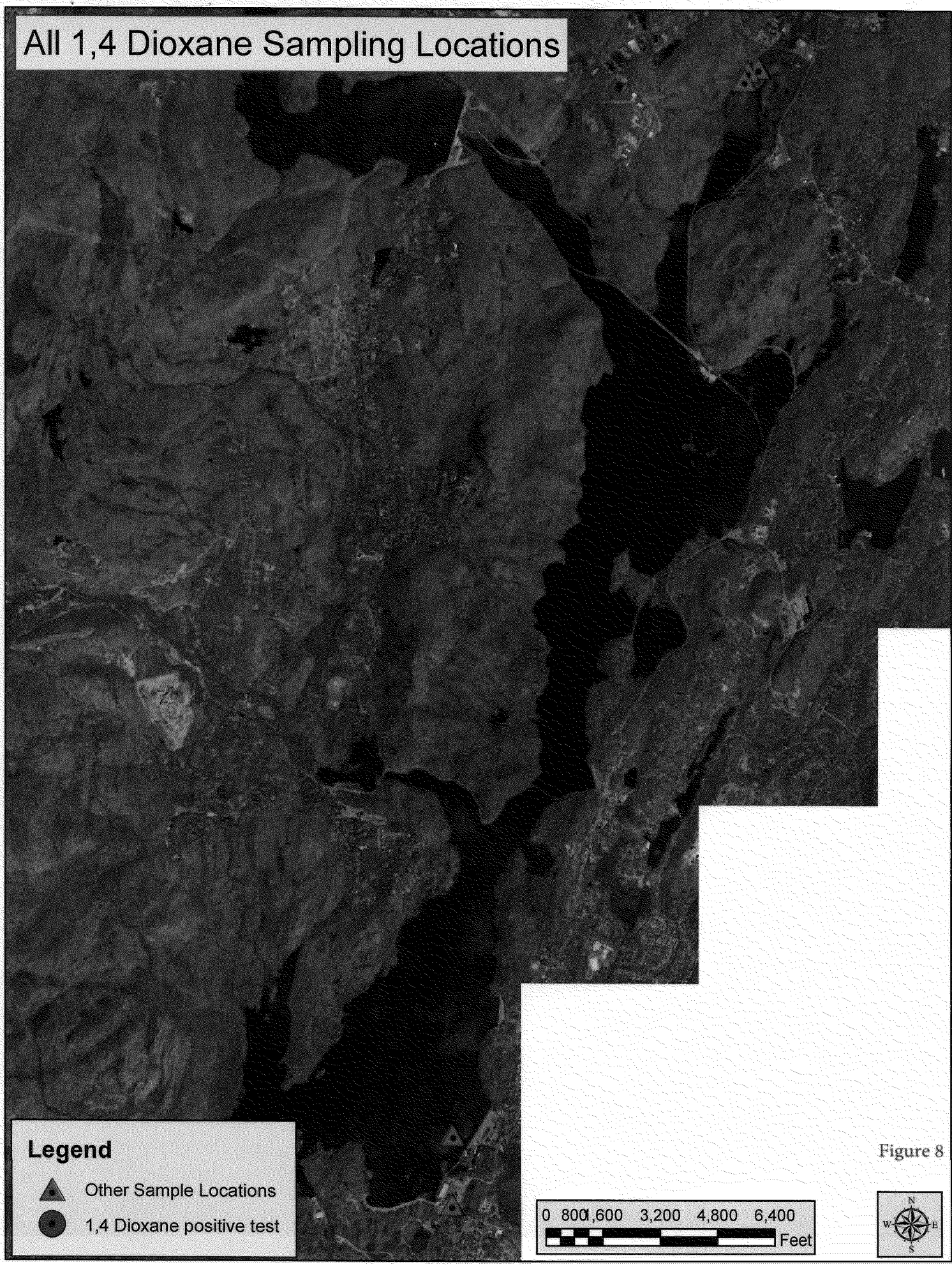
All 1,4 Dioxane Sampling Locations
Legend
Other Sample Locations
1,4 Dioxane positive test
0 800 1,600 3,200 4,800 6,400
Feet
N
W
E
S

Figure 8

Shooting Range Site
With Ford Site in View
Legend
Other Sample Locations
1,4 Dioxane positive test
0 205410 820 1,230 1,640
Feet
N
W
E
S

Figure 9

Shooting Range Site
Legend
Other Sample Locations
1,4 Dioxane positive test
0 20 40 80 120 160
Feet
N
W
E
S

Figure 10

APPENDIX A

Technical Fact Sheet – 1,4-Dioxane

United States Environmental Protection Agency (EPA)

United States Environmental Protection Agency

Technical Fact Sheet – 1,4-Dioxane

January 2014

At a Glance

- Flammable liquid and a fire hazard. Potentially explosive if exposed to light or air.
- Found at many federal facilities because of its widespread use as a stabilizer in certain chlorinated solvents, paint strippers, greases and waxes.
- Short-lived in the atmosphere, may leach readily from soil to groundwater, migrates rapidly in groundwater and is relatively resistant to biodegradation in the subsurface.
- Classified by the EPA as "likely to be carcinogenic to humans" by all routes of exposure.
- Short-term exposure may cause eye, nose and throat irritation; long-term exposure may cause kidney and liver damage.
- No federal maximum contaminant level (MCL) has been established for 1,4-dioxane in drinking water.
- Federal screening levels, state health-based drinking water guidance values and federal occupational exposure limits have been established.
- Modifications to existing sample preparation procedures may be required to achieve the increased sensitivity needed for detection of 1,4-dioxane.
- Common treatment technologies include advanced oxidation processes and bioremediation.

Introduction

This fact sheet, developed by the U.S. Environmental Protection Agency (EPA) Federal Facilities Restoration and Reuse Office (FFRRO), provides a summary of the contaminant 1,4-dioxane, including physical and chemical properties; environmental and health impacts; existing federal and state guidelines; detection and treatment methods; and additional sources of information. This fact sheet is intended for use by site managers who may address 1,4-dioxane at cleanup sites or in drinking water supplies and for those in a position to consider whether 1,4-dioxane should be added to the analytical suite for site investigations.

1,4-Dioxane is a likely human carcinogen and has been found in groundwater at sites throughout the United States. The physical and chemical properties and behavior of 1,4-dioxane create challenges for its characterization and treatment. It is highly mobile and has not been shown to readily biodegrade in the environment.

What is 1,4-dioxane?

- 1,4-Dioxane is a synthetic industrial chemical that is completely miscible in water (EPA 2006).
- Synonyms include dioxane, dioxan, p-dioxane, diethylene dioxide, diethylene oxide, diethylene ether and glycol ethylene ether (EPA 2006; Mohr 2001).
- 1,4-Dioxane is unstable at elevated temperatures and pressures and may form explosive mixtures with prolonged exposure to light or air (DHHS 2011; HSDB 2011).
- 1,4-Dioxane is a likely contaminant at many sites contaminated with certain chlorinated solvents (particularly 1,1,1-trichloroethane [TCA]) because of its widespread use as a stabilizer for chlorinated solvents (EPA 2013a; Mohr 2001)
- It is used as: a stabilizer for chlorinated solvents such as TCA; a solvent for impregnating cellulose acetate membrane filters; a wetting and dispersing agent in textile processes; and a laboratory cryoscopic solvent for molecular mass determinations (ATSDR 2012; DHHS 2011; EPA 2006).
- It is used in many products, including paint strippers, dyes, greases, varnishes and waxes. 1,4-Dioxane is also found as an impurity in antifreeze and aircraft deicing fluids and in some consumer products (deodorants, shampoos and cosmetics) (ATSDR 2012; EPA 2006; Mohr 2001).

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What is 1,4-dioxane? (continued)

- 1,4-Dioxane is used as a purifying agent in the manufacture of pharmaceuticals and is a by-product in the manufacture of polyethylene terephthalate (PET) plastic (Mohr 2001).
- Traces of 1,4-dioxane may be present in some food supplements, food containing residues from packaging adhesives or on food crops treated with pesticides that contain 1,4-dioxane as a solvent or inert ingredient (ATSDR 2012; DHHS 2011).

Exhibit 1: Physical and Chemical Properties of 1,4-Dioxane
(ATSDR 2012; Howard 1990; HSDB 2011)

Property	Value
Chemical Abstracts Service (CAS) Number	123-91-1
Physical Description (physical state at room temperature)	Clear, flammable liquid with a faint, pleasant odor
Molecular weight (g/mol)	88.11
Water solubility	Miscible
Melting point (°C)	11.8
Boiling point (°C) at 760 mm Hg	101.1 °C
Vapor pressure at 25°C (mm Hg)	38.1
Specific gravity	1.033
Octanol-water partition coefficient (log K_{ow})	-0.27
Organic carbon partition coefficient (log K_{oc})	1.23
Henry's law constant at 25 °C (atm-m^3/mol)	4.80 X 10^{-6}

Abbreviations: g/mol – grams per mole; °C – degrees Celsius; mm Hg – millimeters of mercury; atm-m^3/mol – atmosphere-cubic meters per mole.

What are the environmental impacts of 1,4-dioxane?

- 1,4-Dioxane is released into the environment during its production, the processing of other chemicals, its use and its generation as an impurity during the manufacture of some consumer products. It is typically found at some solvent release sites and PET manufacturing facilities (ATSDR 2012; Mohr 2001).
- It is short-lived in the atmosphere, with an estimated 1- to 3-day half-life as a result of its reaction with photochemically produced hydroxyl radicals (ATSDR 2012; DHHS 2011). Breakdown products include aldehydes and ketones (Graedel 1986).
- It may migrate rapidly in groundwater, ahead of other contaminants and does not volatilize rapidly from surface water bodies (DHHS 2011; EPA 2006).
- Migration to groundwater is weakly retarded by sorption of 1,4-dioxane to soil particles; it is expected to move rapidly from soil to groundwater (EPA 2006; ATSDR 2012).
- It is relatively resistant to biodegradation in water and soil and does not bioconcentrate in the food chain (ATSDR 2012; Mohr 2001).
- As of 2007, 1,4-dioxane had been identified at more than 31 sites on the EPA National Priorities List (NPL); it may be present (but samples were not analyzed for it) at many other sites (HazDat 2007).

What are the routes of exposure and the health effects of 1,4-dioxane?

- Potential exposure could occur during production and use of 1,4-dioxane as a stabilizer or solvent (DHHS 2011).
- Exposure may occur through inhalation of vapors, ingestion of contaminated food and water or dermal contact (ATSDR 2012; DHHS 2011).
- Inhalation is the most common route of human exposure, and workers at industrial sites are at greatest risk of repeated inhalation exposure (ATSDR 2012; DHHS 2011).

What are the routes of exposure and the health effects of 1,4-dioxane? (continued)

- 1,4-Dioxane is readily adsorbed through the lungs and gastrointestinal tract. Some 1,4-dioxane may also pass through the skin, but studies indicate that much of it will evaporate before it is absorbed. Distribution is rapid and uniform in the lung, liver, kidney, spleen, colon and skeletal muscle tissue (ATSDR 2012).
- Short-term exposure to high levels of 1,4-dioxane may result in nausea, drowsiness, headache, and irritation of the eyes, nose and throat (ATSDR 2012; EPA 2013b; NIOSH 2010).
- Chronic exposure may result in dermatitis, eczema, drying and cracking of skin and liver and kidney damage (ATSDR 2012; HSDB 2011).
- 1,4-Dioxane is weakly genotoxic and reproductive effects in humans are unknown; however, a developmental study on rats indicated that 1,4-dioxane may be slightly toxic to the developing fetus (ATSDR 2012; Giavini and others 1985).
- Animal studies showed increased incidences of nasal cavity, liver and gall bladder tumors after exposure to 1,4-dioxane (DHHS 2011; EPA IRIS 2013).
- EPA has classified 1,4-dioxane as "likely to be carcinogenic to humans" by all routes of exposure (EPA IRIS 2013).
- The U.S. Department of Health and Human Services states that 1,4-dioxane is reasonably anticipated to be a human carcinogen based on sufficient evidence of carcinogenicity from studies in experimental animals (DHHS 2011).
- The American Conference of Governmental Industrial Hygienists (ACGIH) has classified 1,4-dioxane as a Group A3 carcinogen — confirmed animal carcinogen with unknown relevance to humans (ACGIH 2011).
- The National Institute for Occupational Safety and Health (NIOSH) considers 1,4-dioxane a potential occupational carcinogen (NIOSH 2010).

Are there any federal and state guidelines and health standards for 1,4-dioxane?

- Federal and State Standards and Guidelines:
  - EPA's Integrated Risk Information System (IRIS) database includes a chronic oral reference dose (RfD) of 0.03 milligrams per kilogram per day (mg/kg/day) based on liver and kidney toxicity in animals and a chronic inhalation reference dose (RfC) of 0.03 milligrams per cubic meter (mg/m^3) based on atrophy and respiratory metaplasia inside the nasal cavity of animals (EPA IRIS 2013).
  - The Agency for Toxic Substances and Disease Registry (ATSDR) has established minimal risk levels (MRLs) for inhalation exposure to 1,4-dioxane : 2 parts per million (ppm) for acute-duration (14 days or less) inhalation exposure; 0.2 ppm for intermediate-duration (15 to 364 days) inhalation exposure; and 0.03 ppm for chronic-duration (365 days or more) inhalation exposure (ATSDR 2012).
  - Oral exposure MRLs have been identified as 5 mg/kg/day for acute-duration oral exposure; 0.5 mg/kg/day for intermediate-duration oral exposure; and 0.1 mg/kg/day for chronic-duration oral exposure (ATSDR 2012).
  - The cancer risk assessment for 1,4-dioxane is based on an oral slope factor of 0.1 mg/kg/day and the drinking water unit risk is 2.9×10^{-6} micrograms per liter (µg/L) (EPA IRIS 2013).
  - EPA risk assessments indicate that the drinking water concentration representing a 1×10^{-6} cancer risk level for 1,4-dioxane is 0.35 µg/L (EPA IRIS 2013).
  - 1,4-Dioxane may be regulated as hazardous waste when waste is generated through use as a solvent stabilizer (EPA 1996b).
  - No federal maximum contaminant level (MCL) for drinking water has been established; however, an MCL is not necessary to determine a cleanup level (EPA 2012).
  - 1,4-Dioxane was included on the third drinking water contaminant candidate list, which is a list of unregulated contaminants that are known to, or anticipated to, occur in public water systems and may require regulation under the Safe Drinking Water Act (EPA 2009).

Are there any federal and state guidelines and health standards for 1,4-dioxane? (continued)

- Federal and State Standards and Guidelines (continued):
  - The EPA has established drinking water health advisories for 1,4-dioxane, which are drinking water-specific risk level concentrations for cancer (10^{-4} cancer risk) and concentrations of drinking water contaminants at which noncancer adverse health effects are not anticipated to occur over specific exposure durations. The EPA established a 1-day health advisory of 4.0 milligrams per liter (mg/L) and a 10-day health advisory of 0.4 mg/L for 1,4-dioxane in drinking water for a 10-kilogram child. EPA also established a lifetime health advisory of 0.2 mg/L for 1,4-dioxane in drinking water (EPA 2012).
  - The EPA's drinking water equivalent level for 1,4-dioxane is 1 mg/L (EPA 2012).
  - EPA has calculated a screening level of 0.67 µg/L for 1,4-dioxane in tap water, based on a 1 in 10^{-6} lifetime excess cancer risk (EPA 2013c). [1, 2]
  - EPA has calculated a residential soil screening level (SSL) of 4.9 milligrams per kilogram (mg/kg) and an industrial SSL of 17 mg/kg. The soil-to-groundwater risk-based SSL is 1.4 x10^{-4} mg/kg (EPA 2013c).
  - EPA has also calculated a residential air screening level of 0.49 micrograms per cubic meter (µg/m^3) and an industrial air screening level of 2.5 µg/m^3 (EPA 2013c).

- Workplace Exposure Limits:
  - The Occupational Safety and Health Administration set a general industry permissible exposure limit of 360 mg/m^3 or 100 ppm based on a time-weighted average (TWA) over an 8-hour workday for airborne exposure to 1,4-dioxane (OSHA 2013).
  - The ACGIH set a threshold limit value of 72 mg/m^3 or 20 ppm based on a TWA over an 8-hour workday for airborne exposure to 1,4-dioxane (ACGIH 2011).
  - The NIOSH has set a ceiling recommended exposure limit of 3.6 mg/m^3 or 1 ppm based on a 30-minute airborne exposure to 1,4-dioxane (NIOSH 2010).
  - NIOSH also has established an immediately dangerous to life or health concentration of 500 ppm for 1,4-dioxane (NIOSH 2010).
- Other State and Federal Standards and Guidelines:
  - Various states have established drinking water and groundwater guidelines, including the following:
    - Colorado has established an interim groundwater quality cleanup standard of 0.35 µg/L (CDPHE 2012);
    - California has established a notification level of 1 µg/L for drinking water (CDPH 2011);
    - New Hampshire has established a reporting limit of 0.25 µg/L for all public water supplies (NH DES 2011); and
    - Massachusetts has established a drinking water guideline level of 0.3 µg/L (Mass DEP 2012).
  - The Food and Drug Administration set 10 mg/kg as the limit for 1-4-dioxane in glycerides and polyglycerides for use in products such as dietary supplements. FDA also surveys raw material and products contaminated with 1,4-dioxane (FDA 2006).
  - 1,4-Dioxane is listed as a hazardous air pollutant under the Clean Air Act (CAA) (CAA 1990).
  - A reportable quantity of 100 pounds has been established under the Comprehensive Environmental Response, Compensation, and Liability Act (EPA 2011).

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[1] Screening Levels are developed using risk assessment guidance from the EPA Superfund program. These risk-based concentrations are derived from standardized equations combining exposure information assumptions with EPA toxicity data. These calculated screening levels are generic and not enforceable cleanup standards but provide a useful gauge of relative toxicity.

[2] Tap water screening levels differ from the IRIS drinking water concentrations because the tap water screening levels account for dermal, inhalation and ingestion exposure routes; age-adjust the intake rates for children and adults based on body weight; and time-adjust for exposure duration or days per year. The IRIS drinking water concentrations consider only the ingestion route, account only for adult-intake rates and do not time-adjust for exposure duration or days per year.

What detection and site characterization methods are available for 1,4-dioxane?

- As a result of the limitations in the analytical methods to detect 1,4-dioxane, it has been difficult to identify its occurrence in the environment. The miscibility of 1,4-dioxane in water causes poor purging efficiency and results in high detection limits (ATSDR 2012; EPA 2006).
- Conventional analytical methods can detect 1,4-dioxane only at concentrations 100 times greater than the concentrations of volatile organic compounds (EPA 2006; Mohr 2001).
- Modifications of existing analytical methods and their sample preparation procedures may be needed to achieve lower detection limits for 1,4-dioxane (EPA 2006; Mohr 2001).
- High-temperature sample preparation techniques improve the recovery of 1,4-dioxane. These techniques include purging at elevated temperature (EPA SW-846 Method 5030); equilibrium headspace analysis (EPA SW-846 Method 5021); vacuum distillation (EPA SW-846 Method 8261); and azeotrophic distillation (EPA SW-846 Method 5031) (EPA 2006).
- The presence of 1,4-dioxane may be expected at sites with extensive TCA contamination; therefore, some experts recommend that groundwater samples be analyzed for 1,4-dioxane where TCA is a known contaminant (Mohr 2001).
- NIOSH Method 1602 uses gas chromatography – flame ionization detection (GC-FID) to determine the concentration of 1,4-dioxane in air. The detection limit is 0.01 milligram per sample (ATSDR 2012; NIOSH 2010).
- EPA SW-846 Method 8015D uses gas chromatography (GC) to determine the concentration of 1,4-dioxane in environmental samples. Samples may be introduced into the GC column by a variety of techniques including the injection of the concentrate from azeotropic distillation (EPA SW-846 Method 5031). The detection limits for 1,4-dioxane in aqueous matrices by azeotropic microdistillation are 12 µg/L (reagent water), 15 µg/L (groundwater) and 16 µg/L (leachate) (EPA 2003).
- EPA SW-846 Method 8260B detects 1,4-dioxane in a variety of solid waste matrices using GC and mass spectrometry (MS). The detection limit depends on the instrument and choice of sample preparation method (ATSDR 2012; EPA 1996a).
- A laboratory study is underway to develop a passive flux meter (PFM) approach to enhance the capture of 1,4-dioxane in the PFM sorbent to improve accuracy. The selected PFM approach will be field tested at 1,4-dioxane contaminated sites. The anticipated projection completion date is 2014 (DoD SERDP 2013b).
- EPA Method 1624 uses isotopic dilution gas chromatography – mass spectrometry (GC-MS) to detect 1,4-dioxane in water, soil and municipal sludges. The detection limit for this method is 10 µg/L (ATSDR 2012; EPA 2001b).
- EPA SW-846 Method 8270 uses liquid-liquid extraction and isotope dilution by capillary column GC-MS. This method is often modified for the detection of low levels of 1,4-dioxane in water (EPA 2007, 2013a)
- GC-MS detection methods using solid phase extraction followed by desorption with an organic solvent have been developed to remove 1,4-dioxane from the aqueous phase. Detection limits as low as 0.024 µg/L have been achieved by passing the aqueous sample through an activated carbon column, following by elution with acetone-dichlormethane (ATSDR 2012; Kadokami and others 1990).
- EPA Method 522 uses solid phase extraction and GC/MS with selected ion monitoring for the detection of 1,4-dioxane in drinking water with detection limits ranging from 0.02 to 0.026 µg/L (EPA 2008).

What technologies are being used to treat 1,4-dioxane?

- Pump-and-treat remediation can treat dissolved 1,4-dioxane in groundwater and control groundwater plume migration, but requires ex situ treatment tailored for the unique properties of 1,4-dioxane (such as, a low octanol-water partition coefficient that makes 1,4-dioxane hydrophilic) (EPA 2006; Kiker and others 2010).
- Commercially available advanced oxidation processes using hydrogen peroxide with ultraviolet light or ozone is used to treat 1,4-dioxane in wastewater (Asano and others 2012; EPA 2006).
- A study is under way to investigate facilitated-transport enabled in situ chemical oxidation to treat 1,4-dioxane-contamined source zones and groundwater plumes effectively. The technical approach consists of the co-injection of strong oxidants (such as ozone) with chemical agents that facilitate the transport of the oxidant (DoD SERDP 2013d).

What technologies are being used to treat 1,4-dioxane? (continued)

- Ex situ bioremediation using a fixed-film, moving-bed biological treatment system is also used to treat 1,4-dioxane in groundwater (EPA 2006).
- Phytoremediation is being explored as a means to remove the compound from shallow groundwater. Pilot-scale studies have demonstrated the ability of hybrid poplars to take up and effectively degrade or deactivate 1,4-dioxane (EPA 2001a, 2013a; Ferro and others 2013).
- Microbial degradation in engineered bioreactors has been documented under enhanced conditions or where selected strains of bacteria capable of degrading 1,4-dioxane are cultured, but the impact of the presence of chlorinated solvent co-contaminants on biodegradation of 1,4-dioxane needs to be further investigated (EPA 2006, 2013a; Mahendra and others 2013).
- Results from a 2012 laboratory study found 1,4-dioxane-transforming activity to be relatively common among monooxygenase-expressing bacteria; however, both TCA and 1,1-dichloroethene inhibited 1,4-dioxane degradation by bacterial isolates (DoD SERDP 2012).
- Several Department of Defense Strategic Environmental Research and Development Program (DoD SERDP) projects are under way to investigate 1,4-dioxane biodegradation in the presence of chlorinated solvents or metals. Laboratory studies will (1) identify microbial cultures as well as biogeochemistry, which generate desirable enzymatic activity for 1,4-dioxane biodegradation; (2) assess biodegradation by methane oxidizing bacteria in coupled anaerobic-aerobic zones; (3) and evaluate branched hydrocarbons as stimulants for the in situ cometabolic biodegradation of 1,4-dioxane and its associated co-contaminants (DoD SERDP 2013c, e and f).
- Photocatalysis has been shown to remove 1,4-dioxane in aqueous solutions. Laboratory studies documented that the surface plasmon resonance of gold nanoparticles on titanium dioxide (Au – TiO_2) promotes the photocatalytic degradation of 1,4-dioxane (Min and others 2009; Vescovi and others 2010).
- Other in-well combined treatment technologies being assessed include air sparging; soil vapor extraction (SVE); and dynamic subsurface groundwater circulation (Odah and others 2005).
- SVE is known to remove some 1,4-dioxane, but substantial residual contamination is usually left behind because of 1,4-dioxane's high solubility, which leads to preferential partitioning into pore water rather than vapor. The DoD SERDP is conducting a project to evaluate and demonstrate the efficacy of enhanced or extreme SVE, which uses a combination of increased air flow, sweeping with drier air, increased temperature, decreased infiltration and more focused vapor extraction to enhance 1,4-dioxane remediation in soils (DoD SERDP 2013a).

Where can I find more information about 1,4-dioxane?

- Asano, M., Kishimoto, N., Shimada, H., and Y. Ono. 2012. "Degradation of 1,4-Dioxane Using Ozone Oxidation with UV Irradiation (Ozone/UV) Treatment." Journal of Environmental Science and Engineering. Volume A (1). Pages 371 to 279.
- Agency for Toxic Substances and Disease Registry (ATSDR). 2012. "Toxicological Profile for 1,4-Dioxane." www.atsdr.cdc.gov/toxprofiles/tp187.pdf
- American Conference of Governmental Industrial Hygienists (ACGIH). 2011. "2011 Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents Biological Exposure Indices." Cincinnati, Ohio.
- California Department of Public Health (CDPH). 2011. "1,4-Dioxane." Drinking Water Systems. www.cdph.ca.gov/certlic/drinkingwater/Pages/1,4-dioxane.aspx
- Clean Air Act Amendments of 1990 (CAA). 1990. "Hazardous Air Pollutants". 42 USC § 7412.
- Colorado Department of Public Health and the Environment (CDPHE). 2012. "Notice of Public Rulemaking Hearing before the Colorado Water Quality Control Commission." Regulation No. 31 and No. 41. www.sos.state.co.us/CCR/Upload/NoticeOfRulemaking/ProposedRuleAttach2012-00387.PDF
- Ferro, A.M., Kennedy, J., and J.C. LaRue. 2013. "Phytoremediation of 1,4-Dioxane-Containing Recovered Groundwater." International Journal of Phytoremediation. Volume 15. Pages 911 to 923.
- Giavini, E., Vismara, C., and M.L Broccia. 1985. "Teratogenesis Study of Dioxane in Rats." Toxicology Letters. Volume 26 (1). Pages. 85 to 88.

Where can I find more information about 1,4-dioxane? (continued)

- Graedel, T.E. 1986. Atmospheric Chemical Compounds. New York, NY: Academic Press.
- Hazardous Substances Data Bank (HSDB). 2011. "1,4-Dioxane." http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB
- HazDat. 2007. "1,4-Dioxane." HazDat Database: ATSDR's Hazardous Substance Release and Health Effects Database. Atlanta, GA: Agency for Toxic Substances and Disease Registry.
- Howard, P.H. 1990. Handbook of Environmental Fate and Exposure Data for Organic Chemicals. Lewis Publishers, Inc., Chelsea, MI. Pages 216 to 221.
- Kadokami, K, Koga, M. and A. Otsuki. 1990. "Gas Chromatography/Mass Spectrometric Determination of Traces of Hydrophilic and Volatile Organic Compounds in Water after Preconcentration with Activated Carbon." Analytical Sciences. Volume 6(6). Pages 843 to 849.
- Kiker, J.H., Connolly, J.B., Murray, W.A., Pearson, S.C.; Reed, S.E., and R.J. Robert. 2010. "Ex-Situ Wellhead Treatment of 1,4-Dioxane Using Fenton's Reagent." Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy. Volume 15, Article 18.
- Mahendra, S., Grostern, A. and L. Alvarez-Cohen. 2013. "The Impact of Chlorinated Solvent Co-Contaminants on the Biodegradation Kinetics of 1,4-Dioxane." Chemosphere. Volume 91 (1). Pages 88 to 92.
- Massachusetts Department of Environmental Protection (Mass DEP). 2012. "Standards and Guidelines for Contaminants in Massachusetts Drinking Waters." www.mass.gov/dep/water/dwstand.pdf
- Min, B.K., Heo, J.E., Youn, N.K., Joo, O.S., Lee, H., Kim, J.H., and H.S. Kim. 2009. "Tuning of the Photocatalytic 1,4-Dioxane Degradation with Surface Plasmon Resonance of Gold Nanoparticles on Titania." Catalysis Communications. Volume 10 (5). Pages 712 to 715.
- Mohr, T.K.G. 2001. "1,4-Dioxane and Other Solvent Stabilizers White Paper." Santa Clara Valley Water District of California. San Jose, California.
- National Institute for Occupational Safety and Health (NIOSH). 2010. "Dioxane." NIOSH Pocket Guide to Chemical Hazards. www.cdc.gov/niosh/npg/npgd0237.html
- New Hampshire Department of Environmental Services (NH DES). 2011 "Change in Reporting Limit for 1,4-Dioxane." http://des.nh.gov/organization/divisions/waste/hwrb/sss/hwrp/documents/report-limits14dioxane.pdf
- Occupational Safety and Health Administration (OSHA). 2013. "Dioxane." Chemical Sampling Information. www.osha.gov/dts/chemicalsampling/data/CH_237200.html
- Odah, M.M., Powell, R., and D.J. Riddle. 2005. "ART In-Well Technology Proves Effective in Treating 1,4-Dioxane Contamination." Remediation Journal. Volume 15 (3), Pages 51 to 64.
- U.S. Department of Defense (DoD). Strategic Environmental Research and Development Program (SERDP). 2012. "Oxygenase-Catalyzed Biodegradation of Emerging Water Contaminants: 1,4-Dioxane and N-Nitrosodimethylamine." ER-1417. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-1417/ER-1417
- DoD SERDP. 2013a. "1,4-Dioxane Remediation by Extreme Soil Vapor Extraction (XSVE)." ER-201326. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-201326/ER-201326
- DoD SERDP. 2013b. "Development of a Passive Flux Meter Approach to Quantifying 1,4-Dioxane Mass Flux." ER-2304. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2304/ER-2304/
- DoD SERDP. 2013c. "Evaluation of Branched Hydrocarbons as Stimulants for In Situ Cometabolic Biodegradation of 1,4-Dioxane and Its Associated Co-Contaminants." ER-2303. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2303/ER-2303
- DoD SERDP. 2013d. "Facilitated Transport Enabled In Situ Chemical Oxidation of 1,4-Dioxane-Contaminated Groundwater." ER-2302. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2302/ER-2302/(language)/eng-US
- DoD SERDP. 2013e. "In Situ Biodegradation of 1,4-Dioxane: Effects of Metals and Chlorinated Solvent Co-Contaminants." ER-2300. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2300/ER-2300

Where can I find more information about 1,4-dioxane? (continued)

- DoD SERDP. 2013f. "In Situ Bioremediation of 1,4-Dioxane by Methane Oxidizing Bacteria in Coupled Anaerobic-Aerobic Zones." ER-2306. www.serdp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2306/ER-2306
- U.S. Department of Health and Human Services (DHHS). 2011. "Report on Carcinogens, Twelfth Edition." Public Health Service, National Toxicology Program. 12th Edition. http://ntp.niehs.nih.gov/ntp/roc/twelfth/roc12.pdf
- U.S. Environmental Protection Agency (EPA). 1996a. "Method 8260B: Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS)." www.epa.gov/osw/hazard/testmethods/sw846/pdfs/8260b.pdf
- EPA. 1996b. "Solvents Study." EPA 530-R-96-017.
- EPA. 2001a. "Brownfields Technology Primer: Selecting and Using Phytoremediation for Site Cleanup." EPA 542-R-01-006. www.brownfieldstsc.org/pdfs/phytoremprimer.pdf
- EPA. 2001b. "Method 1624." Code of Federal Regulations. Code of Federal Regulations. 40 CFR Part 136. Pages 274 to 287.
- EPA. 2003. "Method 8015D: Nonhalogenated Organics Using GC/FID." SW-846. www.epa.gov/osw/hazard/testmethods/pdfs/8015d_r4.pdf
- EPA. 2006. "Treatment Technologies for 1,4-Dioxane: Fundamentals and Field Applications." EPA 542-R-06-009. www.epa.gov/tio/download/remed/542r06009.pdf
- EPA. 2007. "Method 8270D: Semivolatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS)."
- EPA. 2008. "Method 522: Determination of 1,4-Dioxane in Drinking Water By Solid Phase Extraction (SPE) and Gas Chromatography/Mass Spectrometry (GC/MS) with Selected Ion Monitoring (SIM)." EPA/600/R-08/101.
- EPA. 2009. "Drinking Water Contaminant Candidate List 3 – Final." Federal Register Notice. www.federalregister.gov/articles/2009/10/08/E9-24287/drinking-water-contaminant-candidate-list-3-final
- EPA. 2011. "Reportable Quantities of Hazardous Substances Designated Pursuant to Section 311 of the Clean Water Act. Code of Federal Regulations." 40 CFR 302.4. www.gpo.gov/fdsys/pkg/CFR-2011-title40-vol28/pdf/CFR-2011-title40-vol28-sec302-4.pdf
- EPA. 2012. "2012 Edition of Drinking Water Standards and Health Advisories." water.epa.gov/action/advisories/drinking/upload/dwstandards2012.pdf
- EPA. 2013a. "1,4-Dioxane." www.clu-in.org/contaminantfocus/default.focus/sec/1,4-Dioxane/cat/Overview/
- EPA. 2013b. "1,4-Dioxane (1,4-Diethyleneoxide)." Technology Transfer Network Air Toxics Website. www.epa.gov/ttnatw01/hlthef/dioxane.html
- EPA. 2013c. Regional Screening Level (RSL) Summary Table. www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/index.htm
- EPA. Integrated Risk Information System (IRIS). 2013. "1,4-Dioxane (CASRN 123-91-1)." www.epa.gov/iris/subst/0326.htm
- U.S. Food and Drug Administration (FDA). 2006. "Food Additives Permitted for Direct Addition to Food for Human Consumption; Glycerides and Polyglycides." Code of Federal Regulations. 21 CFR 172.736.
- Vescovi, T., Coleman, H., and R. Amal. 2010. "The Effect of pH on UV-Based Advanced Oxidation Technologies - 1,4-Dioxane Degradation." Journal of Hazardous Materials. Volume 182. Pages 75 to 79.

Additional information on 1,4-dioxane can be found at www.cluin.org/contaminantfocus/default.focus/sec/1,4-Dioxane/cat/Overview

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