Technical Memorandum

TO: Mr. Chris Wend, Washington State Department of Ecology

FROM: Ben Lee, PE, and Piper Roelen, PE, Landau Associates, Inc.; Joan Davenport, City of Yakima

DATE: April 16, 2019

RE: **Final – Groundwater/Surface Water Interaction**
Closed City of Yakima Landfill Site
Yakima, Washington
1148008.040.042

Landau Associates, Inc. (LAI) has prepared the following technical memorandum on behalf of the City of Yakima (City) to describe the interaction of groundwater with the surface water of the Yakima River downgradient of the closed City of Yakima Landfill Site (Landfill Site) located in Yakima, Washington (Figure 1). This memorandum was prepared pursuant to Section VII and Exhibit C of Agreed Order (AO) No. 15861. The Landfill Site is located in the City of Yakima, Washington at the southern end of the former Boise Cascade Mill and Plywood Facility (Mill Facility; Figure 2).

Site Background

The Landfill Site is located on the eastern edge of the City. The Interstate 82 (I-82) right-of-way (ROW) is located to the east of the Landfill Site, and the Yakima River (river) is proximate to the east of I-82. The Landfill Site is at the southern end of the approximately 207-acre Mill Facility, and south of BNSF Railway Company-owned ROW with railroad tracks that run in an east-west orientation. The closed municipal solid waste (MSW) Landfill Site was operated by the City between approximately 1963 and 1970. As part of landfill operations, MSW was placed in a former log pond that originally occupied the site (City of Yakima 1996). When landfill operations ceased, the MSW was covered and the area brought to grade with a mixture of fill soil and wood debris. The Landfill Site was then used until 2010 as a log yard, including temporary log storage and log chipping operations.

Based on prior investigations, including the interim remedial investigation (RI; LAI 2015a) and supplemental RI investigations (LAI 2015b), the subsurface conditions at the site are generally characterized by the presence of buried wood debris associated with the historic mill activities, and MSW deposited at the site during the landfill's operational years. Extensive soil and groundwater investigations have been conducted to evaluate the presence of a wide variety of contaminants.

Screening has eliminated all but dissolved metals (arsenic, iron, manganese, and sodium), nitrate, pH, and vinyl chloride in groundwater as contaminants of concern (COCs). Nitrate and vinyl chloride were detected above the most conservative screening levels in only one monitoring well each and only during one quarter of groundwater sampling. These are, therefore, not indicative of site-wide groundwater conditions. Further, they are not considered indicator hazardous substances for the

Landfill Site. Dissolved metals are primarily present in groundwater due to the reducing conditions associated with degradation of wood debris and organic materials in the MSW.

Groundwater/Surface Water Interaction Evaluation

The City is required to evaluate the interaction between groundwater downgradient of the former landfill and the surface water of the Yakima River. This evaluation includes describing seasonal variations and chemical and physical characteristics of groundwater as it approaches the groundwater/surface water interface. The evaluation ultimately describes water parameters at potential groundwater discharges to the river.

The following sections provide details on the methodology and results of the evaluation of the interaction between groundwater downgradient of the former landfill and the surface water of the Yakima River. This evaluation is based on existing groundwater and surface water elevation data and groundwater quality data at and near the Landfill Site. LAI evaluated the data using generally accepted groundwater modeling techniques.

Seasonal Evaluation of Groundwater Discharge to River

The groundwater/surface water evaluation assesses the annual periods when the river is gaining or losing groundwater. The AO obligates the City to use this information to assess the chemical and physical characteristics of the groundwater as it approaches the interface (see AO Exhibit C). Using groundwater and surface water elevation data collected in 2014 and 2015 during the remedial investigation (see Figure 3 and Attachment 1), and geologic information collected from various Mill Facility and Landfill Site exploration activities, a geologic and hydraulic cross-section (Figure 4) was created through the Landfill Site along the direction of groundwater flow, which is generally to the southeast toward the river (Figure 3 shows the cross-section location). Cross-sectional groundwater table surfaces were created using seasonal high and low groundwater and surface water elevation data (from September 2014 and March 2015) to evaluate variation in groundwater discharge to or from the river (see Figure 4).

The groundwater table elevations and gradients (shown on the cross section) show:

- Groundwater elevations are generally highest in late summer/early fall and lowest in the late winter/early spring; and
- Conversely, river elevations are generally lowest late summer/early fall and highest in late winter/early spring.

This is consistent with many areas of the Yakima valley. Dry season irrigation tends to raise groundwater elevations and river flows are typically lower, due to lower levels of precipitation and snow melt in the mountains. River elevations are typically higher in the wet season when there are higher levels of precipitation and snow melt in the mountains and groundwater tables are lower without wide-spread regional irrigation. Attachment 2 includes historical weather and precipitation data for Yakima for the same four months when groundwater and surface water elevations were collected (September and December 2014; March and June 2015).

The groundwater table elevation and gradient data shown on the cross section also show that the river adjacent to the Landfill Site consistently gains groundwater throughout the year. This general condition is, therefore, assumed for additional evaluation and modeling of groundwater/surface water interaction in the Geochemical Modeling sections below.

Evaluation of Groundwater Redox Conditions

Groundwater quality data from within and downgradient of the Mill Facility/Landfill Site collected during the RI includes reduction/oxidation (redox)-related groundwater data: measurements and analysis of dissolved oxygen (DO), oxidation reduction potential (ORP), total organic carbon (TOC), nitrate, sulfate, and dissolved arsenic, iron, and manganese. Redox indicator data from June 2015 groundwater monitoring is included in Figure 5.

Low concentrations or values of DO, ORP, nitrate, and sulfate, and relatively high concentrations of TOC and dissolved arsenic, iron, and manganese all indicate that groundwater under the Landfill Site and Mill Facility is in a reduced/anaerobic condition. This is typical of the redox conditions of groundwater in areas where soil and/or groundwater contain high organic carbon content, such as in wetlands, peat bogs, log yard material storage areas, and unlined landfills and composting facilities, which create a naturally high oxygen demand, resulting in reducing conditions.

Data from cross-gradient of the Landfill Site is assumed to be representative of background conditions. The cross-gradient data indicates that groundwater outside of the Mill Facility/Landfill Site (i.e., where redox conditions are not impacted by the presence of MSW and wood debris) is naturally more aerobic/oxidizing. For example, data from monitoring wells MW-9A, MW-100, and MW-109 (the first located upgradient and the others located cross-gradient of the landfill boundaries) show DO and ORP levels indicative of aerobic conditions, and much lower dissolved metals concentrations are present as compared to locations within the landfill boundaries. Data from downgradient of the Landfill Site indicate that groundwater becomes gradually less reducing (more aerobic) the farther downgradient from the Landfill Site data is collected. For example, June 2015 data from monitoring wells MW-106, MW-8, MW-17, and MW-14 (located roughly and sequentially along a groundwater flow path from within the landfill boundary to a downgradient location near the banks of the Yakima River, respectively) generally indicate sequentially higher DO, ORP, nitrate, and sulfate levels, and decreasing TOC and dissolved metals concentrations (see table below).

Monitoring Well										
MW-8	20	0.14	-109.5	0.047	<0.26	4.3	1,800	24,000	4.1	Strongly Reducing
MW-14	1,750	2.45	38.0	0.25	3.8	0.88	<2.0	<50	<0.45	Moderately Oxidizing

µg/L = micrograms per liter
As = arsenic
DO = dissolved oxygen
Fe(III) = ferrous (soluble) iron
ft = feet
mg/L = milligrams per liter
Mn(II) = soluble manganese
mV = millivolts
n/a = not applicable
NO_3 = nitrate
ORP = oxidation reduction potential
SO_4^{2-} = sulfate
TOC = total organic carbon

The oxidation of reduced groundwater originating from the Mill Facility/Landfill Site is more pronounced in wells adjacent to the river where evidence of reducing conditions significantly declines. For example, data from MW-15 shows relatively low dissolved metals concentrations and the data from MW-14 indicates groundwater has completely reverted to oxidizing conditions. Physical evidence of oxidizing conditions has also been observed at MW-15, where groundwater samples consistently exhibit rust-colored staining, indicating oxidation and precipitation of dissolved iron as groundwater approaches the river. This rapid conversion of redox conditions in groundwater from anaerobic to aerobic in close proximity to the river suggests that these wells are located within the transitional zone/hyporheic zone, where mixing of aerobic surface water interacts with groundwater and results in more rapid oxidation of the groundwater. Due to the rapid oxidation of groundwater in the hyporheic zone, dissolved metals of concern (arsenic, iron, and manganese) will precipitate out and concentrations thereof will be reduced to below regulatory standards and/or background concentrations before discharging to the Yakima River. This phenomenon is discussed and evaluated in greater detail in the Geochemical Modeling sections below.

Geochemical Modeling

To simulate the fate and transport of landfill leachate-impacted groundwater from the site, geochemical modeling was performed using the PHREEQC numerical geochemical model code (Parkhurst and Appelo 2013). This section describes relevant components of the conceptual hydrogeologic model of the site and the numerical modeling performed to represent contaminant transport at the site.

Conceptual Model

The hydrogeologic conceptual model at the site is based on earlier reporting (LAI 2015b). Groundwater flows across the site in a southeastward direction and discharges to the river. The dominant soil layer through which groundwater flows from the site toward the river is characterized as gravelly sand. The hydraulic gradient of groundwater flow across the site is approximately 0.004 feet/foot (ft/ft). Assuming a hydraulic conductivity value of 10 ft/day—within the reported range for gravelly sand—and an effective porosity of 0.25 (Fetter 2001), groundwater seepage velocity across the site is approximately 0.16 ft/day.

As groundwater flows beneath the site, it is mixed with leachate and degrading organic material originating from MSW on the site and wood debris on and upgradient of the site (collectively "leachate"). For the purposes of this modeling, the potential constituents of concern (COCs) include iron, manganese, and arsenic. Once in the groundwater, the COCs likely undergo the contaminant fate and transport processes of advection, dispersion, chemical reaction, and sorption.

As groundwater flows toward the river from the Landfill Site, it likely mixes with transitional zone water originating from the surface water and flowing through relatively permeable deposits in an assumed hyporheic zone adjacent to the river. For the purposes of the current geochemical modeling, the hyporheic zone was assumed to extend at least 150 ft (45 meters [m]) upgradient from the river and the degree of mixing between groundwater and surface water was assumed to vary linearly based on lineal distance from the river. At the river's edge, subsurface water is assumed to be made up primarily of surface water; 75 ft (23 m) from shore, subsurface water is assumed to be a 50-50 mix of groundwater and surface water; 150 ft (45 m) from shore, subsurface water is assumed to be made up primarily of groundwater.[1] As groundwater mixes with the oxygen-rich surface water, oxidizing conditions predominate, leading to chemical oxidation by oxygen of dissolved phases of iron (Fe[II]) and manganese (Mn[III]) to more insoluble phases (Fe[III] and Mn[IV], respectively). Groundwater samples from the hyporheic zone (i.e., monitoring well MW-15) are consistently stained with reddish-brown iron oxides, indicating that oxidation and precipitation of iron occurs within the hyporheic zone. This also suggests that within the hyporheic zone, groundwater redox conditions become completely aerobic (i.e., no longer reducing) resulting in demobilization of metals through sorption and precipitation.

A number of monitoring wells are used to measure groundwater levels and groundwater quality at the site (LAI 2015b). For the purposes of this model, background groundwater quality is assumed to be represented by monitoring well TP-MW-1, which is upgradient of the Landfill Site (and outside of the observed footprint of deposited wood debris on the Mill Facility). Quality of groundwater that is impacted by leachate at the Landfill Site is assumed to be represented by monitoring wells MW-107 and MW-108. Surface water quality of the river is assumed to be represented by river gauge

[1] Based on a linear relationship with distance from the river.

12484500, operated by the US Geological Survey (USGS) upstream of the site at Umtanum. It is assumed that, in the absence of leachate-impacted groundwater, background groundwater would flow into the hyporheic zone, mix with surface water, and eventually discharge to the river. The presence of leachate-impacted groundwater, however, creates the reducing conditions that mobilizes the COCs to the upgradient end of the hyporheic zone, where they are advected, dispersed, oxidized, precipitated, and/or sorbed at varying rates during transport toward the river. Monitoring well MW-15 is located within the assumed hyporheic zone approximately 130 ft (40 m) upgradient from the river and represents groundwater quality that has been transported through a portion of the hyporheic zone.

Dissolved ferrous iron (Fe[II]) oxidizes in the presence of oxygen to ferric iron (Fe[III]), which combines with hydroxide ions to form iron hydroxides, which are highly insoluble in water (Stumm and Lee 1961). Similarly, dissolved manganese (Mn[II]) oxidizes in the presence of oxygen to Mn(IV), which sorbs to iron hydroxide precipitates (Harvey and Fuller 1998; Richard et al. 2013). Dissolved arsenic, typically as arsenite (As[III]) has been shown to sorb strongly to insoluble iron hydroxides (Lowry and Lowry 2002). For the purposes of the current geochemical modeling, it is assumed that the majority of Fe(III) and Mn(IV) precipitates out as iron hydroxides and manganese hydroxides, respectively, and that arsenic sorbs to the iron hydroxides (Darland and Inskeep 1997; Harvey and Fuller 1998; LAI 2006; Lowry and Lowry 2002). Precipitated or sorbed species are assumed to remain in the soil of the hyporheic zone. The remaining dissolved species are assumed to discharge to the river at concentrations below regulatory standards.

Numerical Model

The geochemical model PHREEQC, version 3, was used for geochemical modeling of COCs through the hyporheic zone at the site. The input file used in the model is included in Attachment 3. The PHREEQC database (for iron and manganese species) and the Wateq4 database (for arsenic species) of geochemical constituents and equilibrium phases was used as the basis for the modeling; however, master species for the COCs were redefined and decoupled for chemical oxidation modeling purposes.[2] A 130-ft (40-m) transport column of 40 cells (3.3 ft, or 1 m, per cell) was used for the basis of modeling. The upgradient end of the column was located at the location of MW-15; the downgradient end of the column was located at the river's edge (Figure 6).

Background groundwater quality was defined based on monitoring results from monitoring well TP-MW-1 (LAI 2015b). Surface water quality was defined based on monitoring results from USGS gauge 12484500 (USGS 2017). Initial water quality of model cell 1 was defined based on monitoring results from monitoring well MW-15 (LAI 2015b). Initial water quality in model cells 2 through 40 were assigned by mixing background groundwater with surface water in ratios based on a linear

[2] Following the code used for Example 9 – Kinetic Oxidation of Dissolved Ferrous Iron with Oxygen in the PHREEQC user manual (Parkhurst and Appelo 2013).

relationship with distance from the river. The water quality of inflowing leachate-impacted groundwater was defined based largely on monitoring results from monitoring wells MW-107 and MW-108 but modified slightly (closer to monitoring results from MW-15) such that simulated COC concentrations in model cell 1 generally remained matched to those observed in MW-15 (LAI 2015b).[3] Water quality values applied to the model to represent background groundwater, leachate-impacted groundwater, hyporheic zone groundwater, and surface water are summarized in Table 1.

Following assignment of initial water quality in all model cells, leachate-impacted groundwater was transported into the model column, beginning with the first cell, for a total of 50 transport steps. This is long enough for model cell 1 to reach COC concentrations observed in MW-15 following initial oxidation processes taking place on initial water quality settings. The time step for each transport step was set to be approximately 20 days. This resulted in a seepage velocity of 0.16 ft/day across each model cell. Kinetic oxidation of iron (Fe[II] to Fe[III]) and manganese (Mn[II] to Mn[IV]) was applied to the model based on Stumm and Lee (1961) and Harvey and Fuller (1998), respectively. Arsenic sorption was applied to the model as surface complexation to iron hydroxides based on Dzombak and Morel (1990) and Parkhurst and Appelo (2013). The oxidation rates applied to the model may be conservatively low, as they do not account for COC removal activity other than kinetic reactions, such as microbial-mediated oxidation, that can play a significant role in reducing the dissolved concentrations of the COCs in actual groundwater systems (Singer and Stumm 1970).

Resulting simulated concentrations of dissolved and precipitated/sorbed phases of iron and manganese and dissolved arsenic over distance along the model column are shown on Figure 7. Table 1 summarizes simulated dissolved COC concentrations in model cell 1 (MW-15) and model cell 40 (discharge to river). Simulated dissolved iron, manganese, and arsenic concentrations in model cell 1 approximately match those observed in monitoring well MW-15.

Based on the results of the model described above, simulated groundwater discharge to the river are 680 micrograms per liter (µg/L) iron, <1.0 µg/L manganese, and 0.7 µg/L arsenic.[4] Each is below applicable or relevant and appropriate requirement (ARAR) criteria/screening levels.

Model Limitations

The model described above is a simplification of a complex natural system. Groundwater flow and contaminant transport properties in the natural system may differ from those simulated in the model.

[3] These modifications are justified because the assumed hyporheic zone begins slightly upgradient of model cell 1.

[4] US Environmental Protection Agency freshwater aquatic life criteria for iron = 1,000 µg/L; secondary maximum contaminant level (MCL) for manganese = 50 µg/L; and State of Washington aquatic life criteria (chronic) for arsenic = 190 µg/L and state groundwater background concentration for arsenic = 5 µg/L (Method A).

Conclusions

The following conclusions can be drawn about the interaction of groundwater downgradient of the Landfill Site and the surface water of the Yakima River based on the data and modeling evaluation presented above:

- While seasonal effects to groundwater and surface water elevations are evident based on site data, the stretch of the Yakima River adjacent/proximate to the Landfill Site is a gaining water body all year.
- Groundwater within the Landfill Site is generally found in a reduced state, as generally evidenced by relatively low concentrations/values of DO, ORP, nitrate, and sulfate, and relatively high concentrations of TOC and dissolved arsenic, iron, and manganese. However, groundwater becomes more oxidized farther downgradient from the Landfill Site, and especially as the groundwater enters the hyporheic zone proximate to the river.
- Groundwater modeling indicates that due to the rapid oxidation of groundwater in the hyporheic zone, dissolved metals of concern (i.e., arsenic, iron, and manganese) will precipitate out and concentrations thereof will be reduced to below regulatory standards and/or background concentrations before discharging to the Yakima River.

Limitations

This technical memorandum has been prepared for the exclusive use of the City of Yakima and the Washington State Department of Ecology for specific application to the Closed City of Yakima Landfill Site. No other party is entitled to rely on the information, conclusions, and recommendations included in this document without the express written consent of LAI. Further, the reuse of information, conclusions, and recommendations provided herein for extensions of the project or for any other project, without review and authorization by LAI, shall be at the user's sole risk. LAI warrants that within the limitations of scope, schedule, and budget, our services have been provided in a manner consistent with that level of care and skill ordinarily exercised by members of the profession currently practicing in the same locality under similar conditions as this project. We make no other warranty, either express or implied.

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Attachments: Figure 1. Site Location Map
Figure 2. Site Diagram - Yakima Landfill Site and Mill Site
Figure 3. Site Map and Cross Section Location
Figure 4. Cross Section A-A’
Figure 5. Reduced-Condition Indicator Analyte Results (June 2015)
Figure 6. PHREEQC Model Setup
Figure 7. PHREEQC Results – COC Concentrations Over Distance
Table 1. Groundwater and Surface Water Quality Input Parameters and Model Results
Attachment 1. Groundwater Contour Maps from Supplemental Remedial Investigation
Attachment 2. Yakima Weather Data – Sept. & Dec. 2014 and March & June 2015
Attachment 3. PHREEQC Model Input File

References

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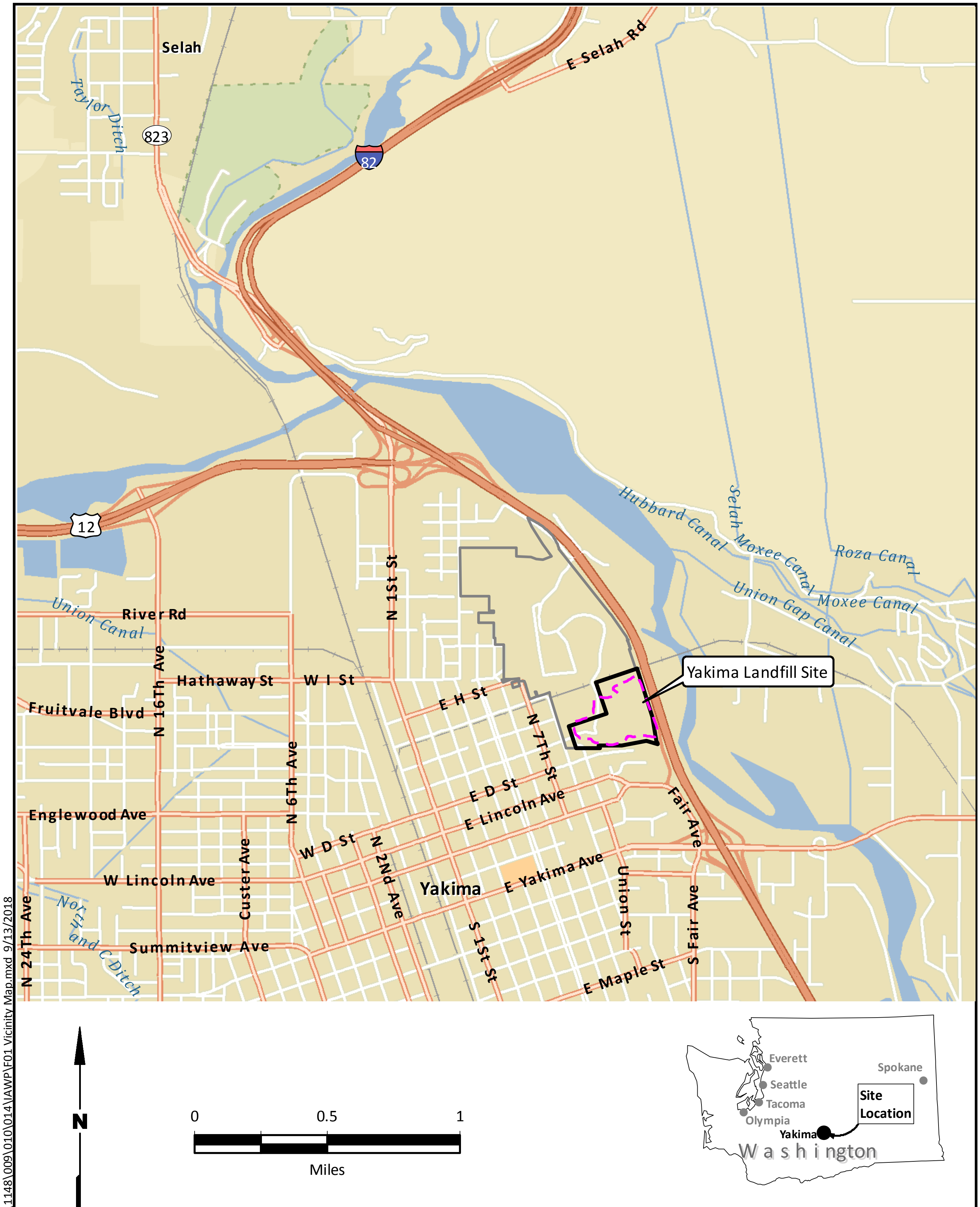

Data Source: Esri 2012

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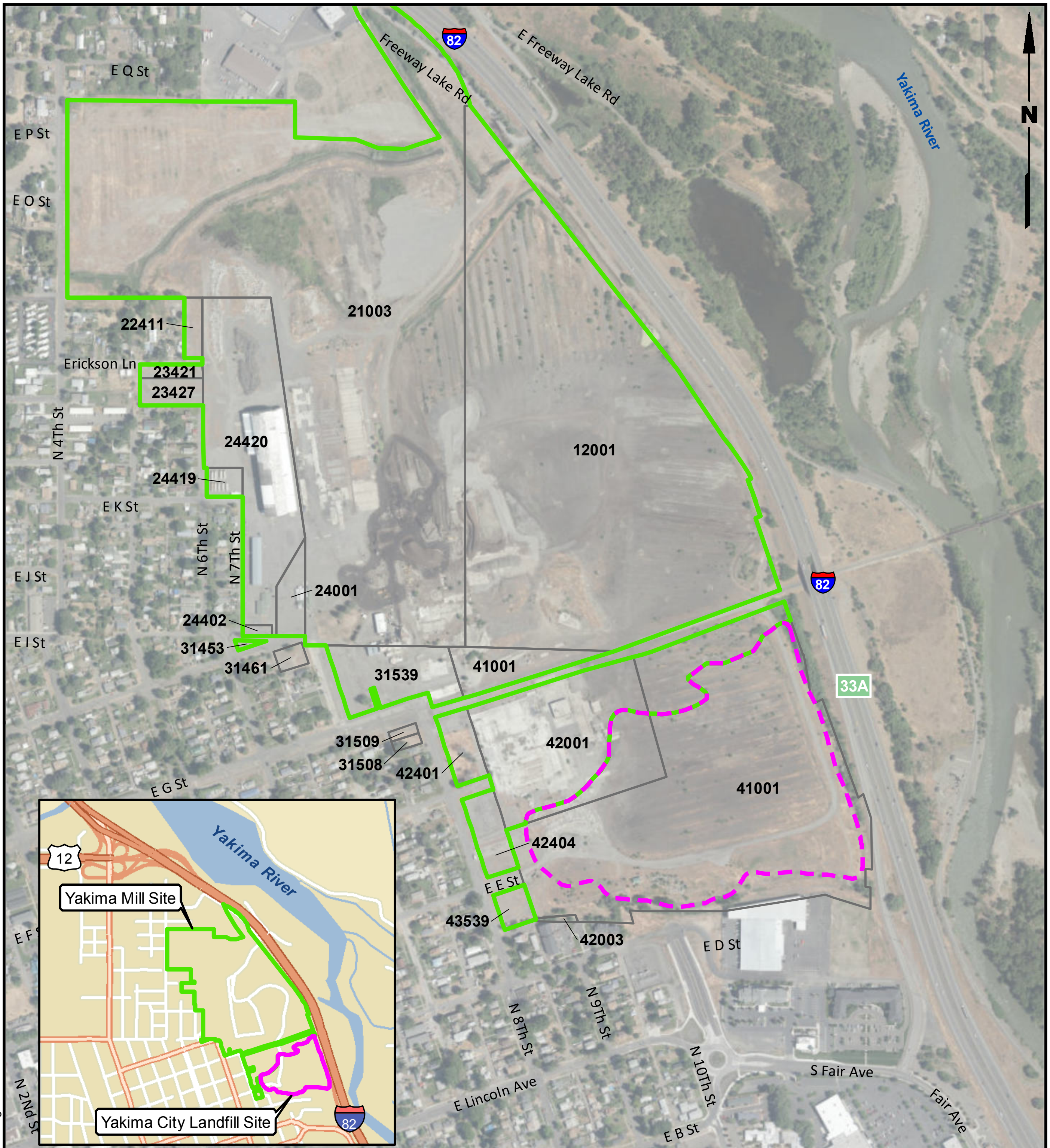
Closed City of Yakima Landfill Site Yakima, Washington	**Vicinity Map**	Figure 1



Legend

Yakima Landfill Site Boundary (AO No. DE 15862)

Yakima Mill Site Boundary (AO No. DE 13959)

Tax Parcels and Parcel Site Number (191318-XXXXX)

Note

1. Black and white reproduction of this color original may reduce its effectiveness and lead to incorrect interpretation.

0 700 1,400

Scale in Feet

Data Source: Yakima County GIS, Esri World Imagery.

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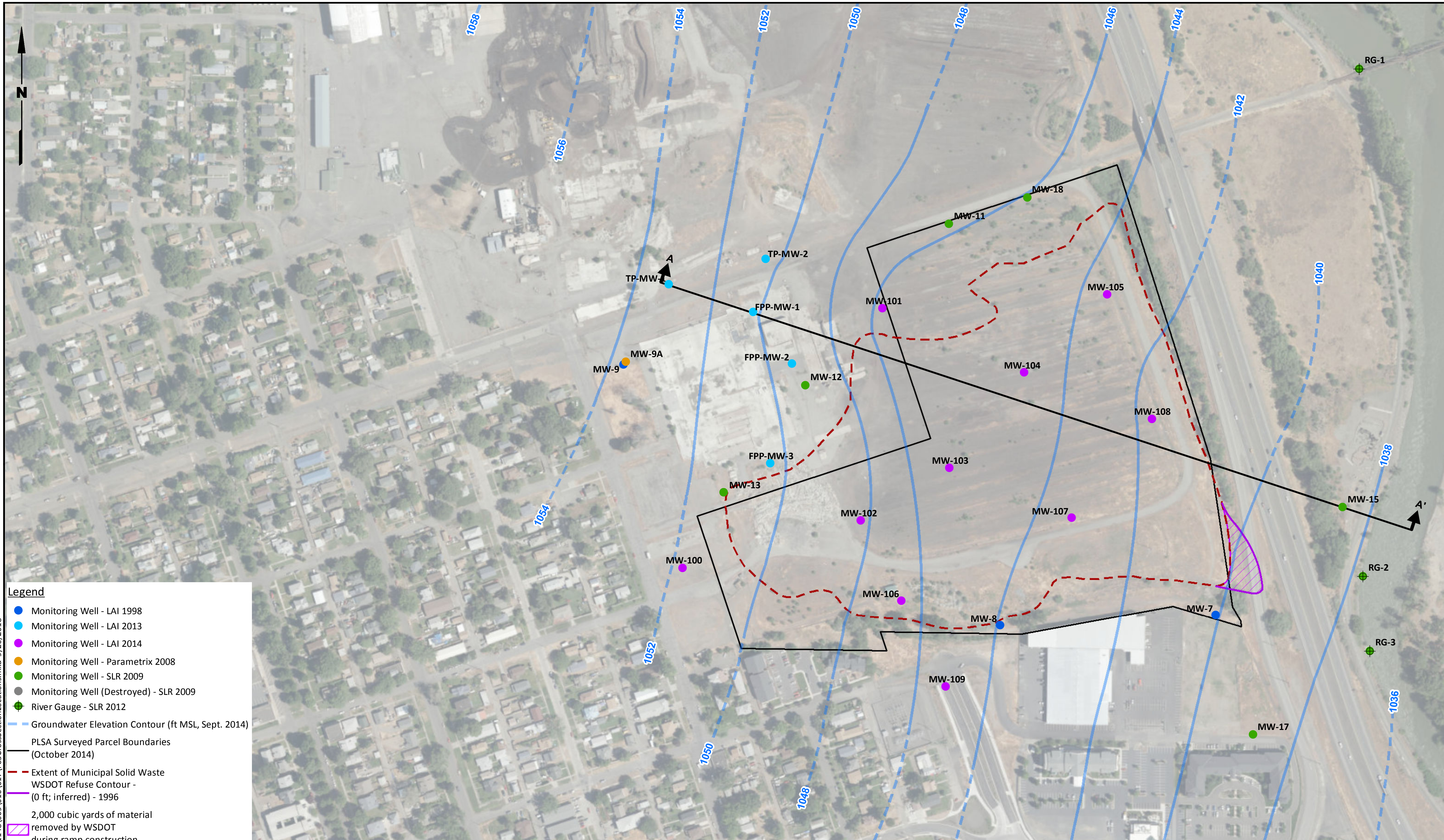
Yakima City Landfill Yakima, Washington	**Site Diagram** **Yakima Landfill Site and Mill Site**	Figure 2



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Data Sources: HLA Engineering and Land Surveying, Inc; SLR; URS; Parametrix; Lochner Engineering; Boise Cascade; Esri World Imagery.

Notes
1. Black and white reproduction of this color original may reduce its effectiveness and lead to incorrect interpretation.

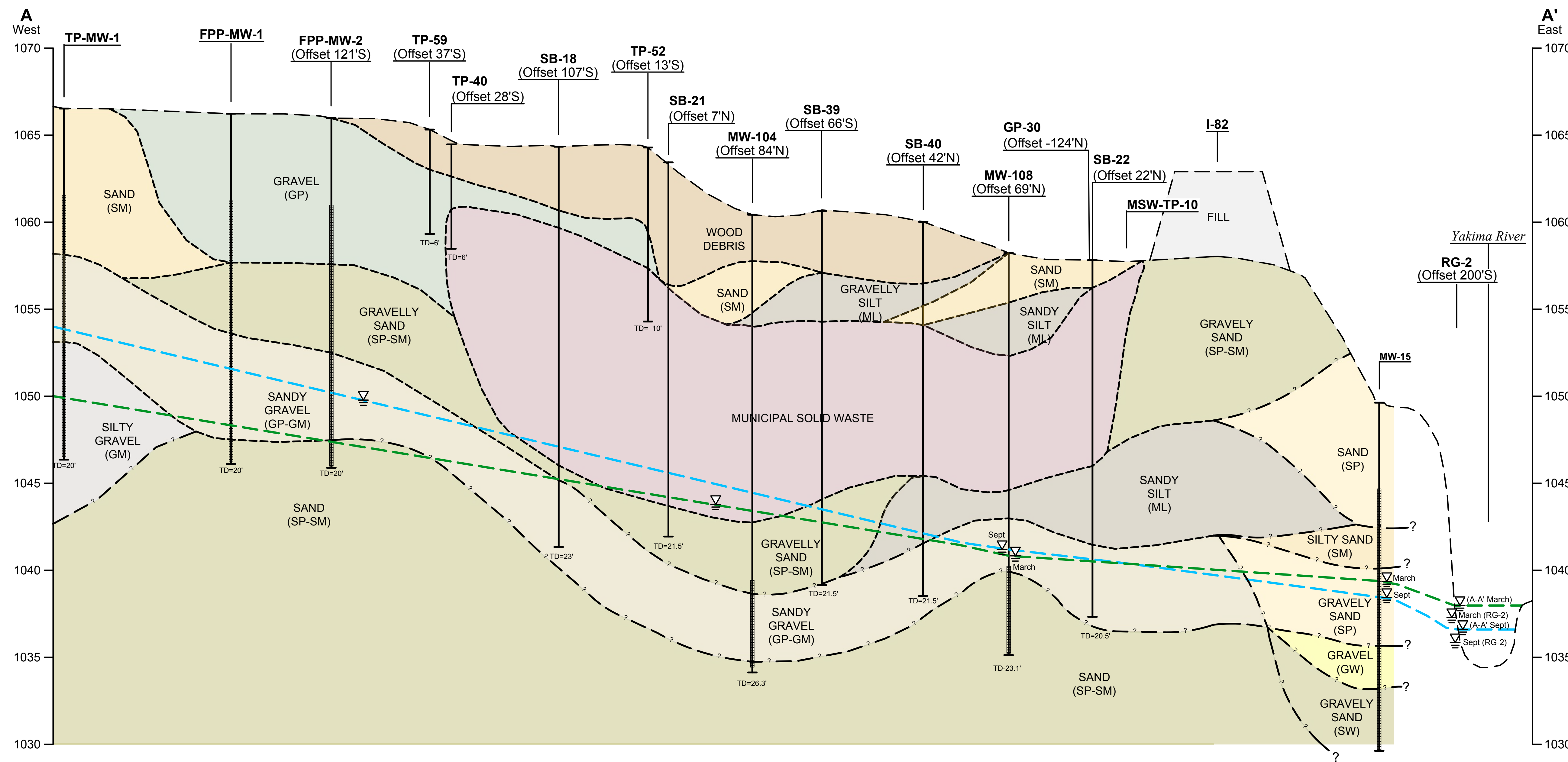
0 300 600
Scale in Feet

Landau Associates

Closed City of Yakima
Landfill Site
Yakima, Washington

Site Map and Cross Section Location

Figure
3



Legend

MW-1 — Project Exploration Designation
(Offset 160' W) — Offset Distance in Feet and Direction
Top of Exploration
Approximate Groundwater Surface, Seasonal High (September 2014)
Approximate Groundwater Surface, Seasonal Low (March 2015)
Inferred Geologic Contact
Well Screen
Bottom of Exploration
TD=14' — Total Depth of Exploration
Inferred Ground Surface
GM — Unified Soil Classification System Symbol

0 200 400
Scale in Feet
30x Vertical

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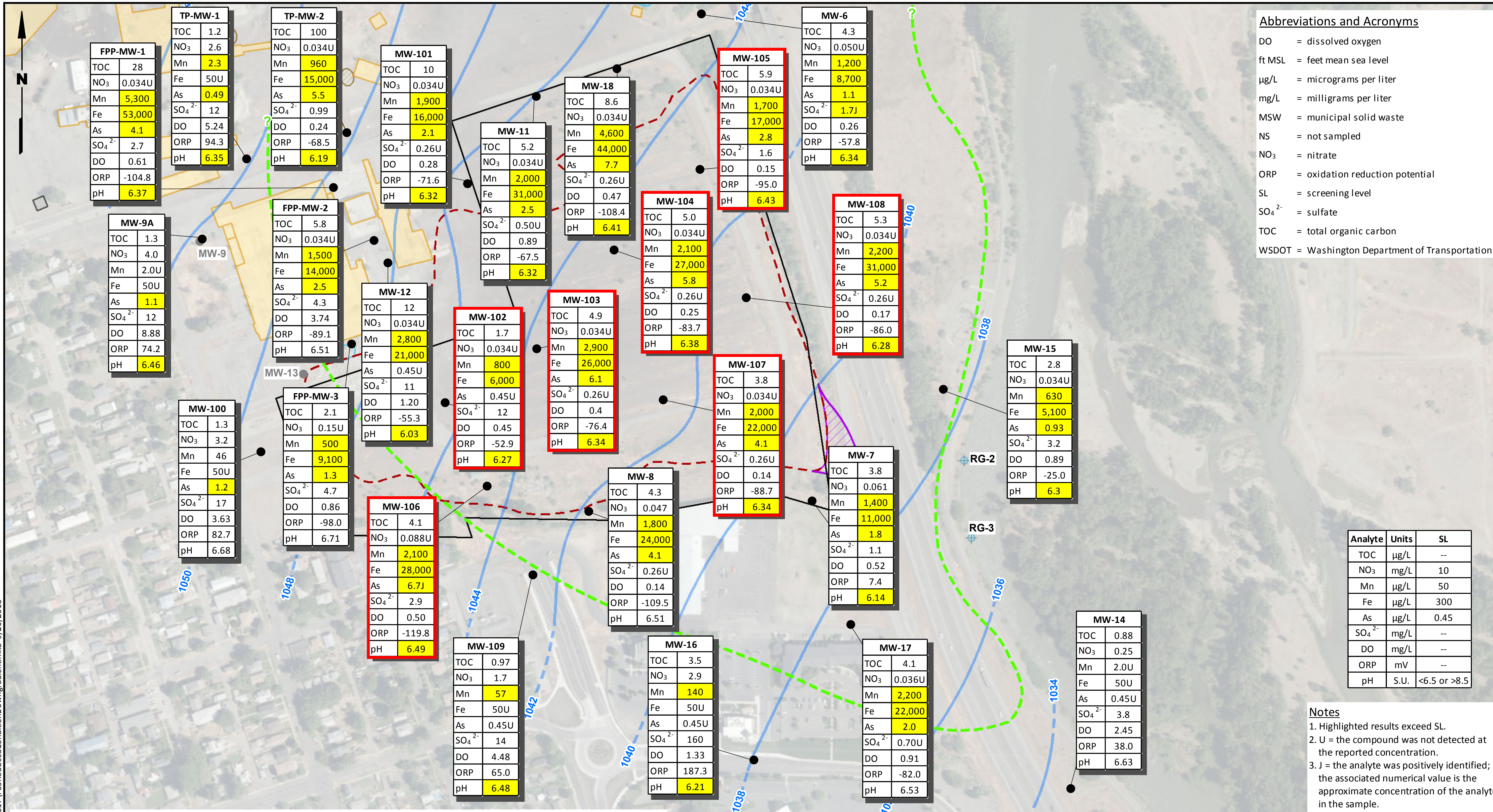
Closed City of Yakima Landfill Site Yakima, Washington	**Cross Section A-A'**	Figure 4



Well	TOC	NO₃	Mn	Fe	As	SO_4^{2-}	DO	ORP	pH
FPP-MW-1	28	0.034U	5,300	53,000	4.1	2.7	0.61	-104.8	6.37
TP-MW-1	1.2	2.6	2.3	50U	0.49	12	5.24	94.3	6.35
TP-MW-2	100	0.034U	960	15,000	5.5	0.99	0.24	-68.5	6.19
MW-101	10	0.034U	1,900	16,000	2.1	0.26U	0.28	-71.6	6.32
MW-18	8.6	0.034U	4,600	44,000	7.7	0.26U	0.47	-108.4	6.41
MW-11	5.2	0.034U	2,000	31,000	2.5	0.50U	0.89	-67.5	6.32
MW-105	5.9	0.034U	1,700	17,000	2.8	1.6	0.15	-95.0	6.43
MW-6	4.3	0.050U	1,200	8,700	1.1	1.7J	0.26	-57.8	6.34
MW-9A	1.3	4.0	2.0U	50U	1.1	12	8.88	74.2	6.46
FPP-MW-2	5.8	0.034U	1,500	14,000	2.5	4.3	3.74	-89.1	6.51
MW-104	5.0	0.034U	2,100	27,000	5.8	0.26U	0.25	-83.7	6.38
MW-108	5.3	0.034U	2,200	31,000	5.2	0.26U	0.17	-86.0	6.28
MW-12	12	0.034U	2,800	21,000	0.45U	11	1.20	-55.3	6.03
MW-102	1.7	0.034U	800	6,000	0.45U	12	0.45	-52.9	6.27
MW-103	4.9	0.034U	2,900	26,000	6.1	0.26U	0.4	-76.4	6.34
MW-15	2.8	0.034U	630	5,100	0.93	3.2	0.89	-25.0	6.3
MW-107	3.8	0.034U	2,000	22,000	4.1	0.26U	0.14	-88.7	6.34
MW-100	1.3	3.2	46	50U	1.2	17	3.63	82.7	6.68
FPP-MW-3	2.1	0.15U	500	9,100	1.3	4.7	0.86	-98.0	6.71
MW-7	3.8	0.061	1,400	11,000	1.8	1.1	0.52	7.4	6.14
MW-8	4.3	0.047	1,800	24,000	4.1	0.26U	0.14	-109.5	6.51
MW-106	4.1	0.088U	2,100	28,000	6.7J	2.9	0.50	-119.8	6.49
MW-109	0.97	1.7	57	50U	0.45U	14	4.48	65.0	6.48
MW-16	3.5	2.9	140	50U	0.45U	160	1.33	187.3	6.21
MW-17	4.1	0.036U	2,200	22,000	2.0	0.70U	0.91	-82.0	6.53
MW-14	0.88	0.25	2.0U	50U	0.45U	3.8	2.45	38.0	6.63

Abbreviations and Acronyms

- DO = dissolved oxygen
- ft MSL = feet mean sea level
- µg/L = micrograms per liter
- mg/L = milligrams per liter
- MSW = municipal solid waste
- NS = not sampled
- NO_3 = nitrate
- ORP = oxidation reduction potential
- SL = screening level
- SO_4^{2-} = sulfate
- TOC = total organic carbon
- WSDOT = Washington Department of Transportation

Analyte	Units	SL
TOC	µg/L	--
NO₃	mg/L	10
Mn	µg/L	50
Fe	µg/L	300
As	µg/L	0.45
SO_4^{2-}	mg/L	--
DO	mg/L	--
ORP	mV	--
pH	S.U.	<6.5 or >8.5

Notes

1. Highlighted results exceed SL.
2. U = the compound was not detected at the reported concentration.
3. J = the analyte was positively identified; the associated numerical value is the approximate concentration of the analyte in the sample.
4. FPP-MW-1 and FPP-MW-2 not analyzed in September 2014.
5. Black and white reproduction of this color original may reduce its effectiveness and lead to incorrect interpretation.

Legend

- Monitoring Well
- Monitoring Well (Decommissioned or Destroyed)
- River Gauge
- Groundwater Elevation and Contour (ft MSL)
- PLSA Surveyed Parcel Boundaries (October 2014)
- Extent of Municipal Solid Waste
- WSDOT Refuse Contour - (0 ft; inferred) - 1996
- Approximate Extent of Reducing Conditions
- 2,000 cubic yards of material removed by WSDOT during ramp construction
- Building
- Former Building
- Existing or Former Pond
- Septic Tank
- Other Features
- Red-Bordered Data Box Indicates Well Installed within Known Extent of MSW

Data Sources: Yakima County GIS; Esri World Imagery; SLR; URS; Parametrix 2008; Boise 1985.

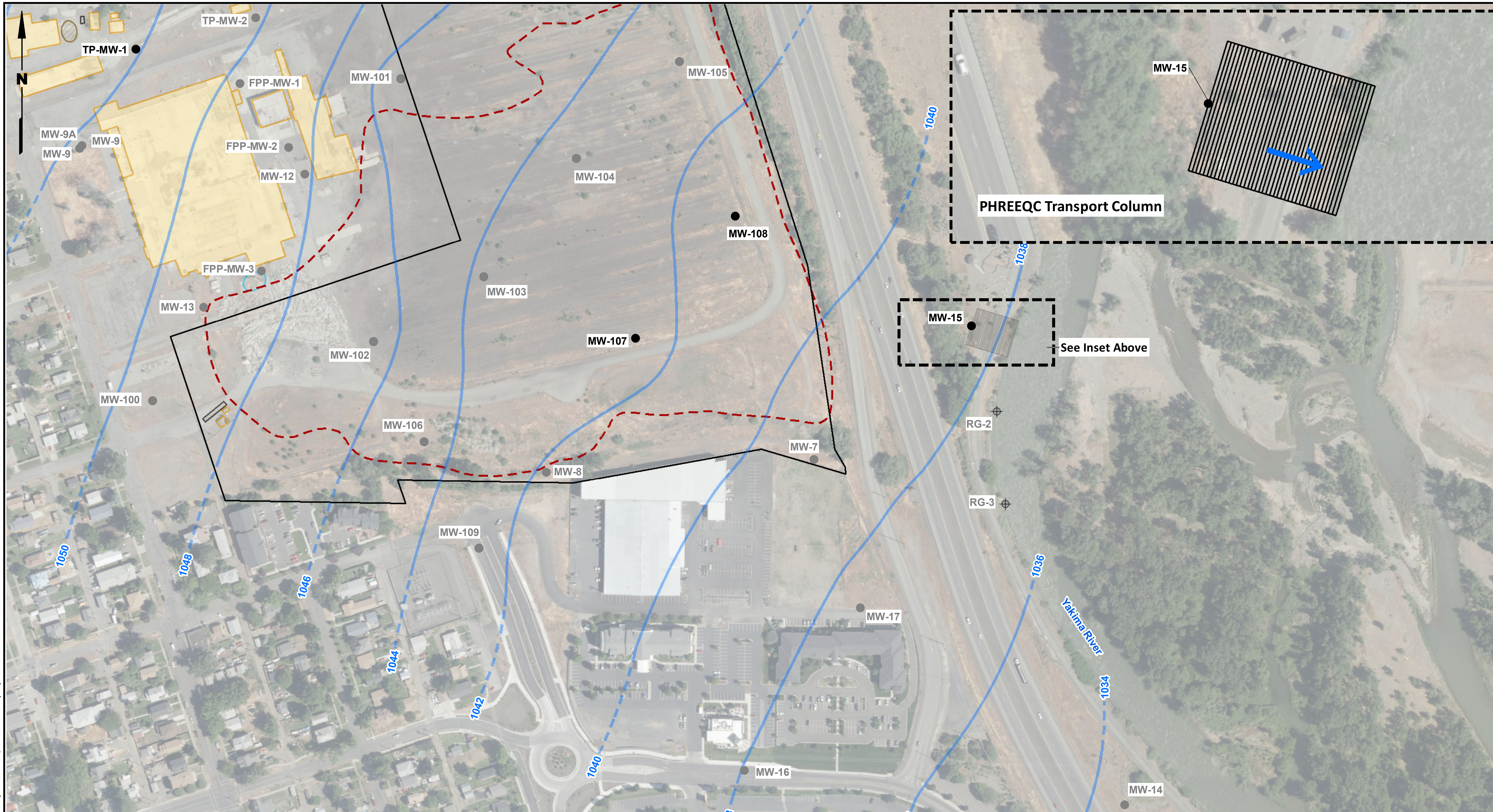
G:\Projects\1148\009\010\017\F05ReducedConditionDowngradient.mxd 9/20/2018

LANDAU ASSOCIATES

Closed City of Yakima Landfill Site
Yakima, Washington

Reduced-Condition Indicator Analyte Results (June 2015)

Figure 5



Legend

- Monitoring Well
- Extent of Municipal Solid Waste
- Groundwater Flow Direction

Notes
1. Figure adapted from LAI 2015.
2. Black and white reproduction of this color original may reduce its effectiveness and lead to incorrect interpretation.

0 250 500
Scale in Feet

Data Sources: Yakima County GIS; Esri World Imagery; SLR; URS; Parametrix 2008; Boise 1985.

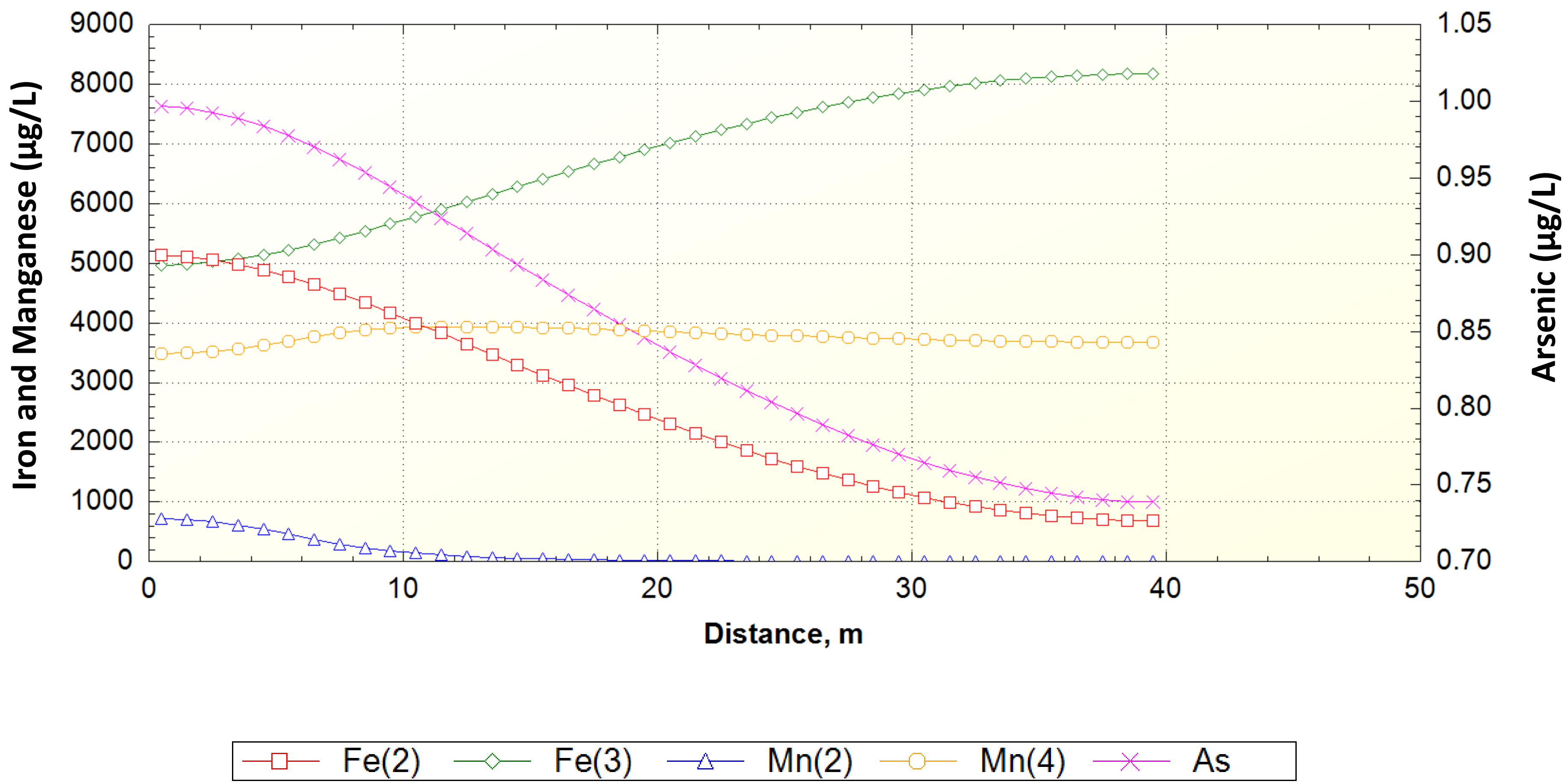
G:\Projects\1148\009\010\017\F06PHREEQCmodel.mxd 9/20/2018

LANDAU ASSOCIATES

Closed City of Yakima
Landfill Site
Yakima, Washington

PHREEQC Model Setup

Figure
6



Note: distances, in meters, correspond to column cell numbers (each cell is 1 meter in length). Cell 1 represents monitoring well MW-15 location; cell 40 represents simulated discharge to Yakima River.

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Closed City of Yakima Landfill Site Yakima, Washington	**PHREEQC Results - COC Concentrations Over Distance**	Figure 7

Table 1
Groundwater and Surface Water Quality Input Parameters and Model Results
Closed City of Yakima Landfill
Yakima, Washington

Parameter	Model Input Parameters (a)				Model Results	
	TP-MW-1 Background Groundwater	MW-107 and MW-108 Contaminated Groundwater at Site	MW-15 Contaminated Groundwater at Hyporheic Zone	USGS Gauge 12484500 Surface Water	Model Cell 1 (matched to MW-15)	Model Cell 40 Discharge to Yakima River
Arsenic	0.5	1.4 (from 5.0)	**1**	--	**1.0**	0.7
Barium	10	60	22	10	--	--
Cadmium	0.5	0.5	0.5	0.4	--	--
Calcium	20,000	37,000	20,000	11,750	--	--
Iron	50	12,000 (from 30,000)	**5,000**	62	**5,100**	680
Lead	0.28	0.28	0.28	--	--	--
Magnesium	10,000	13,000	7,800	5,200	--	--
Manganese	8	5,000 (from 2,200)	**700**	8.3	**710**	<1
Potassium	3,500	7,200	2,900	1,000	--	--
Sodium	11,000	20,000	9,000	4,880	--	--
Chloride	10,000	18,000	10,000	1,600	--	--
Fluoride	250	200	160	--	--	--
Nitrate as	1,000	50	60	--	--	--
Alkalinity	120,000	200,000	100,000	--	--	--
Temperature (°C)	15	16	16	10.2	--	--
pH (SU)	6.5	6	6	7.8	--	--
pE (SU) (b)	4.1	2.1	3.7	13	--	--
Dissolved Oxygen, partial pressure (log k) (c)	-1.0	-2.0	-1.8	-0.67	--	--

Notes:

a) Input parameters are based on qualitative general approximations or averages of values representative of groundwater observations made from 2014 to 2015 (LAI 2015b).

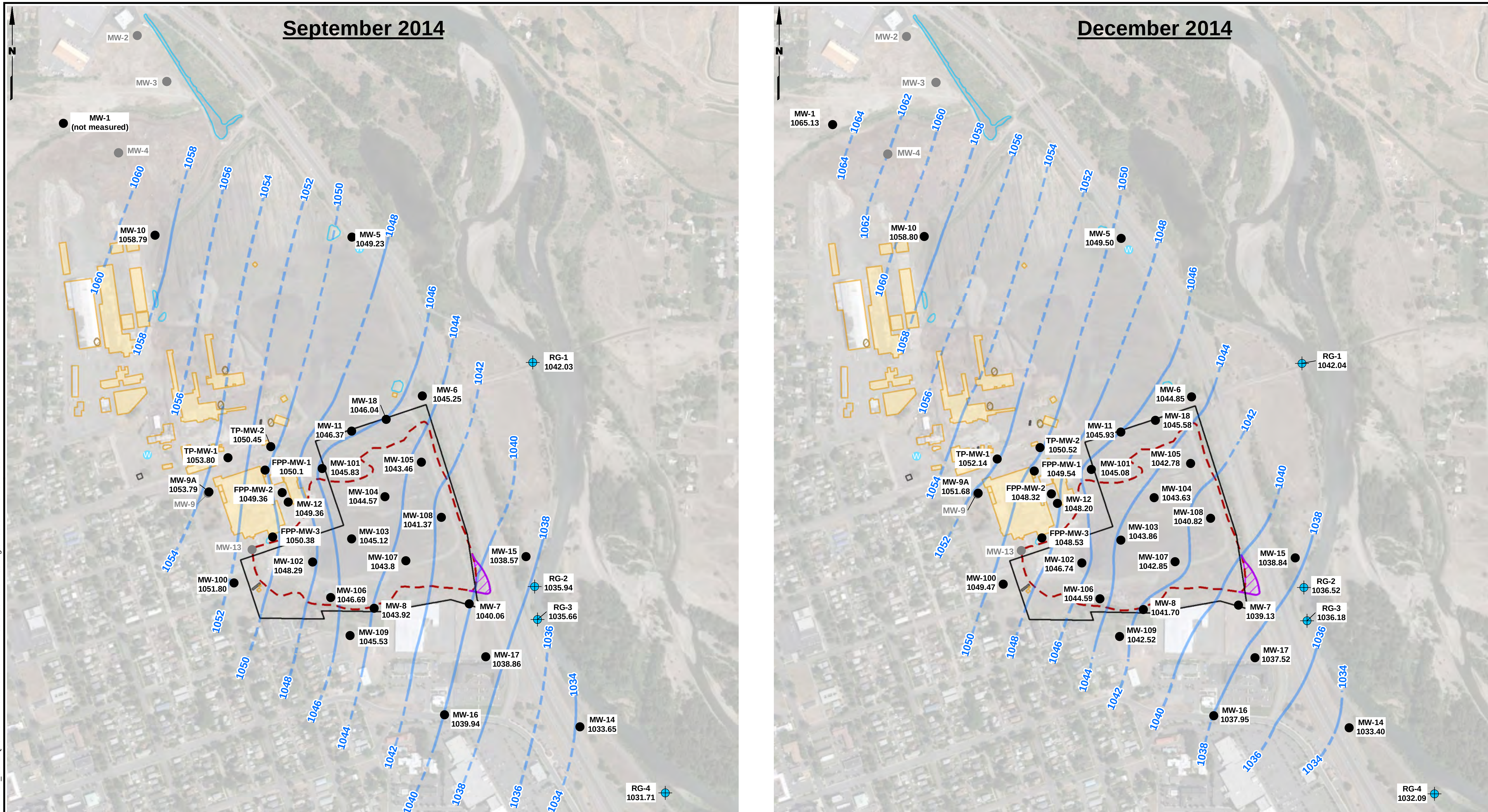
b) pE of groundwater was calculated for each representative component based on temperature and oxidation-reduction potential of individual samples, following Lower reference; pE of surface water was assumed based on Lower reference.

c) Log k of dissolved oxygen partial pressure based on average partial pressures calculated from temperature, atmospheric pressure, specific conductance, and measured dissolved oxygen (mg/L) for individual sample results, following USGS 2011, and averaged.

°C = degrees Celsius
µg/L = micrograms per liter
COC = contaminant of concern
mg/L = milligrams per liter
All values are in units of µg/L, unless otherwise noted.
Bold font indicates MW-15 or model cell 1 COC concentrations.
Boxed values represent simulated COC concentrations in model cell 40, representing simulated discharge to the Yakima River.

ATTACHMENT 1

Groundwater Contour Maps from Supplemental Remedial Investigation



Legend

- Monitoring Well
- Monitoring Well (Abandoned, Destroyed, or Not Found)
- Water Well
- River Gauge
- Groundwater Elevation and Contour (ft MSL)
- PLSA Surveyed Parcel Boundaries (October 2014)
- Extent of Municipal Solid Waste
- WSDOT Refuse Contour - (0 ft; inferred) - 1996
- Existing or Former Pond
- Septic Tank
- Other Features
- 2,000 cubic yards of material removed by WSDOT during ramp construction
- Building
- Former Building

Notes

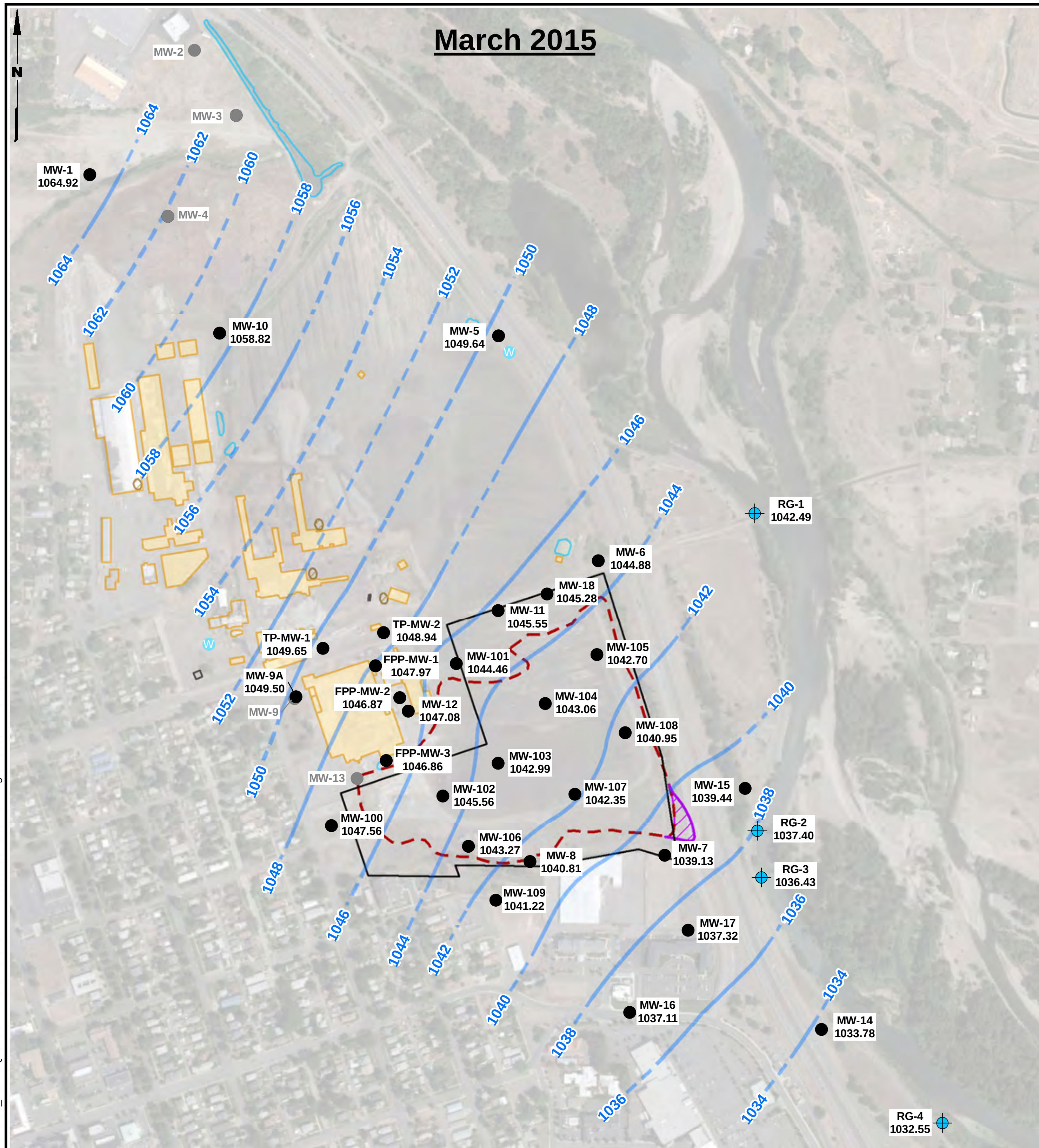
1. River Gauges 1 through 4 (RG-1 through RG-4) were not used in generation of groundwater contours.
2. WSDOT = Washington Department of Transportation ft MSL = feet mean sea level.
3. Locations of site features and sample locations are approximate.
4. Black and white reproduction of this color original may reduce its effectiveness and lead to incorrect interpretation.

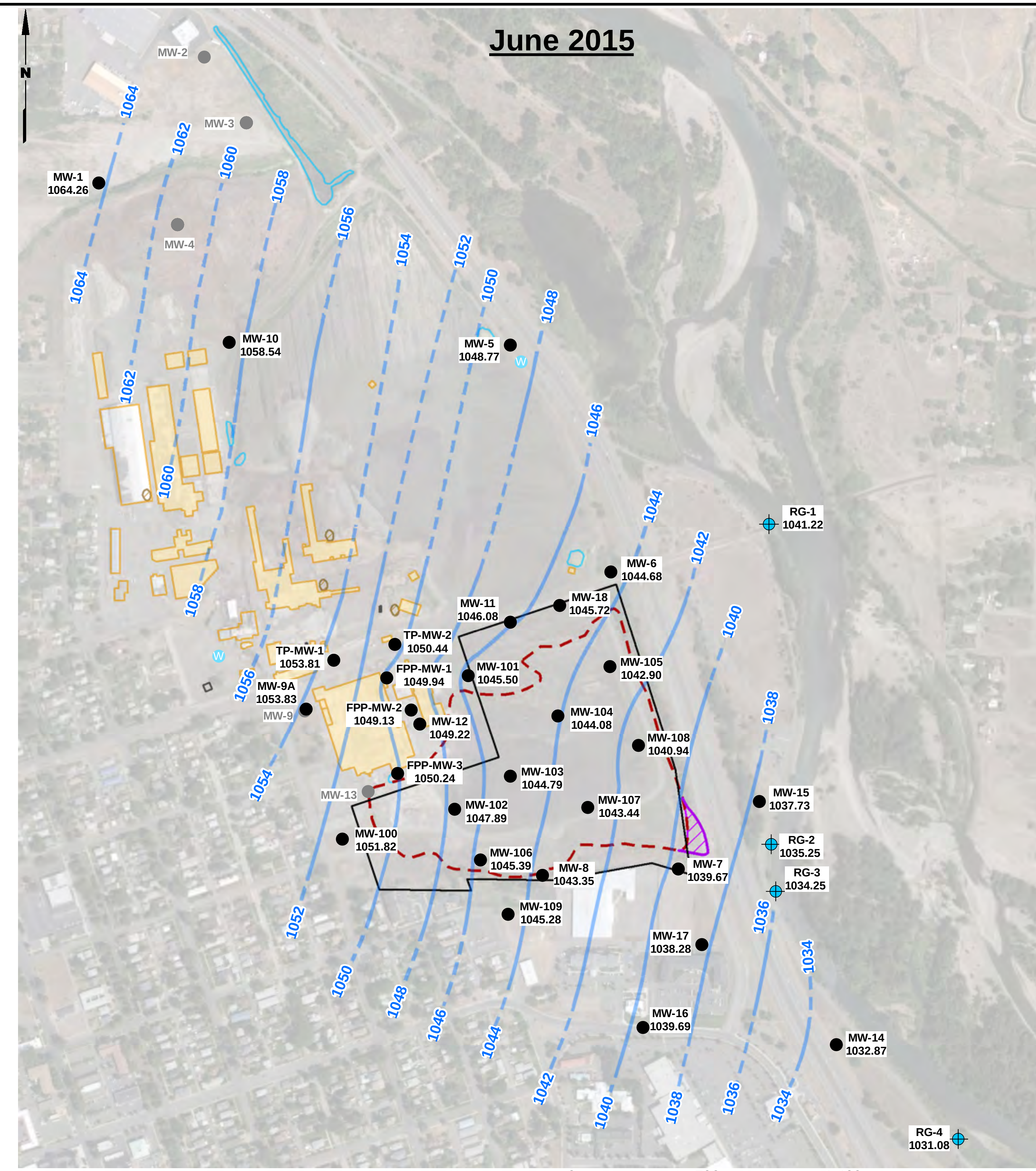
Data Sources: Yakima County GIS; Esri World Imagery; SLR; URS; Parametrix 2008; Boise 1985.

G:\Projects\1148\008\030\034\RI\F05_3rd4thQ2014GW.mxd 8/17/2015 NAD 1983 StatePlane Washington South FIPS 4602 Feet

LANDAU ASSOCIATES

Closed City of Yakima Landfill Site Yakima, Washington	Groundwater Elevation Contours September and December 2014	Figure 5





G:\Projects\1148\008\030\034\RI\F06_1st2ndQ2015GW.mxd 8/17/2015 NAD 1983 StatePlane Washington South FIPS 4602 Feet

Legend

- Monitoring Well
- Monitoring Well (Abandoned, Destroyed, or Not Found)
- Water Well
- River Gauge
- Groundwater Elevation and Contour (ft MSL)
- PLSA Surveyed Parcel Boundaries (October 2014)
- Extent of Municipal Solid Waste
- WSDOT Refuse Contour - (0 ft; inferred) - 1996
- Existing or Former Pond
- Septic Tank
- Other Features
- 2,000 cubic yards of material removed by WSDOT during ramp construction
- Building
- Former Building

Notes

1. River Gauges 1 through 4 (RG-1 through RG-4) were not used in generation of groundwater contours.
2. WSDOT = Washington Department of Transportation ft MSL = feet mean sea level.
3. Locations of site features and sample locations are approximate.
4. Black and white reproduction of this color original may reduce its effectiveness and lead to incorrect interpretation.

0 700 1,400

Scale in Feet

Data Sources: Yakima County GIS; Esri World Imagery; SLR; URS; Parametrix 2008; Boise 1985.

LANDAU ASSOCIATES

Closed City of Yakima Landfill Site Yakima, Washington	**Groundwater Elevation Contours March and June 2015**	Figure 6

ATTACHMENT 2

Yakima Weather Data
September and December 2014 &
March and June 2015

Weather history Yakima september 2014

Day	High (°F)	Low (°F)	Precip. (inch)	Snow (inch)	Snow depth (inch)
1 sep 2014	81.0	45.0	0.00	0.00	0.00
2 sep 2014	82.9	46.0	T	0.00	0.00
3 sep 2014	75.0	46.9	0.00	0.00	0.00
4 sep 2014	79.0	43.0	0.00	0.00	0.00
5 sep 2014	84.0	44.1	0.00	0.00	0.00
6 sep 2014	88.0	45.0	0.00	0.00	0.00
7 sep 2014	90.0	45.0	0.00	0.00	0.00
8 sep 2014	87.1	45.0	0.00	0.00	0.00
9 sep 2014	82.0	50.0	0.00	0.00	0.00
10 sep 2014	75.0	48.0	0.00	0.00	0.00
11 sep 2014	69.1	42.1	0.00	0.00	0.00
12 sep 2014	77.0	37.0	0.00	0.00	0.00
13 sep 2014	81.0	39.0	0.00	0.00	0.00
14 sep 2014	82.0	39.0	0.00	0.00	0.00
15 sep 2014	87.1	42.1	0.00	0.00	0.00
16 sep 2014	88.0	51.1	0.00	0.00	0.00
17 sep 2014	84.9	54.0	T	0.00	0.00
18 sep 2014	80.1	54.0	0.00	0.00	0.00
19 sep 2014	84.0	50.0	0.00	0.00	0.00
20 sep 2014	88.0	51.1	0.00	0.00	0.00
21 sep 2014	89.1	50.0	0.00	0.00	0.00
22 sep 2014	84.9	54.0	T	0.00	0.00
23 sep 2014	73.9	53.1	0.02	0.00	0.00
24 sep 2014	66.0	59.0	0.30	0.00	0.00
25 sep 2014	66.0	46.9	0.14	0.00	0.00
26 sep 2014	73.0	44.1	T	0.00	0.00
27 sep 2014	80.1	44.1	0.00	0.00	0.00
28 sep 2014	80.1	46.9	0.00	0.00	0.00
29 sep 2014	81.0	45.0	T	0.00	0.00
30 sep 2014	72.0	43.0	0.00	0.00	0.00

T = Trace

Past weather Yakima - september 2014

Average high temperature:	80.4°F (normal: 78°F)
Average low temperature:	46.8°F (normal: 44°F)
Average temperature:	63.6°F (normal: 61°F)
Total Precipitation:	0.46 inch (normal: 0.35 inch)
Total snowfall:	0 inch
Highest max temperature:	90.0°F
Lowest max temperature:	66.0°F
Highest min temperature:	59.0°F
Lowest min temperature:	37.0°F

Source:

https://www.usclimatedata.com/climate/yakima/washington/united-states/uswa0502/2014/9

U.S. climate data

Temperature - Precipitation - Sunshine - Snowfall

US Climate Data on

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Monthly | History | Geo & Map | Weather Forecast

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2014 | December

Weather history Yakima december 2014

Day	High (°F)	Low (°F)	Precip. (inch)	Snow (inch)	Snow depth (inch)
1 dec 2014	29.1	10.2	0.00	0.00	0.00
2 dec 2014	33.1	7.2	0.00	0.00	0.00
3 dec 2014	34.0	16.2	0.00	0.00	0.00
4 dec 2014	35.1	30.2	0.11	0.00	0.00
5 dec 2014	37.0	33.1	T	0.00	0.00
6 dec 2014	46.0	28.2	0.13	0.00	0.00
7 dec 2014	41.0	29.1	0.00	0.00	0.00
8 dec 2014	45.0	37.9	0.00	0.00	0.00
9 dec 2014	45.0	39.0	0.06	0.00	0.00
10 dec 2014	53.1	39.9	0.04	0.00	0.00
11 dec 2014	52.0	37.0	0.13	0.00	0.00
12 dec 2014	51.1	32.0	0.00	0.00	0.00
13 dec 2014	53.1	27.1	0.00	0.00	0.00
14 dec 2014	44.1	23.2	0.00	0.00	0.00
15 dec 2014	42.1	30.2	0.00	0.00	0.00
16 dec 2014	41.0	36.0	0.08	0.00	0.00
17 dec 2014	43.0	37.0	0.03	0.00	0.00
18 dec 2014	43.0	39.0	0.02	0.00	0.00
19 dec 2014	45.0	34.0	0.03	0.00	0.00
20 dec 2014	44.1	36.0	0.20	0.00	0.00
21 dec 2014	59.0	39.0	0.03	0.00	0.00
22 dec 2014	55.9	36.0	0.00	0.00	0.00
23 dec 2014	50.0	31.1	0.00	0.00	0.00
24 dec 2014	48.0	29.1	0.01	0.00	0.00
25 dec 2014	51.1	25.2	0.00	0.00	0.00
26 dec 2014	46.0	21.2	0.00	0.00	0.00
27 dec 2014	46.9	24.3	0.00	0.00	0.00
28 dec 2014	42.1	26.2	0.05	0.00	0.00
29 dec 2014	37.0	25.2	T	T	0.00
30 dec 2014	30.2	11.1	0.00	0.00	0.00
31 dec 2014	27.1	10.2	0.00	0.00	0.00

T = Trace

Past weather Yakima - december 2014

Average high temperature:	43.6°F (normal: 36°F)
Average low temperature:	28.4°F (normal: 21°F)
Average temperature:	36°F (normal: 29°F)
Total Precipitation:	0.92 inch (normal: 1.54 inch)
Total snowfall:	0 inch
Highest max temperature:	59.0°F
Lowest max temperature:	27.1°F
Highest min temperature:	39.9°F
Lowest min temperature:	7.2°F

Source:

https://www.usclimatedata.com/climate/yakima/washington/united-states/uswa0502/2014/12

U.S. climate data

Temperature - Precipitation - Sunshine - Snowfall

US Climate Data on

Weather history Yakima march 2015

Day	High (°F)	Low (°F)	Precip. (inch)	Snow (inch)	Snow depth (inch)
1 mar 2015	54.0	23.2	0.00	0.00	0.00
2 mar 2015	51.1	33.1	T	0.00	0.00
3 mar 2015	50.0	26.2	0.00	0.00	0.00
4 mar 2015	55.0	21.2	0.00	0.00	0.00
5 mar 2015	57.9	24.3	0.00	0.00	0.00
6 mar 2015	64.9	30.2	0.00	0.00	0.00
7 mar 2015	69.1	33.1	0.00	0.00	0.00
8 mar 2015	68.0	31.1	0.00	0.00	0.00
9 mar 2015	73.9	31.1	0.00	0.00	0.00
10 mar 2015	69.1	31.1	0.00	0.00	0.00
11 mar 2015	68.0	45.0	0.01	0.00	0.00
12 mar 2015	71.1	35.1	0.00	0.00	0.00
13 mar 2015	68.0	37.0	0.00	0.00	0.00
14 mar 2015	72.0	51.1	T	0.00	0.00
15 mar 2015	63.0	45.0	0.27	0.00	0.00
16 mar 2015	62.1	32.0	0.00	0.00	0.00
17 mar 2015	62.1	45.0	T	0.00	0.00
18 mar 2015	66.0	33.1	0.00	0.00	0.00
19 mar 2015	64.9	34.0	0.00	0.00	0.00
20 mar 2015	63.0	37.0	0.00	0.00	0.00
21 mar 2015	64.9	36.0	0.00	0.00	0.00
22 mar 2015	59.0	33.1	T	0.00	0.00
23 mar 2015	60.1	33.1	0.12	0.00	0.00
24 mar 2015	61.0	37.0	0.29	0.00	0.00
25 mar 2015	62.1	44.1	0.04	0.00	0.00
26 mar 2015	73.9	39.0	0.00	0.00	0.00
27 mar 2015	80.1	42.1	0.00	0.00	0.00
28 mar 2015	66.9	43.0	0.00	0.00	0.00
29 mar 2015	70.0	41.0	0.00	0.00	0.00
30 mar 2015	71.1	37.9	0.00	0.00	0.00
31 mar 2015	62.1	39.9	0.00	0.00	0.00

T = Trace

Past weather Yakima - march 2015

Average high temperature:	64.7°F (normal: 56°F)
Average low temperature:	35.6°F (normal: 30°F)
Average temperature:	50.15°F (normal: 43°F)
Total Precipitation:	0.73 inch (normal: 0.63 inch)
Total snowfall:	0 inch
Highest max temperature:	80.1°F
Lowest max temperature:	50.0°F
Highest min temperature:	51.1°F
Lowest min temperature:	21.2°F

Source:

https://www.usclimatedata.com/climate/yakima/washington/united-states/uswa0502/2015/3

U.S. climate data
Temperature - Precipitation - Sunshine - Snowfall

US Climate Data on

Home United States Washington Enter a location

Monthly | History | Geo & Map | Weather Forecast

You are here: United States > Washington > Yakima

2015 June

Weather history Yakima june 2015

Day	High (°F)	Low (°F)	Precip. (inch)	Snow (inch)	Snow depth (inch)
1 jun 2015	84.9	55.9	T	0.00	0.00
2 jun 2015	77.0	55.9	0.00	0.00	0.00
3 jun 2015	75.0	55.0	0.00	0.00	0.00
4 jun 2015	82.9	46.0	0.00	0.00	0.00
5 jun 2015	90.0	55.0	0.00	0.00	0.00
6 jun 2015	96.1	54.0	0.00	0.00	0.00
7 jun 2015	100.9	57.0	0.00	0.00	0.00
8 jun 2015	105.1	60.1	0.00	0.00	0.00
9 jun 2015	100.9	60.1	0.00	0.00	0.00
10 jun 2015	98.1	64.0	0.00	0.00	0.00
11 jun 2015	96.1	61.0	0.00	0.00	0.00
12 jun 2015	84.9	59.0	0.00	0.00	0.00
13 jun 2015	82.0	42.1	0.00	0.00	0.00
14 jun 2015	86.0	51.1	0.00	0.00	0.00
15 jun 2015	91.0	50.0	0.00	0.00	0.00
16 jun 2015	93.9	53.1	0.00	0.00	0.00
17 jun 2015	93.9	48.9	0.00	0.00	0.00
18 jun 2015	91.9	64.0	0.00	0.00	0.00
19 jun 2015	82.9	53.1	0.00	0.00	0.00
20 jun 2015	86.0	48.0	0.00	0.00	0.00
21 jun 2015	84.0	62.1	0.00	0.00	0.00
22 jun 2015	89.1	52.0	0.00	0.00	0.00
23 jun 2015	90.0	50.0	0.00	0.00	0.00
24 jun 2015	91.0	66.9	0.00	0.00	0.00
25 jun 2015	98.1	55.0	0.00	0.00	0.00
26 jun 2015	104.0	63.0	0.00	0.00	0.00
27 jun 2015	108.0	66.9	0.00	0.00	0.00
28 jun 2015	108.0	68.0	0.00	0.00	0.00
29 jun 2015	102.0	75.0	0.01	0.00	0.00
30 jun 2015	100.9	64.9	0.00	0.00	0.00

T = Trace

Past weather Yakima - june 2015

Average high temperature:	92.5°F (normal: 80°F)
Average low temperature:	57.2°F (normal: 48°F)
Average temperature:	74.85°F (normal: 64°F)
Total Precipitation:	0.01 inch (normal: 0.63 inch)
Total snowfall:	0 inch
Highest max temperature:	108.0°F
Lowest max temperature:	75.0°F
Highest min temperature:	75.0°F
Lowest min temperature:	42.1°F

Source:

https://www.usclimatedata.com/climate/yakima/washington/united-states/uswa0502/2015/6

ATTACHMENT 3

PHREEQC Model Input File

```
TITLE Yakima Landfill - PHREEQC Transport Modeling
SURFACE_MASTER_SPECIES
      Hfo_w       Hfo_wOH        #As sorption to Hfo:
https://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/mail/msg00413.html
SURFACE_SPECIES
  Hfo_wOH  + H+ = Hfo_wOH2+
       log_k  7.18

  Hfo_wOH = Hfo_wO- + H+
       log_k  -8.82
  Hfo_wOH + H3ArseniteO3 = Hfo_wH2ArseniteO3 + H2O
       log_k   5.41                                              #5.41
SOLUTION_MASTER_SPECIES
      Fe_di              Fe_di+2    0.0     Fe_di              55.847
      Fe_tri             Fe_tri+3   0.0     Fe_tri             55.847
      Arsenite           H3ArseniteO3     0.0   74.9216     74.9216
      Mn_di              Mn_di+2    0.0     Mn_di              54.938
      Mn_four            Mn_four+4  0.0     Mn_four            54.938
SOLUTION_SPECIES
      Fe_di+2 = Fe_di+2
            log_k   0.0
      Fe_tri+3 = Fe_tri+3
            log_k   0.0
      Mn_di+2 = Mn_di+2
            log_k   0.0
      Mn_four+4 = Mn_four+4
            log_k   0.0
      H3ArseniteO3 = H3ArseniteO3
        log_k           0
      H3ArseniteO3 = H2ArseniteO3- + H+
        log_k           -9.228
      H3ArseniteO3 = HArseniteO3-2 + 2H+
        log_k           -21.33
      H3ArseniteO3 = ArseniteO3-3 + 3H+
        log_k           -34.744
      H3ArseniteO3 + H+ = H4ArseniteO3+
        log_k           -0.305
#
# Fe+2 species
#
Fe_di+2 + H2O = Fe_diOH+ + H+
        log_k   -9.5
        delta_h 13.20   kcal
#
#... and also other Fe+2 species
#
Fe_di+2 + Cl- = Fe_diCl+
        log_k   0.14
Fe_di+2 + CO3-2 = Fe_diCO3
        log_k   4.38
Fe_di+2 + HCO3- = Fe_diHCO3+
        log_k   2.0
Fe_di+2 + SO4-2 = Fe_diSO4
        log_k   2.25
        delta_h 3.230   kcal
Fe_di+2 + HSO4- = Fe_diHSO4+
        log_k   1.08
```

```
Fe_di+2 + 2HS- = Fe_di(HS)2
        log_k   8.95
Fe_di+2 + 3HS- = Fe_di(HS)3-
        log_k   10.987
Fe_di+2 + HPO4-2 = Fe_diHPO4
        log_k   3.6
Fe_di+2 + H2PO4- = Fe_diH2PO4+
        log_k   2.7
Fe_di+2 + F- = Fe_diF+
        log_k   1.0
#
# Fe+3 species
#
Fe_tri+3 + H2O = Fe_triOH+2 + H+
        log_k   -2.19
        delta_h 10.4    kcal
#
#... and also other Fe+3 species
#
Fe_tri+3 + 2 H2O = Fe_tri(OH)2+ + 2 H+
        log_k   -5.67
        delta_h 17.1    kcal
Fe_tri+3 + 3 H2O = Fe_tri(OH)3 + 3 H+
        log_k   -12.56
        delta_h 24.8    kcal
Fe_tri+3 + 4 H2O = Fe_tri(OH)4- + 4 H+
        log_k   -21.6
        delta_h 31.9    kcal
2 Fe_tri+3 + 2 H2O = Fe_tri2(OH)2+4 + 2 H+
        log_k   -2.95
        delta_h 13.5    kcal
3 Fe_tri+3 + 4 H2O = Fe_tri3(OH)4+5 + 4 H+
        log_k   -6.3
        delta_h 14.3    kcal
Fe_tri+3 + Cl- = Fe_triCl+2
        log_k   1.48
        delta_h 5.6     kcal
Fe_tri+3 + 2 Cl- = Fe_triCl2+
        log_k   2.13
Fe_tri+3 + 3 Cl- = Fe_triCl3
        log_k   1.13
Fe_tri+3 + SO4-2 = Fe_triSO4+
        log_k   4.04
        delta_h 3.91    kcal
Fe_tri+3 + HSO4- = Fe_triHSO4+2
        log_k   2.48
Fe_tri+3 + 2 SO4-2 = Fe_tri(SO4)2-
        log_k   5.38
        delta_h 4.60    kcal
Fe_tri+3 + HPO4-2 = Fe_triHPO4+
        log_k   5.43
        delta_h 5.76    kcal
Fe_tri+3 + H2PO4- = Fe_triH2PO4+2
        log_k   5.43
Fe_tri+3 + F- = Fe_triF+2
        log_k   6.2
        delta_h 2.7     kcal
```

```
Fe_tri+3 + 2 F- = Fe_triF2+
        log_k   10.8
        delta_h 4.8     kcal
Fe_tri+3 + 3 F- = Fe_triF3
        log_k   14.0
        delta_h 5.4     kcal
#
# Mn species
#
Mn_di+2 + H2O = Mn_diOH+ + H+
      -log_k      -10.59
      -delta_h 14.40    kcal
      -gamma      5.0   0
Mn_di+2 + 3H2O = Mn_di(OH)3- + 3H+
      -log_k  -34.8
      -gamma      5.0   0
Mn_di+2 + Cl- = Mn_diCl+
      -log_k      0.61
      -gamma      5.0   0
      -Vm   7.25  -1.08  -25.8  -2.73  3.99  5  0  0  0  1 # ref. 2
Mn_di+2 + 2 Cl- = Mn_diCl2
      -log_k      0.25
      -Vm   1e-5  0  144 # ref. 2
Mn_di+2 + 3 Cl- = Mn_diCl3-
      -log_k      -0.31
      -gamma      5.0   0
      -Vm   11.8  0  0  0  2.4  0  0  0  3.6e-2  1 # ref. 2
Mn_di+2 + CO3-2 = Mn_diCO3
      -log_k      4.9
Mn_di+2 + HCO3- = Mn_diHCO3+
      -log_k      1.95
      -gamma      5.0   0
Mn_di+2 + SO4-2 = Mn_diSO4
      -log_k      2.25
      -delta_h 3.370    kcal
      -Vm  -1.31  -1.83  62.3  -2.7 # ref. 2
Mn_di+2 + 2 NO3- = Mn_di(NO3)2
      -log_k      0.6
      -delta_h -0.396   kcal
      -Vm  6.16  0  29.4  0  0.9 # ref. 2
Mn_di+2 + F- = Mn_diF+
      -log_k      0.84
      -gamma      5.0   0
2H2O = O2 + 4H+ + 4e-
            log_k   -100
            delta_h 134.79 kcal
PHASES
Goethite
        Fe_triOOH + 3 H+ = Fe_tri+3 + 2 H2O
        log_k   -1.0
Hausmannite
      Mn_di3O4 + 8 H+ + 2 e- = 3 Mn_di+2 + 4 H2O
      -log_k      61.03
      -delta_h -100.640 kcal
Manganite
      Mn_diOOH + 3 H+ + e- = Mn_di+2 + 2 H2O
        log_k   25.34
```

```
Pyrochroite
      Mn_di(OH)2 + 2 H+ = Mn_di+2 + 2 H2O
      -log_k      15.2
END
SOLUTION 0  Upgradient Loading Groundwater MW-107 and MW-108
       units            ppb
       temp             16.0
       pH               6.0
       pe               2.1    O2(g)   -2.0
       Ba               60
       Ca               37000
       Fe_di            12000             #30000
       Mg               13000
       Mn_di            5000              #2200
       Na               20000
       Cl               18000 #charge  #charge here temporarily
       Arsenite         1.4               #5.0
       Ba               60
       Cd               0.5
       Pb               0.28
       K                7200
       F                200
       N(+5)            50
       Alkalinity       200000
SOLUTION 1  Groundwater MW-15
       units            ppb
       temp             16.0
       pH               6.0
       pe               3.7   O2(g)   -1.8
       Ba               22
       Ca               20000
       Fe_di            5000
       Mg               7500
       Mn_di            700
       Na               9000
       Cl               10000 #charge  #charge here temporarily
       Arsenite         1
       Cd               0.5
       Pb               0.28
       K                2900
       F                160
       N(+5)            60
       Alkalinity       100000
SOLUTION 555 Upgradient Background Groundwater TP-MW-1
      units             ppb
      temp              15.0
      ph                6.5
      pe                4.1   O2(g)   -1.0
      Ba                10.0
      Ca                20000
      Fe_di             50
      Mg                10000
      Mn_di             8.0
      Na                11000
      Cl                10000 #charge
      Arsenite          0.5
      Ba                10
```

```
      Cd                 0.5
      Pb                 0.28
      K                  3500
      F                  250
      N(+5)              1000
      Alkalinity         120000
SOLUTION 999 Yakima River at Umtanum USGS Gauge 12484500
      units              ppb
      temp               10.2
      ph                 7.8
      pe                 13.0    O2(g)   -0.67   #pe of nat'l waters exposed
to air 13 (Lower pg 14)
      Ba                 10.0
      Ca                 11750
      Fe_di              62.0
      Mg                 5200
      Mn_di              8.3
      Na                 4880
      Cl                 1600 #charge
      Arsenite           0
      Ba                 10
      Cd                 0.4
      K                  1000
END
MIX 1
      555         0.9
      999         0.1
SAVE solution 2-5
END
MIX 2 #mix of 555 and 999
      555         0.8
      999         0.2
SAVE solution 6-10
END
MIX 3 #mix of 555 and 999
      555         0.7
      999         0.3
SAVE solution 11-15
END
MIX 4 #mix of 555 and 999
      555         0.6
      999         0.4
SAVE solution 16-20
END
MIX 5 #mix of 555 and 999
      555         0.5
      999         0.5
SAVE solution 21-25
END
MIX 6 #mix of 555 and 999
      555         0.4
      999         0.6
SAVE solution 26-30
END
MIX 7 #mix of 555 and 999
      555         0.3
      999         0.7
```

```
SAVE solution 31-35
END
MIX 8 #mix of 555 and 999
      555         0.2
      999         0.8
SAVE solution 36-40
END
RATES
Fe_di_ox
  -start
  10  Fe_di = TOT("Fe_di")
  20  if (Fe_di <= 0) then goto 200
  30  p_o2 = SR("O2(g)")
  40  moles = (2.91e-9 + 1.33e12 * (ACT("OH-"))^2 * p_o2) * Fe_di * TIME
#from Singer Stumm 1970   and PHREEQC manual ex 9
  200 SAVE moles
  -end
Mn_di_ox
  -start
  10 Mn_di = TOT("Mn_di")
  20 if (Mn_di <= 0) then goto 200
  30 p_o2 = SR("O2(g)")
  40 moles = 1.4e-6 * Mn_di * TIME  #from Harvey & Fuller 1998 (gamma = 1.4e-
6 sec-1)
  200 SAVE moles
  -end
KINETICS 7-40
Fe_di_ox
        -formula  Fe_di  -1.0  Fe_tri  1.0
        -steps 100 400 3100 10800 21600 5.04e4 8.64e4 1.728e5 1.728e5 1.728e5
1.728e5
        -step_divide 1e-4
Mn_di_ox
        -formula  Mn_di  -1.0  Mn_four  1.0
        -steps 100 400 3100 10800 21600 5.04e4 8.64e4 1.728e5 1.728e5 1.728e5
1.728e5
INCREMENTAL_REACTIONS true
SELECTED_OUTPUT
        -file 1148_008_g.sel
        -reset false
USER_PUNCH
        -headings Days  Fe(2)  Fe(3)  Na Mn(2) Mn(4) pH As
  10 PUNCH SIM_TIME / 3600 / 24, TOT("Fe_di"), TOT("Fe_tri"), TOT("Na"),
TOT("Mn_di"), TOT("Mn_four"), -LA("H+"), TOT("Arsenite")
END
SURFACE 7-40
      Hfo_wOH     2e-4        600.        0.05
END
TRANSPORT
      -cells                  40
      -lengths                1
      -shifts                 50
      -time_step              1771200
      -flow_direction         forward
      -boundary_conditions    flux flux
      -dispersivities         30
      -correct_disp           true
```

```
      -diffusion_coefficient  0.0
      -punch_cells            1-40
      -punch_frequency        1
      -print_cells            1-40
      -print_frequency        1
USER_GRAPH 1 Yakima Landfill Iron Oxidation - Distance with As
#http://phreeqcusers.org/index.php/topic,187.msg782.html#msg782
        -headings _time_ Fe(2) Fe(3) Mn(2) Mn(4) As
        -chart_title "Oxidation of Ferrous Iron - Distance with As"
        -axis_titles "Distance, m" "Microgram per Liter"
        #-axis_scale secondary_y_axis 2.0 9.0 1.0 0.5
        #-axis_scale y_axis 0 25000
  -start
  10 if (step_no <> 50) then goto 100
  20 GRAPH_X dist
  30 GRAPH_Y TOT("Fe_di")*56e6, TOT("Fe_tri")*56e6, TOT("Mn_di")*55e6,
TOT("Mn_four")*55e6
  40 GRAPH_SY TOT("Arsenite")*72.9416e6
  100 REM end
  -end
      -active     true
USER_GRAPH 2 Yakima Landfill Iron Oxidation - Time with As - Cell 1
        -headings _time_ Fe(2) Fe(3) Mn(2) Mn(4) As
        -chart_title "Oxidation of Ferrous Iron - Time with As - Cell 1"
        -axis_titles "Time, in days" "Microgram per Liter"
        #-axis_scale secondary_y_axis 2.0 9.0 1.0 0.5
        #-axis_scale y_axis 0 25000
  -start
  10 if (cell_no<>1) then goto 100
  20 GRAPH_X TOTAL_TIME / 3600 / 24
  30 GRAPH_Y TOT("Fe_di")*56e6, TOT("Fe_tri")*56e6, TOT("Mn_di")*55e6,
TOT("Mn_four")*55e6
  40 GRAPH_SY TOT("Arsenite")*72.9416e6
  100 REM end
  -end
      -active     true
END
```