Appendix 9 C

Water Quality Modeling for Evaluation
of Surface Water and Groundwater Impacts
Aurora Gold Mining Project, Guyana

Water Quality Modeling for Evaluation of Surface Water and Groundwater Impacts: Aurora Gold Project, Guyana

Executive Summary

This appendix summarizes results of a water quality modeling study conducted to evaluate potential surface water and groundwater impacts from the Aurora Gold Project (Project). It consists of two separate technical memoranda:

- **Attachment 1:** Hydrodynamic and Water Quality Modeling for Evaluation of Potential Surface Water Impacts for the Aurora Gold Project, Guyana
- **Attachment 2:** Flow and Transport of Selected Constituents of Interest in the Saturated and Unsaturated Zones of the Aurora Gold Project

The modeling study was focused on two different sources of potential constituents of interest (PCOIs), originating from (a) the detoxified process tailings stream deposited in the Project's Tailings Management Area (TMA), and (b) the runoff and infiltration water from open pit and underground mining operations, which is collected and routed to the Mine Water Pond (MWP). The potential surface water impacts from the TMA were modeled using the EFDC[1] and WMS[2] models via pathways that include TMA Diversion Ponds 1 and 2 and the receiving stream. Groundwater pathways were modeled using WHI Unsat Suite[3] and MODFLOW[4] models through the unsaturated zone under the TMA and through the underlying aquifer. The impacts from the MWP were modeled using the EFDC and WMS models for surface water pathways through the MWP and to the receiving stream, and by using Visual MODFLOW for constituent seepage potentially impacting groundwater beneath the MWP.

The PCOIs for the MWP included selected leachate metals (As, Cr, Cu, Ni), benzene (as a representative petroleum hydrocarbon from a theoretical vehicle spill scenario), and total suspended solids (TSS) for the surface water model only. Representative PCOIs selected for the TMA included free and total cyanide, As, and TSS (also only for the surface water model). The weak acid dissociable (WAD) components of cyanide (CN_{WAD}) were not considered in the modeling analysis, as the laboratory measurement of CN_{WAD} at the site indicates that the majority is in the form of free cyanide. For all effluents, the PCOI concentrations were compared to the effluent values in Table 1 of the International Finance Corporation (IFC)

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[1] EFDC US Environmental Protection Agency (EPA) 2002 version, with ENVIRON-modified code
[2] WMS Version 9.1 (AquaVeo, 2013)
[3] WHI Unsat Suite Plus Version 2.2.0.5 (Schlumberger Water Services, updated 2006)
[4] Visual MODFLOW Version 2011 .1 Premium (Schlumberger Water Services, updated 2013)

"Environmental, Health, and Safety Guidelines for Mining"[5] at the physical points of discharge into the environment.

The results from the **surface water modeling study** for both the TMA and MWP sources showed that predicted discharge concentrations of leachate metals are expected to be below the IFC effluent guidelines. Similarly, at the MWP, the predicted discharge concentration of benzene for an assumed accidental spill is also expected to be less than the IFC effluent guideline. For effluent from TMA Diversion Pond 2, the concentrations of free and total cyanide are predicted to be below the IFC guidelines. However, the predicted discharge concentrations of TSS slightly exceed the IFC guideline during wet seasons for TMA Diversion Pond 2. At the MWP, TSS discharges significantly exceed the IFC guidelines during most of the mine's operational lifetime, except for dry seasons. Additional settling and dilution/treatment ponds, especially below the MWP, are therefore recommended for consideration as part of final mine design and water management strategy, sized as necessary to ensure TSS values are reduced below IFC guidelines.

The results from the **groundwater modeling study** showed that, over the life of the mine, for seepage from the MWP through the groundwater, constituent plumes reach only one extraction well among all the extraction wells that are used to dewater the open pit mine, and would therefore be recycled back to the MWP. For seepage under the TMA, model results indicate that over the life of the mine, constituent plumes do not reach the vadose zone, and there is no risk of impact to the aquifer beneath the TMA.

[5] IFC, 2007. Environmental, Health and Safety Guidelines for Mining, World Bank/International Finance Corporation, Washington, D.C. December 10, 2007.

ATTACHMENT 1

MEMORANDUM

To: Alex Riley
Environmental Manager,
Guyana Goldfields, Inc.

From: Cheegwan Lee, PhD, PE
Felix Kristanovich, PhD, PE
ENVIRON International Corp (ENVIRON)

Subject: **Hydrodynamic and Water Quality Modeling for Evaluation of Potential Surface Water Impacts for the Aurora Gold Project, Guyana**

CC: Glenn Mills, ENVIRON
Reed Huppman, ENVIRON

Introduction

This hydrodynamic and water quality modeling study was performed to evaluate the potential surface water quality impacts from the proposed design and operation of the Aurora Gold Project (Project). The Project site is located in the Cuyuni Greenstone Belt in north-western Guyana. The site is low-lying, with small hills near the Cuyuni River and in the southwest part of the Project site, and is covered with dense tropical forest.

The proposed site plan defined by the latest Project feasibility study[6] consists of eleven drainage basins totaling about 1090 ha, all of which eventually drain into the Cuyuni River through several large creeks (Figure 1-1). Watershed diversion structures are provided to divert drainage around the open pit (and eventually, underground) mines, water management and tailings management facilities, and waste rock stockpiles. Potentially contaminated water and sediment from the mine pits will be collected and pumped into the Mine Water Pond (MWP), where dilution is provided by runoff and overflow from the fresh water pond (FWP) before discharge to the environment. Tailings Management Area (TMA) diversion pond 2 (TMA-D2) receives contaminated overflows from the TMA, where detoxified tailings from the mill/mineral separation plant are deposited, and then discharged to environment after dilution by runoff and clean overflow from the TMA diversion pond 1 (TMA-D1).

Potential constituents of interest (PCOIs) include total suspended solids (TSS), petroleum hydrocarbons, and abundant leachate metals (e.g., arsenic, copper, chromium, nickel) originating from the mine pits, as well as residual cyanide and iron from the TMA. These PCOIs will be naturally attenuated through complex physical and chemical processes such as dilution, biodegradation, volatilization, adsorption and other chemical reactions in the water diversions (and, in the TMA, the tailings mass). The MWP and TMA-D2 should be designed with sufficient retention time and dilution water to attenuate the incoming PCOI concentration to the discharge levels defined by Table 1 of the International Finance Corporation (IFC) Environmental, Health and Safety Guidelines for Mining" (IFC, 2007).

[6] See "NI 43-101 Technical Report: Updated Feasibility Study, Aurora Gold Project, Guyana, South America"; (TetraTech, 2013).

However, short-circuiting of PCOI plumes can reduce actual retention time due to channelized currents, and incomplete mixing can occur due to the complex geometry of diversion ponds and suboptimal location of freshwater inflows (as the diversion systems are generally designed to fit natural topography). Thus, a two-dimensional modeling approach was adopted to consider the spatial variability of the system that can impact discharge concentrations.

This modeling study focuses on the evaluation of the proposed design of the MWP and TMA-D2, which are impacted by PCOIs but are designed to discharge directly to environment in normal operational conditions. Our investigation involved conducting a two-dimensional hydrodynamic and water quality modeling analysis using a variety of information processed for model inputs. The study's specific objectives include:

- Estimating potential PCOIs loadings to diversion systems from normal mining operation;
- Understanding hydraulic dispersion and potential short-circuiting of the PCOI plume that determine the discharge concentration;
- Evaluating the discharge concentrations of PCOIs at the outlets to the environment after dilution and natural attenuation in the diversion ponds; and
- Evaluating potential downstream pathways and natural attenuation after discharge to the environment.

The technical approach focused on the prediction of discharge concentration of the selected PCOIs at the outlet in the diversion ponds with reference to the IFC receiving water quality standard (IFC, 2007). The PCOIs were selected based on the laboratory leachate and tailing materials test data (KCB, 2012; AMEC, 2010c). Loadings from upstream drainage area were estimated by simple hydrologic and mass balance calculations using available site characteristics data. The hydraulic model was validated with a water balance calculation developed in the feasibility study. A conservative estimation of water quality input data based on laboratory test results and literatures was made. A sensitivity analysis for water quality modeling was also conducted to estimate a range of modeling uncertainty, and is partially reported in this memo as necessary for explanation of the modeling results. The modeling study used the monthly average operational conditions[7] in a scenario that assumes 22 years of mining operations. The potential effectiveness of the proposed designs in attenuation of PCOIs was evaluated by comparing discharge concentration with the guidelines (IFC, 2007) as well as inflow concentration.

[7] These include a wide range of monthly-average (January through December) water balance data assuming monthly average productions of dewatering and tailings.

Model Development

Description of Hydrodynamic and Water Quality Model

The EFDC hydrodynamic and water quality model was used for this study, which is supported by United States Environmental Protection Agency (USEPA)[8]. This model is a dynamic, three-dimensional, coupled hydrodynamic and water quality model that can simulate the transport and fate of sediments and PCOIs in various phases; it was originally developed at the Virginia Institute of Marine Science (Hamrick, 1992), and it has been used to simulate hydrodynamics and water quality in numerous surface water systems. The EFDC uses an orthogonal curvilinear numerical grid, which makes it possible to represent relatively complex geometry and bathymetry over a variable range of spatial scales.

The model was set up for two-dimensional, depth-averaged condition that can provide realistic simulation of hydrodynamics and water quality parameters in two focused study areas (i.e., the MWP and TMA-D2). Density-driven circulation due to temperature stratification is not significant within the site, but the buoyancy effects of suspended sediments are considered in this study. Model development required the following information:

- Topography, geometry, and dimensions of hydraulic structures;
- Meteorological and water balance data over the operational phase of the mine; and
- Water quality kinetics of the PCOIs.

Model Domain, Grid and Bathymetry, and Hydraulic Structures

Realistic simulation of hydrodynamic dispersion and natural attenuation of PCOIs within the study areas necessitated using accurate numerical grids depicting the study areas. PCOIs generated by mining activities are diverted into the MWP and TMA-D2 before discharge to the environment, and all inflow conditions can be estimated for the proposed mining design and operation scenarios. The MWP and TMA-D2 diversion ponds are hydraulically separate systems with water pond areas of 29 and 20 hectares, respectively; therefore, two separate models are developed with two separate model domains.

Topography input for the hydrodynamic model was specified using data and information from two sources: Light Detection and Ranging (LiDAR) survey and site plan drawings[9]. Digital elevation data were produced from the LiDAR survey conducted in 2010 by Airborne Solutions International LLC (Figure 2-1). The geo-referenced site plans were overlaid onto the digital elevation data to ensure the match of two boundary lines of model domain. Then, model bathymetry data were interpolated onto numerical grid cells by averaging all data points within each cell. Grid coordinates are referenced to UTM, PSAD56-South America, Zone 21, and all elevations are determined by applying the EGM-96 Geoid Model.

The numerical grids were constructed by overlay onto the geo-referenced site plans and digital elevation data. The boundary-fitted numerical grids contain 370 cells for the MWP and 501 cells for the TMA-D2 (Figure 2-2 and 2-3). The numerical grid resolution is sufficiently fine to properly

[8] http://www.epa.gov/athens/wwqtsc/html/efdc.html
[9] Data source: Tetra Tech Inc., Golden, CO.

resolve a range of spatial scales of dispersed PCOI plumes and circulation patterns affecting mixing processes. Average grid cell sizes are about 23 meters for the MWP and 17 meters for the TMA-D2.

Using hydraulic structure information (e.g., pipeline and spillway location, elevation, and size) provided by the client's design engineer (Tetra Tech), the inflow and outflow cells were allocated appropriately at the corresponding structure locations.

Hydraulic Boundary Conditions (Inflow and Outflow)

Hydraulic boundary conditions primarily drive hydrodynamic mixing and dispersion of the PCOIs in the diversion ponds. They include inflows and outflows in a site water balance which are calculated using site-specific meteorological data and drainage information. Several years onsite precipitation data was available but they were not sufficient for long-term (22 years) model simulations; therefore, the precipitation was inferred using publicly available data from the Timehri (Cheddi Jagan) International Airport, approximately 170 km from Aurora project site (AMEC, 2012a).

The Aurora site has a humid, tropical climate with high annual rainfall of approximately 2500 mm (98.3 in). The wet seasons are from mid-April to mid-August and from mid-November to around the end of January (AMEC 2012a). The average monthly precipitation is 102 mm during February (dry season) and 337 mm during June (wet season). About 55 percent of average annual rainfall is evaporated. Water diversion structures are designed to withstand at least a 100-yr storm. The rainfall depth for the 100-yr event with 24 hour duration is 374 mm (AMEC, 2012a).

The water balance comprises evaporation, inflows from the mine pits (A2) and freshwater pond (A6), and watershed runoff for the MWP (A5), and inflows from the tailings management area (A7) and diversion 1 (A8), and watershed runoff for the TMA-D2 (A9) (Figure 2-4). The inflows from the mine pits include all the collected water in the sump area originated from precipitation runoff and groundwater dewatering. The inflows from the tailings management pond include water pressed out from deposited tailings and precipitation runoff. Drainage data and assumptions for the water balance calculation are presented in Table 1.

Table 1- Drainage Data and Assumptions for Water Balance Calculation

					Percent coverage			
Sub-basin	Description	Watershed area (ha)	Elevation-spillway outflow (m)/Pump	Water pool area (ha)	Natural ground	Open pit slopes	Tailings pond and beach	Runoff coeff.
Drainage Contributing to MWP								
A2	MPs	110.5	Pumped	N/A	15	85	N/A	84
A5	MWP	113.4	56 [a]	29.0	74.4	N/A	25.6	63
A6	FWP	140.9	63	56.2	60.1	N/A	39.9	70
Drainage Contributing to TMA-D2								
A7	TMA	222.5	64, 69, 73	207.0	7.0	N/A	93.0	97
A8	TMA-D1	162.2	64	5.6	96.5	N/A	3.5	52
A9	TMA-D2	62.3	61	12.3	80.3	N/A	19.7	60

Notes:

Source: (Tetra Tech, 2013)

MP- mine pits, MWP- mine water pond, TMA- tailings management area

FWP- fresh water pond, TMA-D1- TMA area diversion 1

TMA-D2- TMA diversion 2

[a] The spillway has 1 m excavation below the 56m of invert elevation of box culvert. No detailed size information was provided at this stage of modeling analysis.

Hydraulic model boundary conditions were specified, using temporal water balance data generated for the proposed mining operation period (YR2012~2034) using the monthly-average precipitation condition (Figures 2-5 and 2-6). The Tetra Tech design team provided the monthly-average water balance data estimated for the proposed site plan. They used simple rational method for runoff calculation. The estimate utilized the monthly average meteorological precipitation data, the drainage characteristics noted in Table 1, storage-stage curves, and spillway elevation information to develop temporal water balances in the MWP and TMA-D2. The mean inflow rates over the operational period are summarized in Table 2.

Table 2- Mean Inflow Rates at Model Boundaries

Mine Water Pond (MWP)		Tailing Management Area Diversion 2 (TMA-D2)	
Description	**Monthly-average (m^3/s)**	**Description**	**Monthly-average (m^3/s)**
Pumped flow from mine pits	0.186	Overflow from TMA	0.079
Runoff	0.048	Runoff	0.028
Overflow from fresh water pond	0.016	Overflow from TMA-D1	0.053
Evaporation	0.013	Evaporation	0.009

Inflow rates depend on the seasonal precipitation and drainage characteristics. It peaks during wet seasons (June and December) and drops during dry season (February through March). For the MWP, the largest contribution occurs from the pumping inflow from the mine pits. Combined flows from local runoff and overflow from the FWP is much smaller than from the mine pits. The MWP storage is filled about a month later from the beginning of operation. However, the overflow from the FWP begins about three years later due to the large pond storage. For the TMA-D2, the largest contribution occurs from the TMA pond overflow. No overflow periods reflect the raise of TMA dam at the beginning (64 m), interim (69 m), and final (73 m) stage of operation. Combined flows from local runoff and overflow from the TMA-D1 is equivalent to the overflow from the TMA pond. The TMA-D2 storage is filled about 5 months later after initiation of mineral processing operations.

Outflows to environment are calculated in the model using the rating curves developed for outlet structures. The rating curves are developed based on the standard engineering method (Lindeburg, 2008). The MWP spillway discharges water through a concrete box culvert on the eastern side of pond. The box culvert would be excavated down like a groove about 1 meter to the existing natural drainage channel[10]. Therefore, water will begin to discharge out at the invert elevation (55 m) of excavated channel at a lower rate until reaching the invert elevation of box culvert. The TMA-D2 spillway discharges water through a generally trapezoidal channel with 61 meter invert elevation. Detailed design information (i.e., dimension of flow control structures in spillway) was not available. As a consequence, we estimated the size based on the 100-yr storm condition in consultation with Tetra Tech design team[11]. The outflow structures were sized to pass the extreme precipitation conditions before reaching the freeboard elevation of dam. The rating curves were developed using the following culvert flow equation assuming partially-full flow.

$$Q = C_d A_0 \sqrt{2gH}$$

where C_d=0.62 for square edge opening, and A_0= culvert area or wetted area, H is the hydraulic head, and g is gravity constant. The estimated spillway rating curves for the MWP and TMA-D2 are presented in Figure 2-7.

Other boundary conditions include wind, which affects overall hydraulic dispersion and the mixing patterns of PCOIs within the system. The model assumed a north wind with an average speed of 1.8 m/sec based on the on-site meteorological measurements from the year 2006 through 2011.

Water Quality Modeling Approach

The current water quality modeling approaches focus on the selected PCOIs and their predominant pathways and attenuation mechanisms (Figure 2-8). More extensive water quality modeling exercises considering all pathways and attenuation processes are beyond the current scope of work. However, in our professional judgment consideration of primary mechanisms with conservative assumptions is sufficient in achieving the current modeling objectives. Our water quality modeling approach consists of the following steps:

[10] Based on Tetra Tech preliminary design document (drawing #: 11431127500-DWG-C0119), 2012
[11] Conference call and E-mail communication with Tetra Tech design team, Feb 20 and March 14, 2013.

- Step 1: Selection of PCOIs;
- Step 2: Evaluation of primary pathways and attenuation processes of PCOIs;
- Step 3: Evaluation of water quality model parameters (e.g., volatilization, adsorption, settling); and
- Step 4: Development of water quality boundary conditions (PCOI influx).

Step 1- Selection of PCOIs

The PCOIs for water quality modeling analysis are potential leachate metals (arsenic, chromium, copper, and nickel), iron, petroleum hydrocarbons, cyanide, and total suspended solids (TSS). The selected metals are abundant in mining rocks; therefore, weathering processes can leach the metals. However, these elemental abundances are not necessarily indicative of environmental availability (i.e., leaching). Actually, the humidity cell test shows that the selected elements are below the IFC guidelines in all the samples, except for arsenic in one sample under site-specific conditions (KCB, 2012). Petroleum hydrocarbons can be generally introduced into the MWP from the open pit areas due to leakage or accidental spill of fuel oils during mining operations. Iron and residual cyanide are of primary interest in the TMA where tailings are deposited after gold leaching and completion of cyanide detoxification processes. Geochemical assessment of tailings materials (decant solution) shows that most soluble metal concentrations are much lower than the effluent guidelines (IFC, 2007), but iron and residual cyanides (total and free cyanide) have potentially higher concentrations close to the IFC guidelines for oxide composite test samples under laboratory conditions (AMEC, 2010b). Weak acid dissociable (WAD) components of cyanide (CN_{WAD}) were not considered in the modeling analysis, as they are the cyanide components readily released from cyanide complexes at a moderate pH (4.5). It includes free cyanide present and cyanide released from nickel, zinc, copper and cadmium complexes (but not iron or cobalt complexes). The laboratory measurement of CN_{WAD} indicates that the majority is in the form of free cyanide (see Table 6 in AMEC 2010c). High TSS can also potentially be generated from watershed runoff erosion processes in the open pit and tailings deposit areas.

Step 2: Evaluation of primary pathways and attenuation processes of PCOIs

Each PCOI undergoes its own pathways and attenuates differently in the diversion system as depicted in Figure 2-8. The leachate metals do not degrade in the environment but settle to the bottom and persist in the surface water system for long periods of time. The primary attenuation mechanism for leachate metals is adsorption to sediment particles that settle to the bottom of the retention structure. The attenuation (settling) rate is dependent on the partitioning between water and sediment phase and TSS properties and concentration. Other attenuation mechanisms such as chemical precipitation are considered insignificant in the diversion systems under natural environmental conditions.

Petroleum is an extremely complex mixture of hydrocarbons and its degradation is complex in a natural ecosystem. Diesel is fairly quickly biodegraded in aerobic condition while some components biodegrade very slowly, depending on site-specific environment conditions such as temperature, oxygen, nutrients, and salinity. A range of first-order degradation rate constants reported in literature can be used for hydrocarbon fate and transport modeling. Hydrocarbons such as benzene also tend to be adsorbed to sediments, comparable to some leachate metals. However, the settling attenuation due to adsorption is insignificant compared to biodegradation.

Tailings deposited in TMA are expected to be routinely detoxified to <0.5 mg/L (TetraTech, 2013) prior to deposition; additional loss of residual cyanide due to several different natural attenuation processes may be expected in the TMA pond, reducing the cyanide concentration to lower levels. Overflow from the TMA spillway introduces the residual cyanide into the TMA-D2 pond before discharge to environment. Quantification of a complete cyanide mass balance is extremely difficult because of its dependence on the water balance, weather conditions, impoundment geometry, and tailing chemistry, all of which may vary significantly over the life of a mine (Botz, M. and Mudder, T, 2000). Natural attenuation of cyanide is a complex process that includes many pathways: volatilization, oxidation, hydrolysis, precipitation, complexation, and sorption (Lötter, 2005). Several studies (Schmidt et al, 1981; Smith and Mudder, 1991; Lye et al., 2004) suggest that volatilization is the predominant attenuation mechanism, accounting for about 90% of cyanide removed from tailing impoundment for the typical pH condition (6~8) expected at the mine site.

Major sources of sediment loading at mine sites can be open pit areas, waste rock and overburden piles, tailing deposits, and drainage area. Sediment-laden surface runoff typically originates as sheet flow and collects in channels, diversion ponds, and open pits. A portion of suspended sediments introduced into the MWP and TMA-D2 would not deposit, resulting in the potential impacts on water quality in the environment. The main factors causing surface erosion include the runoff volume and velocity, soil properties and vegetation, slope and length of overland flow, and operational erosion control plans. The primary attenuation mechanism for TSS is settling in the MWP and TMA diversion ponds. The settling rate is dependent on the particle size distribution and flocculation processes.

Step 3: Evaluation of water quality model parameters

Based on the evaluation of primary attenuation pathways and mechanisms, key water quality modeling parameters corresponding to the PCOIs were identified as follow:

- Residual cyanides (total and free cyanide) - volatilization, adsorption;
- Iron - adsorption;
- Leachate metals - adsorption;
- Petroleum hydrocarbon (benzene) - biodegradation/volatilization, adsorption; and
- TSS - settling

Attenuation parameter values found in the literature and public web sources are summarized in Table 3. Due to large uncertainties in the parameter values, we adopted a conservative approach in predicting the discharge concentration.

Table 3- Key Attenuation Parameters

Facility	PCOIs	Primary Attenuation Mechanisms and Model Parameter Values		
		Volatilization (day^{-1})	Adsorption (log L/kg) K_{OC}	Settling (mm/s)
TMA	[a] CN_T	[b] 0.186	[c] 0.996	-
	[a] CN_F	[b] 0.186	[c] 0.996	-
	Fe	-	[c] -0.7	-
	TSS	-	-	Silt size-0.88 Clay size-2×10^{-4}
MWP	As	-	1.398	-
	Cr	-	3.079	-
	Cu	-	1.602	-
	Ni	-	1.204	-
	Benzene	0.2	1.82	-
	TSS	-	-	Silt size- 0.88 Clay size- 2×10^{-4}

'-' : not applicable or insignificant

Note:

a) Total cyanide (CN_T) is the sum of all the different forms of cyanide present in a system except CNO and CNS produced as result of detoxification processes. Free cyanide (CN_F) is the sum of hydrogen cyanide (HCN) and cyanide ion (CN-). Current modeling does not consider weak acid dissociable cyanide (CN_{WAD}) the cyanide components that are readily released from cyanide complexes when pH is lowered to 4.5. It includes free cyanide present and cyanide released from nickel, zinc, copper and cadmium complexes (but not iron or cobalt complexes). The laboratory measurement of CN_{WAD} indicates that the majority is free cyanide (see Table 6 in AMEC 2010c).

b) Only hydrogen cyanide (HCN) volatilizes. The volatilization rate for cyanide is a conservative (low) value from Broderius and Smith (1980) with similar environment conditions (T= 25 oC, pH=7.9, [CNF]=0.025~0.2 mg/L, no air flow). Assumes photolysis releasing cyanide ion and precipitation of metal-cyanide complexes is very small (6.29~51.4×10-4 day-1) relative to volatilization rate.

c) Adsorption coefficients values except for iron were obtained from GSI chemical database (http://www.gsi-net.com/en/publications/gsi-chemical-database/). The coefficients values for iron was based on the USGS paper (Proceedings of the Technical Meeting Charleston South Carolina March 8-12, 1999--Volume 1 of 3--Contamination From Hard-Rock Mining, Water-Resources Investigation Report 99-4018A).

The volatilization rate depends on fluid mechanical regimes between water body and lower atmosphere. In the environment, these are often unpredictable and can change rapidly within a short time which can lead to change of rate by up to a factor of 10 (Mackay, 1977). Given these constraints, an appropriate modeling strategy for cyanide is to utilize a volatilization rate constant available in literature based on the combined laboratory and field measurements on many tailing facilities. It is assumed that the air and water bodies are well mixed, therefore that background concentrations in the atmospheres are negligible, and that diffusion in the water is not limited by such as thermocline. It has been found in various studies that cyanide volatilization from water body follows first-order kinetics in thin surface layer with respect to the concentration of aqueous cyanide (Broderius and Smith, 1980; Huiatt et al, 1983; Adams, 1990). This is based on the assumption that the species within water will be vertically well mixed by diffusion and advection, which is reasonable assumption for the shallow TMA-D2 pond.

Because volatilization occurs only across the water surface, the first-order rate constant (k) is estimated by $k=(A/V)\cdot k_v$ where k_v= volatilization rate constant, A= surface area of pond, and V= volume of pond.

Adsorption rates (i.e., partitioning coefficients) of the PCOIs are dependent on individual physico-chemical characteristics and various geochemical characteristics of sediments. These generally vary in wide range in the natural environment. A literature survey (EPA, 1999; GSI chemical database; Nordstrom ,1999; Allison and Allison, 2005) was conducted to obtain equilibrium partitioning coefficients to describe the partitioning of metals between sediment and water phase. For consistency, conservative values from the GSI database were selected except for iron, which was unavailable. The partitioning coefficient of iron was back-calculated from the measurement data in the USGS paper (Nordstrom, 1999). In the water quality model, a solid fraction (F_p) of total PCOIs is calculated by the equilibrium partitioning formula, $F_p=K_d\cdot C/(1+K_d\cdot C)$, where K_d = partitioning coefficient (L/kg) and C = TSS concentration (kg/m^3).

Benzene was selected for representation of petroleum hydrocarbon leaked from accidental spills in the mine pit area. The degradation rate constant for BTEX (benzene, toluene, ethylbenzene, xylenes) was estimated using field and laboratory data from 115 sites (Newell and Rifai). Bulk attenuation coefficients values for aerobic condition are selected for this modeling study. The median value is consistent with other spill studies reviewed in Atlas (1981) and Adcroft et al. (2010).

Cohesive sediments (< 60 μm) tend to aggregate to form large, low-density units. This process is strongly dependent upon the type of sediment, the type and concentration of ions in the water, and flow condition (Mehta et al. 1989). Settling velocity of cohesive sediments is given $w_s=\phi_{floc}\cdot w_{so}$, with ϕ_{floc}=flocculation factor, and w_{so}=sediment fall velocity of single suspended particle (van Rijn, 1984; 1993; 2007; Lee et al., 2005). The flocculation factor is function of sediment concentration (C^α) with α=calibration parameter; the parameter α was calibrated against the observed TSS value for the gold mine site located in vicinity of the current site (Nkofi, 1994). Single sediment fall velocities were calculated using the particle size distribution data of laboratory tailing samples (AMEC, 2010c). The particle diameters of 75 and 25 percentile weight passing were 35 μm and 4 μm, representing silt and clay sizes, respectively.

Many studies found that the decay (i.e., volatilization and biodegradation) of PCOIs generated by mining activities or in natural environment occurs according to a first order rate equation (Monod, 1942; Simovic, 1984; Botz, M. and Mudder, T, 2000). It is assumed that natural attenuation of PCOIs is a first-order reaction process expressed as the following equation in the water quality model.

$$\frac{d[C]}{dt} = -k[C]$$

where [C]= the concentration of the constituent of interest and k= the first order rate constant.

Step 4: Development of water quality boundary conditions (PCOI influx)

Water quality boundary conditions are the mass influx of PCOIs into the diversion ponds. The development of water quality boundary conditions is based on the laboratory test results and standard engineering method with some assumptions. Water quality inputs included the following information:

- Tailings Management Area
  - PCOIs (CN_T, CN_F, Fe, TSS) concentrations of spillway overflow from the TMA pond;
  - TSS concentration of spillway overflow from the TMA-D1;
  - TSS concentration from local runoffs
- Mine Water Pond
  - PCOIs (As, Cr, Cu, Ni, Benzene, TSS) concentrations of the pumped inflow from the mine pit sump areas.
  - TSS concentration from local runoffs

Estimated model input values are presented in Table 4. A conservative approach was adopted, (using the upper bound of laboratory test data and engineering calculations) in developing the input concentrations.

Table 4- Model Input Concentrations of PCOIs

Facility	PCOI	Model Input Concentration of PCOIs and Data				IFC Effluent Standard (mg/L)
		Runoff Conc.-modeling (mg/L)	Leaching Conc.-Lab Test (mg/L)	Decant Conc.-modeling. (mg/L)	Decant-Conc.-Lab Test (mg/L)	
TMA	CN_T	N/A	N/A	0.36	0.29	1
	CN_F	N/A	N/A	0.04	0.02	0.1
	Fe	N/A	N/A	0.66	1.82	2
	TSS-decant -runoff	[a] Seasonal variation (average: 114)	N/A	[a] Seasonal variation (average: 72)	-	50
MWP	As	0.027	0.027	N/A	N/A	0.1
	Cr	0.0035	0.0035	N/A	N/A	0.1
	Cu	0.019	0.019	N/A	N/A	0.3
	Ni	0.0023	0.0023	N/A	N/A	0.5
	Benzene	95	N/A	N/A	N/A	10(total oil and grease)
	TSS-pumped -runoff	[a] Seasonal variation (average: 1183, 268)	-	-	-	50

Notes:

N/A - not applicable or insignificant.
[a] Seasonal variation of TSS was estimated using GSSHA Kilinc-Richardson model (Kilinc and Richardson, 1973) and monthly-average runoff.

Cyanide inflow concentration assumes nominal performance (CN_T=1 mg/L and CN_F=0.1 mg/L) of the CN detoxification plant and dilution by local runoff in the tailing management area (A7). The laboratory test results of decant solutions of detoxified tailing samples are below the IFC effluent standard. However, the nominal performance assumption is considered more conservative scenario that can happen in variable environment conditions. The total cyanide (CN_T) was calculated from the ratio of the laboratory test result between total and free cyanide. Then, the concentration (C_{TMA}) in the TMA pond was calculated by mass balance equation, $C_{TMA}=C_{mill,\ nominal}*Q_{mill}/(Q_{mill}+Q_{runoff})$ to consider the dilution effects from local runoff. The calculated cyanide concentrations in the TMA are shown in Table 4, column 5.

Iron inflow concentration also followed the above method similar to cyanide based on the upper bound of laboratory concentration (1.82 mg/L). After dilution by local runoff in the TMA, the inflow concentration is estimated to be 0.66 mg/L as shown in Table 4, column 5.

Leachate metals concentrations in the pumped water from the mine pit area are very conservative extracted from the kinetic humidity cell test (KCB, 2012). Note that the laboratory leaching concentrations used for this model input are the averaged values of the largest value of each sample test for total eighteen samples. The results of the kinetic humidity cell testing indicate a near-neutral to slightly alkaline pH leachate due to the abundance of carbonate buffering potential of waste rock materials with a low sulphide content. Therefore, the possibility seems very low of high leachate concentration due to chemical dissolution.

Benzene spill concentration in the mine pits were determined based on the maximum amount of a spill from CAT 740B truck, assuming one event (230 gallons) distributed over a nominal 12 hour pumping period. The concentration for average pumped flow into the MWP is estimated by the mass balance equation, $C_{pump}=M_{spill}/Q_{pump}$=766 kg/8042 m^3=95 mg/L.

TSS loadings were estimated using the GSSHA Kilinc-Richardson model (Kilinc and Richardson, 1973) for soil erosion from the monthly runoff conditions. Then, considering dilution and trapping effects, the overflow concentrations (C_{TSS}) from the TMA decant pond (A7) and TMA-D1 (A8) to the TMA-D2 were estimated based on water balance, sediment settling, and retention time information, as well as from the MP (A2) and the FWP (A6) to the MWP. Detailed calculation procedures are as follow.

$$C_{runoff} = q_{GSSHA} \cdot P_{pool} \cdot (1 - T_{land}) \cdot f_D / Q_{runoff}$$

$$C_{TSS} = \frac{Q_{runoff} \cdot C_{runoff} + Q_{in} \cdot C_{in}}{Q_{runoff} + Q_{in}} \Big/ \left(1 + \frac{w_s}{D} \cdot T\right)$$

where C_{runoff}= local runoff TSS concentration (kg/m^3), q_{GSSHA}=GSSHA sediment transport rate (kg/m·s), P_{pool}=pool perimeter (m), T_{land}= overland trap efficiency, f_D=dilution factor by other inflow such as groundwater, Q_{runoff}= local runoff (m^3/s), C_{TSS}= average TSS concentration in pond (kg/m^3), Q_{in}=inflow rate from other sources (m^3/s) including mill plant, C_{in}=inflow TSS concentration (m^3/s), w_s= flocculated settling velocity (m/day), D=average water depth (m), and T=average retention time (day).

In the above TSS estimation, it was assumed that no settling occurs in the mine pit sump areas because of no nominal storage volume available due to continuous pumping. Potentially the pump may not remove all sediments in the mine pit sump but our assumption would be that all sediments would be removed. Considering the sediment trapping effects in overland flow (Helmers, 2005), fifty percent of eroded mass was assumed to enter the pool area. In the mine pits, clean groundwater seepage dilutes local runoff TSS concentration (f_D=0.33). Our calculation indicates large reduction of TSS concentration from the FWP and TMA-D1 due to settling. However, high TSS concentration in local runoffs and inflow from the TMA pond and mine pits are expected due to large soil erosion and from the absence of storage effects in the sump. Significant seasonal variations are predicted according to precipitation runoff. After settling of large size particles in the TMA pond, smaller (clay) size particles would be dominated in the TMA overflow; we have assumed 80 % clay and 20 % silt. It is assumed that other inflow has the same portion of clay and silt size distribution. A different distribution of particles affects the settling rate, and thus the discharge concentration.

Model Initialization

Initial conditions were specified for hydrodynamic and water quality model simulation. For simulation of long-term, monthly-average, meteorological conditions, the initial PCOI concentrations in the MWP and TMA-D2 are set to zero as the PCOIs will be introduced after the start of mining operation. The initial water surface elevations were set to 56 m in the MWP and 61 m in the TMA-D2. Flow field in the pond is driven by inflows and outflow, as well as wind stress at the water surface. Velocity response to these forcing mechanisms is generally quick. Therefore, the initial velocity fields are set to zero in the entire model domain.

Evaluation of Design Alternatives

Water quality modeling analyses were performed to evaluate design alternatives for the impacts of PCOIs on surface water quality in the receiving waters (i.e., tributary streams and Cuyuni River). The focus of this evaluation is to predict the concentration of PCOIs discharged to environment (C_{out}) relative to IFC limits under normal mine operation conditions (IFC, 2007). The predictions will allow the evaluation of water quality impacts of the proposed design alternatives and accidental spills that can happen during mining operations. Essentially, the discharge concentration is determined by the PCOIs loadings and the combined effects of water balance, geometric characteristics of diversion system, and natural attenuation rates of specific PCOIs . The predicted discharge concentrations compared to the (IFC, 2007) effluent guidelines are summarized in Table 5 below.

Table 5- Predicted Discharge Concentrations at Outlet.

PCOIs	Predicted Average (mg/L)	Predicted Maximum (mg/L)	$^{a}C_{out}/C_{in}$ (Ave Ratio/Max Ratio)	IFC standard (mg/L)
MWP				
Arsenic (As)	0.0209	0.0237	0.77/0.88	0.1
Chromium (Cr)	0.0027	0.0031	0.77/0.89	0.1
Copper (Cu)	0.0147	0.0167	0.77/0.88	0.3
Nickel (Ni)	0.0018	0.0020	0.78/0.87	0.5
Benzene	0.0032	0.4354	3.4E-5/4.6E-3	10 (total oil)
TSS	**79.1**	**145.0**	0.07/0.12	50
TMA				
Total Cyanide (CN_T)	0.129	0.241	0.37/0.69	1
Free Cyanide (CN_F)	0.006	0.013	0.15/0.35	0.1
Iron (Fe)	0.261	0.481	0.40/0.73	2
TSS	21.0	**62.9**	0.29/0.55	50

Note:

[a] C_{out} is the predicted average/maximum concentration over the entire operational period at outlet and C_{in} is average input concentration from mine pits and tailings management pond.

The model results indicate that the concentrations of cyanide are below the IFC standard assuming nominal performance (CN_T=1 mg/L and CN_F=0.1 mg/L) of detoxification plant but TSS may exceed the (IFC, 2007) standard. Other constituent concentrations are expected to be below the IFC standard. The followings sections relate to the detailed analyses of modeling results.

Mining Water Pond

Predicted spatial distributions and temporal variations at the outlet of the concentrations of PCOIs (As, Cr, Cu, Ni, benzene, and TSS) for the monthly-average operation conditions are shown in Figure 3-1 through 3-7. The 2D snapshots of metal concentration and TSS were taken at YR1 (Jan 30th in 2014), YR2 (Jan 30th in 2015), YR13 (Jan 30th in 2026), and YR22 (Dec 30th in 2034) at the end of simulation. The 2D snapshot of predicted benzene concentration was taken at YR11 (Jan 17th in 2024) two days after an assumed accidental spill. The second wet season starts usually from Mid-November and ends around the January. Thus, the January snapshots likely belong to the dry season. Overall, the temporal variations of discharge concentration follow the influx variations of pumped mine pit water but are damped by the dilution and attenuation.

The predicted discharge concentrations of metals from mine pits are well below the IFC guidelines because the leachate input concentrations are very low under the site-specific geochemical conditions. Dilution is the primary controlling factor, and is generated by the local runoffs and freshwater inflow from the FWP; the average combined runoff and freshwater inflow is about a third of inflow pumped from the mine pits. Adsorption to sediment particles is estimated to be insignificant (< 1%) compared to total mass fraction in water column. However, elevated constituent concentrations would be expected in the deposited sediments due to accumulation effects. The distributions of metal concentration have downgradient variation along the plume trajectory from the pumping location in the northwest channel corner. The dispersion of PCOIs within the MWP is governed by the combined hydrodynamics of all inflows and average wind-driven circulation (1.8 m/s by north wind). Due to the proximity of FWP spillway inflow to the outlet, the dilution near the outlet becomes prominent particularly during wet season.

The predicted discharge concentration of benzene (Figure 3-5) from the mine pits is far below the IFC guideline for the accidental spill scenario (C_{in}=95 mg/L for 12 hours) in spite of the conservative inflow concentration higher than the guideline (10 mg/L for total oil and grease). The model prediction indicates that the biodegradation is single predominant parameter that determines the discharge concentration ($C_{out}/C_{in}=3.4\times10^{-5}\sim4.6\times10^{-3}$) for highly attenuated constituents such as benzene. The spilled benzene is quickly attenuated by degradation and dilution in a large storage volume and by other inflows when transported by the currents. Two days after the spill, the benzene concentration decreases below 20 mg/L anywhere in the MWP.

The predicted discharge concentration (C_{ave}=79 mg/L and C_{max}=145 mg/L) of TSS at the outlet exceeds significantly the IFC guideline (50 mg/L) during most of the operation period except short dry seasons. This is mainly attributed to high TSS input concentration (C_{in}=1183 mg/L) from the mine pits. Higher concentration of TSS plumes is predicted along the channel which the current induced by the pumping inflow is strong. This channel area is expected to get higher sediment deposition unless a large storm event resuspends it. The wet season (YR22) shows much higher concentration than the dry seasons (YR1, YR2, YR13). Interestingly, the predicted TSS figures (Figure 3-6) show the current and TSS distribution different from other PCOIs. The current patterns are modified by the density-driven circulation caused by the buoyancy effects of suspended sediments particles. However, the velocity is still relatively small (<2 cm/s). Due to no site-specific TSS data being available, we expect large uncertainties in model input concentrations and flocculated settling velocity which could introduce some uncertainties in the model prediction results.

Short-circuiting of PCOI plume seems not being prominent for the monthly-average operation conditions. This is mainly attributed to the remoteness of outlet from the pumping inflow location. Wind-driven circulation in the deeper east pond area enhances large-scale mixings. This effect is less apparent in the TSS distribution. Despite small velocity (< 2 cm/s), wind-generated circulation is dominant dispersion mechanism that contributes to turbulent mixing at larger scale than molecular diffusion. The sensitivity analysis indicated the wind direction has no notable effects on the discharge concentration.

Predicted minimum and maximum concentrations of PCOIs in the MWP and at outlet during the each snapshot year are summarized below in Table 6. The concentrations in the MWP were averaged over the entire model domain while the concentrations at outlet were taken at the cell corresponding to the outlet location (see Figure 2-2).

Table 6- Predicted Minimum and Maximum Concentration of PCOIs in MWP Diversion System

PCOIs	**Year**	**MWP**		**Outlet**	
Concentration (mg/L)		Min	Max	Min	Max
As	YR1	0.0021	0.0241	0.0010	0.0237
	YR2	0.0219	0.0241	0.0210	0.0237
	YR13	0.0212	0.0241	0.0175	0.0236
	YR22	0.0212	0.0241	0.0175	0.0236
Cr	YR1	0.0011	0.0031	0.0010	0.0031
	YR2	0.0028	0.0031	0.0027	0.0031
	YR13	0.0028	0.0031	0.0023	0.0031
	YR22	0.0028	0.0031	0.0023	0.0031
Cu	YR1	0.0018	0.0170	0.0010	0.0167
	YR2	0.0154	0.0170	0.0148	0.0167
	YR13	0.0149	0.0170	0.0123	0.0166
	YR22	0.0149	0.0169	0.0123	0.0166
Ni	YR1	0.0011	0.0021	0.0010	0.0020
	YR2	0.0019	0.0021	0.0018	0.0020
	YR13	0.0018	0.0021	0.0015	0.0020
	YR22	0.0018	0.0021	0.0015	0.0020
Benzene	YR1	0.0000	0.0000	0.0000	0.0000
	YR2	0.0000	0.0000	0.0000	0.0000
	YR13	0.0000	0.0000	0.0000	0.0000
	YR22	0.0000	0.0000	0.0000	0.0000
TSS	YR1	8.0	220.7	0.0	144.6
	YR2	64.5	220.6	41.1	144.3
	YR13	64.6	217.4	39.2	134.7
	YR22	64.6	216.6	40.1	134.3

Note: Benzene spill scenarios occurred in YR4, YR12, and YR20.

Tailings Management Area Diversion 2

Predicted spatial distributions and temporal variations at the outlet of the concentrations of PCOIs (free cyanide, total cyanide, Fe, and TSS) for the monthly-average operation conditions are shown in Figure 3-8 through 3-12. The 2D snapshots of cyanide, iron and TSS were taken at YR1 (Jan 30th in 2014), YR2 (Jan 30th in 2015), YR13 (Jan 30th in 2026), and YR22 (Dec 30th in 2034) at the end of simulation. The YR1 and 13 snapshots are taken during a period of dam raise at the beginning (64 m) and interim (69 m) stage. No overflow from the TMA spillway occurs during this period. Generally, the temporal variations of discharge concentration follow the influx variation of TMA overflow but are damped by the dilution and attenuation.

The predicted discharge concentrations of residual cyanide from the TMA overflow are below the (IFC,2007) effluent guidelines for free cyanide and above for total cyanide. It should be noted that the estimate of inflow concentration assumed the nominal performance (CN_T=1 mg/L and CN_F=0.1 mg/L) of the detoxification plant. The laboratory tailing sample test demonstrated the decant concentration far below the IFC guideline (see Table 4). Therefore, we presume our prediction is very conservative that may happen for a worst case operation scenario. The model prediction shows that the volatilization of free cyanide is the single predominant parameter that determines the discharge concentration. The predicted average and maximum discharge concentrations are 0.03 mg/L and 0.0006 mg/L at outlet for free cyanide with a volatilization rate of (k=0.186 day^{-1}). Large attenuation of free cyanide is due to a long residence time with the monthly-average operation condition; the average retention time of the pond is about 99 days assuming Continuously Stirred Tank Reactors (CSTRs). In addition to dilution along the course of the plume trajectory, the free cyanide volatilizes quickly while the release of cyanide ions from cyanide complexes are very slow ($k_{photolysis}$= 6.3~51.4×10^{-4} day^{-1}). For total cyanide, the concentration is sum of free cyanide and cyanide complexes that do not volatilize directly. Photolysis mechanisms releasing cyanide ion are not significant when compared to volatilization, and precipitation and adsorption to sediment particles is also considered insignificant. Within current site-specific neutral pH range (pH 6~8), we presume the cyanide species distribution is relatively stable (Botz and Mudder, 2000). Therefore, the primary attenuation of total cyanide occurs due to free cyanide volatilization. There might be some potential releasing the cyanide ions in environment when favorable geochemical conditions (e.g. low pH) are established. Further investigation of this possibility is beyond the current scope of study.

The predicted discharge concentration (C_{max}=0.48 mg/L) of iron originated from the TMA overflow is below the IFC guideline because the nominal input concentration (0.66 mg/L for overflow and 1.82 mg/L from mill plant) is already lower than the guideline. The dilution is primarily controlled by the local runoffs and freshwater inflow from the TMA-D1; the average combined runoff and freshwater inflow is about same with the overflow from the TMA pond. The adsorption to sediment particles is estimated insignificant (< 1%) in total mass fraction in water column. However, elevated iron concentration would be expected in the deposited sediments due to accumulation effects.

The predicted discharge concentration (C_{ave}=21 mg/L and C_{max}=62 mg/L) of TSS slightly exceeds the IFC guideline (50 mg/L) only during wet seasons. This is mainly caused by higher TSS loading (C_{max}=151 mg/L × Q_{ave}=208,098 m^3/mon) in the clay size class (low settling velocity) from the TMA overflow after the first stage settling of large silt size particles in the decant pond. TSS input concentration (C_{max}=181 mg/L) from the local runoffs is higher, but the sediment loading is significantly lower due to the smaller inflow rate (Q_{ave}=72,698 m^3/s). Also, a significant portion of large silt size particles settle more quickly after entering the pond and the small clay size particles are diluted with the large amount (Q_{ave}=139,672 m^3/mon) of fresh water inflow from the TMA-D1. TSS input from TMA-D1 is much smaller amount because of the first stage dilution and deposition in the TMA-D1 before they are conveyed to the TMA-D2. No overflow from the TMA spillway occurs at YR1 and YR13 during the TMA dam raise, showing low TSS concentration. Therefore, the discharge concentration is determined as the results of mixing of only local runoff TSS with the freshwater from TMA-D1. During the period of TMA overflow, higher TSS plumes are predicted in the deeper north pond area near the spillway. This area is expected to get higher sediment deposition. TSS tends to deposit along the plume trajectory. A wet season (YR22) shows much higher concentration than a dry season (YR2). Interestingly, the current patterns are modified by the density-driven circulation caused by buoyancy effects of suspended sediments particles, resulting in distribution patterns for TSS that are different from the other PCOIs.

Generally, the predicted discharge concentrations are higher than the theoretical steady state concentrations assuming Continuously Stirred Tank Reactors (CSTRs). Due to the proximity of the discharge outlet to the TMA spillway, short-circuiting of PCOI plumes occurs despite a large design detention time for the pond. Notably, a significant amount (67 % of TMA overflow) of fresh water from the TMA-D1 keeps the PCOI concentration lower generally in the south pond area, causing incomplete mixing. The wind-generated circulation is dominant but the velocity is still very small (< 2 cm/s). However, it contributes significantly to turbulent mixing at larger scale than molecular diffusion. The sensitivity analysis indicated that the wind direction has no notable effects on the discharge concentration. The distributions of PCOI concentration except for TSS have relatively higher concentration in the west circulation cell directly introducing the PCOIs from the TMA overflow. A part of PCOI plume from the TMA spillway is introduced into the more channelized current flowing to the discharge outlet. The PCOIs introduced are further diluted by the overflow traveled from the TMA-D1 and local runoffs.

Predicted minimum and maximum concentrations of PCOIs in the TMA and TMA-D2 and at outlet during the each snapshot year are summarized below in Table 7.

Table 7- Predicted Minimum and Maximum Concentration of PCOIs in TMA Diversion System

PCOIs	**Year**	**TMA**		**TMA-D2**		**Outlet**	
Concentration (mg/L)		Min	Max	Min	Max	Min	Max
CN_F	YR1	0.0000	0.0000	0.0000	0.0008	0.0000	0.0008
	YR2	0.0322	0.0549	0.0000	0.0093	0.0000	0.0114
	YR13	0.0234	0.0439	0.0000	0.0000	0.0000	0.0000
	YR22	0.0234	0.0439	0.0060	0.0106	0.0079	0.0126
CN_T	YR1	0.0000	0.0000	0.0000	0.0018	0.0000	0.0018
	YR2	0.3220	0.5493	0.0000	0.1799	0.0000	0.2213
	YR13	0.2670	0.4393	0.0000	0.0000	0.0000	0.0000
	YR22	0.2339	0.4393	0.1808	0.1907	0.2167	0.2312
Fe	YR1	0.0000	0.0000	0.0012	0.0099	0.0010	0.0099
	YR2	0.5861	0.9997	0.0098	0.3615	0.0097	0.4384
	YR13	0.4258	0.7995	0.0098	0.0099	0.0097	0.0099
	YR22	0.4258	0.7995	0.3597	0.3850	0.4267	0.4628
TSS	YR1	112.32	112.32	0.7	16.3	0.0	15.4
	YR2	50.62	76.15	6.0	33.8	4.9	44.0
	YR13	62.98	86.04	6.0	16.2	4.9	15.3
	YR22	62.98	86.04	10.9	45.3	10.5	61.5

The concentrations in the TMA and TMA-D2 were averaged over the entire model domain while the concentrations at outlet were taken at the cell corresponding to the outlet location (see Figure 2-3).

Potential Downstream Impacts in Watershed

Potential downstream impacts of all PCOIs except TSS on the Cuyuni River were evaluated with different attenuation rates based on available literature and public sources (Lötter, 2005; Newell, and Rifai). Downstream pathways were inferred from the site topographic drainage information (see Figure 2-1). The overflow from the MWP drains to Cuyuni River through relatively short drainage channels (length=1.7 km, slope=0.003). The discharge from the TMA-D2 flows through a relatively long stream (length=7.9 km, slope=0.0017), and eventually drains to Cuyuni River. Travel time was calculated using Manning's open channel flow equation assuming channel geometry inferred from the LiDAR topographic data. Using the downstream travel time and PCOI attenuation coefficient (k) values, a bounding analysis for potential attenuation (C_{cy}/C_{out}) of constituents entering the Cuyuni River was performed and is summarized in Table 8 below.

Table 8- Attenuation of Discharge Concentration in Watershed at the Cuyuni River (C_{cy}/C_{out})

Discharge from Mine Water Pond					
	Travel time (hours)	Metals (k=0.0)	Hydrocarbon (k=0.04)	Hydrocarbon (k=0.22)	Hydrocarbon (k=0.36)
Monthly-average	1.12	1.00	1.00	0.99	0.98
Discharge from Tailings Management Area Diversion 2					
	Travel time (hours)	Iron (k=0.0)	Cyanide (k=0.01)	Cyanide (k=0.19)	Cyanide (k=0.93)
Monthly-average	7.46	1.00	1.00	0.94	0.75

This conservative bounding analysis shows that the attenuation of PCOIs due to natural decay is insignificant because of the short travel time. Further dilution is not considered; but would be expected to occur from rainfall runoff in sub-basins. The effect would be small for the discharge from the MWP due to the small amount of drainage involved. However, the effect could be potneitally quite significant for the discharge from TMA-D2, which has a large sub-basin area.

Summary and Conclusion

Two-dimensional, depth-averaged hydrodynamic and water quality models of the MWP and TMA/TMA D2 were developed and applied for this study. The primary objective of this study was to evaluate the potential surface water quality impacts from the proposed design and operation of the Aurora Gold Project. The PCOIs included selected leachate metals (As, Cr, Cu, Ni), benzene, TSS, and residual cyanides. Model calibration was not feasible because no site-specific data are available. However, comparison with analytical solutions indicated that the model prediction is valid at least within the CSTR conditions.

The water quality model was used to calculate the spatial distribution of current velocity, PCOI concentration, and temporal variation of discharge concentration at the outlet to environment for the monthly-average operation conditions. Further bounding analysis was also conducted to evaluate the downstream attenuation before entering Cuyuni River.

The key findings from this study are summarized as follows:

1) MWP
   - Predicted discharge concentrations of leachate metals are far below the IFC guidelines. Under the site-specific geochemical conditions, the possibility of exceeding the IFC guideline would appear to be very low.
   - The predicted discharge concentration of petroleum hydrocarbon (benzene) for assumed accidental spills is far below the IFC guideline. Significant attenuation (99.5 % reduction with k=0.2) is expected due to quick biodegradation.
   - Predicted discharge concentration of TSS significantly exceeds (Cave=79 mg/L and Cmax=145 mg/L) the IFC guideline (50 mg/L) during most of the operational period except during dry seasons. This is attributed to a high TSS input concentration (Cin=1183 mg/L in average) from the mine pits. However, a careful interpretation of results is needed because large uncertainties in input parameter values are unavoidable.

2) TMA-D 2
   - Predicted discharge concentrations of free cyanide are expected to be below the IFC guideline due to significant volatilization loss and dilution.
   - Predicted discharge concentrations of total cyanide are also expected to be below the IFC guideline during the operation except the periods of the TMA dam raise in which no overflow from the decant pond occurs. It should be noted that the estimate of inflow concentration assumed the nominal performance of detoxification plant. However, the laboratory tailing sample test showed the decant cyanide concentration to be well below the IFC guideline. Therefore, the model prediction is considered to be conservative and may correspond to a worst case operational scenario.
   - The predicted discharge concentrations of TSS slightly exceed the IFC guideline during wet seasons.

Potential natural downstream attenuation in stream or drainage channel due to biodegradation and/or volatilization is expected to be small or insignificant. The attenuation in sub-basin before entering the Cuyuni River is generally minimal due to short travel time. However, the further dilution proportional to drainage area will occur from runoffs in sub-basins. The effect would be larger for discharge from the TMA-D2 but smaller for discharge from the MWP.

Overall, model predictions showed more prominent short-circuiting (incomplete mixing) of PCOI plumes in the TMA-D2 than in the MWP due to the proximity of outlet to the TMA spillway. This short-circuiting problem may get worse in large storm event that can generate strong channelize flow. The intensified short-circuiting may result in elevated discharge concentrations of PCOIs.

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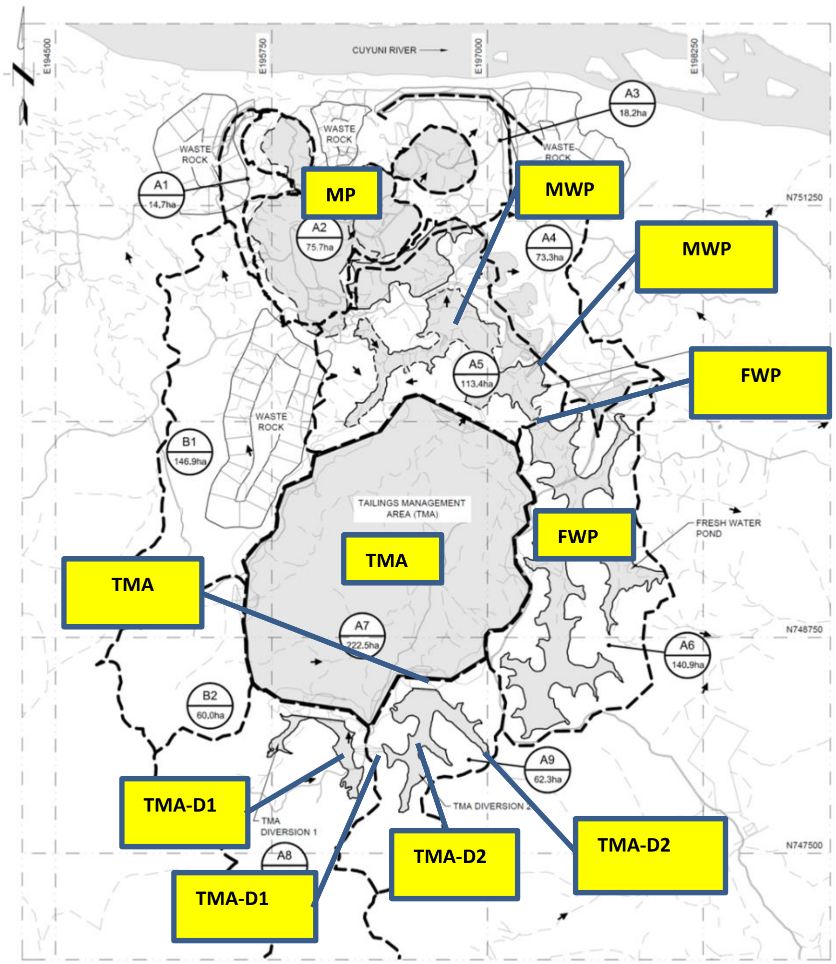

BASIN A1 - STAGE STORAGE TABLE				
ELEV	AREA (ha)	DEPTH (m)	INC. VOL. (cu. m)	TOTAL VOL. (cu. m)
57.000	4.80	N/A	N/A	0.000
58.000	33.59	1.000	17023	17023
59.000	83.63	1.000	56731	73754
60.000	138.26	1.000	109809	183563
61.000	217.92	1.000	176585	360148
62.000	300.73	1.000	258212	618361

BASIN A5 - STAGE STORAGE TABLE				
ELEV	AREA (ha)	DEPTH (m)	INC. VOL. (cu. m)	TOTAL VOL. (cu. m)
52.000	53.76	N/A	N/A	0.000
53.000	139.62	1.000	93351	93351
54.000	202.69	1.000	170194	263545
55.000	245.13	1.000	223574	487118
56.000	289.80	1.000	267155	754274
57.000	327.91	1.000	308660	1062934
58.000	367.84	1.000	347686	1410620
59.000	405.60	1.000	386568	1797188
60.000	446.23	1.000	425757	2222945

BASIN A6 - STAGE STORAGE TABLE				
ELEV	AREA (ha)	DEPTH (m)	INC. VOL. (cu. m)	TOTAL VOL. (cu. m)
54.000	10.47	N/A	N/A	0.000
55.000	32.28	1.000	20379	20379
56.000	83.79	1.000	56024	76402
57.000	136.06	1.000	108872	185274
58.000	206.66	1.000	170141	355416
59.000	288.24	1.000	246328	601744
60.000	370.04	1.000	328286	930030
61.000	437.30	1.000	403200	1333230
62.000	499.29	1.000	467951	1801180
63.000	562.63	1.000	530643	2331823

BASIN A7 - TAILINGS MANAGEMENT AREA (TMA) STAGE STORAGE TABLE				
ELEV	AREA (ha)	DEPTH (m)	INC. VOL. (cu. m)	TOTAL VOL. (cu. m)
54.000	52.70	N/A	N/A	0.000
55.000	140.63	1.000	93134	93134
56.000	283.01	1.000	207712	300846
57.000	446.43	1.000	361627	662473
58.000	571.40	1.000	507630	1170103
59.000	739.73	1.000	653758	1823861
60.000	933.48	1.000	834733	2658594
61.000	1,156.41	1.000	1042961	3701555
62.000	1,248.91	1.000	1202362	4903918
63.000	1,370.90	1.000	1309431	6213349
64.000	1,443.18	1.000	1406888	7620237
65.000	1,512.48	1.000	1477696	9097932
66.000	1,600.09	1.000	1556078	10654011
67.000	1,657.33	1.000	1628625	12282635
68.000	1,798.45	1.000	1727412	14010047
69.000	1,834.42	1.000	1816407	15826454
70.000	1,879.77	1.000	1857049	17683503
71.000	1,907.24	1.000	1893491	19576994
72.000	1,932.48	1.000	1919847	21496841
73.000	1,956.96	1.000	1944708	23441550
74.000	1,980.67	1.000	1968807	25410357
75.000	2,004.10	1.000	1992375	27402732
76.000	2,026.85	1.000	2015464	29418196
77.000	2,049.04	1.000	2037936	31456132
78.000	2,070.85	1.000	2059939	33516071

BASIN A8 - TMA DIVERSION 1 STAGE STORAGE TABLE				
ELEV	AREA (ha)	DEPTH (m)	INC. VOL. (cu. m)	TOTAL VOL. (cu. m)
62.000	5.97	N/A	N/A	0
63.000	17.94	1.000	11418.478	11418
64.000	56.05	1.000	35235.283	46653
65.000	80.57	1.000	67946.730	114600
66.000	100.67	1.000	90443.690	205044
67.000	128.46	1.000	114284.574	319328
68.000	156.14	1.000	142075.115	461403
69.000	185.05	1.000	170389.709	631793
70.000	214.12	1.000	199405.923	831199
71.000	240.87	1.000	227363.921	1058563

BASIN A9 - TMA DIVERSION 2 STAGE STORAGE TABLE				
ELEV	AREA (ha)	DEPTH (m)	INC. VOL. (cu. m)	TOTAL VOL. (cu. m)
58.000	5.91	N/A	N/A	0.000
59.000	39.90	1.000	20386	20386
60.000	83.60	1.000	60418	80805
61.000	122.72	1.000	102535	183340
62.000	153.55	1.000	137847	321187
63.000	178.47	1.000	165855	487042
64.000	204.22	1.000	191199	678241
65.000	231.54	1.000	217738	895979

NOTES:

1. ALL ELEVATIONS, GRID COORDINATES AND DIMENSIONS ARE IN METERS.
2. GRID COORDINATES ARE REFERENCED TO UTM, PSAD56-SOUTH AMERICA, ZONE 21.
3. ALL ELEVATIONS ARE ORTHOMETRIC AND WERE DETERMINED BY APPLYING EGM-96 GEOID MODEL.
4. EXISTING GROUND CONTOUR DATA PRODUCED FROM THE LIDAR SURVEY FLOWN JANUARY 13TH – 17TH, 2010,BY AIRBORNE SOLUTIONS INTERNATIONAL LLC.
5. WATERCOURSES (CREEKS) AND DRAINAGE CHANNELS SHOWN ARE INFERRED.

LEGEND:

- BASIN BOUNDARY
- SURFACE WATER FLOW DIRECTION
- A7 / 54.2ha — DRAINAGE BASIN IDENTIFICATION; AREA IN ha

0 125m 250m 375m 500m 625m 1250m
SCALE IN METERS

ENVIRON

FIGURE 1-1 Site and Surface Water Management Plan

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

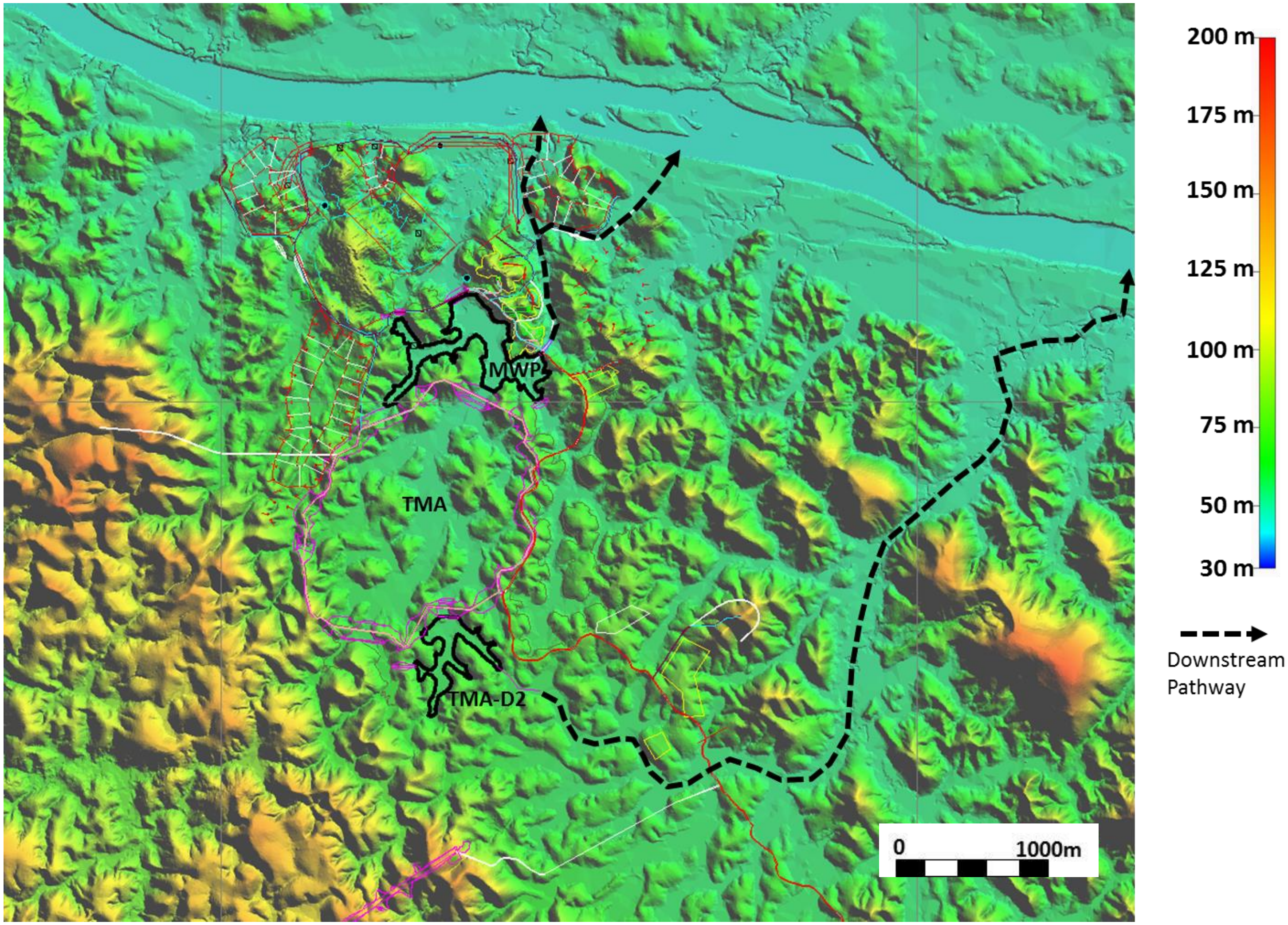

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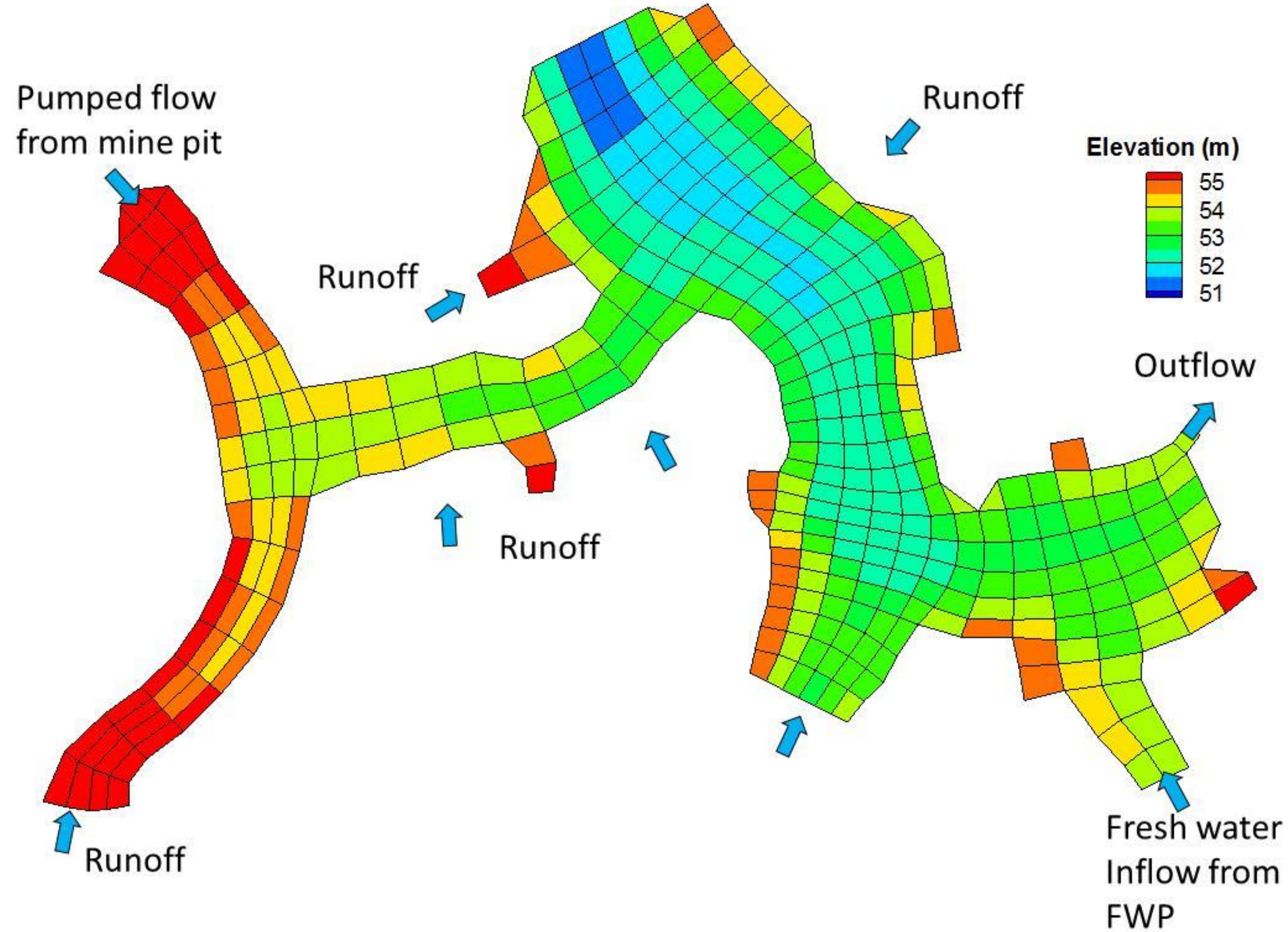
FIGURE 2-1 Site Topography Data

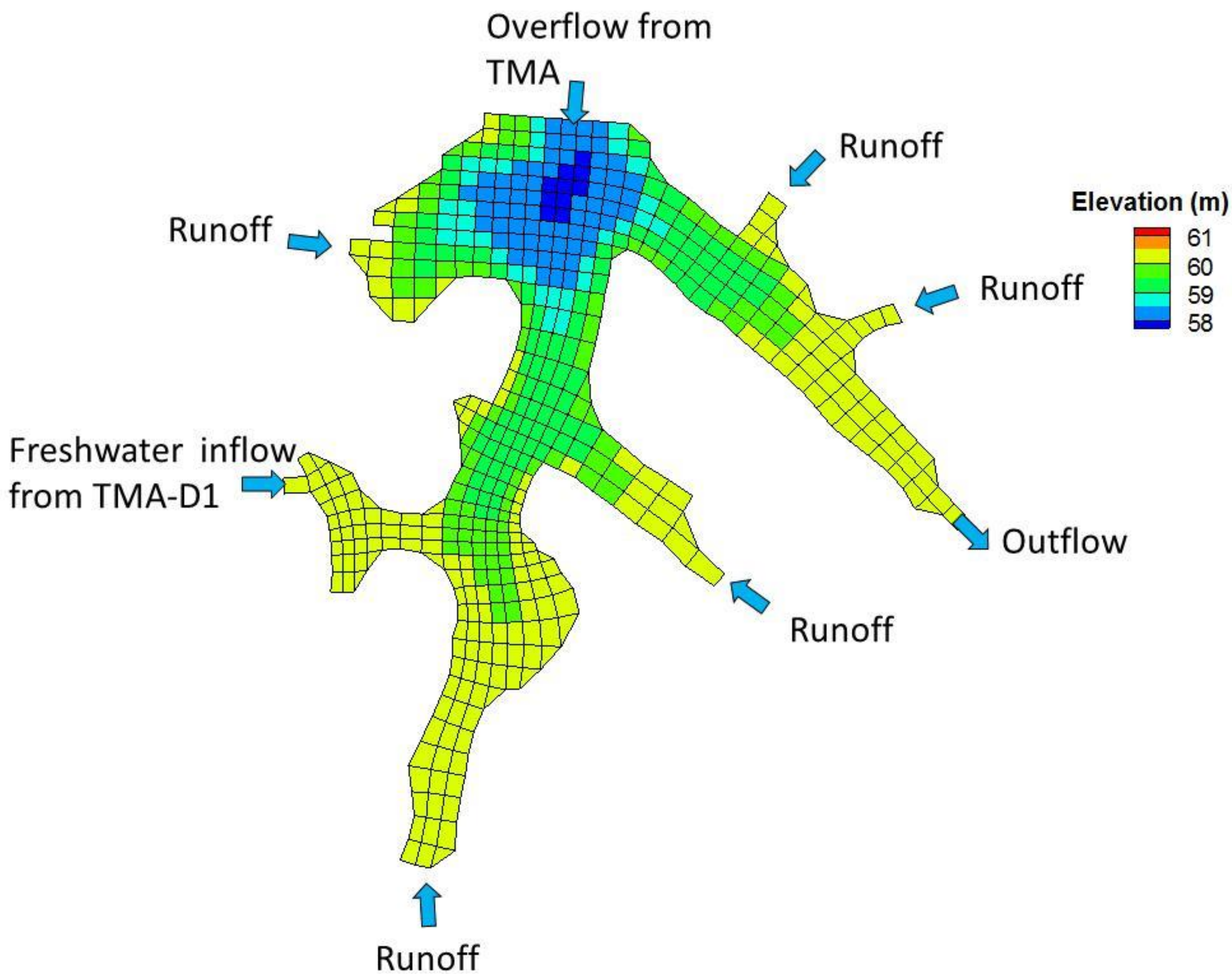
Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013



ENVIRON

FIGURE 2-2 Numerical Model Grid for Mine Water Pond

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013



ENVIRON

FIGURE 2-3 Numerical Model Grid for Tailings Management Area Diversion 2

Prepared by: C. Lee   Reviewed by: F. Kristanovich   Project Number: 0129301B   Date: 6/11/2013

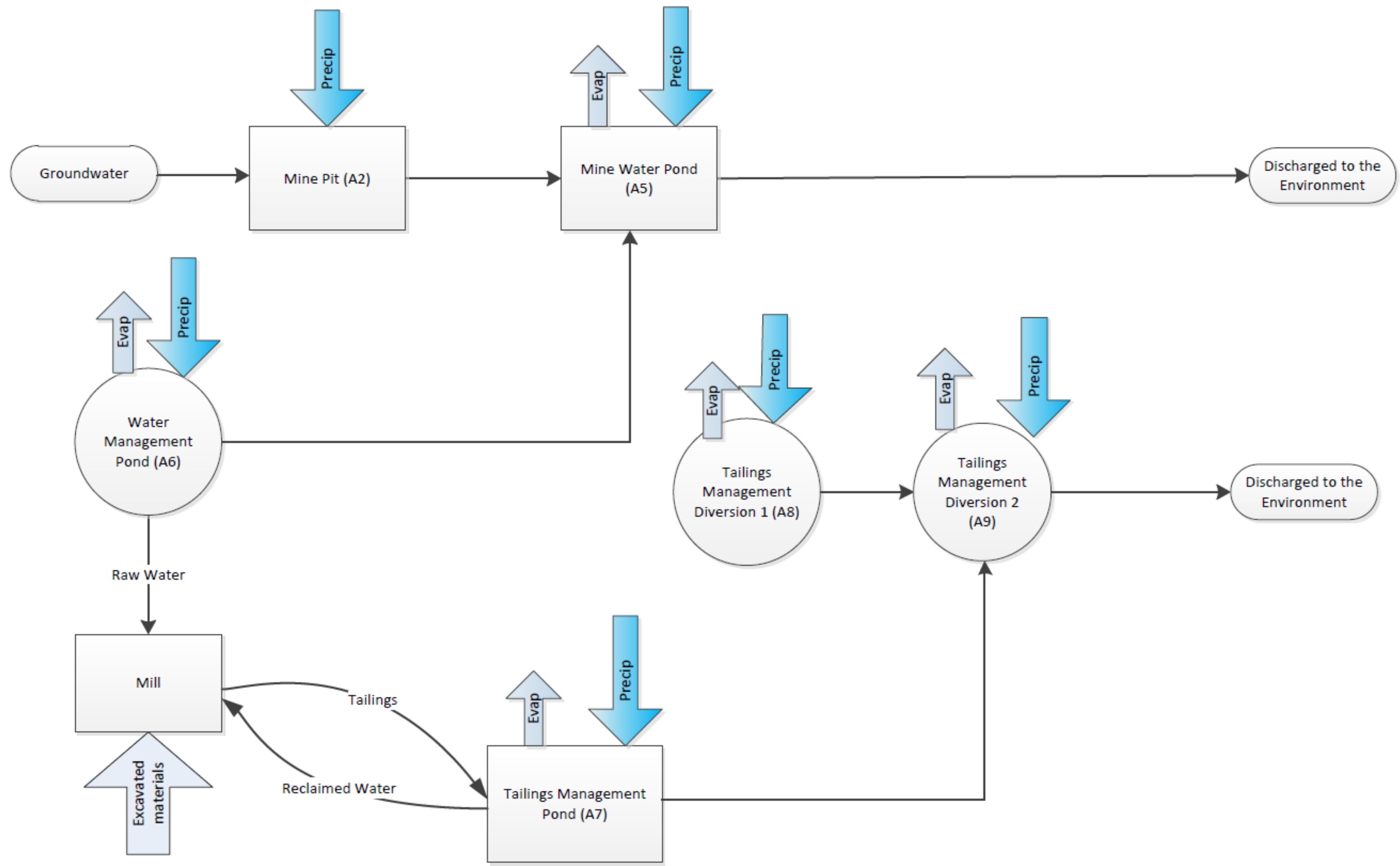


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FIGURE 2-4 Water Balance for Aurora Mine Operation
(Source: TetraTech, 2013)

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

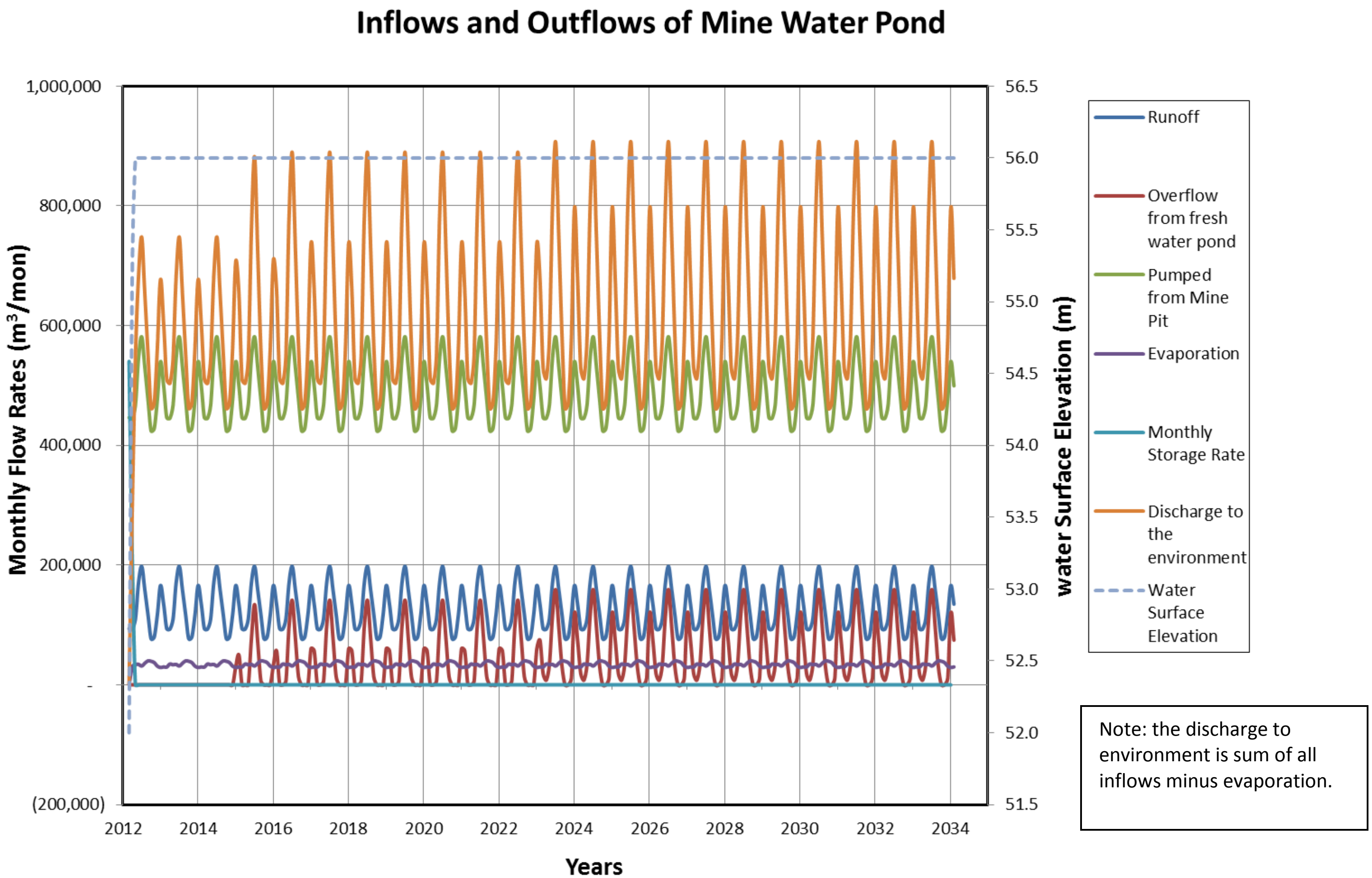

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FIGURE 2-5 Monthly-Average Water Balance for Mine Water Pond

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

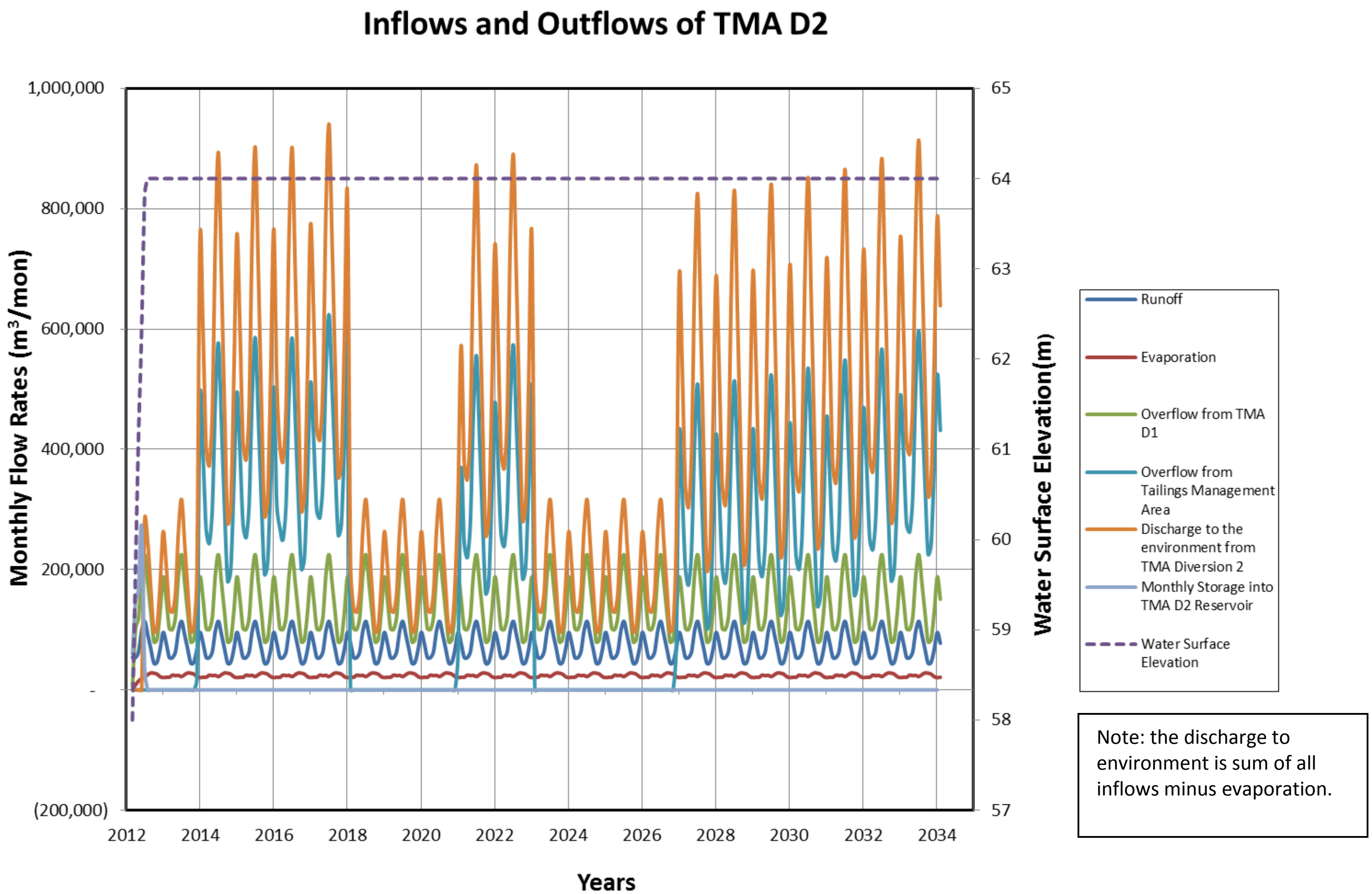

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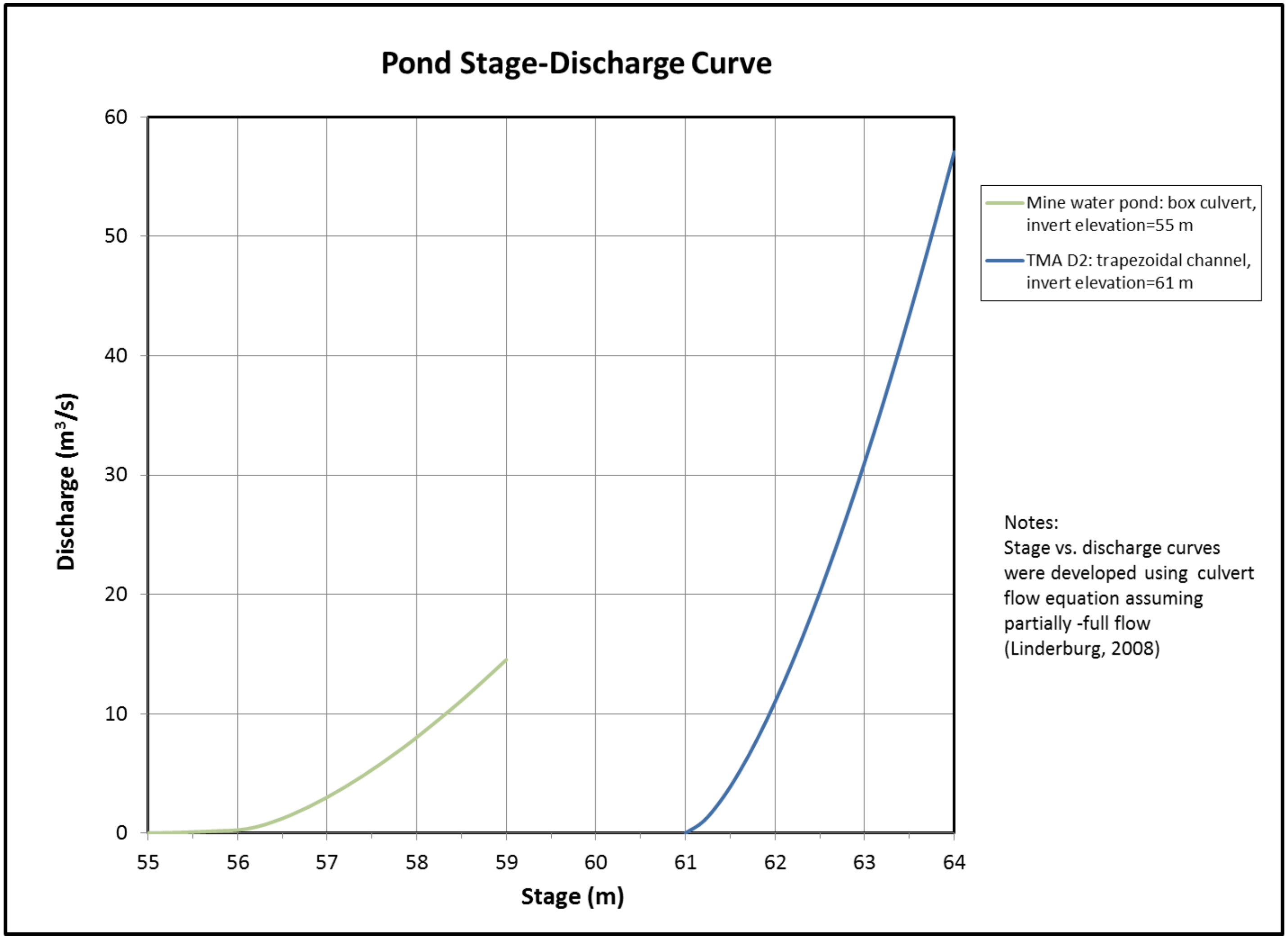
FIGURE 2-6 Monthly-Average Water Balance for Tailings Management Area Diversion 2

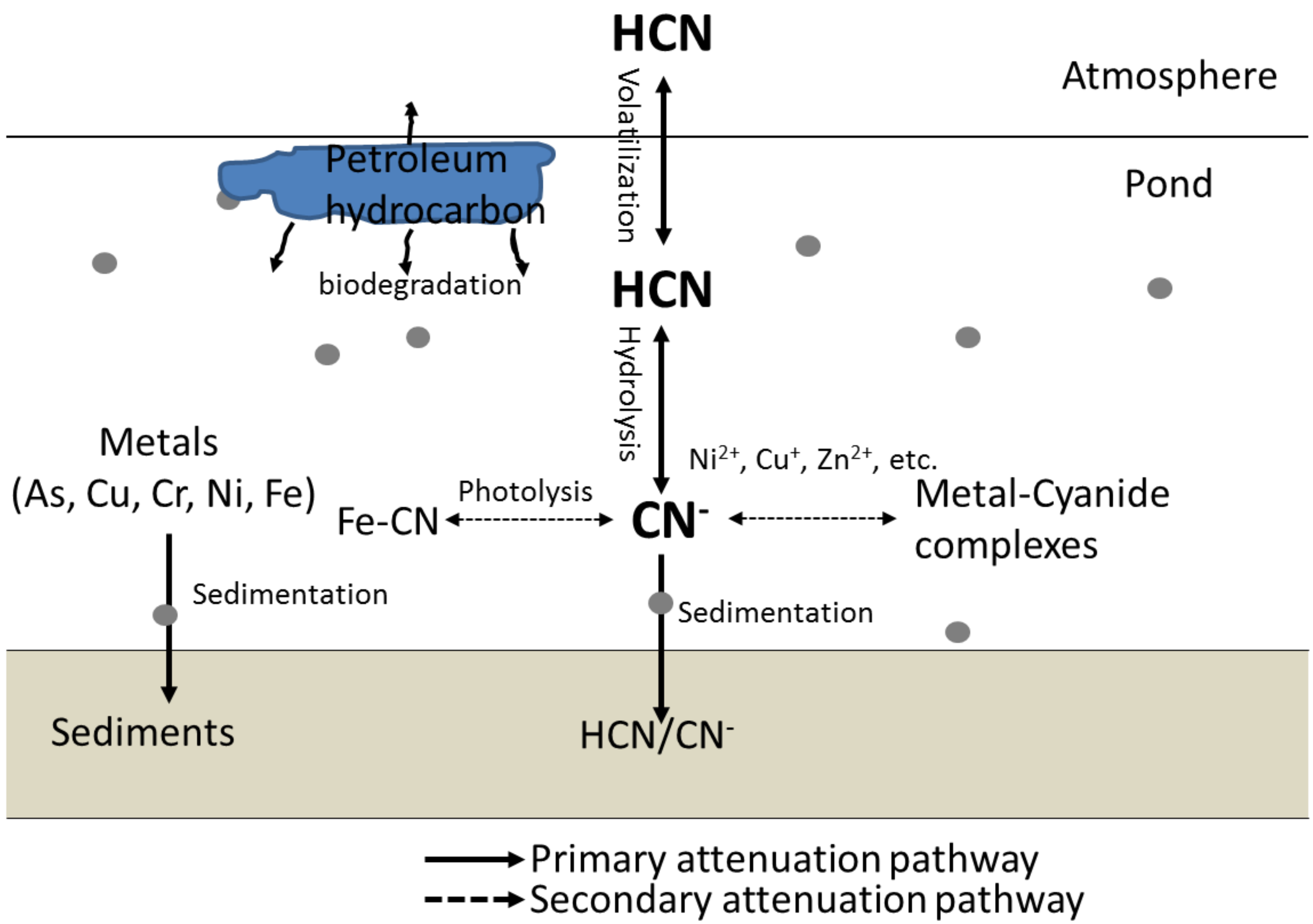
Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013



ENVIRON

FIGURE 2-7 Rating Curves for Pond Discharge

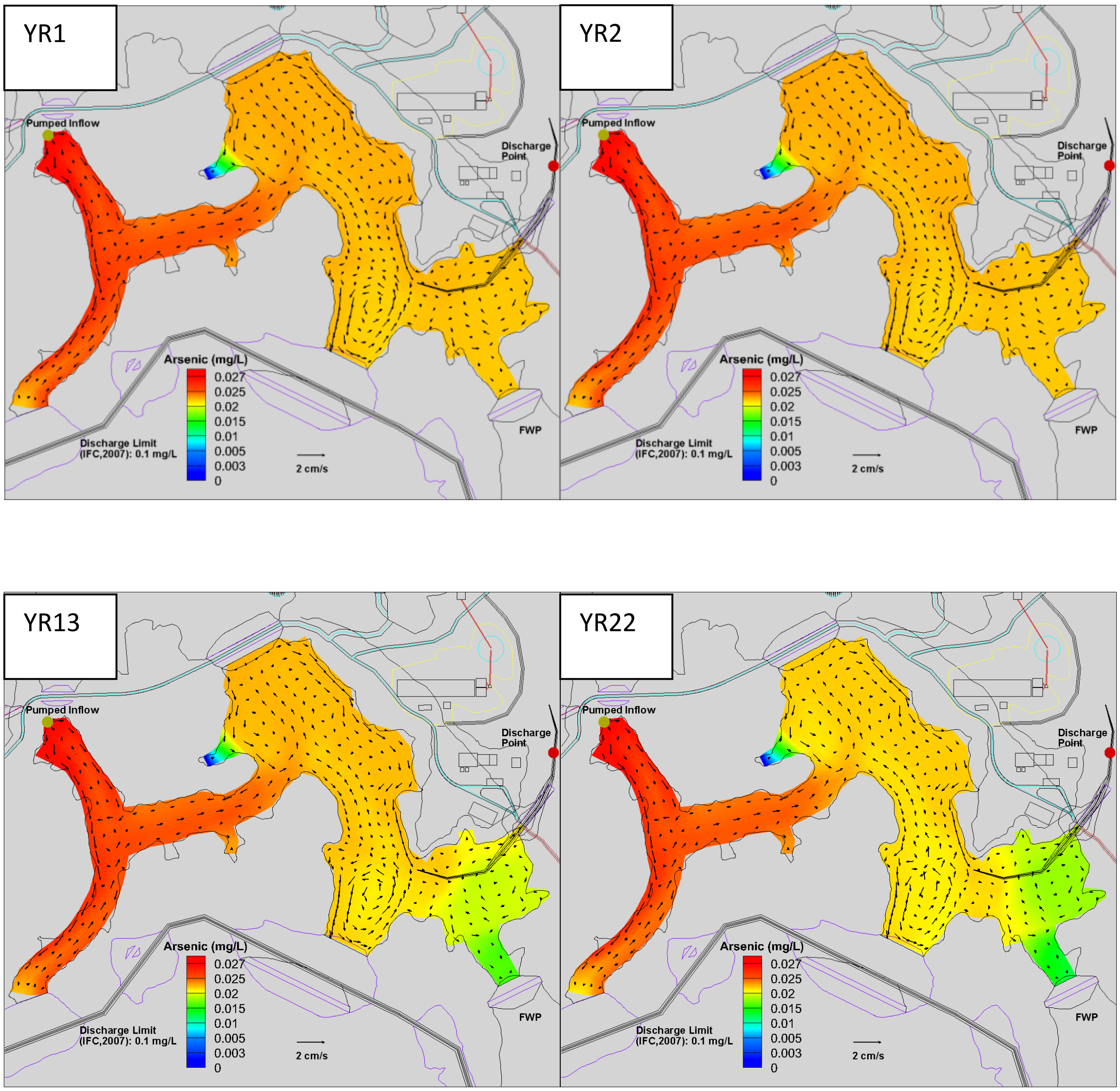
Prepared by: C. Lee   Reviewed by: F. Kristanovich   Project Number: 0129301B   Date: 6/11/2013



ENVIRON

FIGURE 2-8 Attenuation Mechanism of PCOIs
(Source: Botz and Mudder, 2000 and Lötter, 2005)

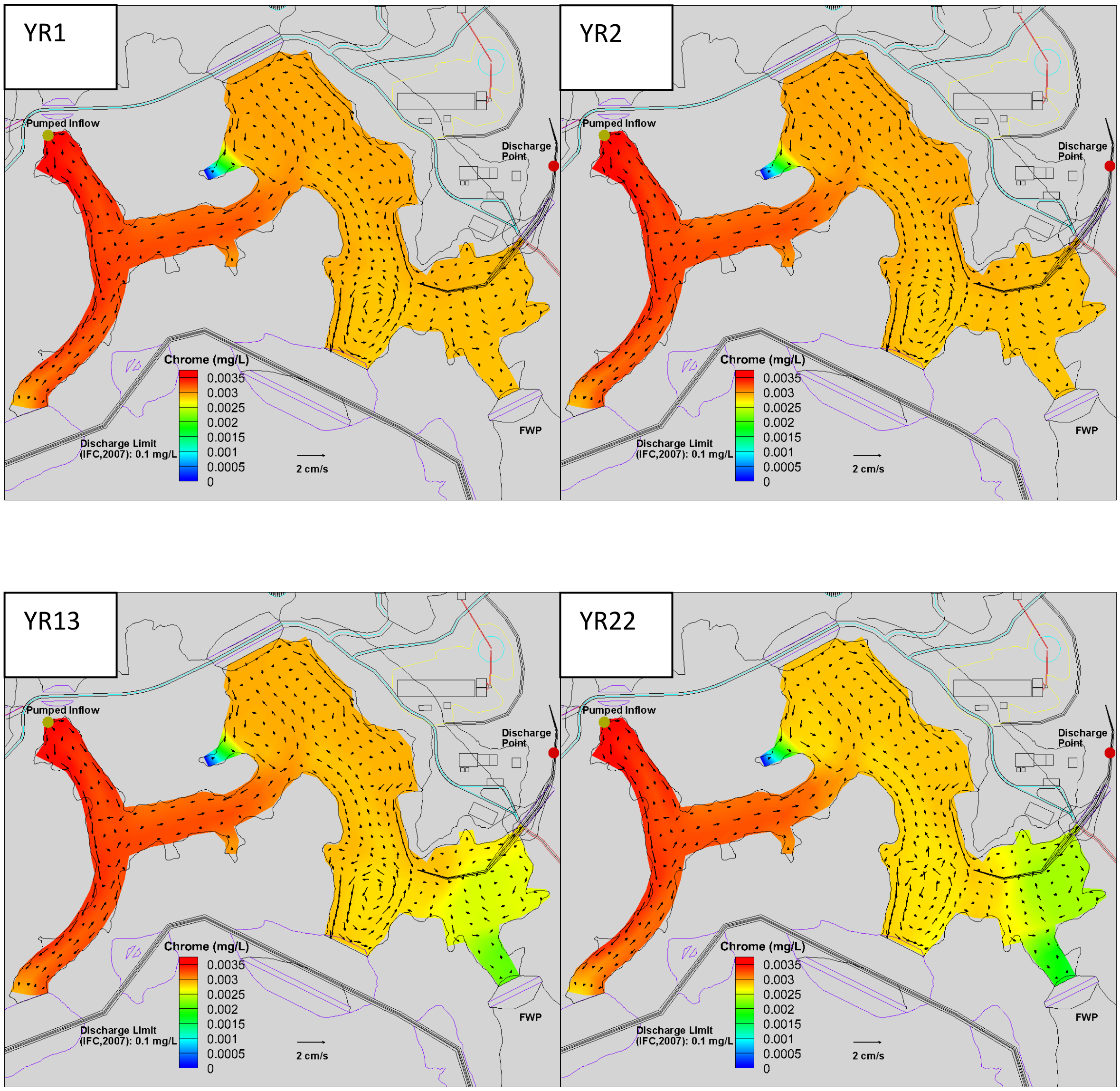
Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013



ENVIRON

FIGURE 3-1 Spatial Distributions of Velocity and Arsenic Concentration for MWP: Monthly Average Operation Conditions

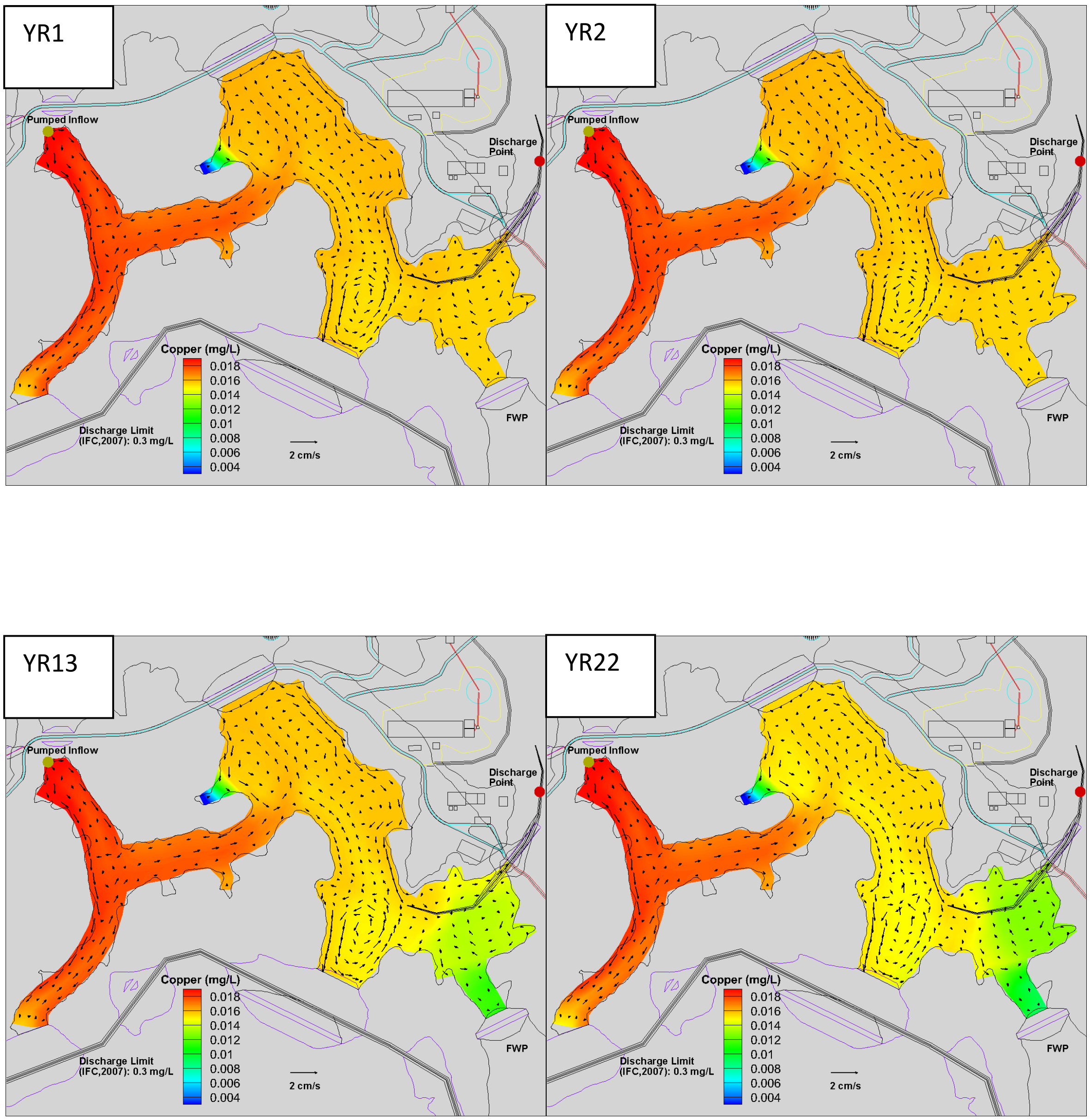
Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013



ENVIRON

FIGURE 3-2 Spatial Distributions of Velocity and Chromium Concentration for MWP: Monthly Average Operation Conditions

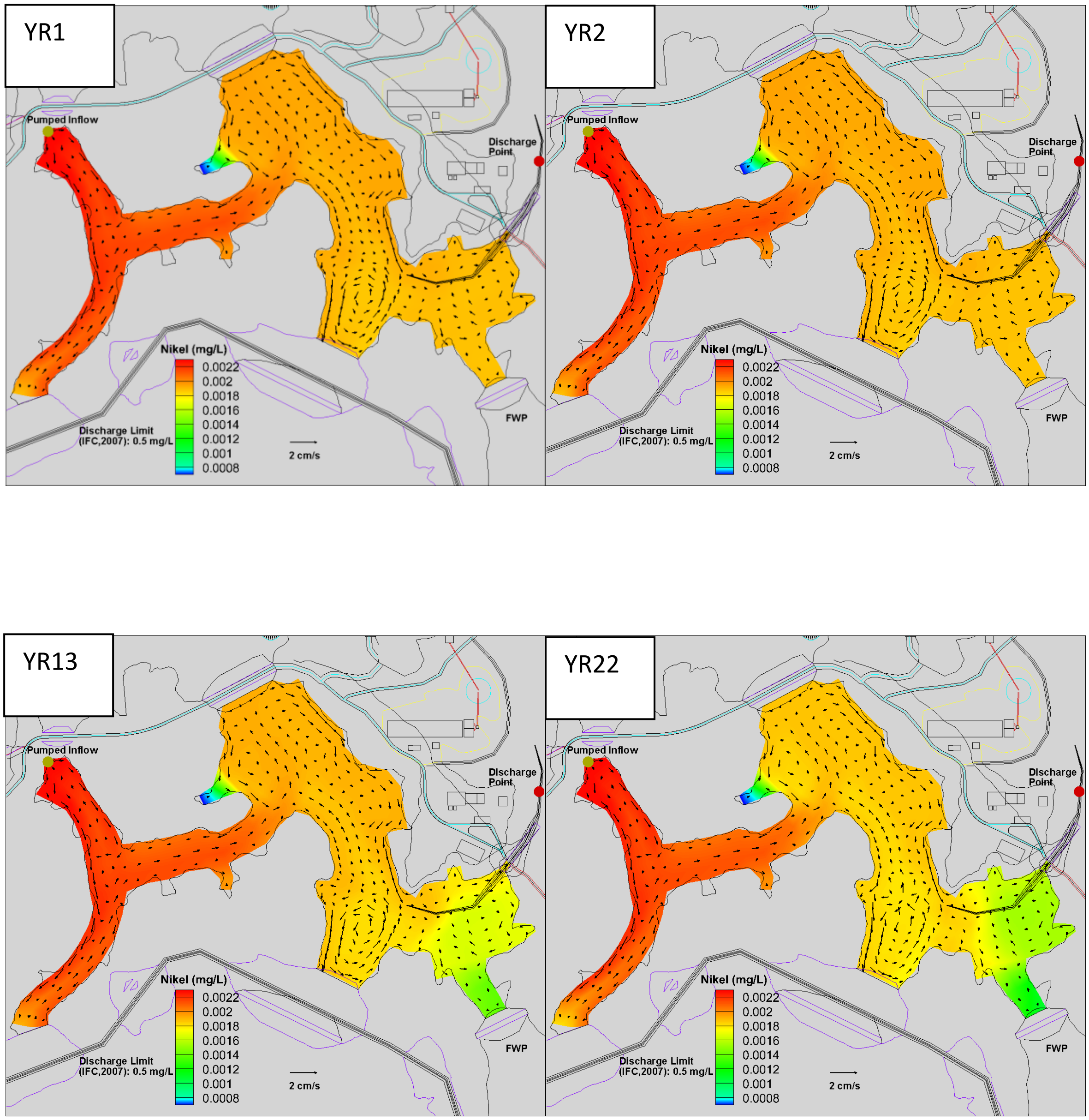
Prepared by: C. Lee   Reviewed by: F. Kristanovich   Project Number: 0129301B   Date: 6/11/2013



ENVIRON

FIGURE 3-3 Spatial Distributions of Velocity and Copper Concentration for MWP: Monthly Average Operation Conditions

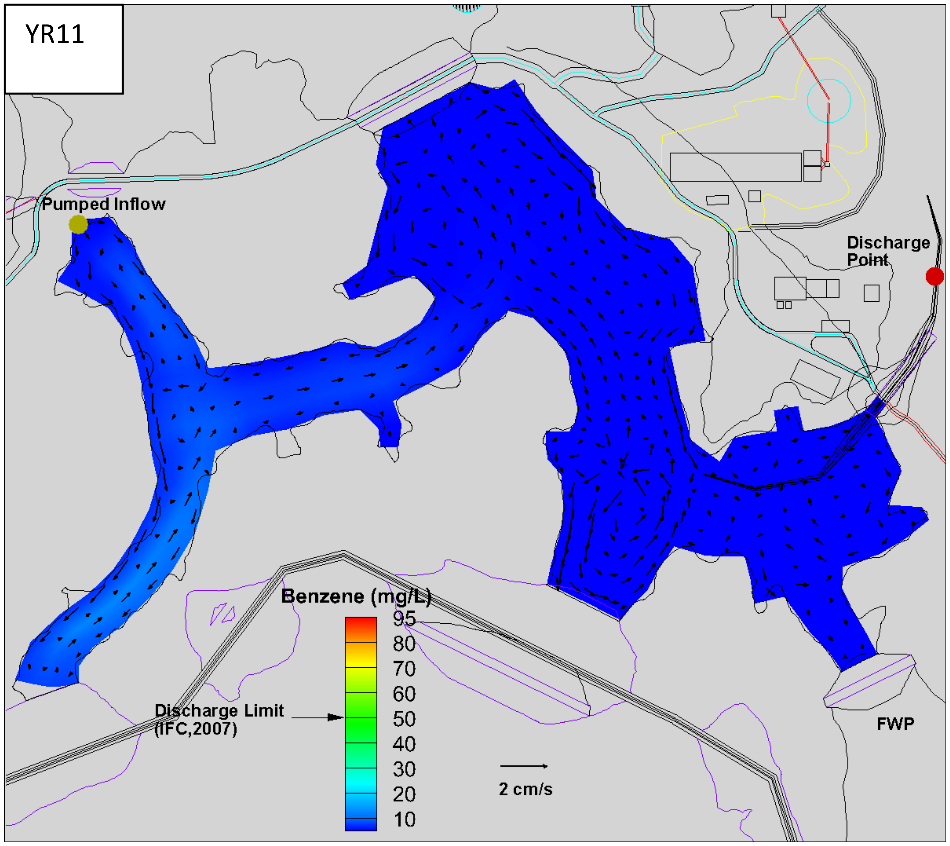
Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013



ENVIRON

FIGURE 3-4 Spatial Distributions of Velocity and Nickel Concentration for MWP: Monthly Average Operation Conditions

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/`1/2013



ENVIRON

FIGURE 3-5 Spatial Distributions of Velocity and Benzene Concentration for MWP: Monthly Average Operation Conditions

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

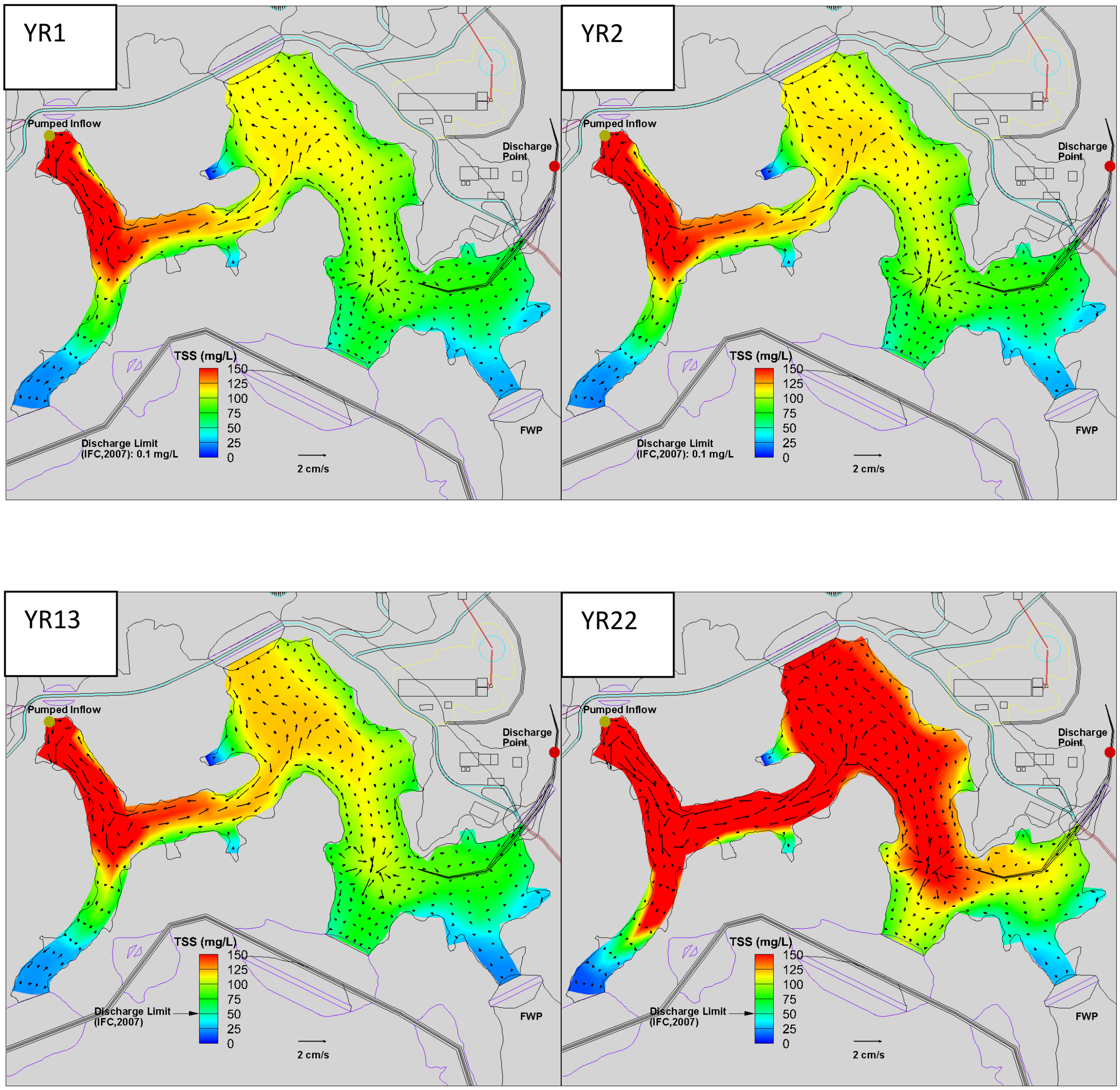


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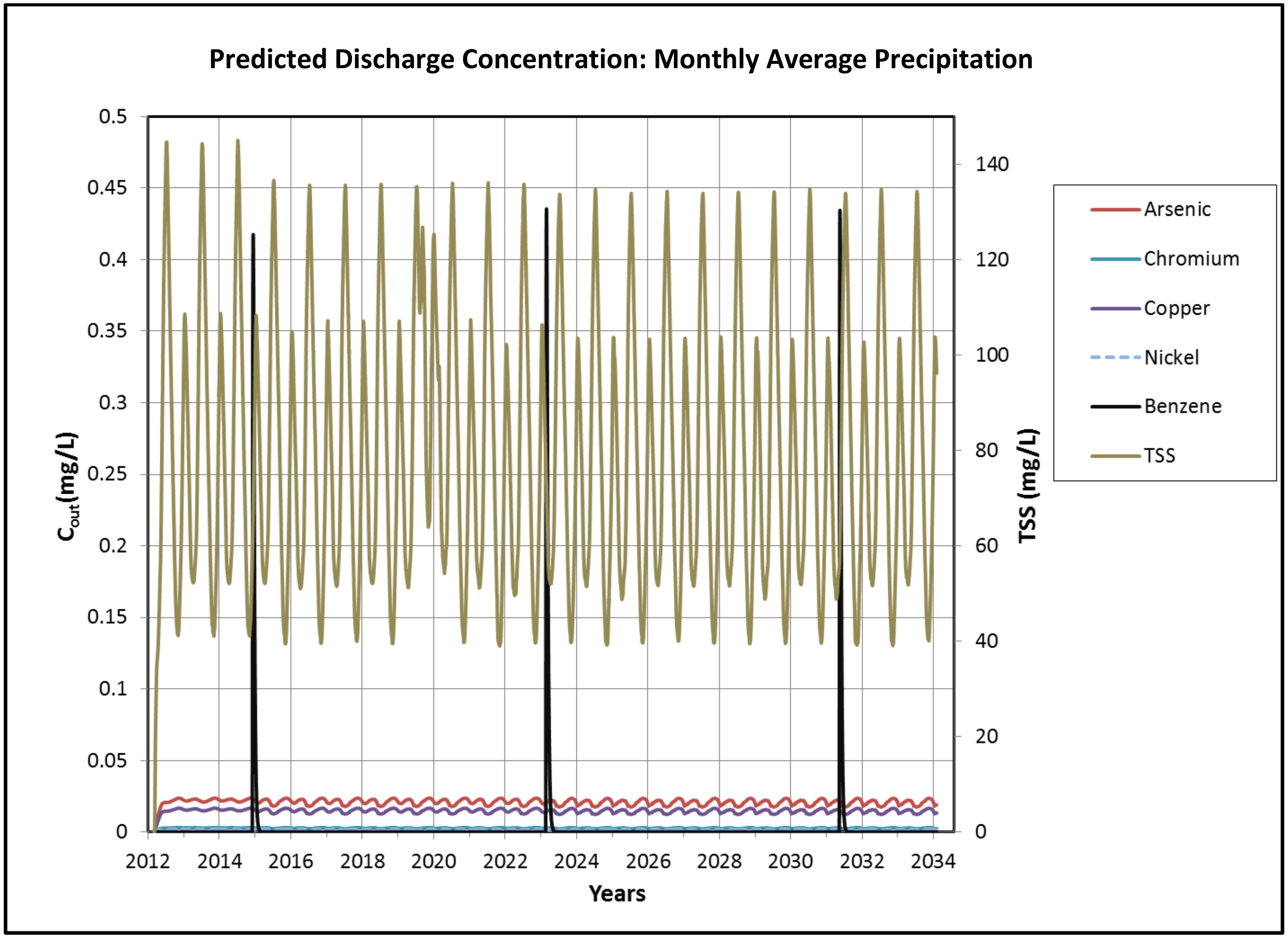
FIGURE 3-6 Spatial Distributions of Velocity and TSS Concentration for MWP: Monthly Average Operation Conditions

Prepared by: C. Lee | Reviewed by: F. Kristanovich | Project Number: 0129301B | Date: 6/11/2013



ENVIRON

FIGURE 3-7 Temporal Variations of Discharge PCOI Concentration for MWP: Monthly Average Operation Conditions

Prepared by: C. Lee   Reviewed by: F. Kristanovich   Project Number: 0129301B   Date: 6/11/2013

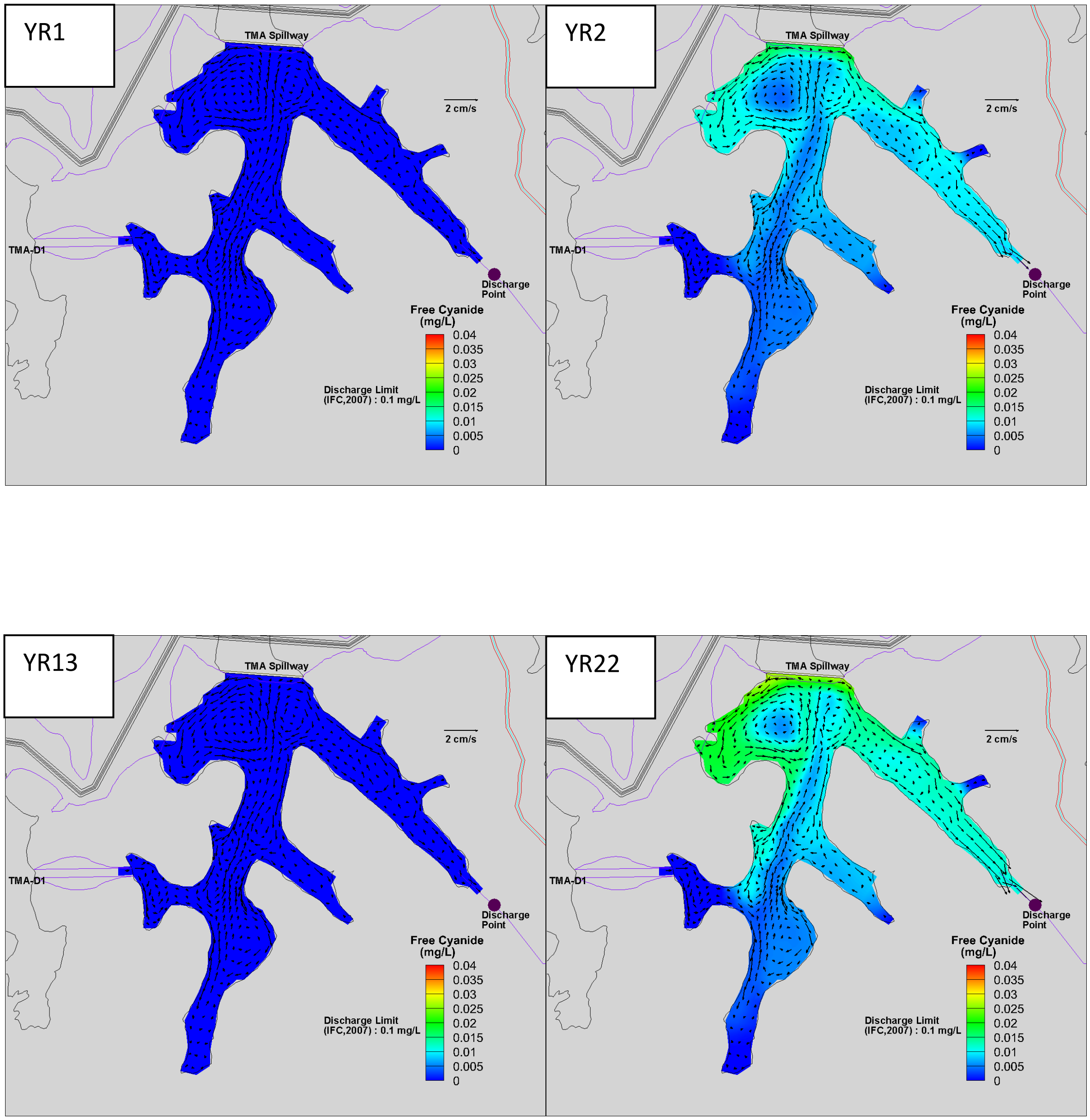


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FIGURE 3-8 Spatial Distributions of Velocity and Free Cyanide Concentration for TMA-D2: Monthly Average Operation Conditions

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

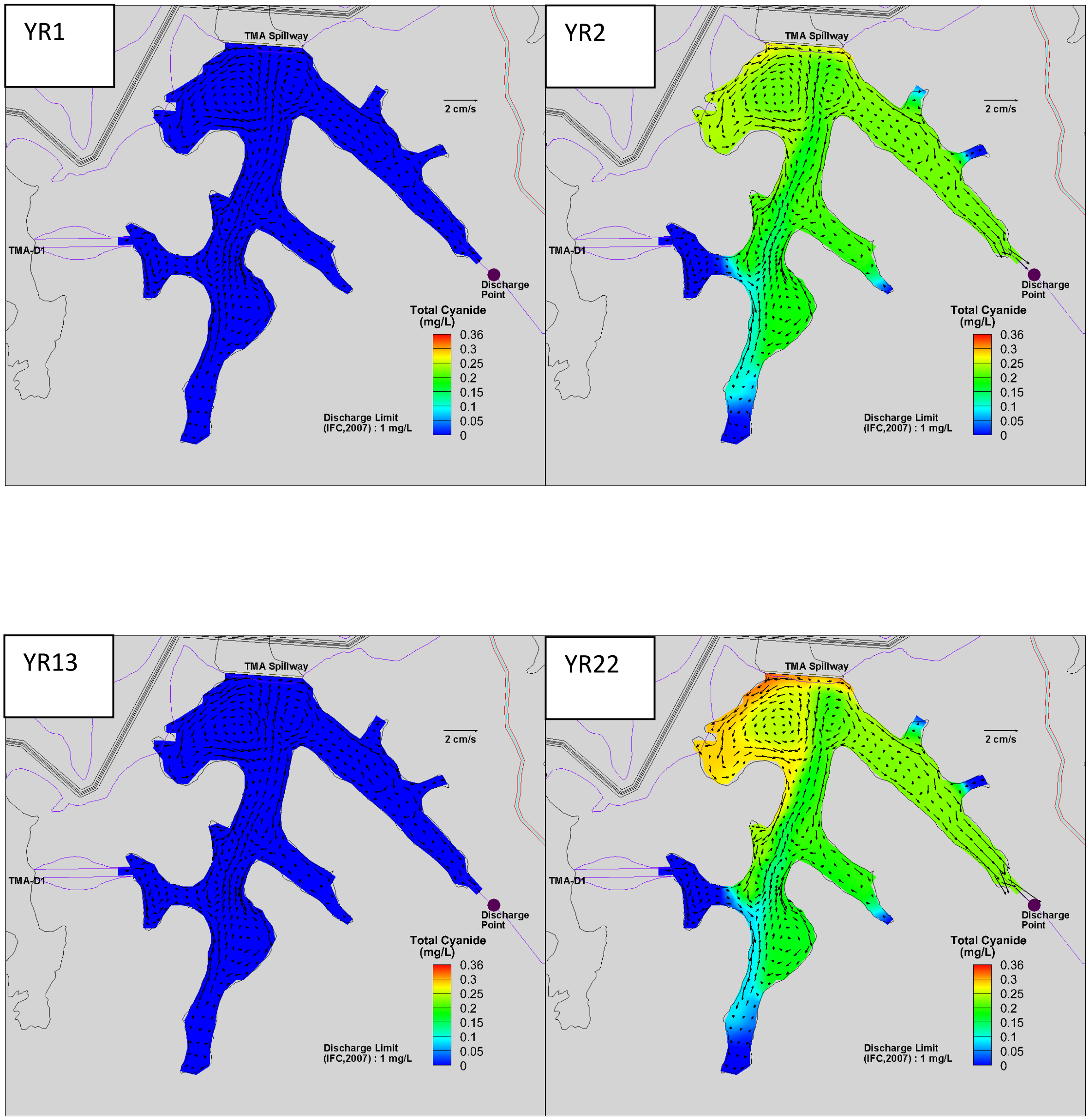

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FIGURE 3-9 Spatial Distributions of Velocity and Total Cyanide Concentration for TMA-D2: Monthly Average Operation Conditions

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

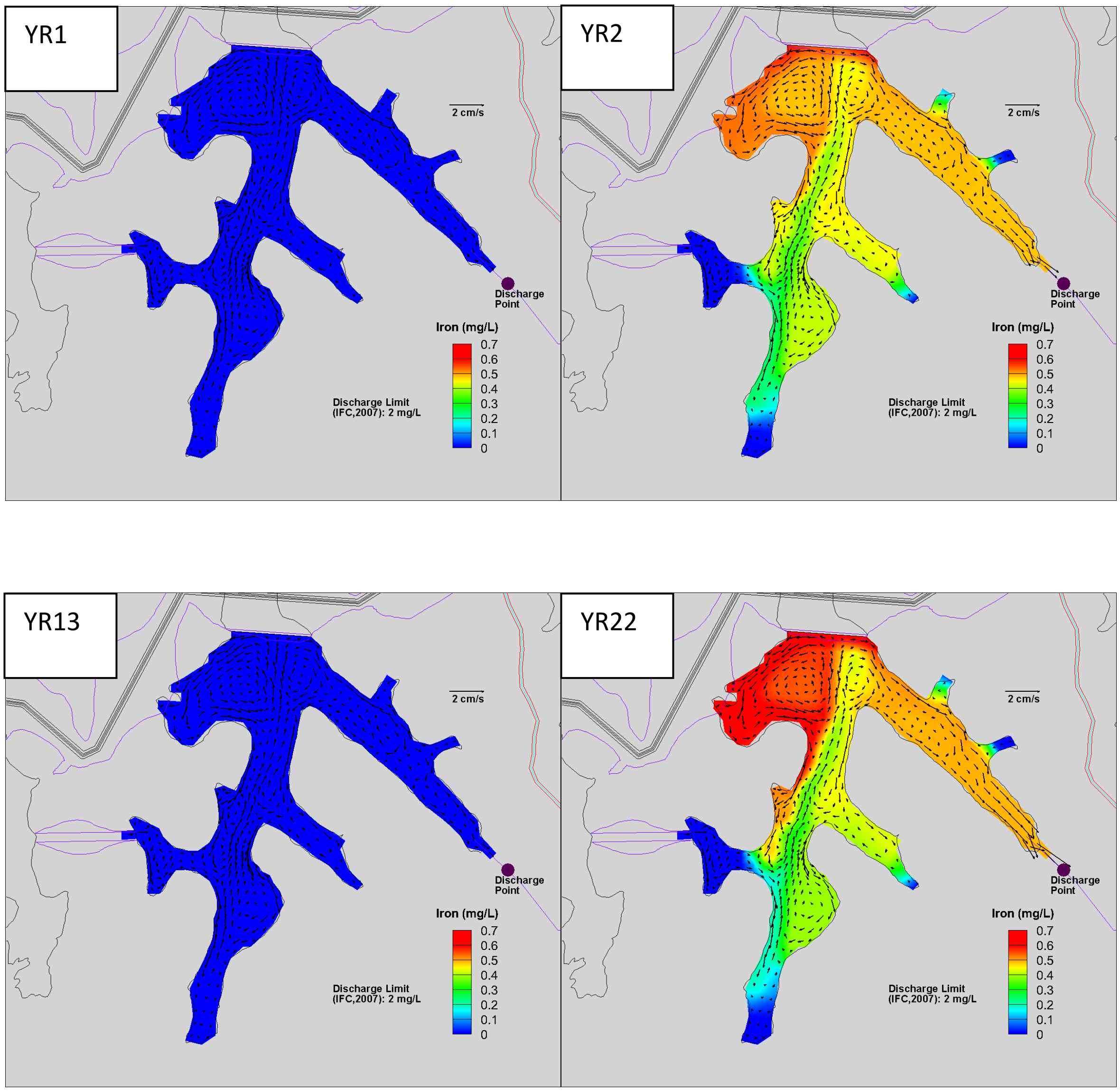

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FIGURE 3-10 Spatial Distributions of Velocity and Iron Concentration for TMA-D2: Monthly Average Operation Conditions

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

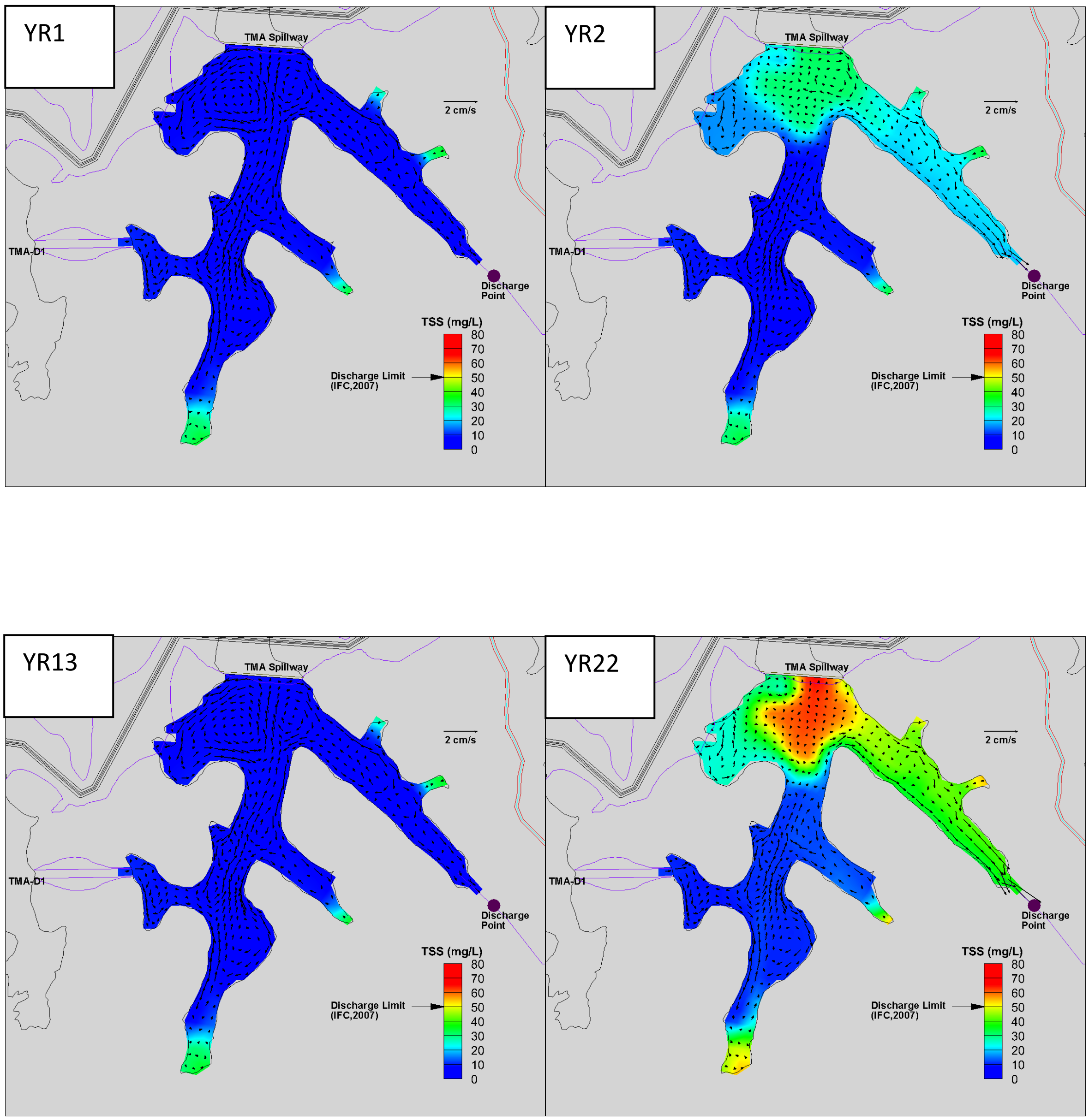

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FIGURE 3-11 Spatial Distributions of Velocity and TSS Concentration for TMA-D2: Monthly Average Operation Conditions

Prepared by: C. Lee Reviewed by: F. Kristanovich Project Number: 0129301B Date: 6/11/2013

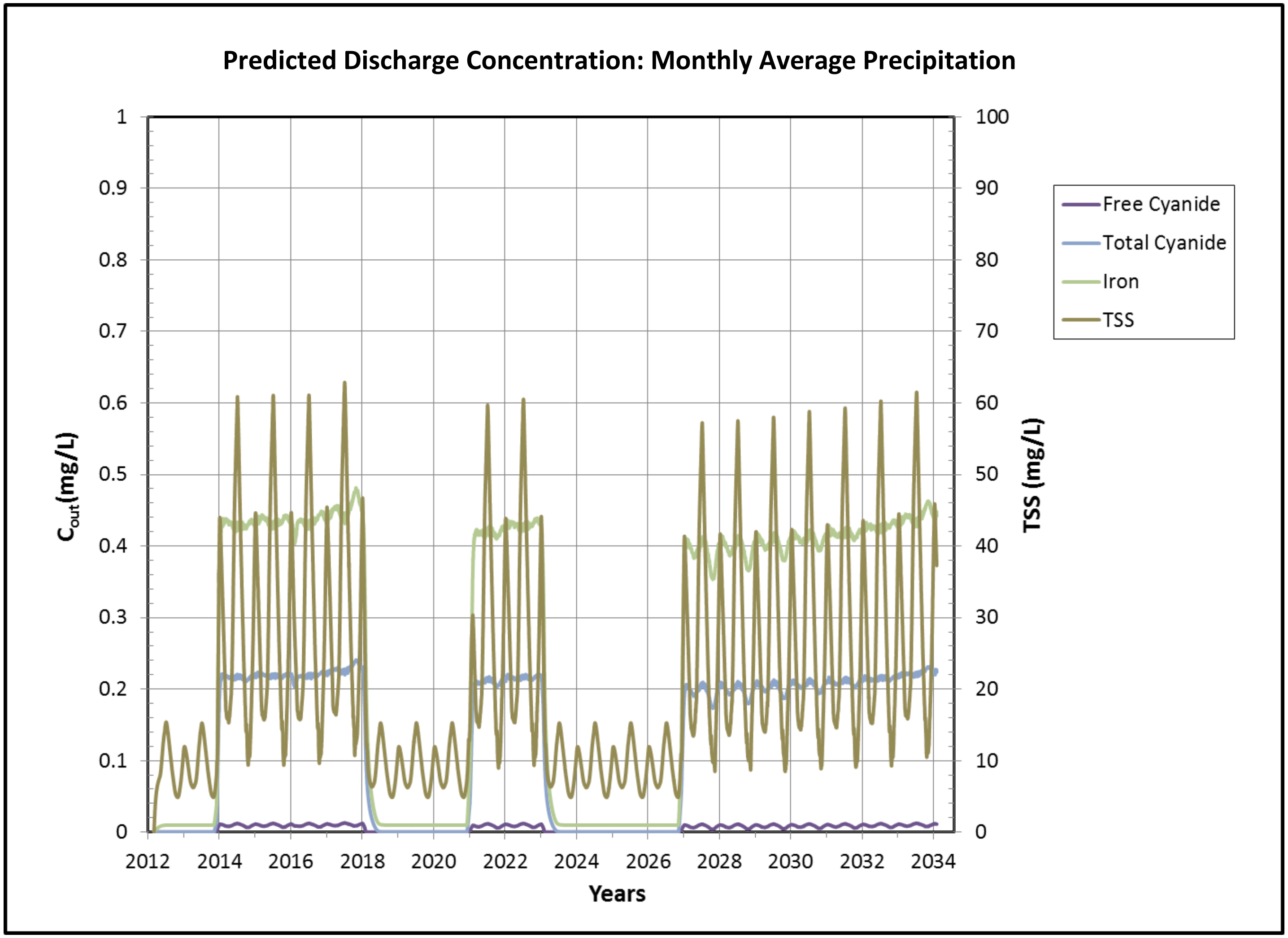

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FIGURE 3-12 Temporal Variations of Discharge PCOI Concentration for TMA-D2: Monthly Average Operation Conditions

Prepared by: C. Lee   Reviewed by: F. Kristanovich   Project Number: 0129301B   Date: 6/11/2013

ENVIRON

ATTACHMENT 2

MEMORANDUM

To:	Alex Riley Environmental Manager, Guyana Goldfields, Inc.
From:	Farid Achour, PhD Felix Kristanovich, PhD, PE ENVIRON International Corp (ENVIRON)
Subject:	**Flow and Transport of Selected Constituents of Interest in the Saturated and Unsaturated Zones of the Aurora Gold Project**
cc:	Glenn Mills, ENVIRON Reed Huppman, ENVIRON

Introduction

A regional, three-dimensional, transient numerical model of groundwater flow and transport of selected constituents of interest was constructed for the Aurora Gold Project (Project) aquifer system, in order to better understand the groundwater flow system and its relation to the infrastructure and mine development assumptions reflected in the latest feasibility study for the Project (TetraTech, 2013). Model results provide a conceptual understanding of the groundwater flow system and the potential concentrations of the noted constituents in relation to key water management structures, i.e., the Tailings Management Area (TMA) and the Mine Water Pond (MWP). The model described in this report can also potentially be used as a tool by Guyana Goldfields, Inc. (GGI) to quantitatively evaluate proposed alternative management strategies that consider the interrelation between groundwater quality and the mining operations.

A three-dimensional (3D) model with the sole purpose of simulating groundwater flow at the Project site was first developed by AMEC in 2010 to support an earlier version of the Project design, using the modular finite-difference groundwater flow (MODFLOW) model. As part of feasibility study updates conducted for GGI in 2012 and 2013, Itasca developed a similar model for the site using a proprietary finite element code, "Mine-DW." The purpose of the Itasca modeling study was to develop an understanding of the potential inflows to the open pit and underground mining areas, using most of the same hydrogeological data inputs as were used for the original AMEC model. Since the final design locations of the MWP and TMA were immediately south of the open pit and underground mining areas, and since modeling of these areas was understood to be based on best available hydrogeological data, a decision was made to adapt the Itasca model for direct use in this study.

The Mine-DW finite *element* model was therefore exported/converted into MODFLOW for use by ENVIRON in evaluating fate and transport of selected constituents of interest in the saturated zone. MODFLOW is a finite *difference* model and perhaps the most widely used groundwater modeling program in the world. ENVIRON also simulated flow and transport of contaminants in the unsaturated zone beneath the TMA, using the “WHI Unsat Suite” software from Schlumberger. The latter consists of a series of software modules that were used to:

- generate daily rainfall estimates using a “weather generator database”;
- simulate flow through the tailings mass and the underlying unsaturated zone, including estimation of the daily percolation rate to the aquifer; and
- simulate the flow of specific constituents of interest as solutes dissolved in groundwater, through the deposited tailings and the unsaturated zone.

Conceptual Model

Hydrostratigraphy and Hydraulic Properties

According to (AMEC, 2010a), the general stratigraphy at the site consists of following major geological units:

- Alluvium – transported soils of alluvial or colluvial origin;
- Residual soil – completely weathered rock with no relic structure of the parent rock;
- Saprolite – rock weathered to a soil but retaining relic rock structure; and
- Fresh bedrock.

These units have been re-grouped into *hydrostratigraphic* units with similar hydraulic characteristics, as follows:

- Alluvium and residual soil overburden;
- Saprolite;
- Weathered bedrock or saprock; and
- Bedrock.

Figure 1 depicts the conceptual hydrogeologic model and the underlying stratigraphy.

Bedrock at the site comprises granite, meta-sedimentary and meta-volcanic rocks of the Cuyuni Formation. Tropical weathering has transformed the upper portion of the rocks into residual soil and saprolite. Granite bedrock is located to the west south-west of the site. The overburden is generally thin (about 2 – 4 meters), except for the some local granite highland areas and the area between the proposed open pit mine and the river, where the average thickness of the alluvium/residual soils increases to approximately 7.5 m.

Representative hydraulic properties of the hydrostratigraphic units presented in Table 1. In “Geochemical and Geotechnical Characterization of Guyana Goldfields Mine Tailing”, (AMEC, 2010c), AMEC shows the distribution of the K-values in bedrock (non-granitic) versus depth. According to the results presented there is a significant scatter in the K-values for the upper 100 m of rock – from 10^{-6} cm/s to 10^{-3} cm/s. Bedrock K values tend to decline with depth, however this trend is quite different between the Rory's Knoll area and a few locations along the river and the rest of the Project site. According to the general trend, bedrock K-values are expected to be in the order of 10^{-7} cm/s to 10^{-6} cm/s at the bottom of the proposed open pit (depth of about 250 m – 270 m below ground surface). According to the trend for the Rory's Knoll-River areas bedrock K-values are expected to remain relatively high at this depth, i.e. in the order of 10^{-4} cm/s.

Recharge and Discharge Zones

As noted in (AMEC, 2010d), based on available climate data for Guyana from 1961 to 1990, the average annual precipitation is expected to be about 2,450 mm. Assuming that evapo-transpiration constitutes about 50% - 60% of the annual precipitation, the combined surface run-off and aquifer recharge is expected to be in the order of 980 mm/yr to 1,225 mm/yr. There are no data available on the local aquifer recharge rate. For the purpose of this study it was assumed that this rate can be in the order of 400 mm/yr – 700 mm/yr. Lower recharge rates are expected to occur on the steep slopes of granite highlands.

Available data suggest that the low-lying areas between the hills can act as both recharge and discharge zones for the underlying aquifer since both downward and upward gradients were recorded at the site. In general, the aquifer system drains into the Cuyuni River, located directly north of the site.

Modeling Fate and Transport of Selected Constituents of Interest in the Unsaturated Zone

In order to simulate transfer of specific constituents in the unsaturated zone beneath the TMA, ENVIRON modeled flow and transport of contaminants trough a 30 m column of soil, i.e., a vertical profile consisting of 27 meters of tailings and 3 meters of native soil. ENVIRON used the "WHI UnSat Suite" Version 2.2.0.5 software from Schlumberger for this part of the modeling exercise. The WHI "UnSat Suite" combines four unsaturated zone models in a graphical environment specifically designed for simulating one dimensional groundwater flow and contaminant transport through the unsaturated zone. The specific models used by ENVIRON were "HELP" and "VS2DT", which are described as follows

- **HELP** (Hydrologic Evaluation of Landfill Performance) is a versatile US Environmental Protection Agency (EPA) model for predicting landfill hydrologic processes and testing the effectiveness of landfill designs, enabling the prediction of landfill design feasibility. HELP is also effective in estimating of groundwater recharge rates. The landfill profile structure can consist of a combination of natural (soil) and artificial materials (waste, geomembranes) with options to install horizontal drainage layers. The HELP model also accounts for the change in slope for different parts of the landfill profile.

  HELP uses numerical solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembranes, or composite liners.

Visual HELP includes a built-in Weather Generator for synthetic generation of daily values of precipitation, mean temperature, and solar radiation. The WHI International Weather Generator includes a global database with data from more than 3000 stations and a GIS feature for locating the nearest stations globally.

- **VS2DT** is a computer program developed by the United States Geological Survey (USGS) that solves problems of water and solute movement in variably saturated porous media. The finite difference method is used to approximate the flow equation, which is developed by combining the law of conservation of fluid mass with a nonlinear form of Darcy's equation, and the advection- dispersion equation. The model can analyze problems in one and two dimensions with planar or cylindrical geometries. There are several options for using boundary conditions that are specific to flow under unsaturated conditions: infiltration with ponding, evaporation, plant transpiration, and seepage faces. Solute transport options include first-order decay, adsorption, and ion exchange.

Simulation of Flow and Transport of Contaminants in the Tailings Management Area (TMA)

In order to simulate water flow in the TMA and in the unsaturated (native) soil underneath, ENVIRON simulated flow through a vertical soil profile of 30 meters, from which 27 meters consisted of loamy sand (tailings), and 3 meters of silty clay (weathered saprolite for the native soil). Because a full 18 years of daily meteorological data were not available for modeling purposes, ENVIRON used the HELP Weather Generator model to generate daily rain and temperature at the closest meteorological station (the Willemstad station); see Figures 2 and 3.

HELP was used to calculate values of water percolating through the TMA and the underlying unsaturated zone (Figure 4); VS2DT was used to simulate the unsaturated flow and transport of the selected constituents of interest [iron and total cyanide (CN_T)] in a dissolved state. Iron and CN_T were selected because they are deemed to be representative of the potential constituents of interest listed in Table 1 of the International Finance Corporation (IFC) “EHS Guidelines for Mining “(IFC, 2007) as well as the results of geochemical analysis of surrogate tailings samples as noted in (AMEC, 2010c).

The simulations were conducted for a period of 18 years, on a daily time step and by imposing constant, continuously applied input concentrations of dissolved constituents at the top of the TMA. The input concentration assumptions were based on the predicted geochemical makeup of tailings as noted in (AMEC, 2010c), but were increased by an order of magnitude to simulate a more conservative worst-case scenario. These assumed concentrations were:

- Iron: 20 mg/L
- CN_T: 2 mg/L

Solute transport was simulated by including a retardation parameter for each solute representing its adsorption onto particles in the subsurface. Adsorption to the soil matrix can reduce the concentration of dissolved contaminants moving through the ground water. The retardation factor is the ratio of the groundwater seepage velocity to the rate that organic chemicals migrate in the groundwater. The degree of retardation depends on both aquifer and constituent properties. The transport parameters are shown on Table 2.

The vertical profile results for each contaminant were calculated for four periods (1, 2, 13 and 18 years after the start of mine operations) and demonstrated that the leading edge of the constituent "plume" stops at a depth of approximately 10 meters and that the modeled constituents do not reach the aquifer (See Figures 5 and 6).

Simulation of Flow and Transport of Contaminants in the Mine Water Pond (MWP)

ENVIRON conducted the same general simulations at the MWP, for the same period of 18 years using the following constituents of interest, and the concentrations shown:

- Arsenic: 0.27 mg/L
- Chromium: 0.035 mg/L
- Copper: 0.19 mg/L
- Nickel: 0.023 mg/L

These constituents also deemed to be representative of those listed in Table 1 of (IFC, 2007); as the MWP is not part of, nor would it be impacted by any part of the Project's cyanide management infrastructure, no cyanide species modeling was required. Note that these concentrations were also based on (AMEC, 2010c), and were also increased by an order of magnitude in order to simulate a conservative worst-case scenario.

The first step estimated the values of daily water percolating through a representative column of soil made up of 2 meters of loamy sand and one meter of silty clay. The daily percolation rates are shown in Figure 7. The results of the simulations (Figures 8 through 11) demonstrated that only a limited portion (a maximum of about 50%) of the constituent plume penetrated into the aquifer.

Modeling Fate and Transport of Contaminants in the Saturated Zone

ENVIRON used Visual MODFLOW, Version 2011 .1 Premium (from Schlumberger Water Services) to simulate flow and also simulate transport of contaminants under transient flow conditions for a period of 18 years and 224 stress periods. The model structure consisted of 22 layers, 63 rows and 68 columns (94,248 cells). Contaminants were simulated as solutes dissolved in groundwater that travel by advection and dispersion. ENVIRON also simulated the retardation of each solute that is by adsorption onto particles in the subsurface (Table 2). The map showing the location of the location of the pumping wells is provided in Figure 12. The hydraulic conductivities for each geological formation are shown in Table 1. More information related to the boundary conditions and the pumping schedule of the dewatering wells are provided in the (AMEC, 2010c) and (Itasca, 2013) reports.

As previously noted, the finite difference model obtained from Itasca was an export of their Mine-DW finite *elemen*t model. As the Itasca model was exclusively developed for the purpose of modeling groundwater flow, the discretization (i.e., the model mesh) was not specifically designed or optimized to simulate transport of contaminants. ENVIRON modelers therefore adjusted the ITASCA model in order to simulate flow and transport under transient conditions. The adjusted model as prepared by ENVIRON was used to simulate transient flow and transport of selected constituents of interest for a period of 18 years, taking into account the variable pumping schedule of 78 pumping wells.

Results

Metals and CN_T

ENVIRON simulated the fate and transport of iron and CN_T in the TMA (Figures 13 and 14), and copper, chromium, nickel in the MWP (Figures 15 through 18). Although the results of the simulations of the unsaturated zone as conducted previously showed that only a portion of these contaminants reached groundwater in the MWP, ENVIRON simulated a continuous concentration release of the copper, chromium, nickel, arsenic during 18 years at the bottom of the MWP (i.e., a worst case scenario). Simulations were performed for a period of 18 years under transient flow conditions. The solute transport was simulated by including a retardation parameter for each solute representing its adsorption onto particles in the subsurface (Table 2).

The results representing the spread of the plume for 1, 2, 13 and 18 years on Figures 13 through 18 indicate that:

- At the TMA, there is very slow movement of the modeled constituents over time, generally in the direction of the open pits (Figures 13 and 14); and

- At the MWP, most of the generated plumes are contained in the area immediately adjacent to the MWP and do not reach the mine pit. (Figures 15 through 18). However, in one area in the northwestern area of the MWP, the plume is captured by dewatering well AH-7.

Benzene

ENVIRON simulated fate and transport of benzene as a representative hydrocarbon from a spill that ultimately reported to the MWP. The simulated scenarios consisted of 18 hypothetical spills with a concentration of 95 mg/L during 12 hours for each spill, and assuming one spill per year. The simulations were conducted by taking into account the retardation factor and degradation, including sorption (linear isotherm with equilibrium controlled). The results for years 1, 2, 13, and 18 (Figure 19) show that the spread of the plume generated by benzene release is limited to the vicinity of the MWP and did not travel downgradient towards the pumping wells in the mine pit. However, in one area in the northwestern area of the MWP, the plume may be captured by dewatering well AH-7.

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Table 1- Water Quality Modeling Parameters - Groundwater

Facility	Contaminants	Primary Attenuation Mechanisms and Model Parameter Values			Model Input Concentration of Contaminants and Data				IFC Effluent Standard (mg/L)
		Volatilization (day^{-1})	Adsorption (log L/kg) K_{OC}	Settling (mm/s)	Runoff Conc.-modeling (mg/L)	Leaching Conc.-Lab Test (mg/L)	Decant Conc.-modeling. (mg/L)	Decant-Conc.-Lab Test (mg/L)	
TMA	[a] CN_T	[b] 0.186	[c] 0.996	N/A	N/A	N/A	[g] 2.6	0.29	1
	Fe	N/A	[c] -0.7	N/A	N/A	N/A	[g] 0.73	1.63	2
MWP	As	N/A	1.398	N/A	[f] 0.5	0.027	N/A	N/A	0.1
	Cr	N/A	3.079	N/A	[f] 0.1	0.0035	N/A	N/A	0.1
	Cu	N/A	1.602	N/A	[f] 0.3	0.019	N/A	N/A	0.3
	Ni	N/A	1.204	N/A	[f] 0.5	0.0023	N/A	N/A	0.5
	Benzene	0.2	1.82	N/A	[h] 95	N/A	N/A	N/A	10 (total oil and grease)

N/A = not applicable or insignificant.

Notes:

[a] Total cyanide (CN_T) is the sum of all the different forms of cyanide present in a system except CNO and CNS produced as result of detoxification processes.

[b] Only hydrogen cyanide (HCN) volatilizes. The volatilization rate for cyanide is a conservative (low) value from Broderius and Smith (1980) with similar environment conditions (T= 25 ^{o}C, pH=7.9, $[CN_F]$=0.025~0.2 mg/L, no air flow).

[c] Adsorption coefficients values except iron were obtained from the GSI chemical database (http://www.gsi-net.com/en/publications/gsi-chemical-database/). The coefficients values for iron was based on the (USGS. 1999) paper (Proceedings of the Technical Meeting Charleston South Carolina March 8-12, 1999--Volume 1 of 3--Contamination From Hard-Rock Mining, Water-Resources Investigation Report 99-4018A).

[f] Assume nominal leaching concentrations for runoff concentration input for MWP. This concentration is very conservative from the kinetic humidity cell test (KCB, 2012). Note that the laboratory leaching concentration in the table are the largest (average of maximum of each sample test) value for 18 sampling tests.

[g] Assumes nominal performance for CN_{WAD} from CN detoxification plant and estimate $[CN_T]$ and $[CN_F]$ based on tailings decant test result. The dilution from runoff was also considered. Tailings decant test result from Table 6 of (AMEC, 2010c): $[CN_T]$=0.29, $[CN_F]$=0.02, $[CN_{WAD}]$=0.02 mg/L at pH=8.5 for Oxide Comp TIs.

[h] Spill concentration were determined based on the maximum amount of a spill from CAT 740B truck (assume one event per year X 230 gallons per spill, to be distributed over a nominal 12 hour pumping period for average pumped flow; $C_{pump}=M_{spill}/Q_{pump}$=766 kg/8042 m^3=95 mg/L.

Table 2: Hydraulic Parameters of Geologic Units in Groundwater Flow Model [Source: Itasca, 2013)]

Formation/Unit		Hydraulic Conductivity (m/day)			Specific Storage (m^{-1})	Specific Yield ( )
		K_x	K_y	K_z		
Unconsolidated Deposits	< 1400 m from the riverbank	1.0E-01	1.0E-01	1.0E-02	1.0E-05	2.0E-01
	> 1400 m from the riverbank	1.8E-01	1.8E-01	1.8E-02	1.0E-05	2.0E-01
Weathered Bedrock	< 200 m from the riverbank	5.0E+01	5.0E+00	5.0E+00	1.0E-06	1.0E-02
	Between 200 and 400 m from the riverbank	4.0E-01	4.0E-02	4.0E-02	1.0E-06	1.0E-02
	Between 400 and 600 m from the riverbank	5.0E-02	5.0E-03	5.0E-03	1.0E-06	1.0E-02
	> 600 m from the riverbank	1.0E-02	1.0E-03	1.0E-03	1.0E-06	1.0E-02
Fresh Bedrock	Upper Bedrock: above -15 mamsl	5.0E-02	5.0E-03	5.0E-03	1.0E-06	5.0E-03
	Middle Bedrock: between -15 mamsl and -195 mamsl	3.2E-02	3.2E-03	3.2E-03	1.0E-06	5.0E-03
	Lower Bedrock: between -195 mamsl and -245 mamsl	4.7E-03	4.7E-04	4.7E-04	1.0E-06	5.0E-03
	Deep Bedrock: below -245 mamsl	3.6E-04	3.6E-05	3.6E-05	1.0E-06	5.0E-03
Zone of Relaxation	for prediction only	5.0E-02	5.0E-02	5.0E-02	5.0E-06	5.0E-03
Dike	for prediction only	1.0E-05	1.0E-05	1.0E-05	1.0E-06	5.0E-03
Shear Zone	for sensitivity analysis only	5.0E-01	5.0E-02	5.0E-02	1.0E-05	5.0E-03

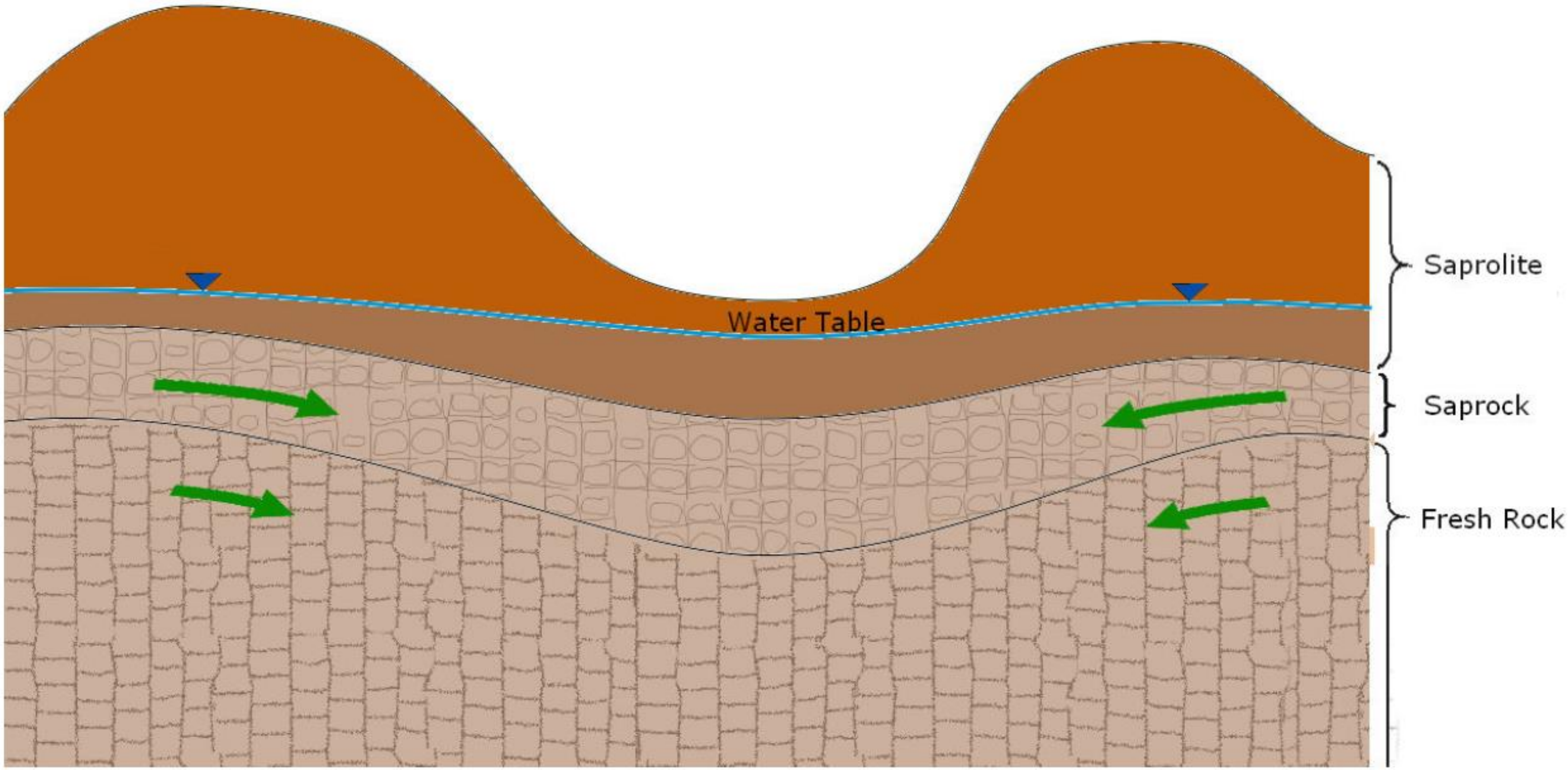

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Figure 1: Conceptual Model Cross Sections [Source: (AMEC, 2010b)]

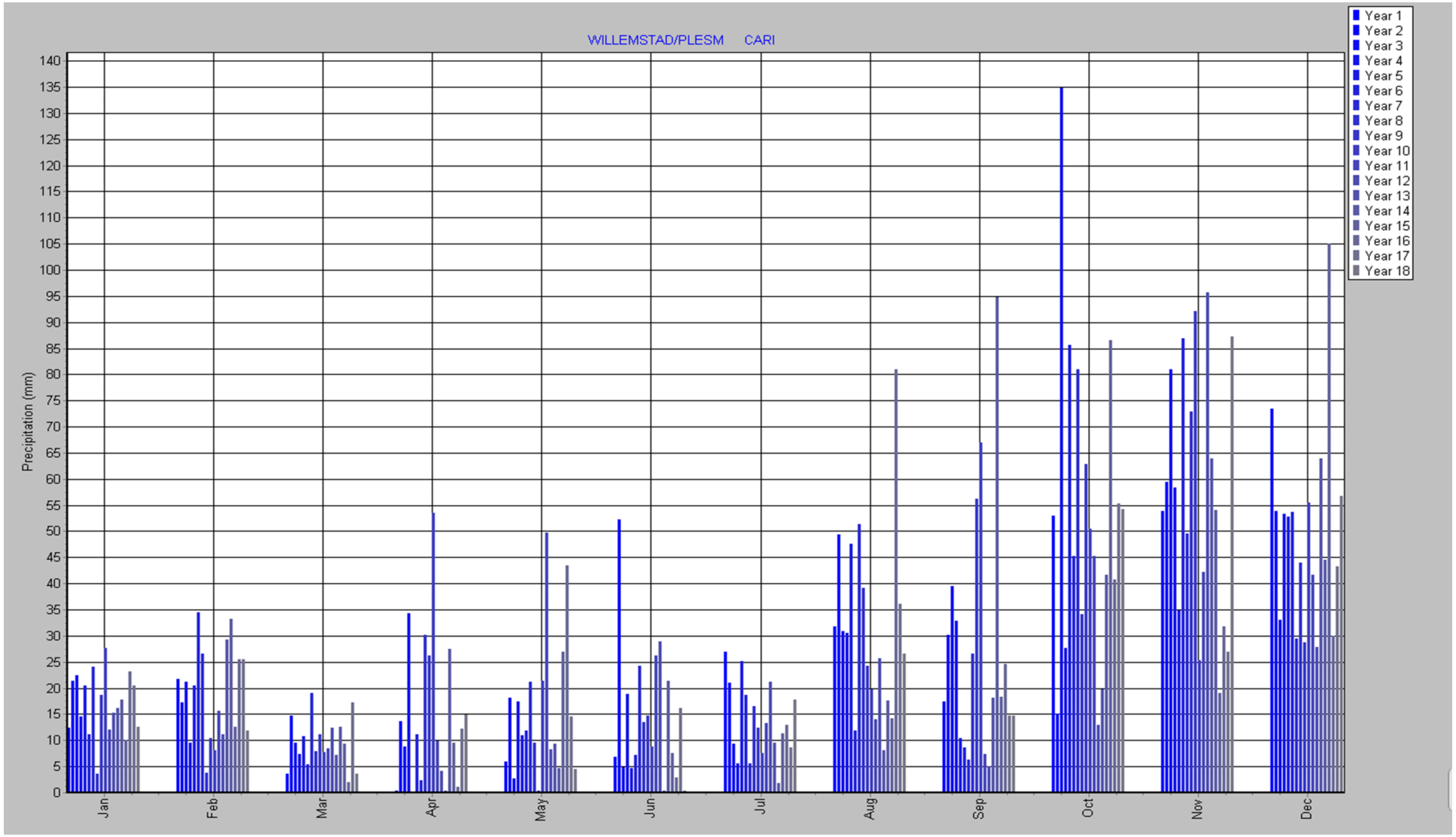

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Figure 2: Generated Monthly Rain (18 years)

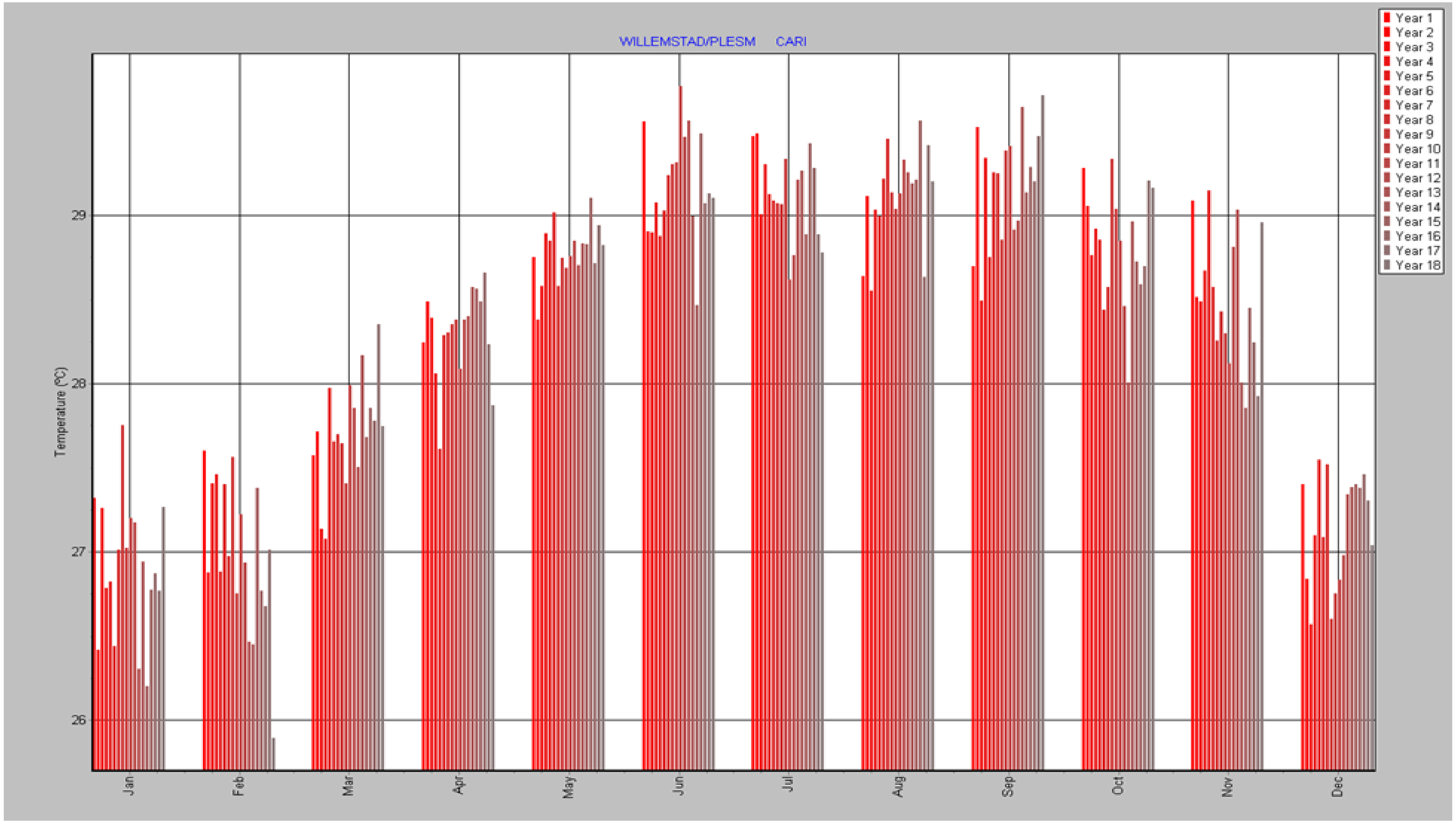

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Figure 3: Generated Average Monthly Temperatures (18 years)

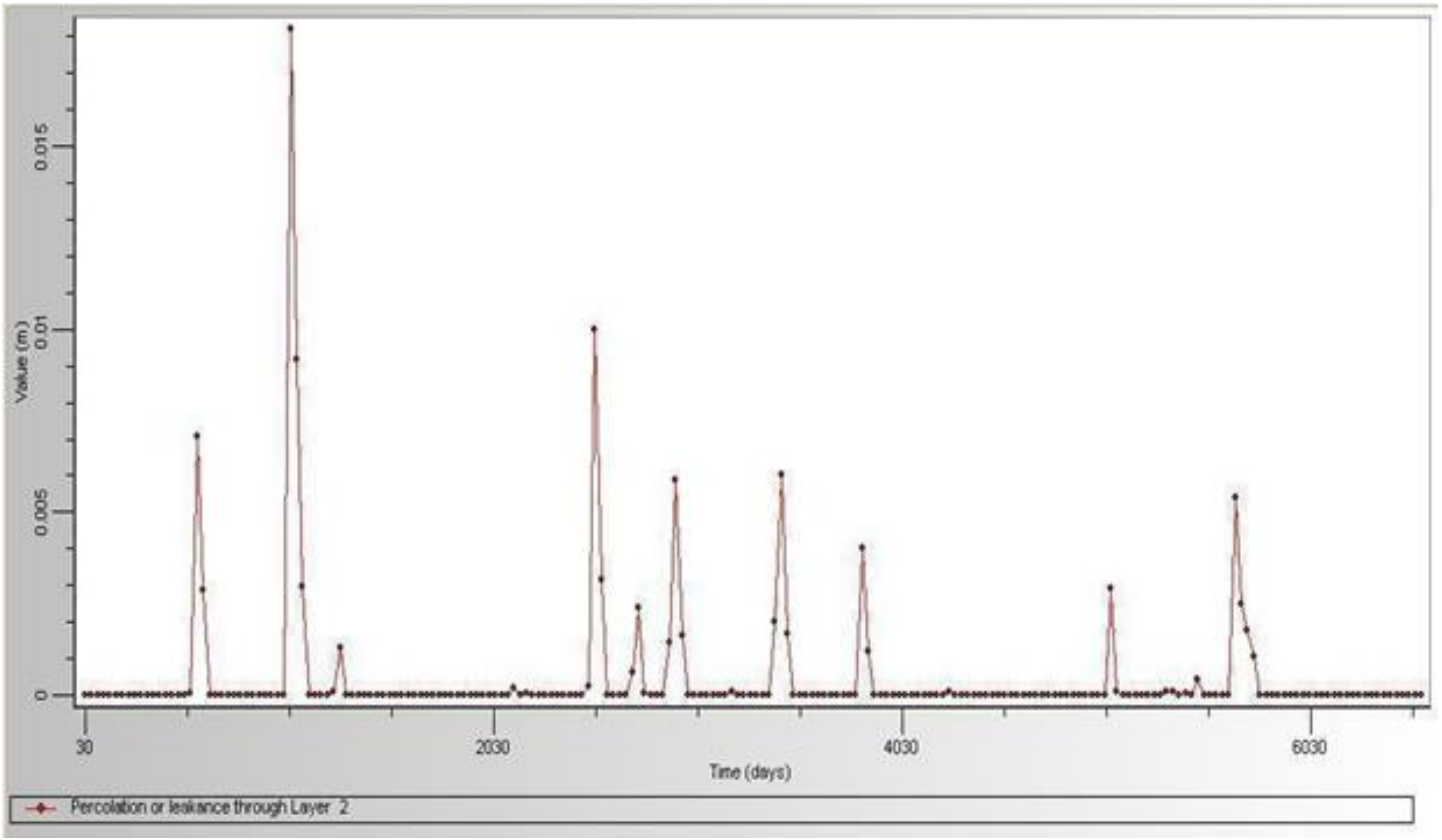

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Figure 4: Daily Percolation or Leakage through Layer 2
(interface between unsaturated and saturated zone) at the Tailing Management Area (TMA)

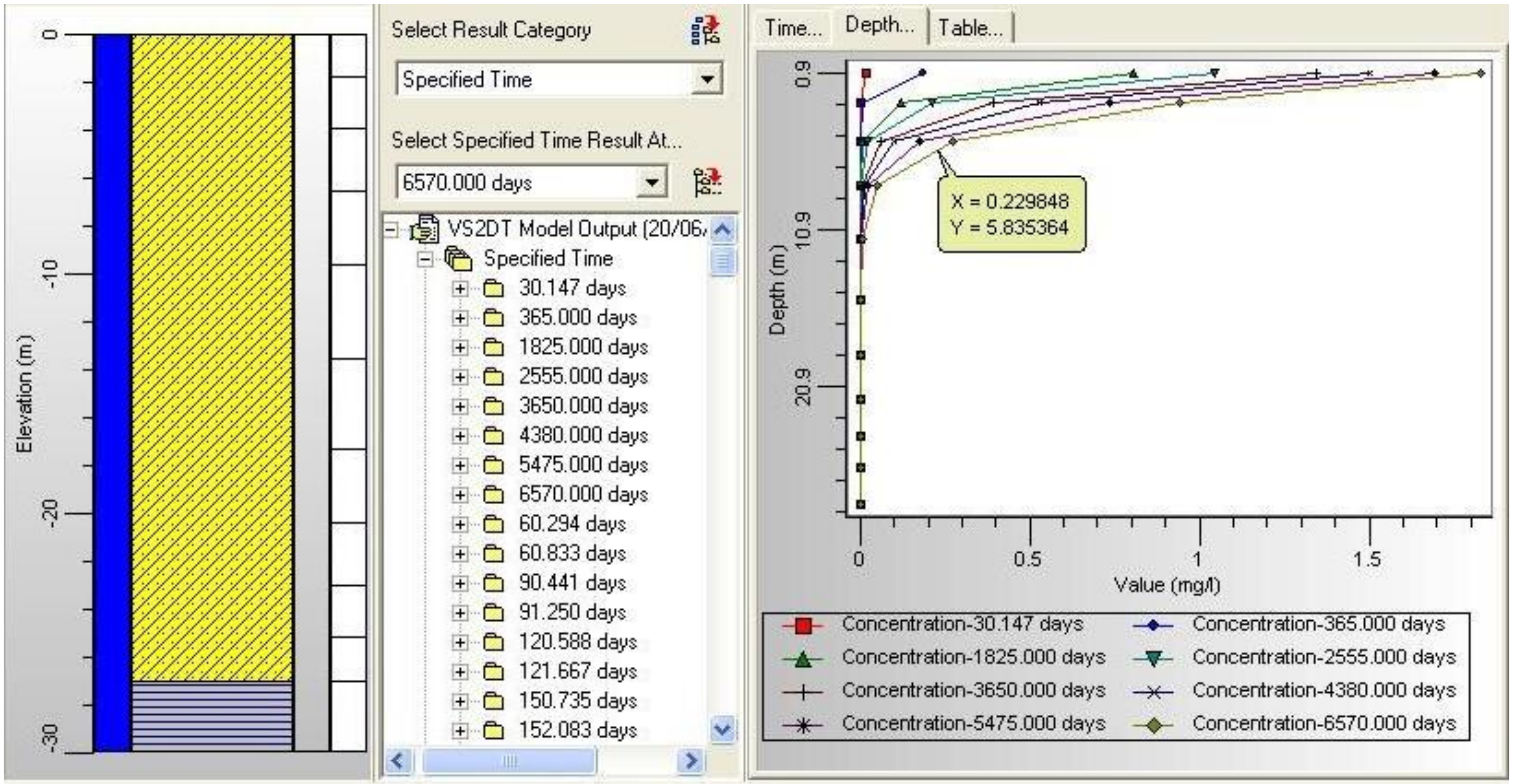

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Figure 5: Vertical Concentration Profile for Cyanide in the TMA for 18 years

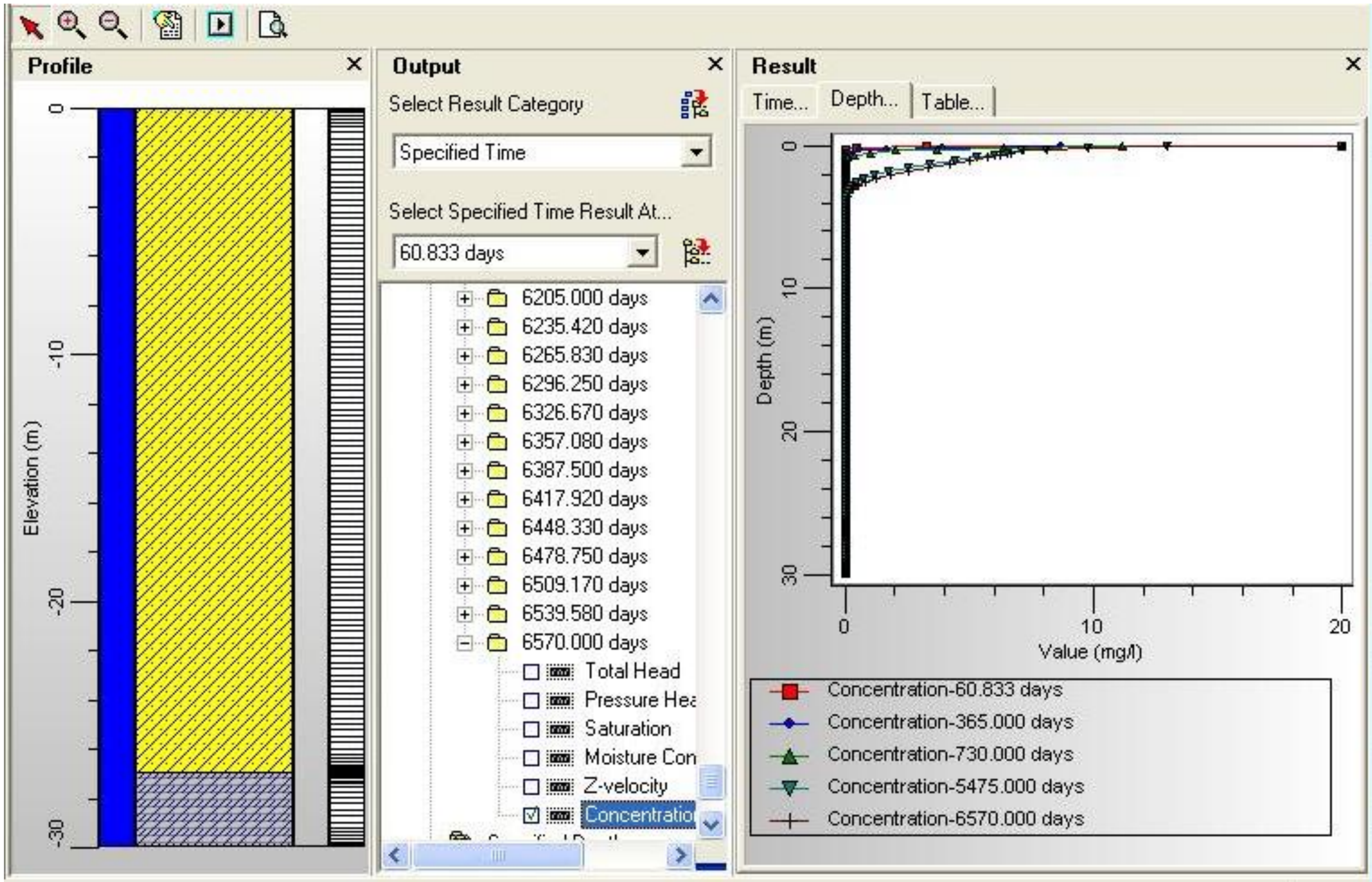

Figure 6: Vertical Concentration Profile for Iron in the TMA for 18 years

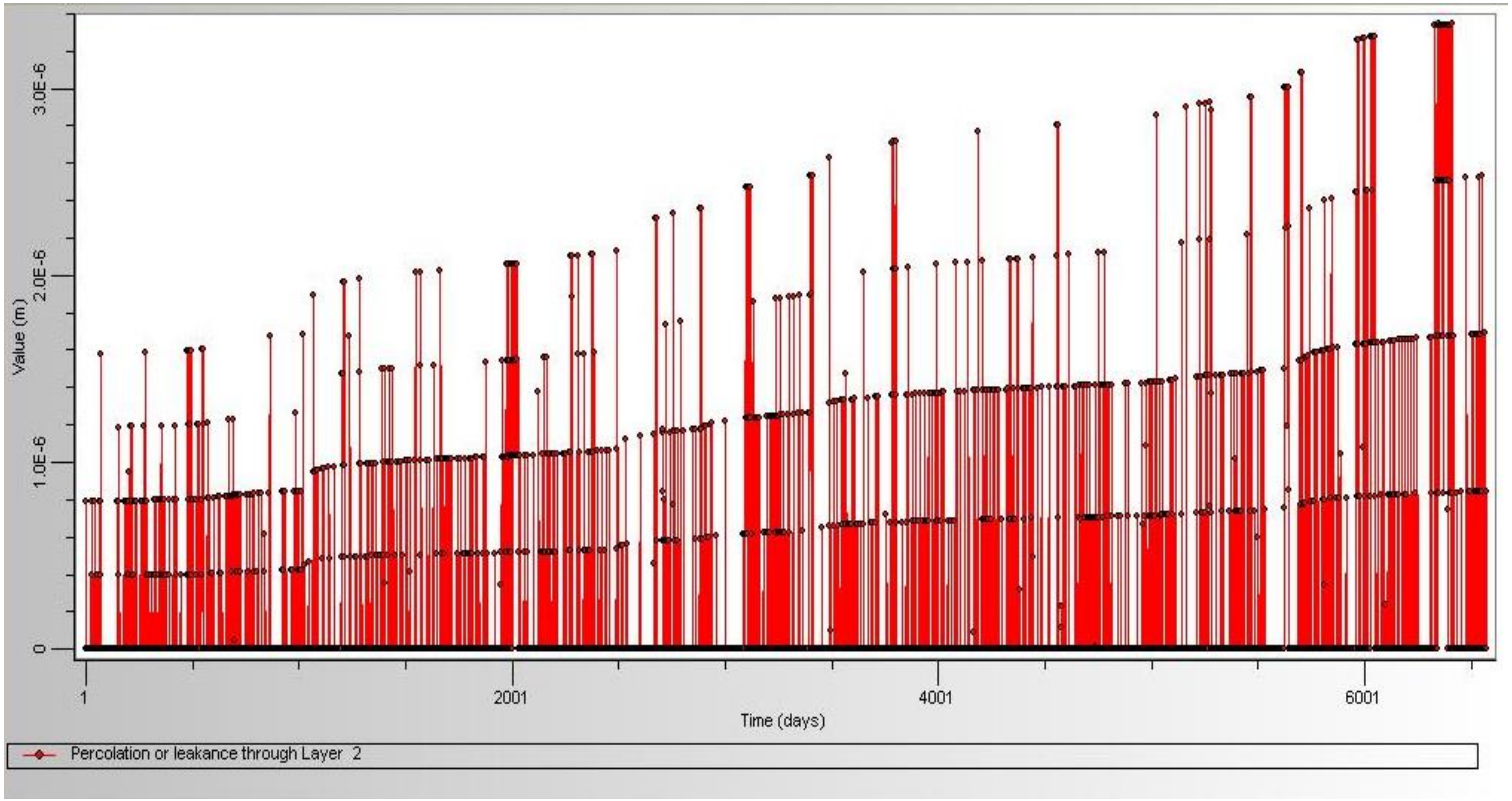

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Figure 7: Daily Percolation or Leakage through Layer 2
(interface between unsaturated and saturated zone) at the Mine Water Pond (MWP)

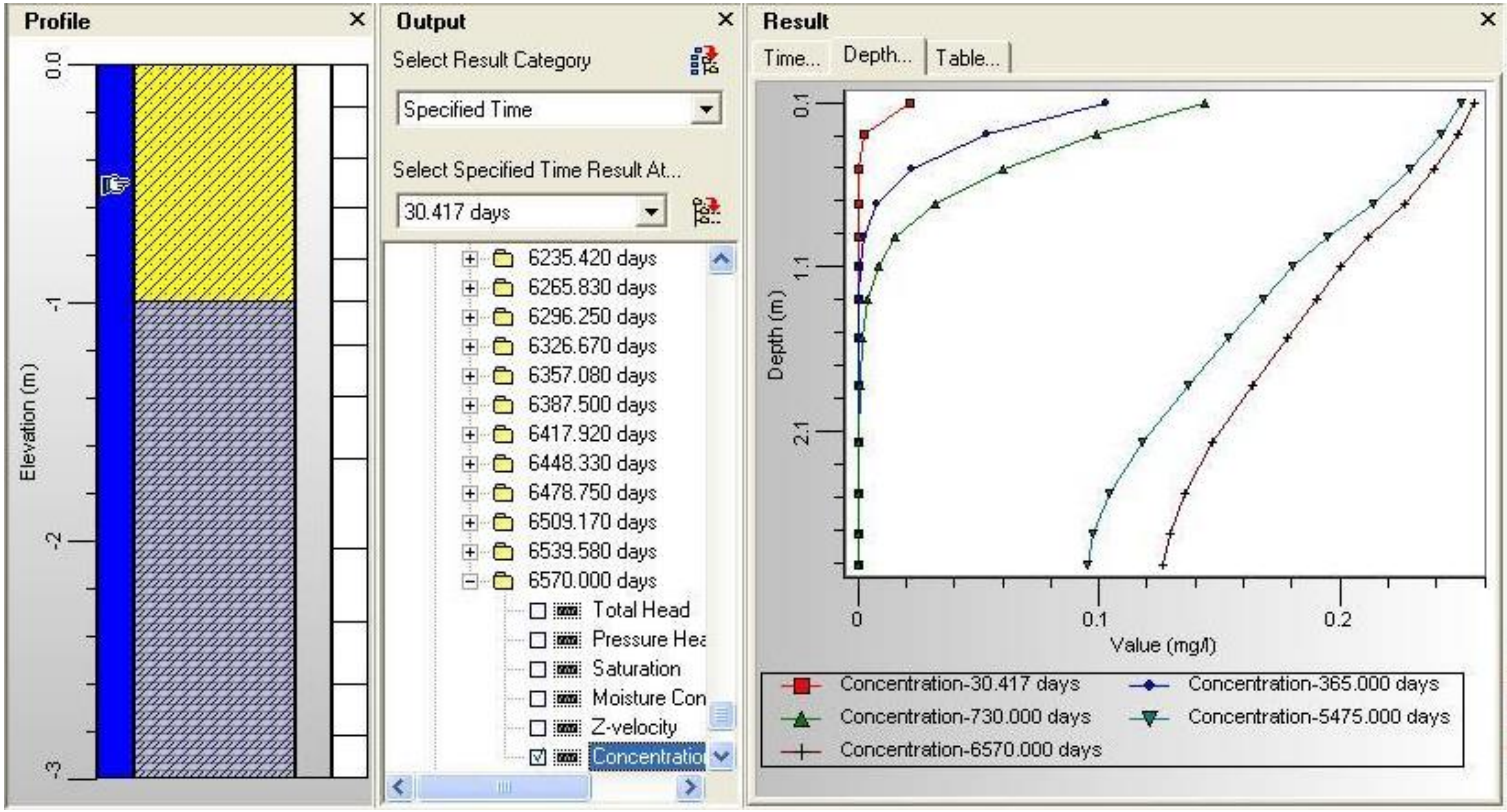

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Figure 8: Vertical Concentration Profile for Arsenic in the MWP for 18 years

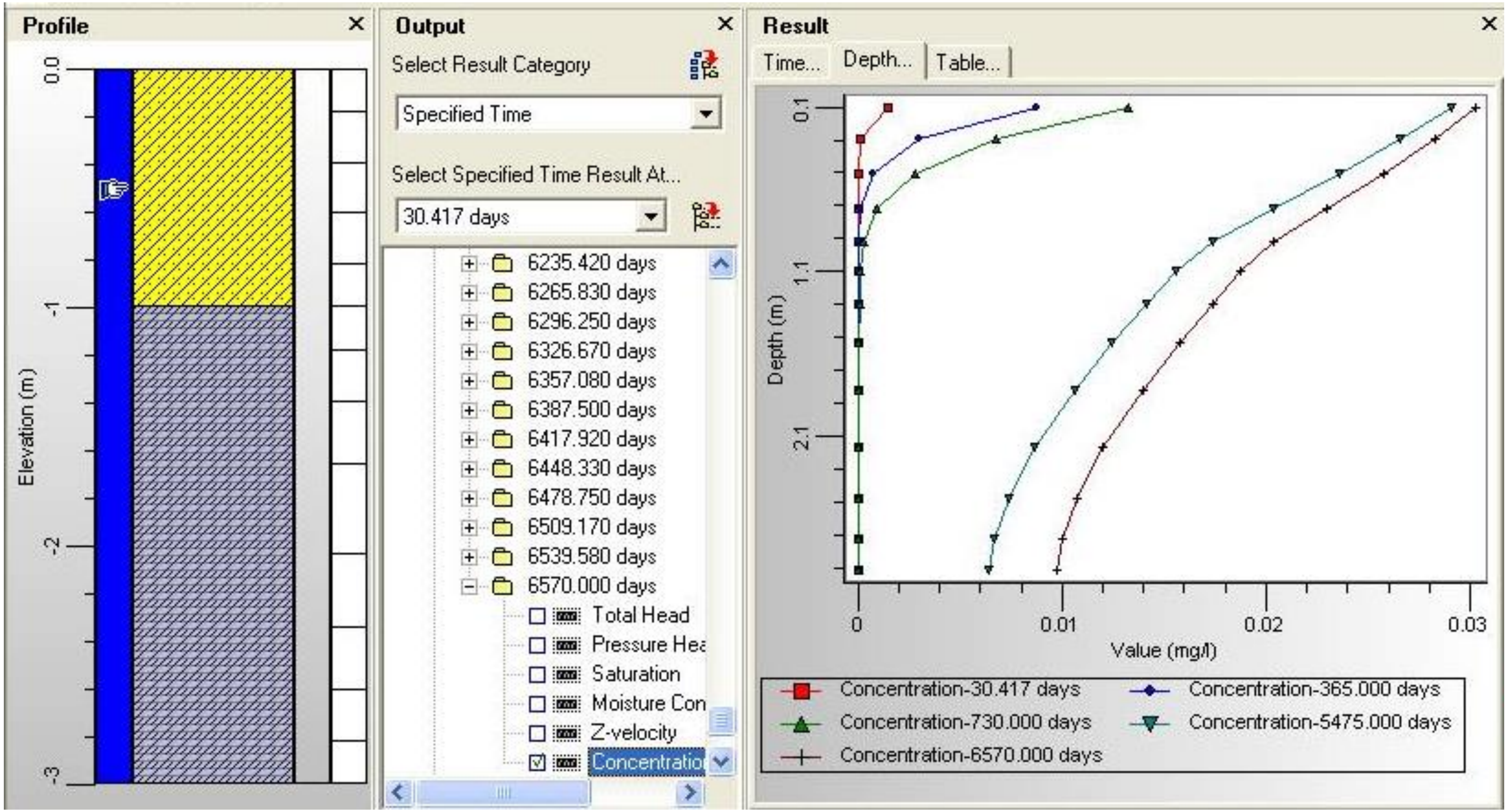

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Figure 9: Vertical Concentration Profile for Chromium in the MWP for 18 years

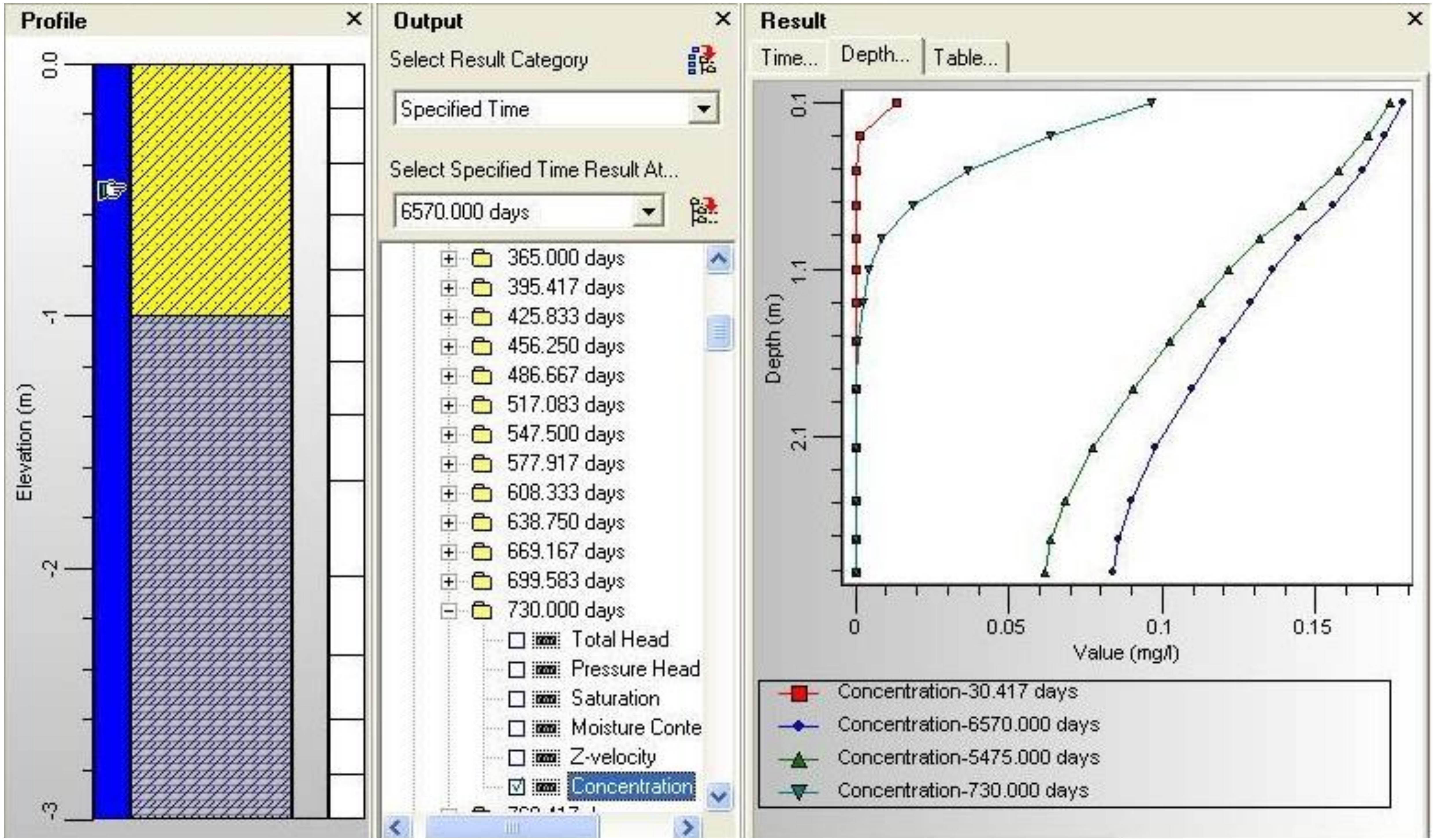

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Figure 10: Vertical Concentration Profile for Copper in the MWP for 18 years

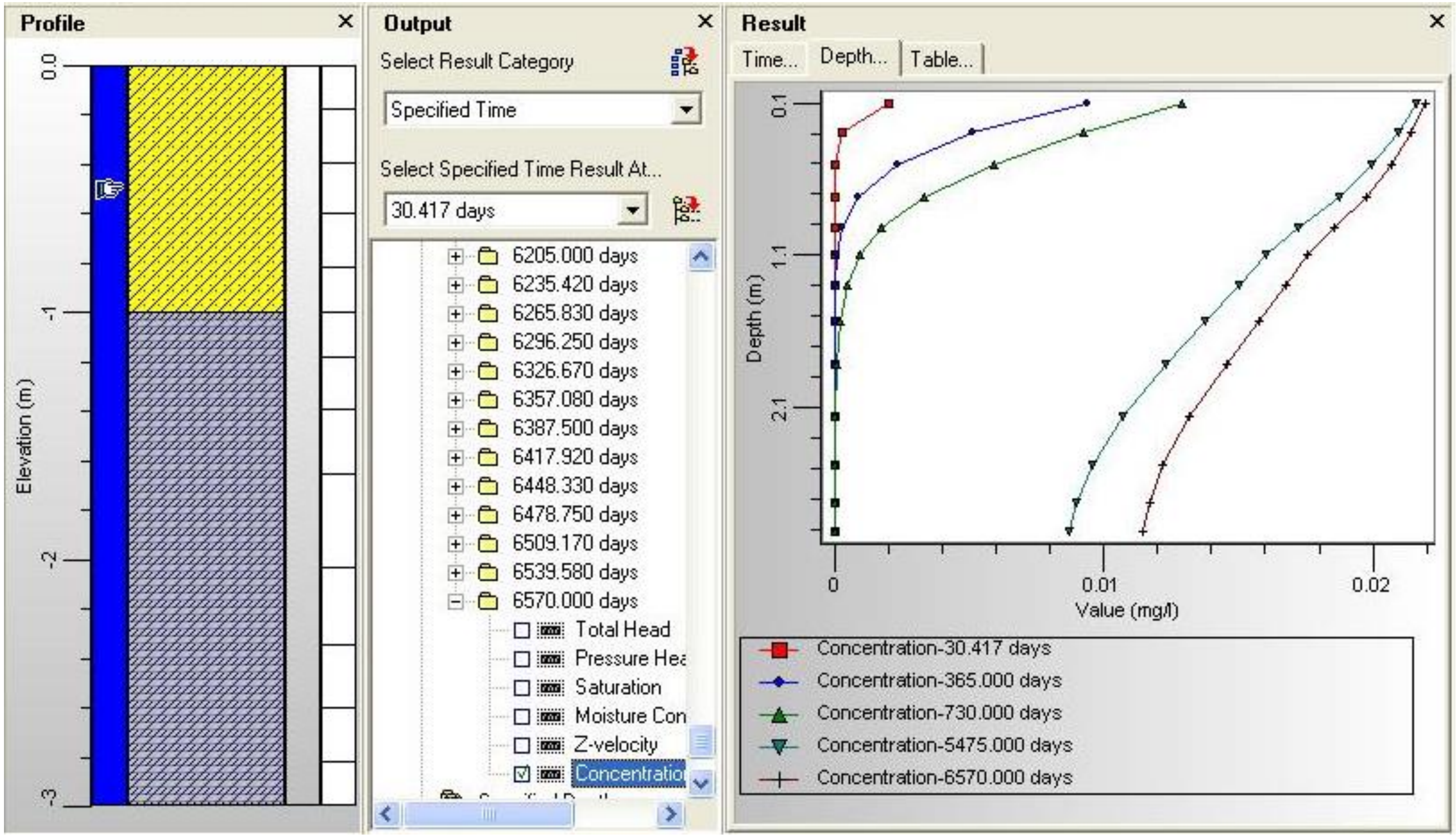

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Figure 11: Vertical Concentration Profile for Nickel in the MWP for 18 years

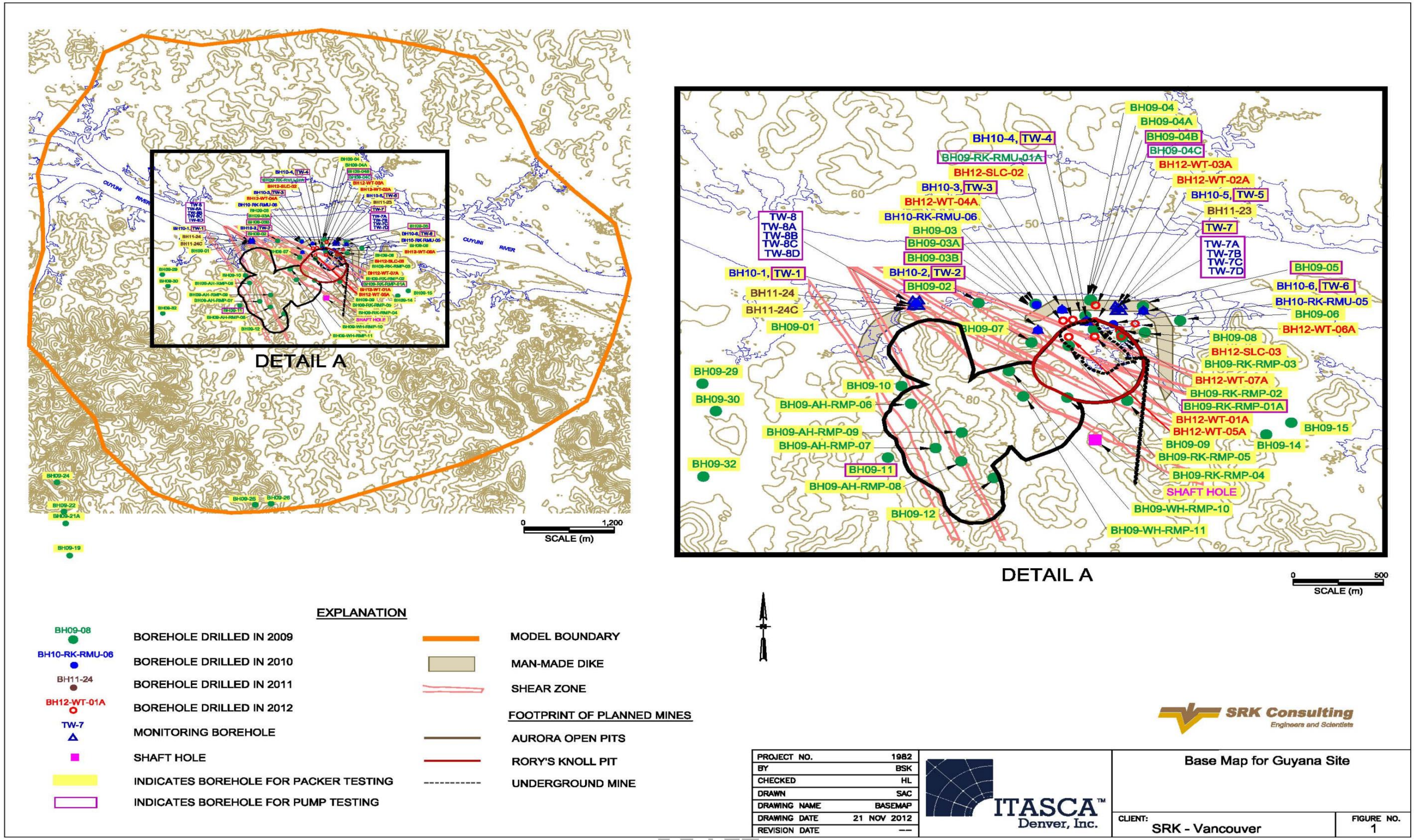

Figure 12: Base Map and Extraction Well Locations
(Source: Itasca, 2013)

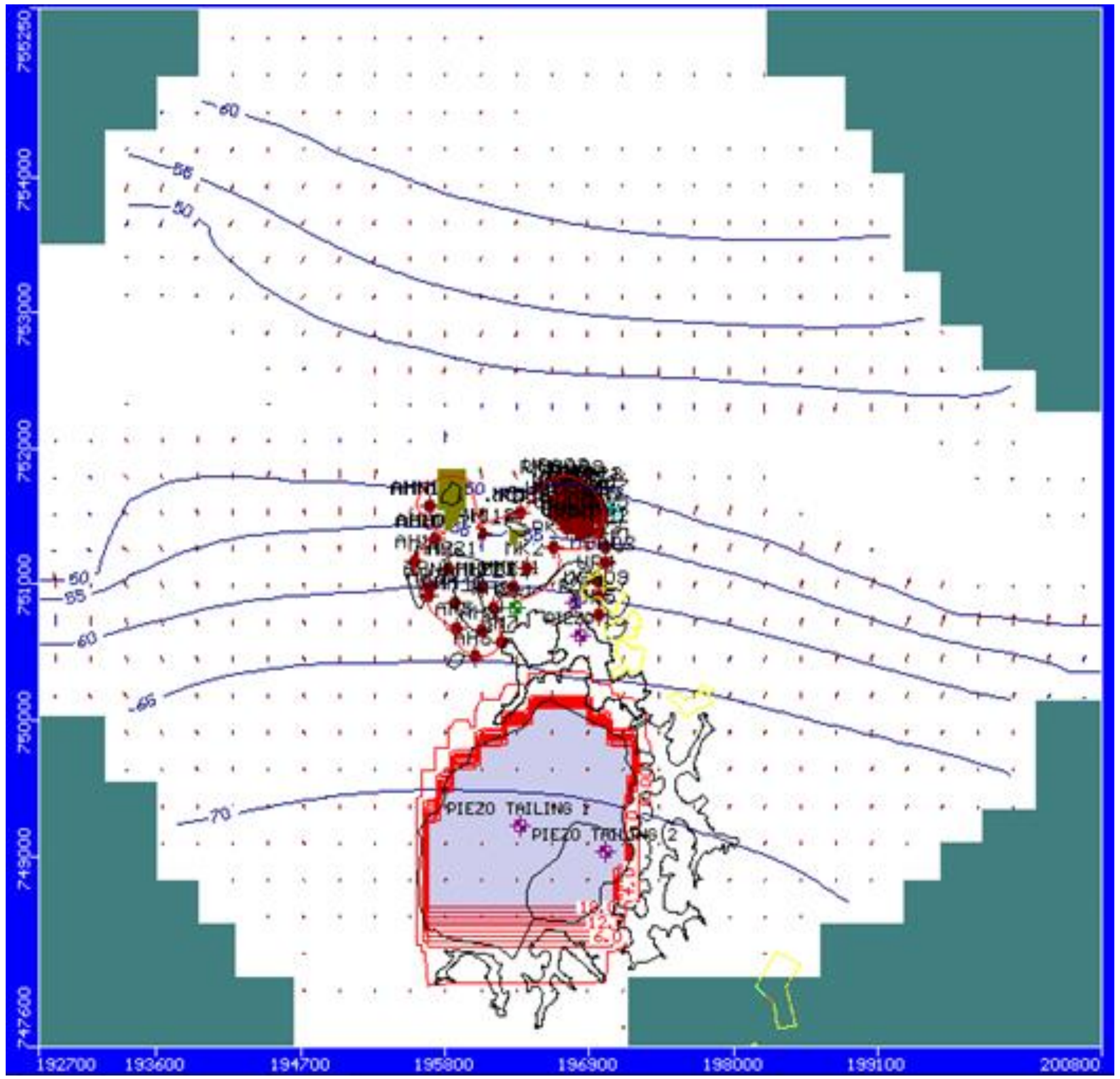

Figure a. Iron plume map after 1 year

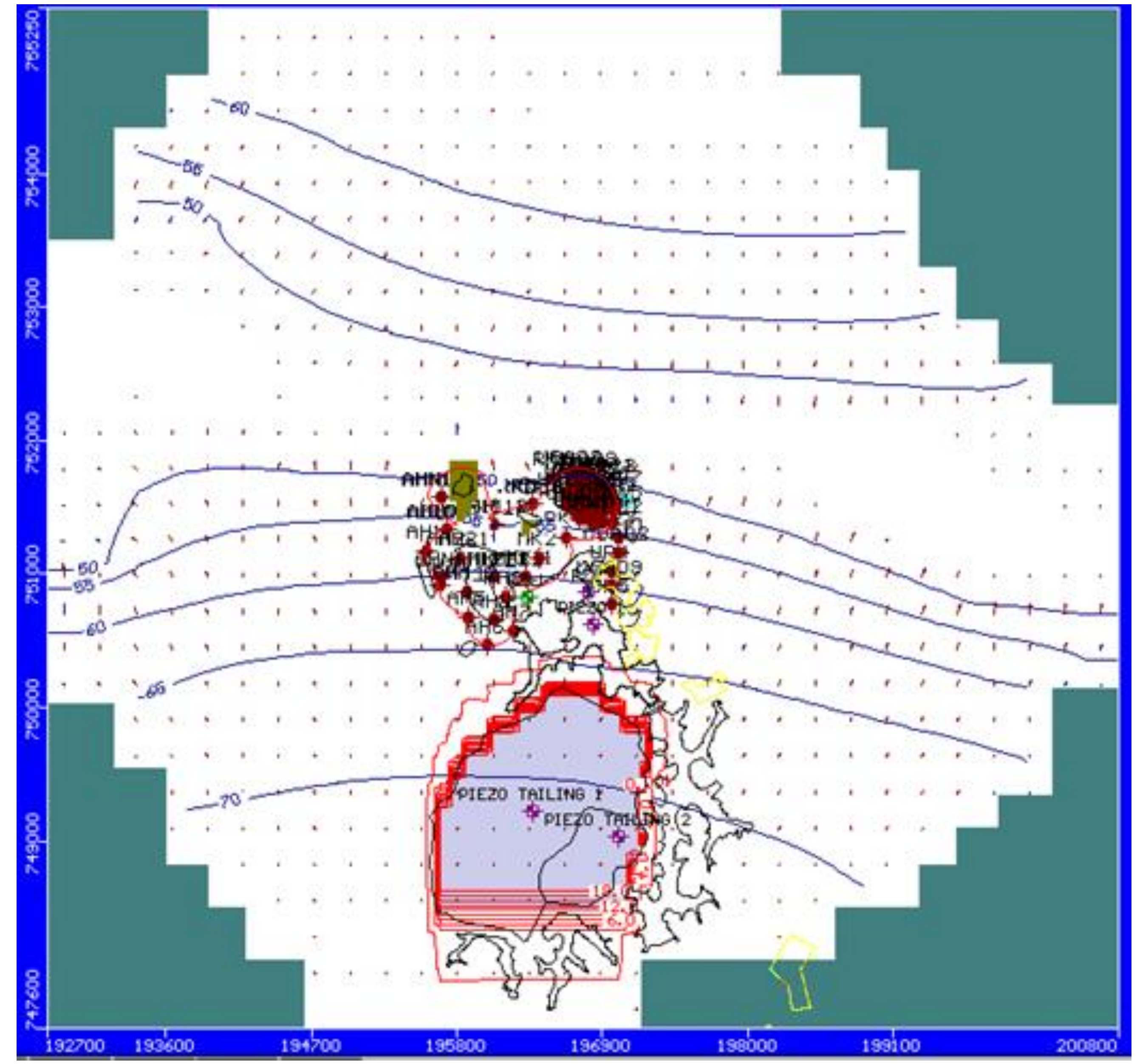

Figure b. Iron plume map after 2 years

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Figure 13: Transient Simulation Results of a Continuous Injection of Iron in the Tailing Management Area at a Concentration of 20 mg/L

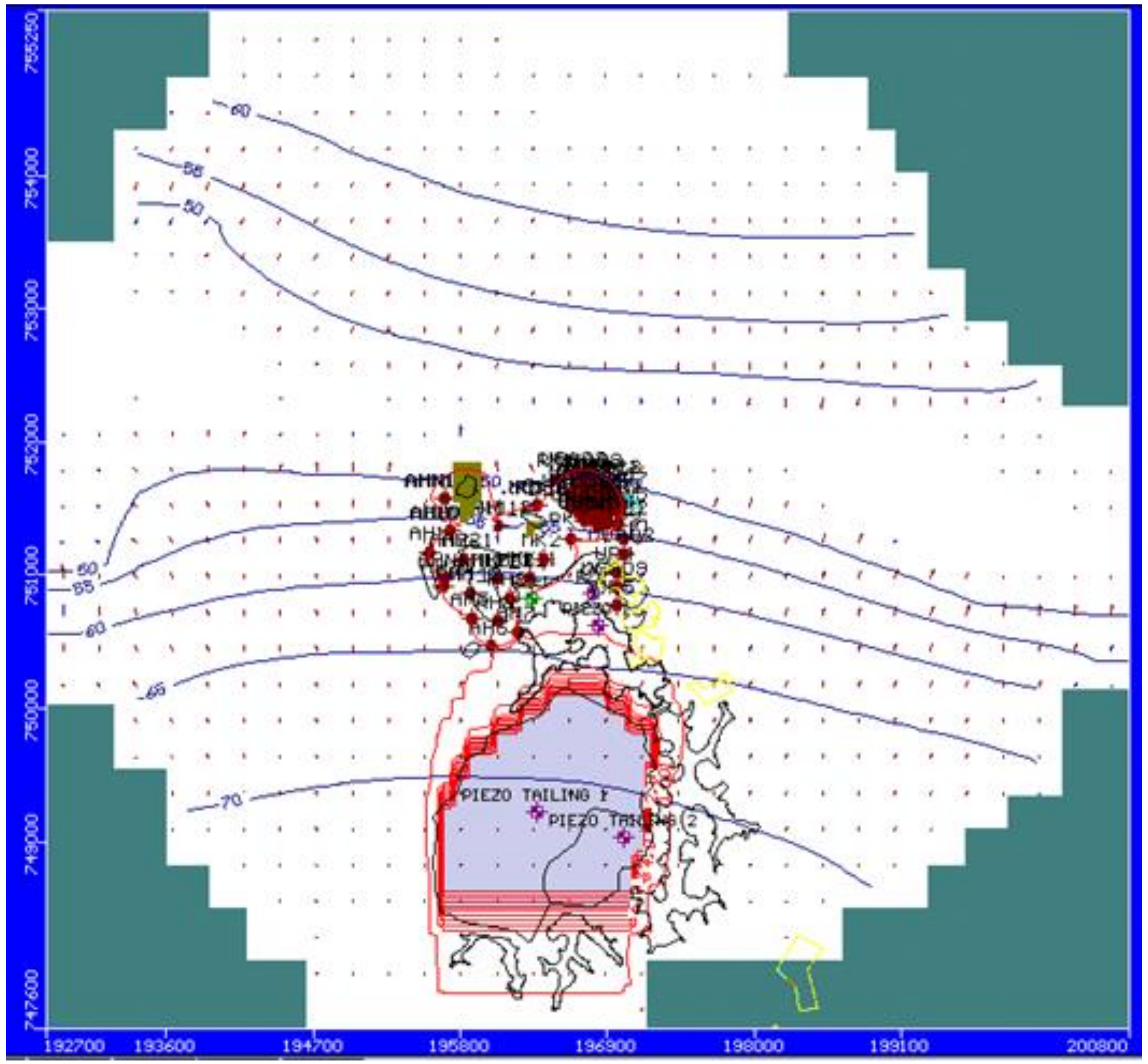

Figure c. Iron plume map after 13 years

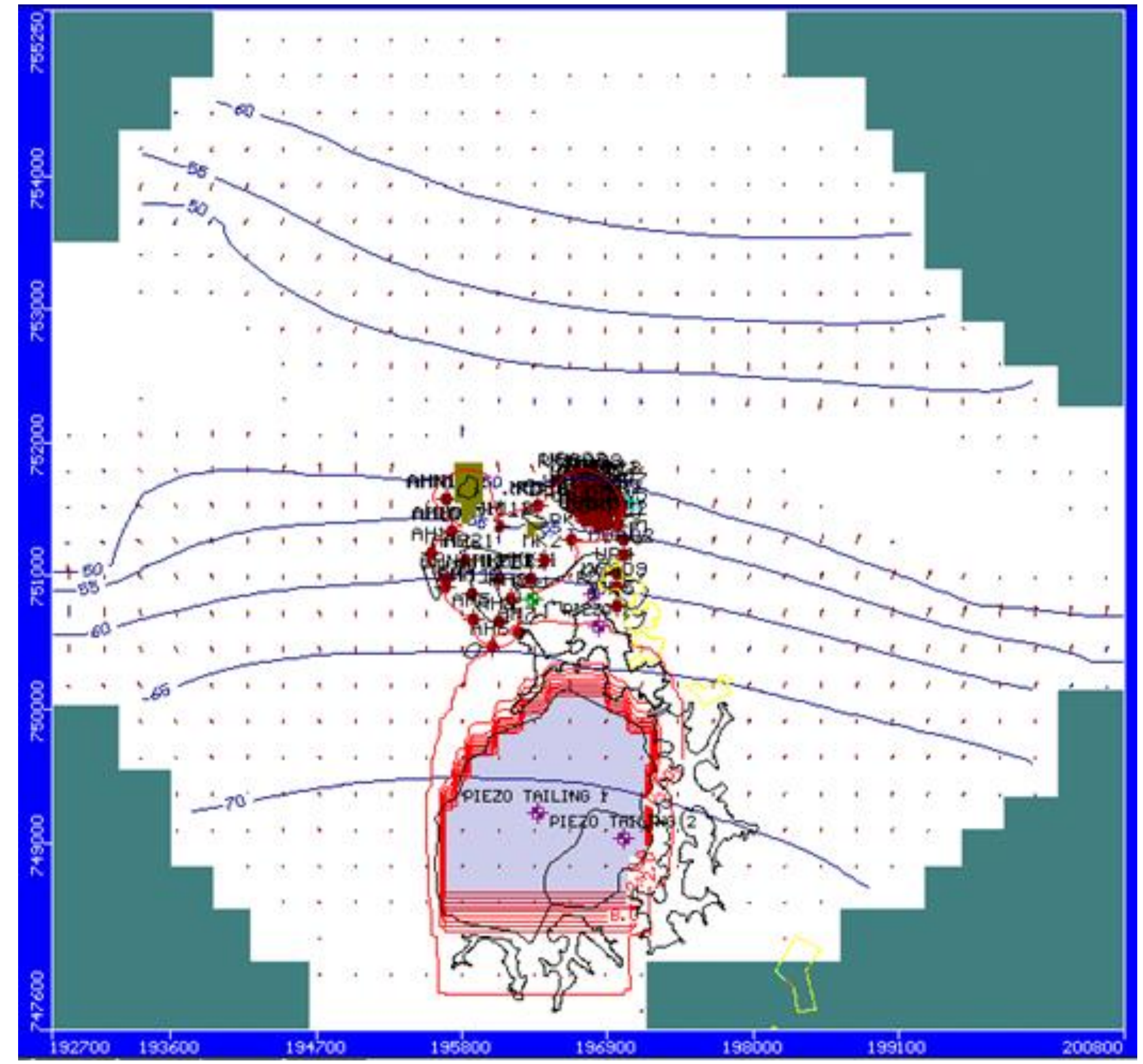

Figure d. Iron plume map after 18 years

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Figure 13 (cont.): Transient Simulation Results of a Continuous Injection of Iron in the Tailing Management Area at a Concentration of 20 mg/L

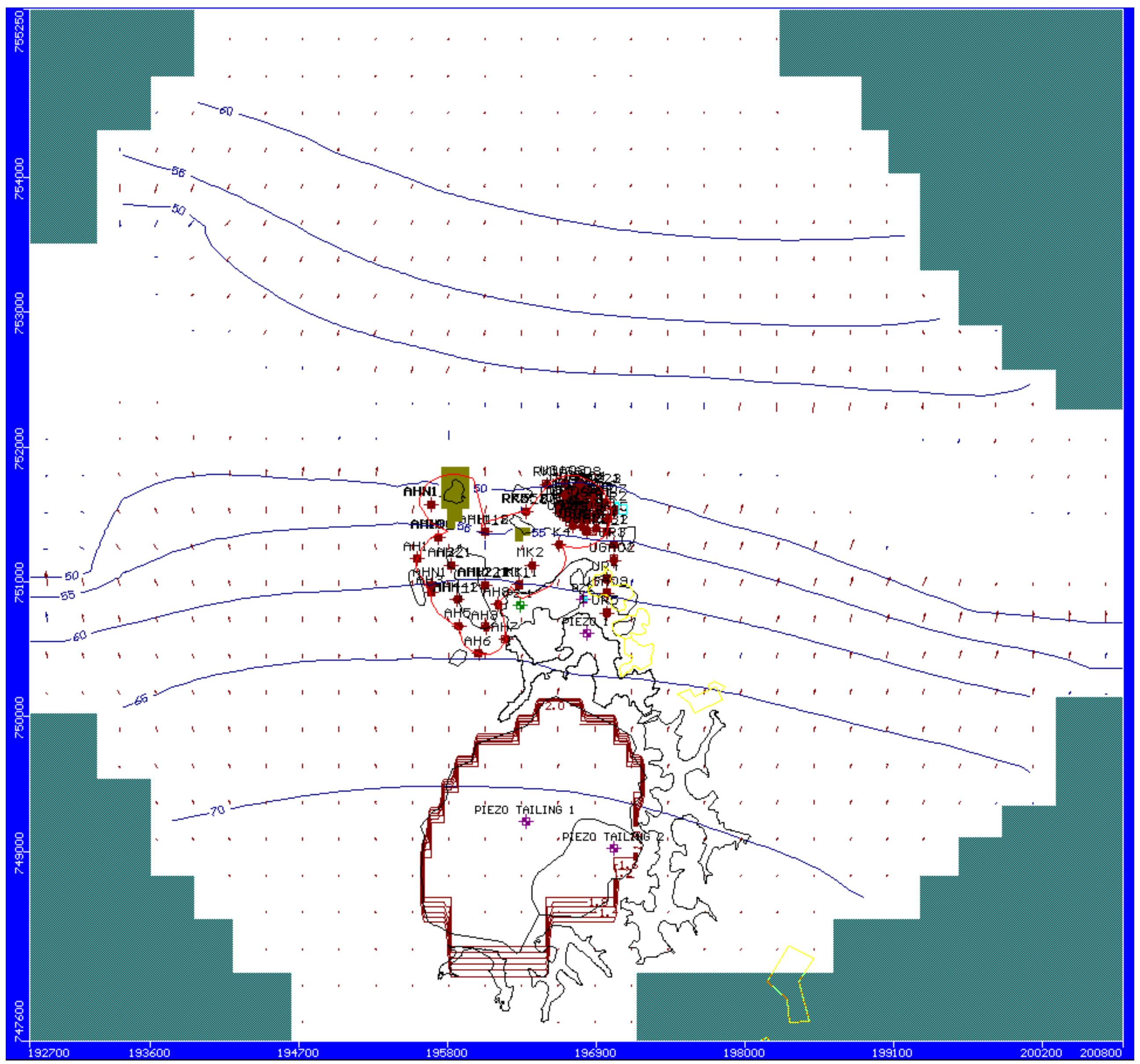

Figure a. Cyanide plume map after 1 year

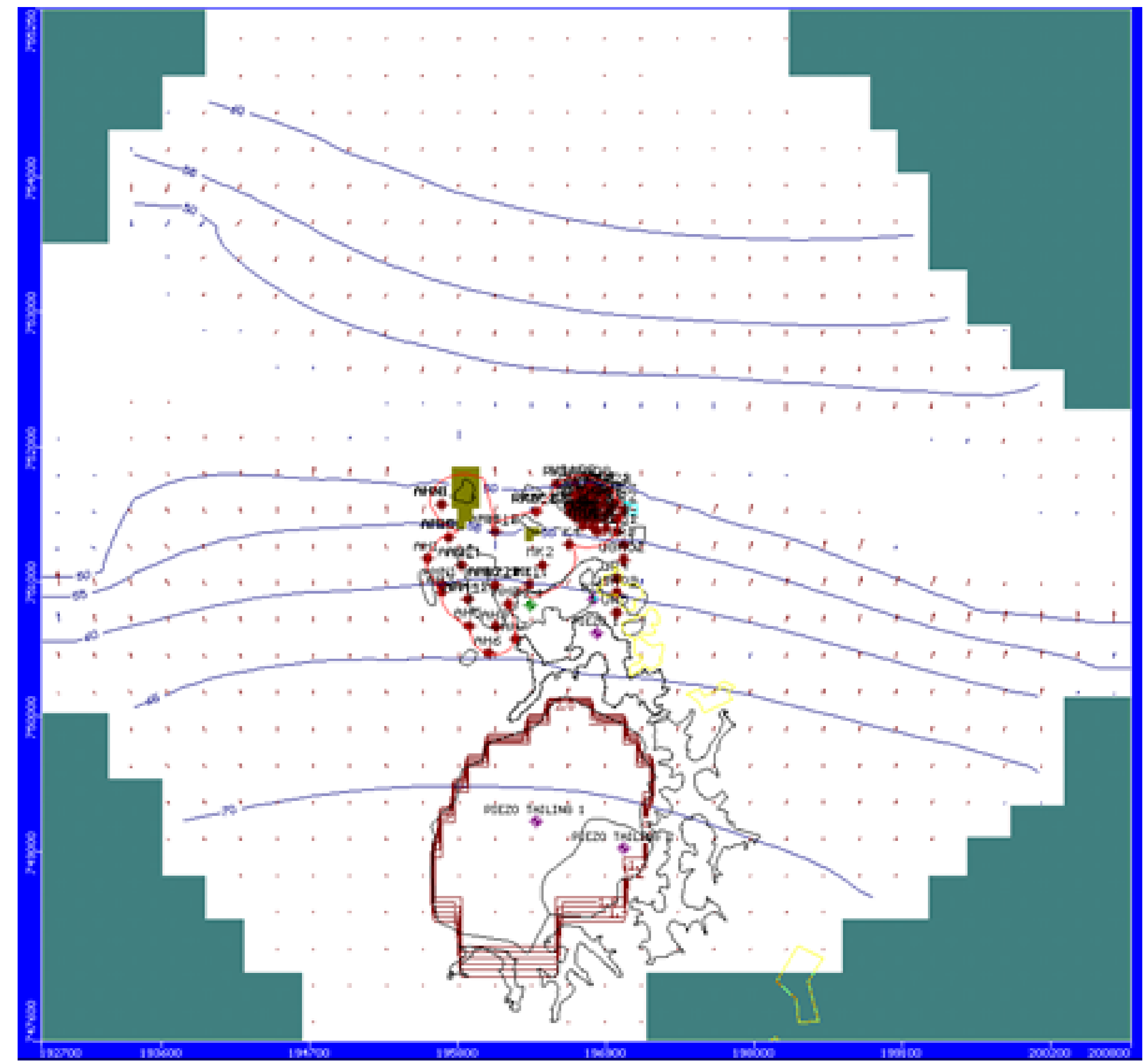

Figure b. Cyanide plume map after 2 years

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Figure 14: Transient Simulation Results of a Continuous Injection of Cyanide in the Tailing Management Area at a Concentration of 2 mg/L

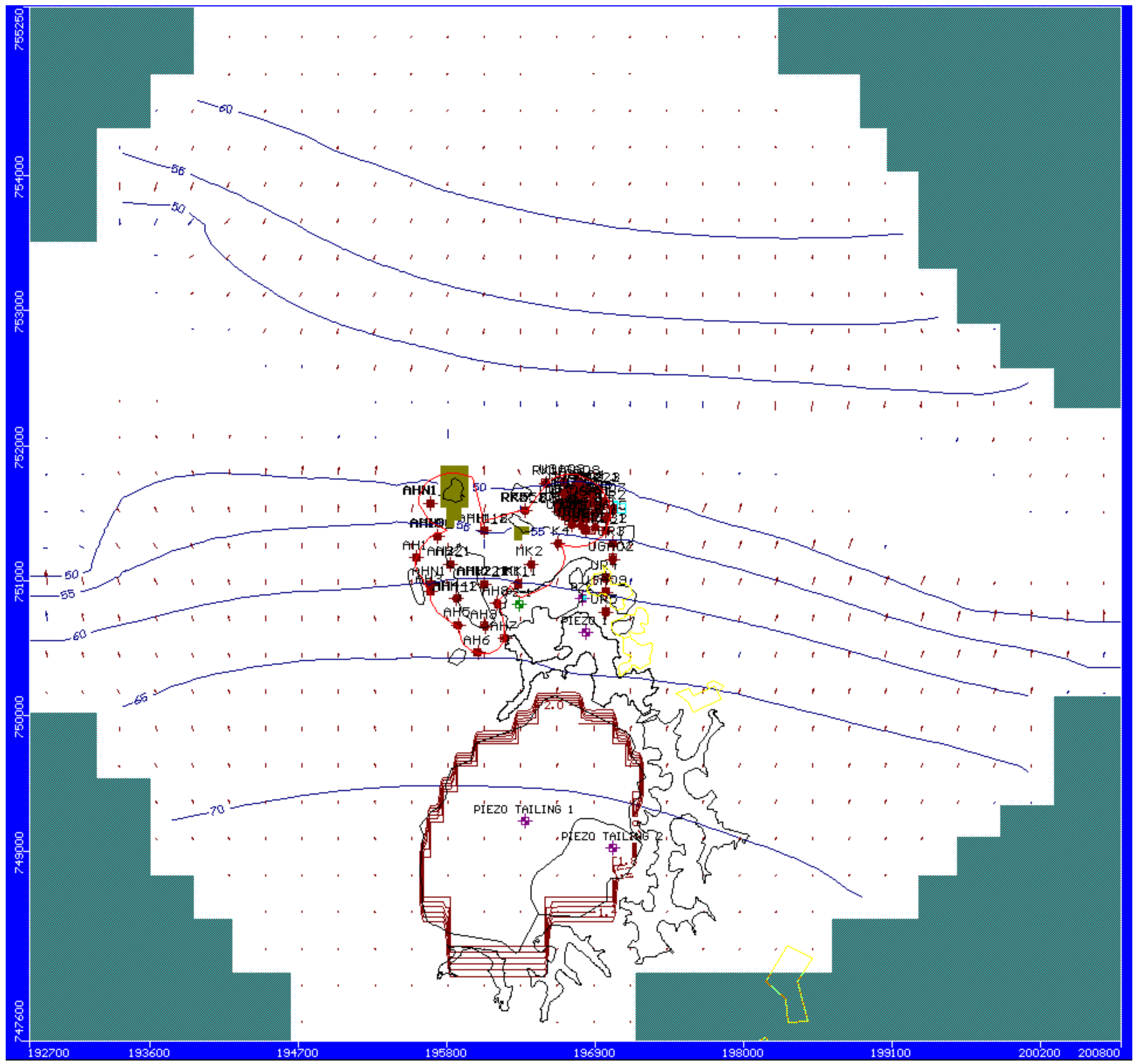

Figure c. Cyanide plume map after 13 years

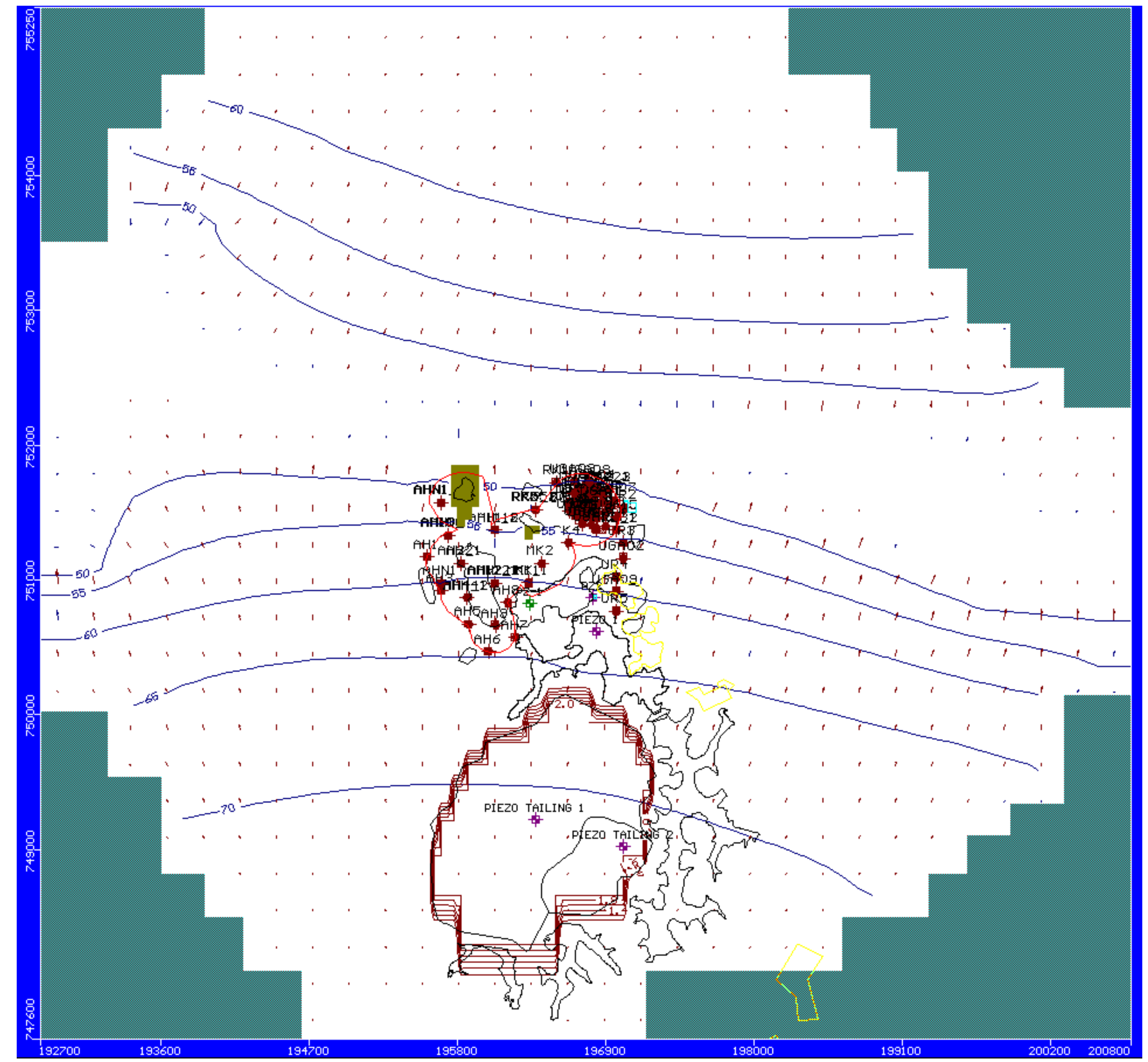

Figure d. Cyanide plume map after 18 years

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Figure 14 (cont.): Transient Simulation Results of a Continuous Injection of Cyanide in the Tailing Management Area at a Concentration of 2 mg/L

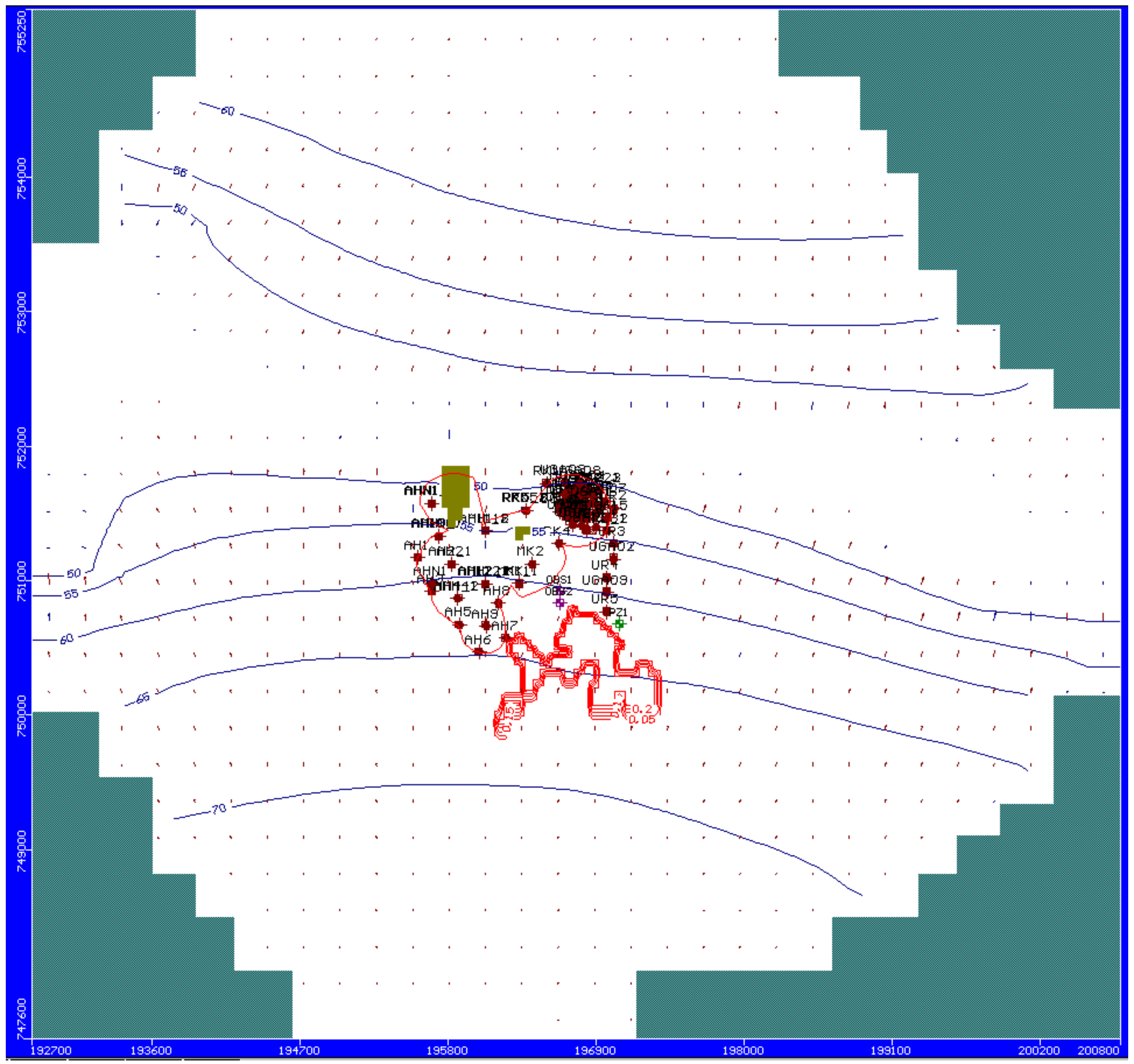

Figure a. Arsenic plume map after 1 year

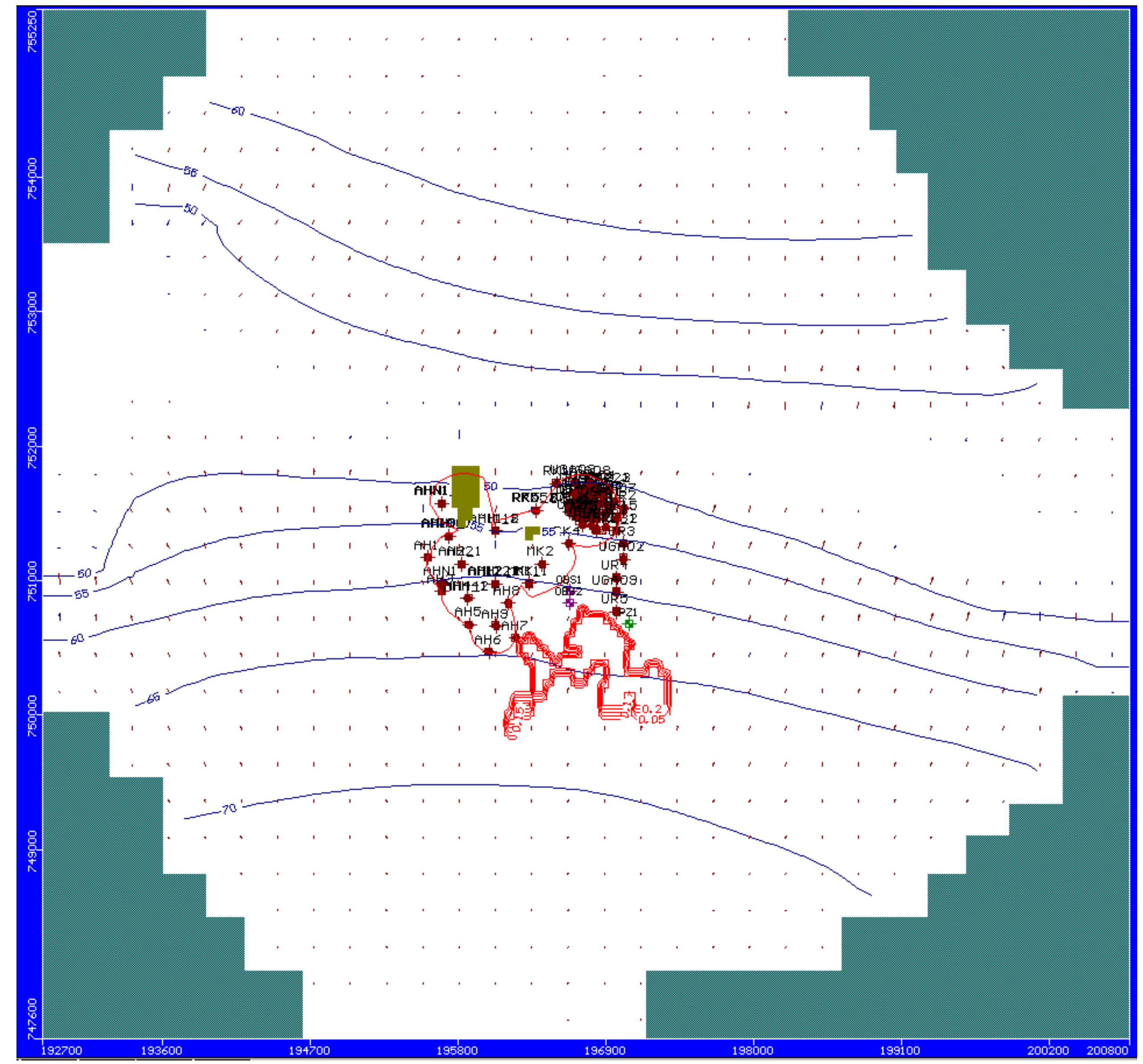

Figure b. Arsenic plume map after 2 years

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Figure 15: Transient Simulation Results of a Continuous Injection of Arsenic in the Mine Water Pond Area at a Concentration of 0.27 mg/L

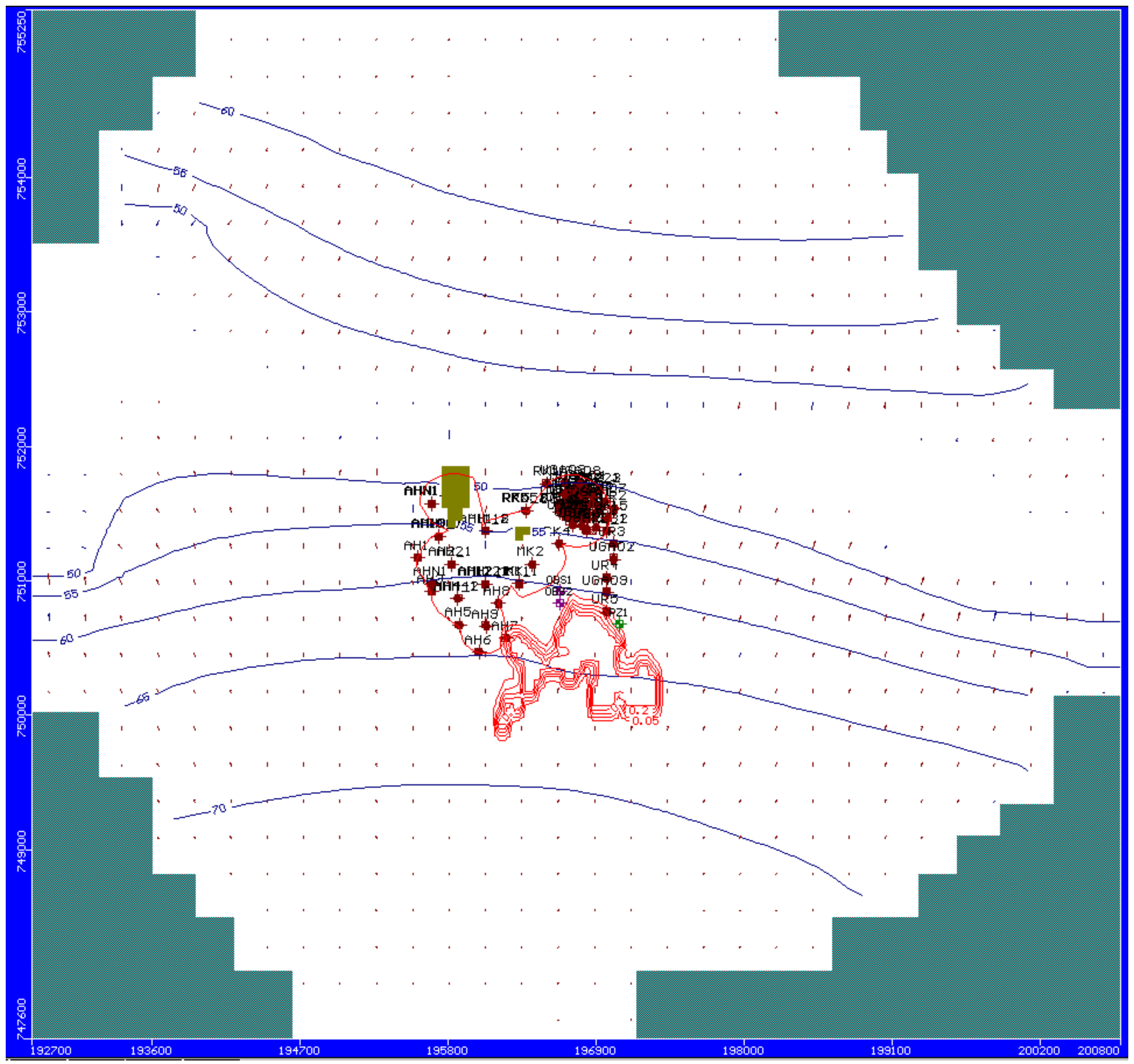

Figure c. Arsenic plume map after 13 years

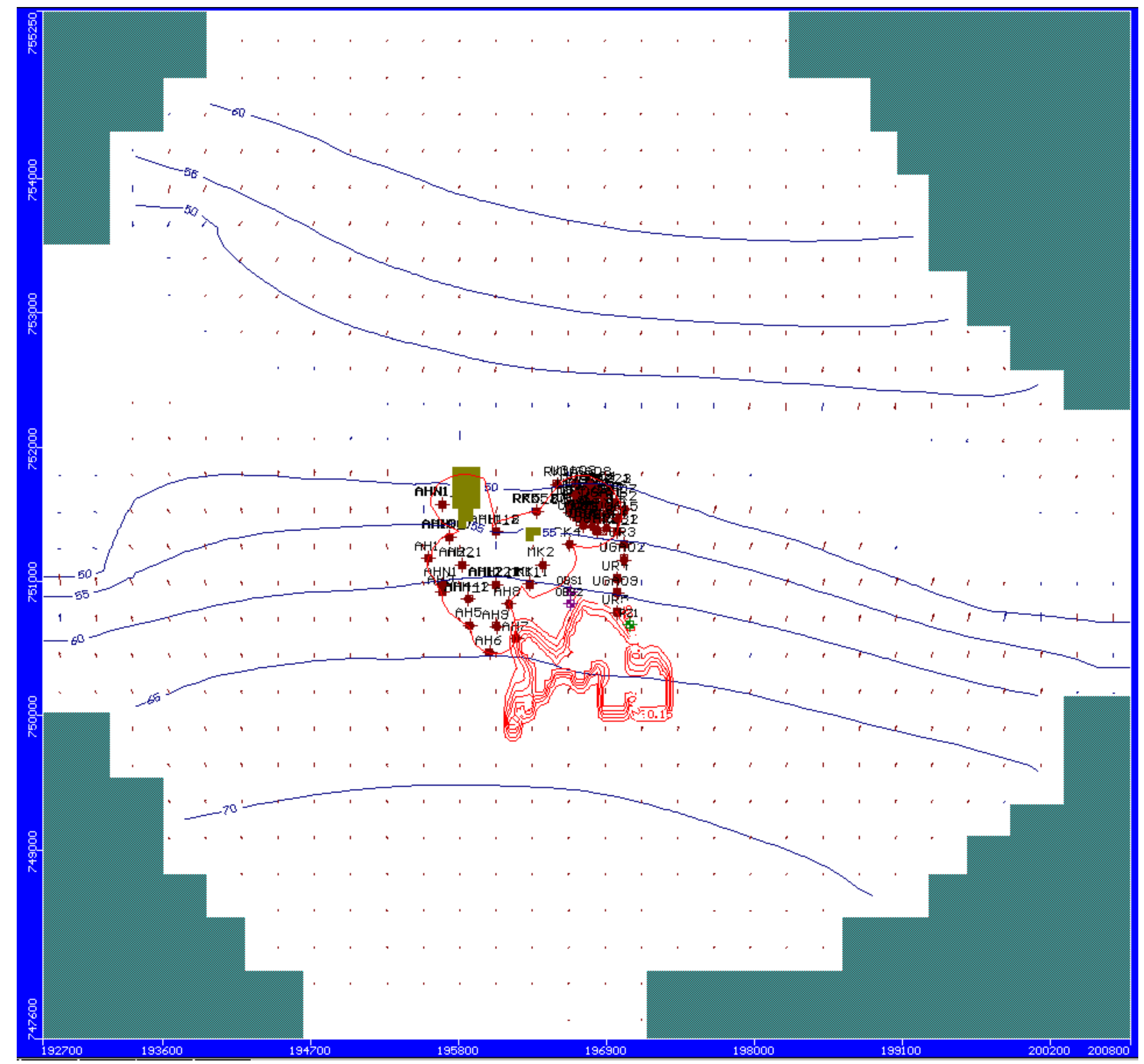

Figure d. Arsenic plume map after 18 years

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Figure 15 (cont.): Transient Simulation Results of a Continuous Injection of Arsenic in the Mine Water Pond Area at a Concentration of 0.27 mg/L

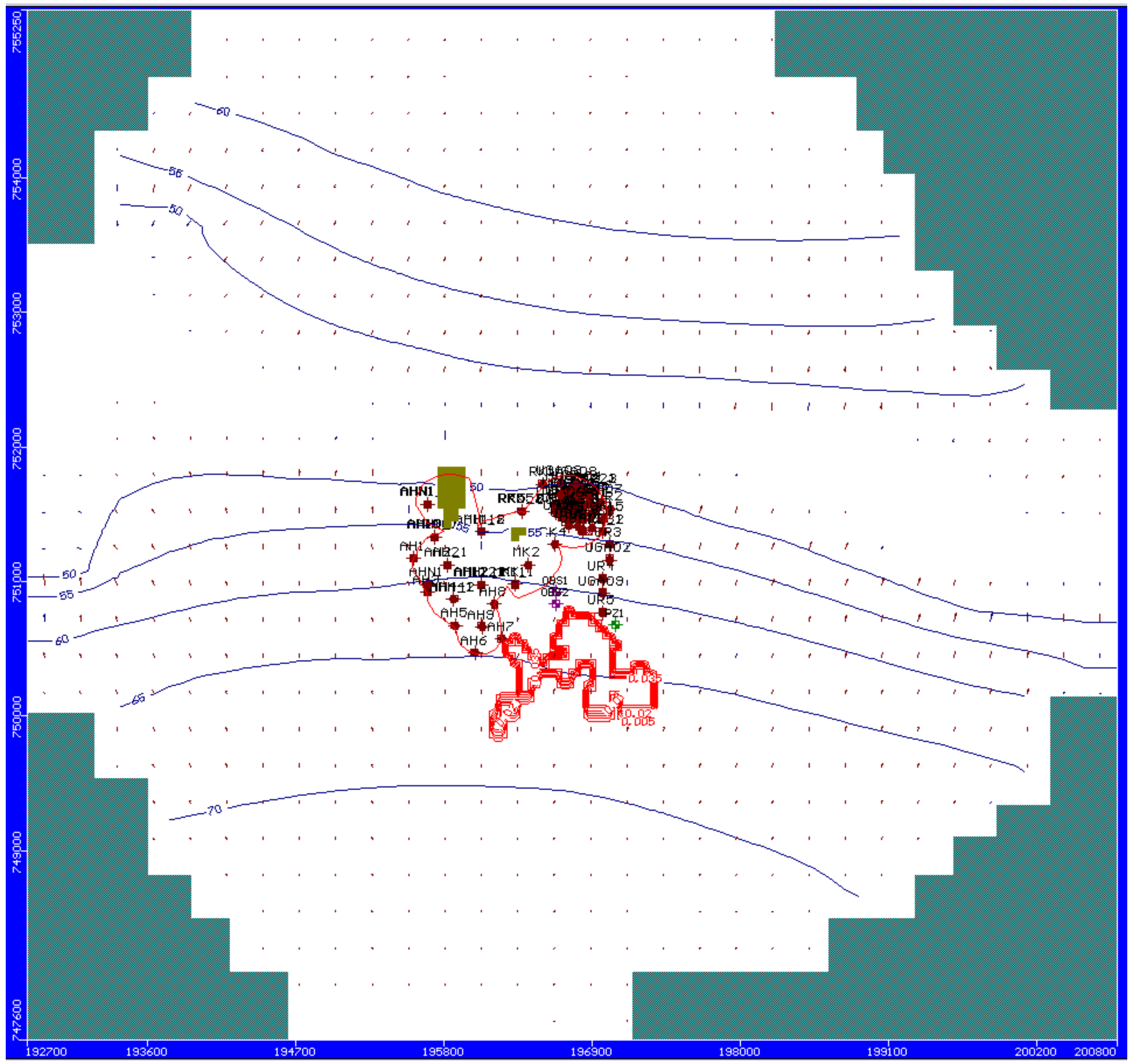

Figure a. Chromium plume map after 1 year

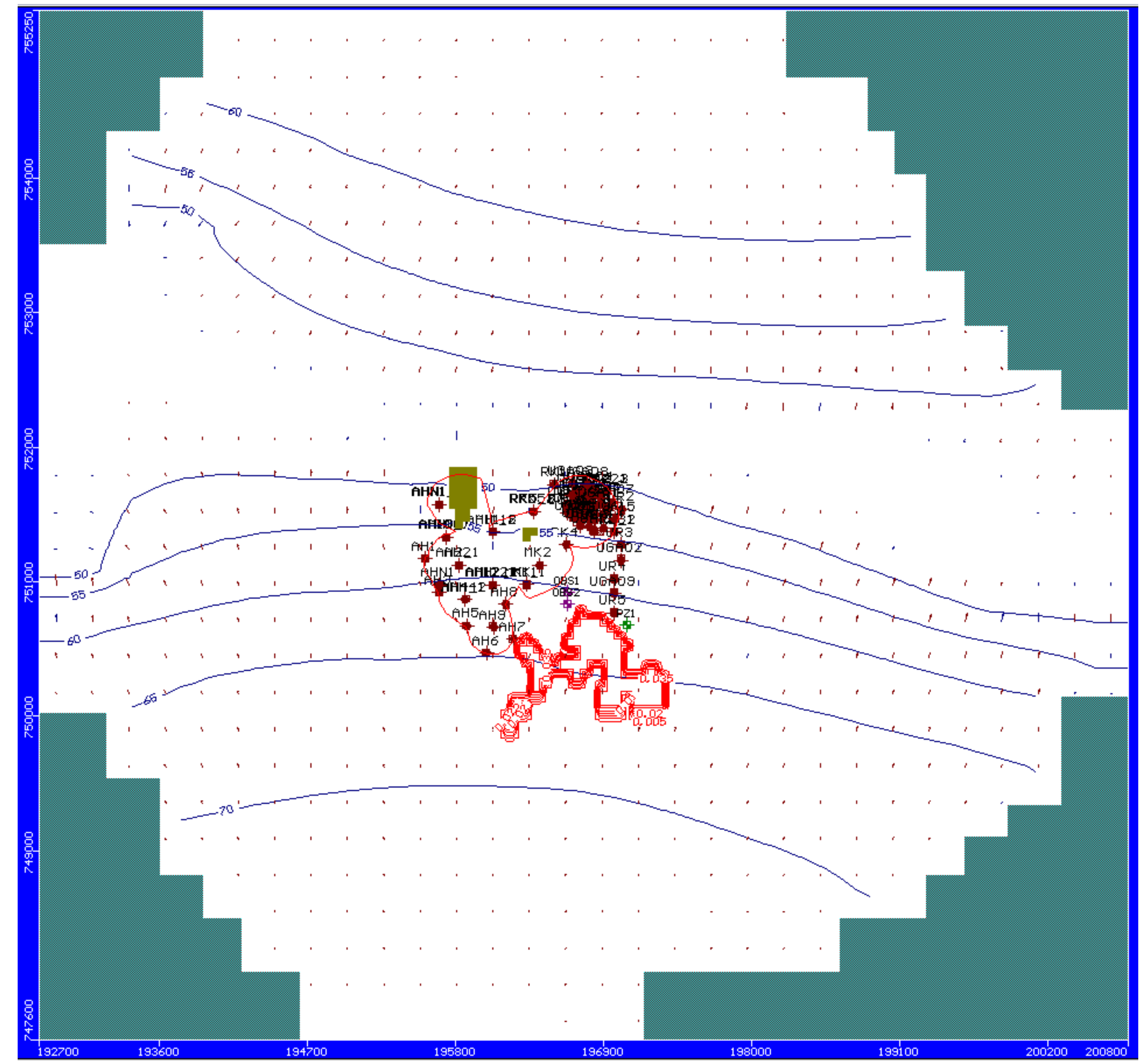

Figure b. Chromium plume map after 2 years

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Figure 16: Transient Simulation Results of a Continuous Injection of Chromium in the Mine Water Pond Area at a Concentration of 0.035 mg/L

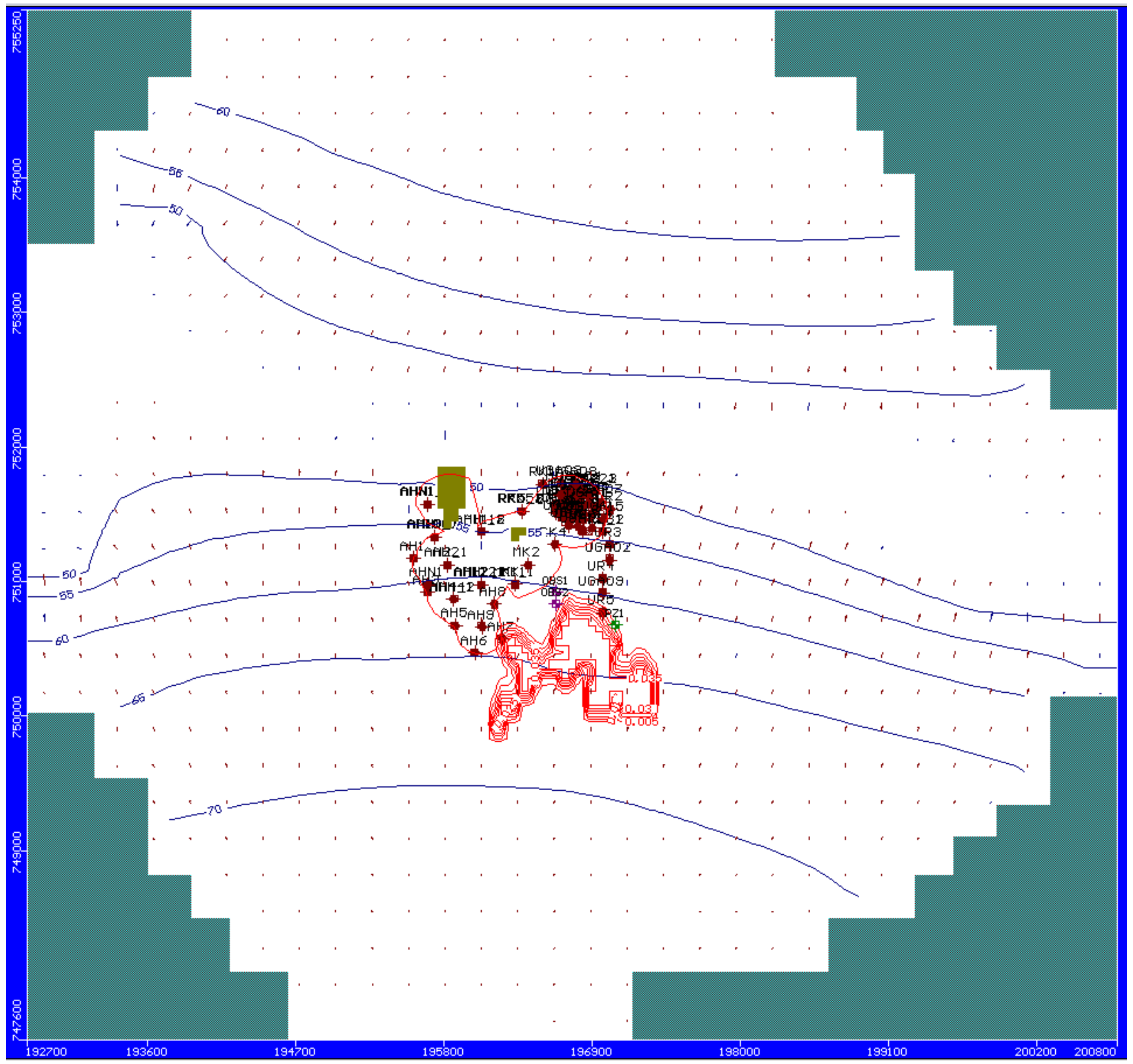

Figure c. Chromium plume map after 13 years

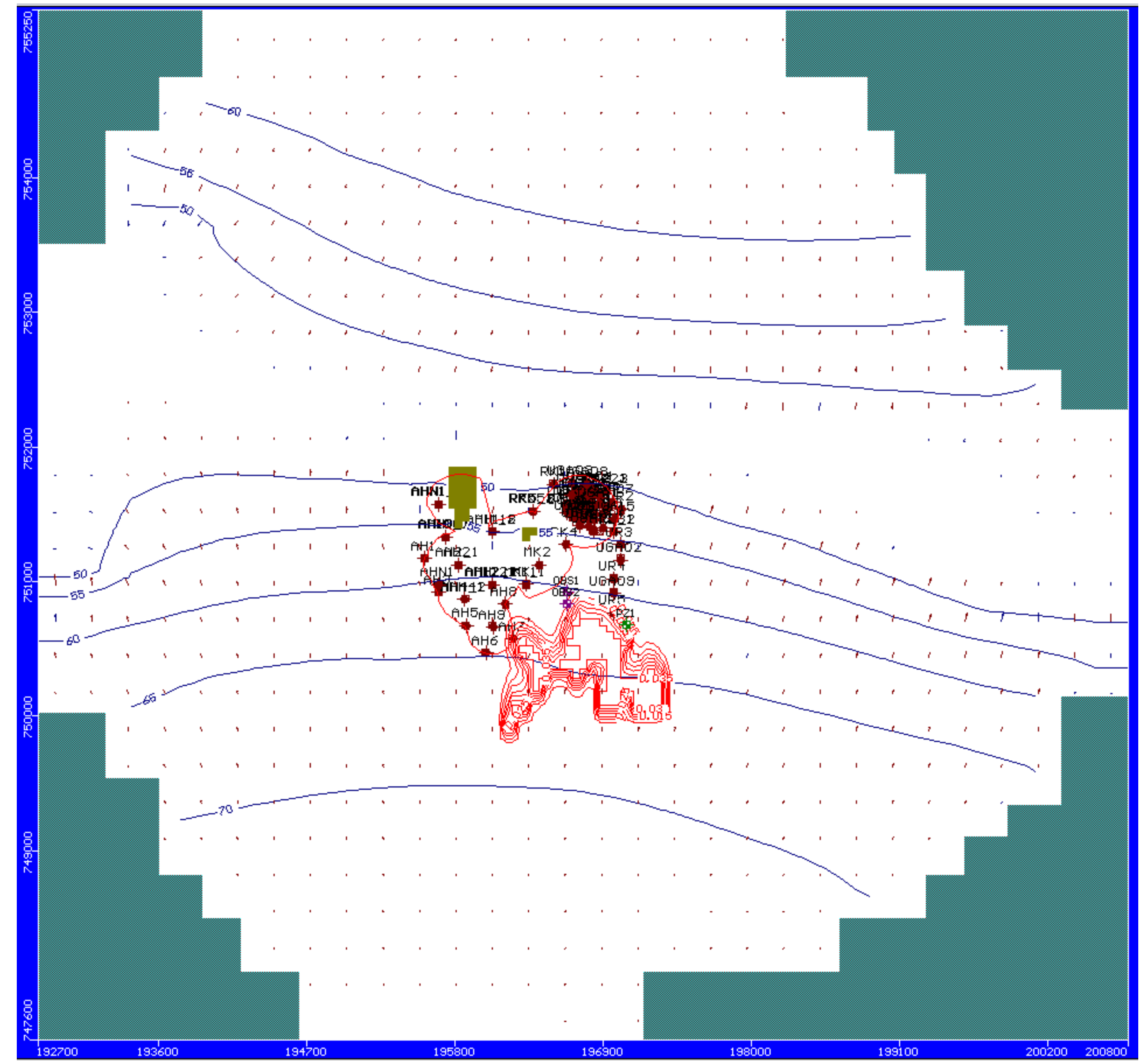

Figure d. Chromium plume map after 18 years

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Figure 16 (cont.): Transient Simulation Results of a Continuous Injection of Chromium in the Mine Water Pond Area at a Concentration of 0.035 mg/L

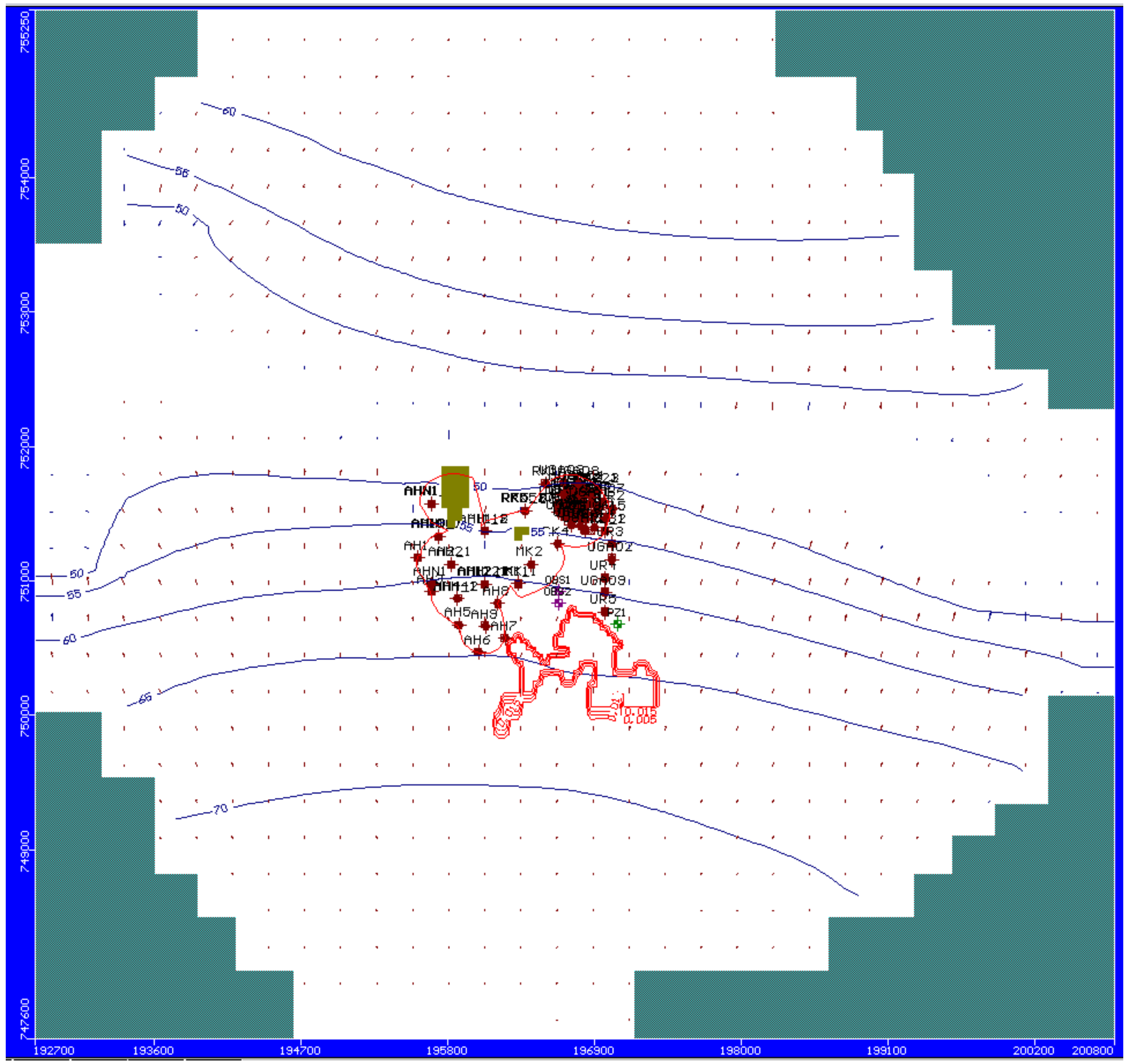

Figure a. Nickel plume map after 1 year

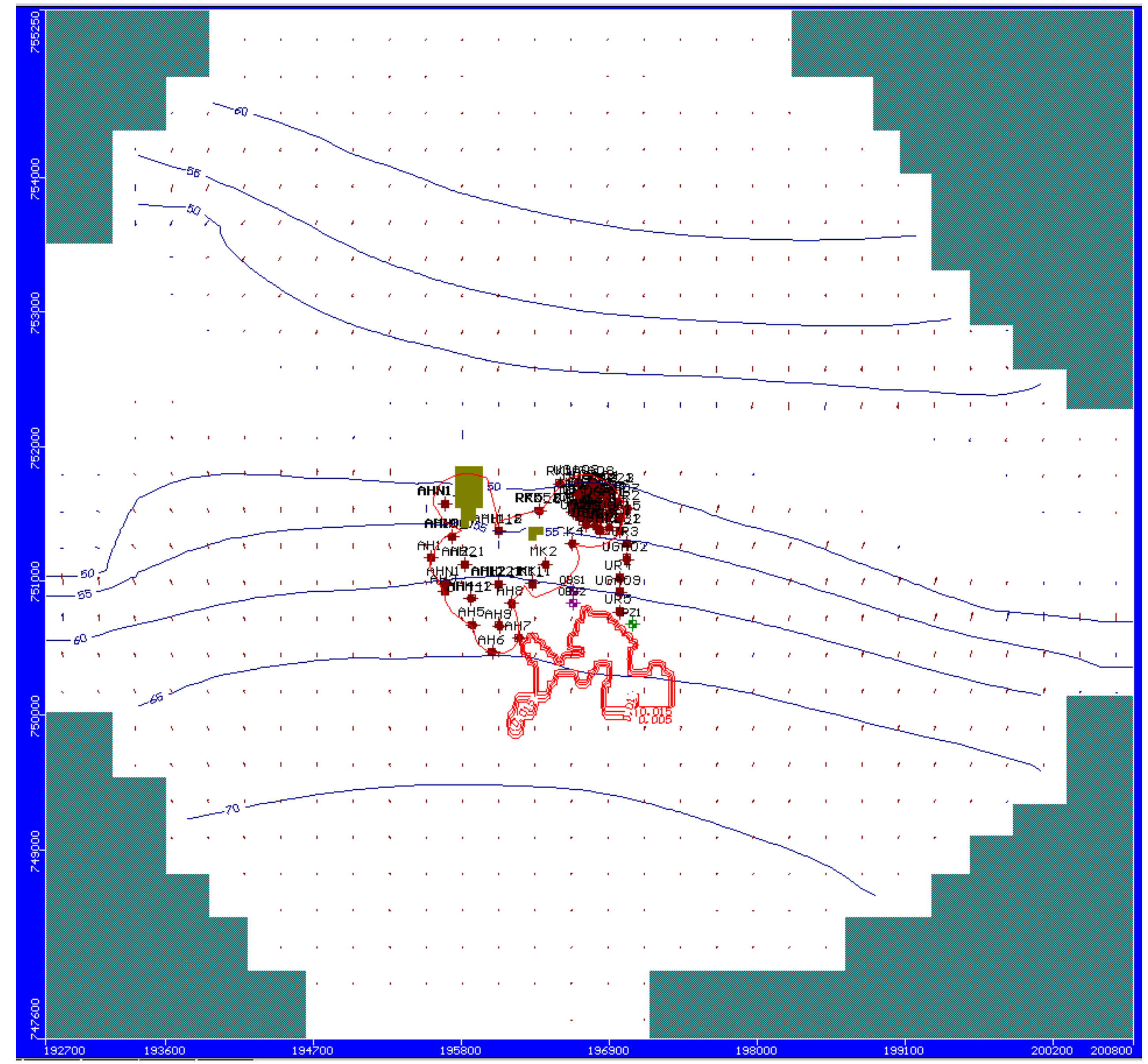

Figure b. Nickel plume map after 2 years

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Figure 17: Transient Simulation Results of a Continuous Injection of Nickel in the Mine Water Pond Area at a Concentration of 0.023 mg/L

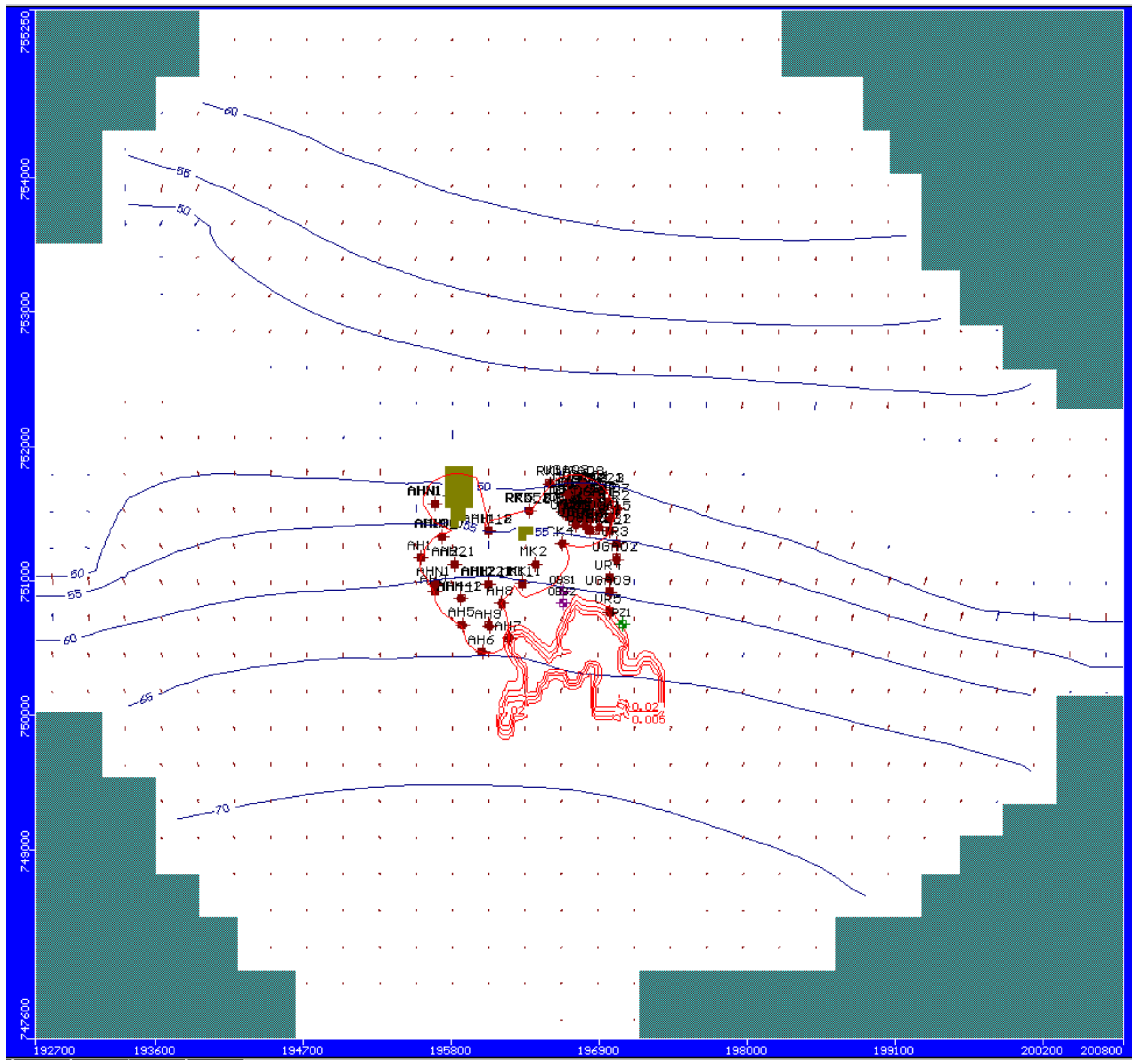

Figure c. Nickel plume map after 13 years

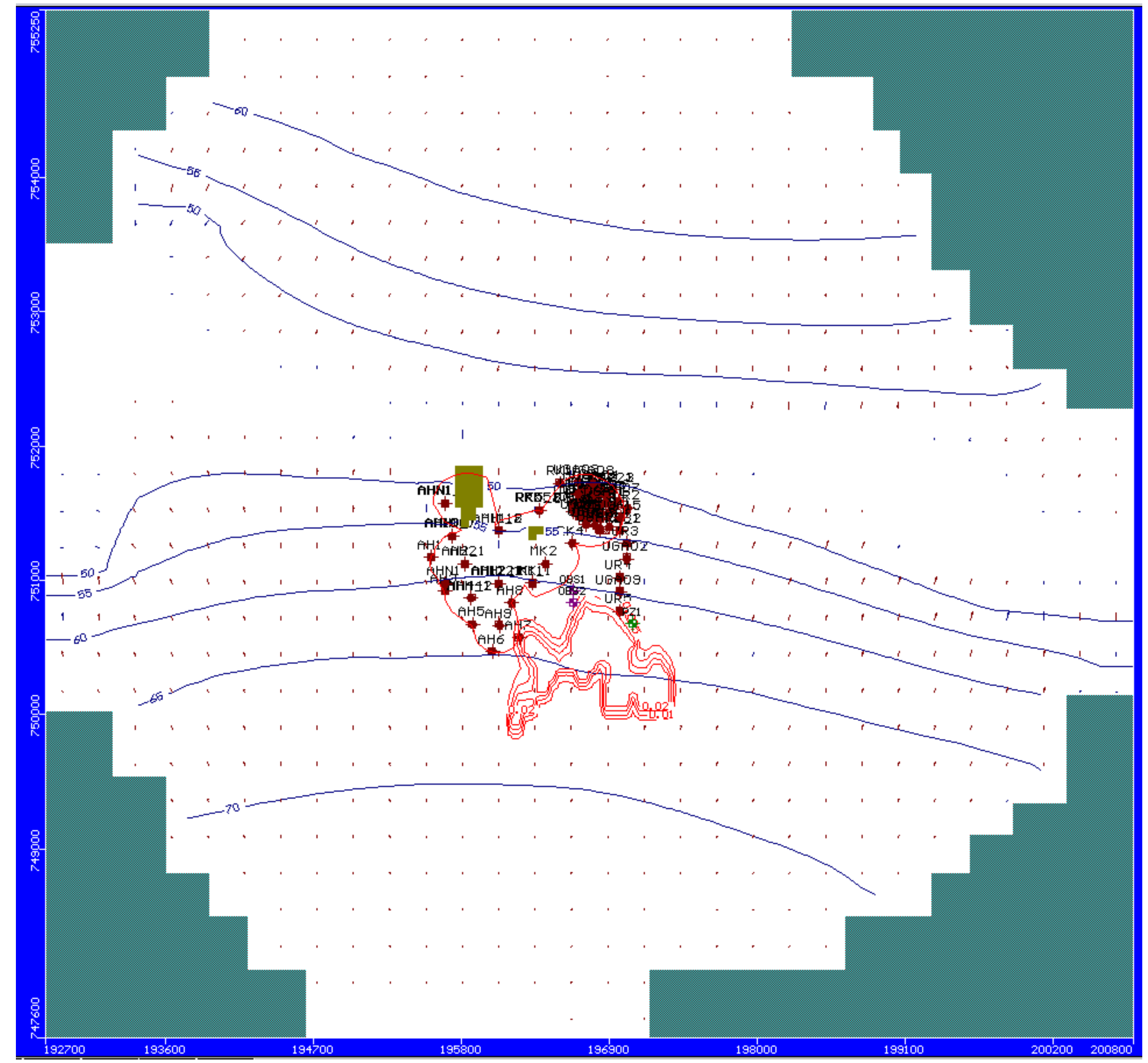

Figure d. Nickel plume map after 18 years

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Figure 17 (cont.): Transient Simulation Results of a Continuous Injection of Nickel in the Mine Water Pond Area at a Concentration of 0.023 mg/L

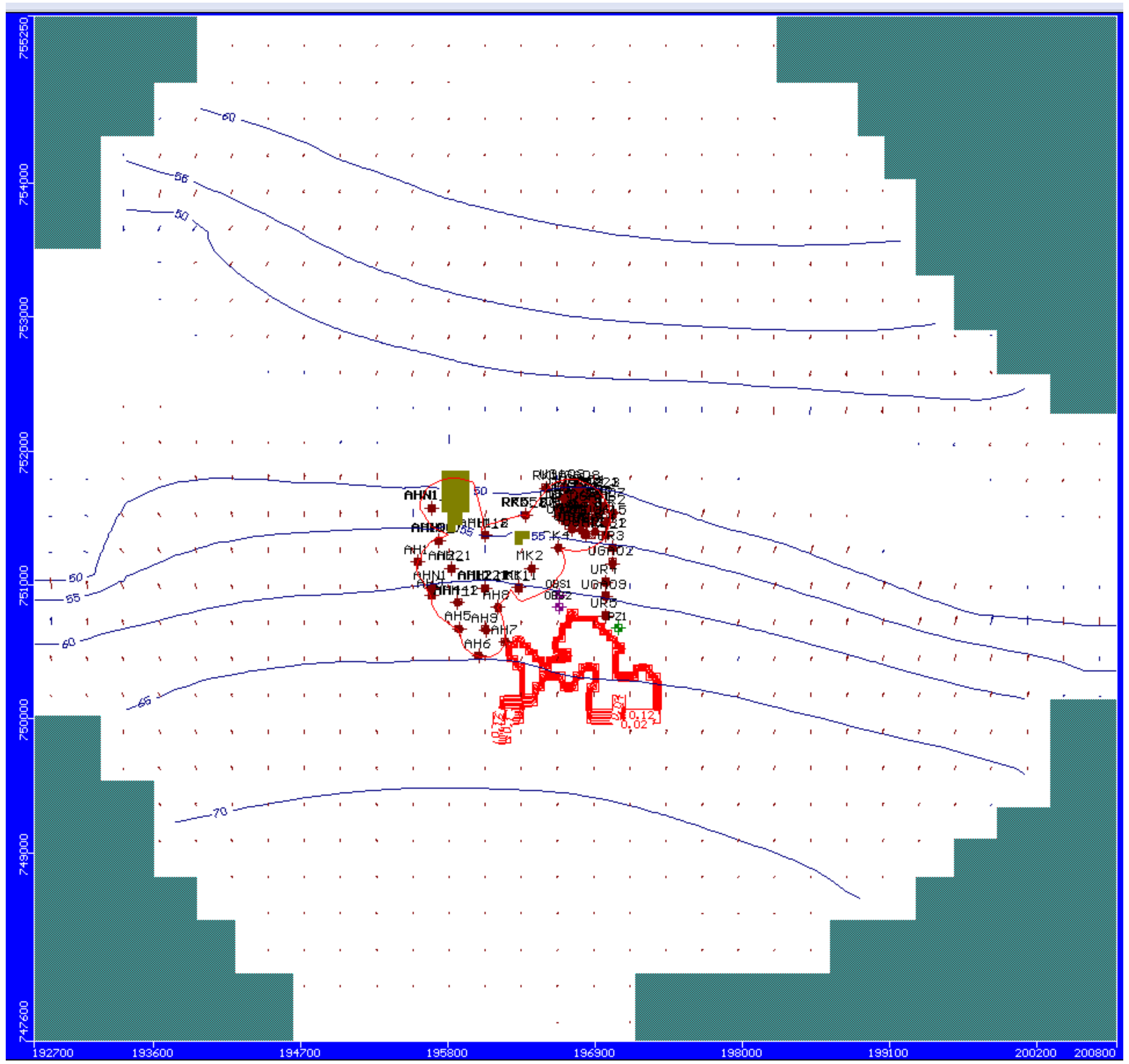

Figure a. Copper plume map after 1 year

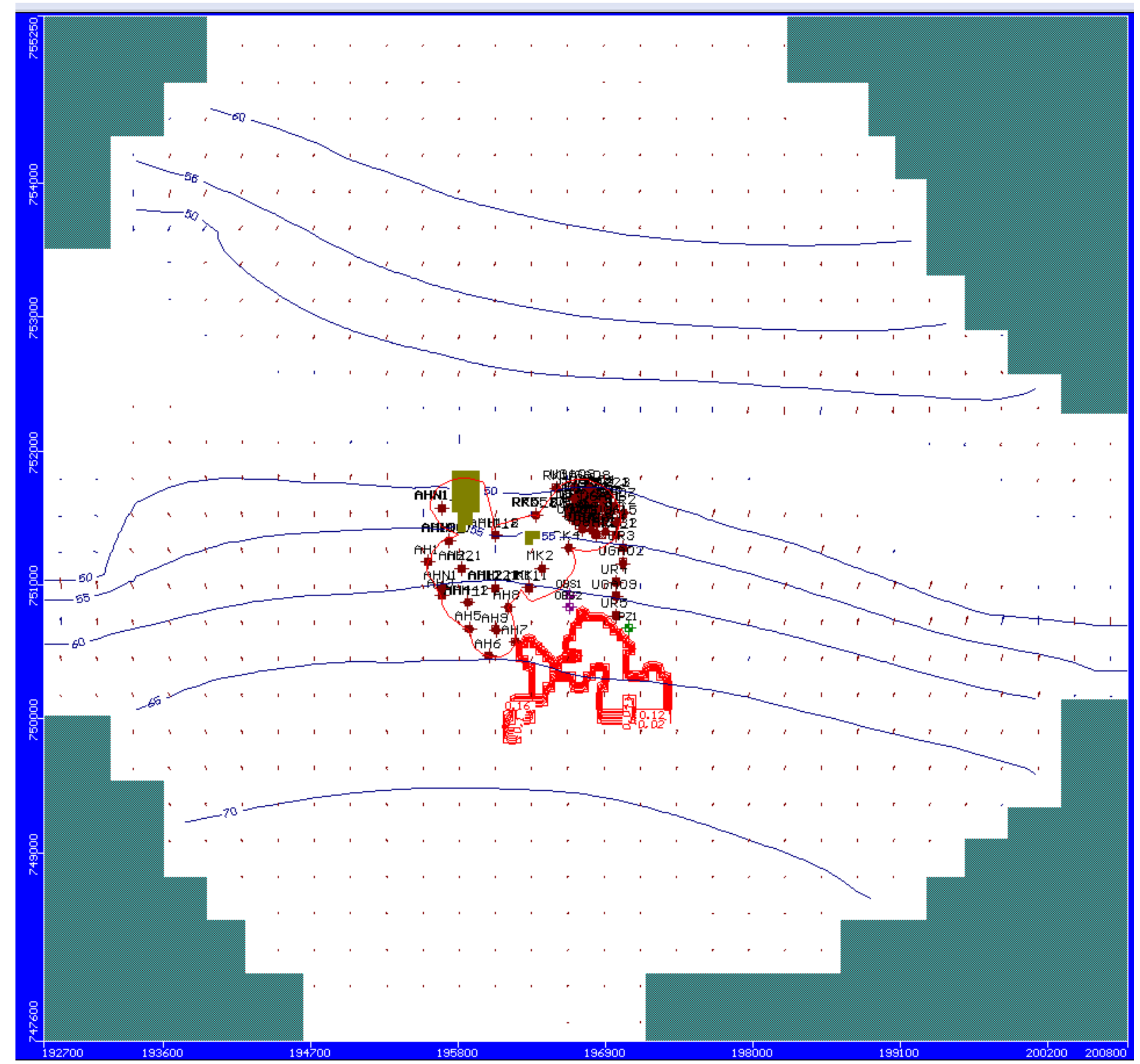

Figure b. Copper plume map after 2 years

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Figure 18: Transient Simulation Results of a Continuous Injection of Copper in the Mine Water Pond Area at a Concentration of 0.19 mg/L

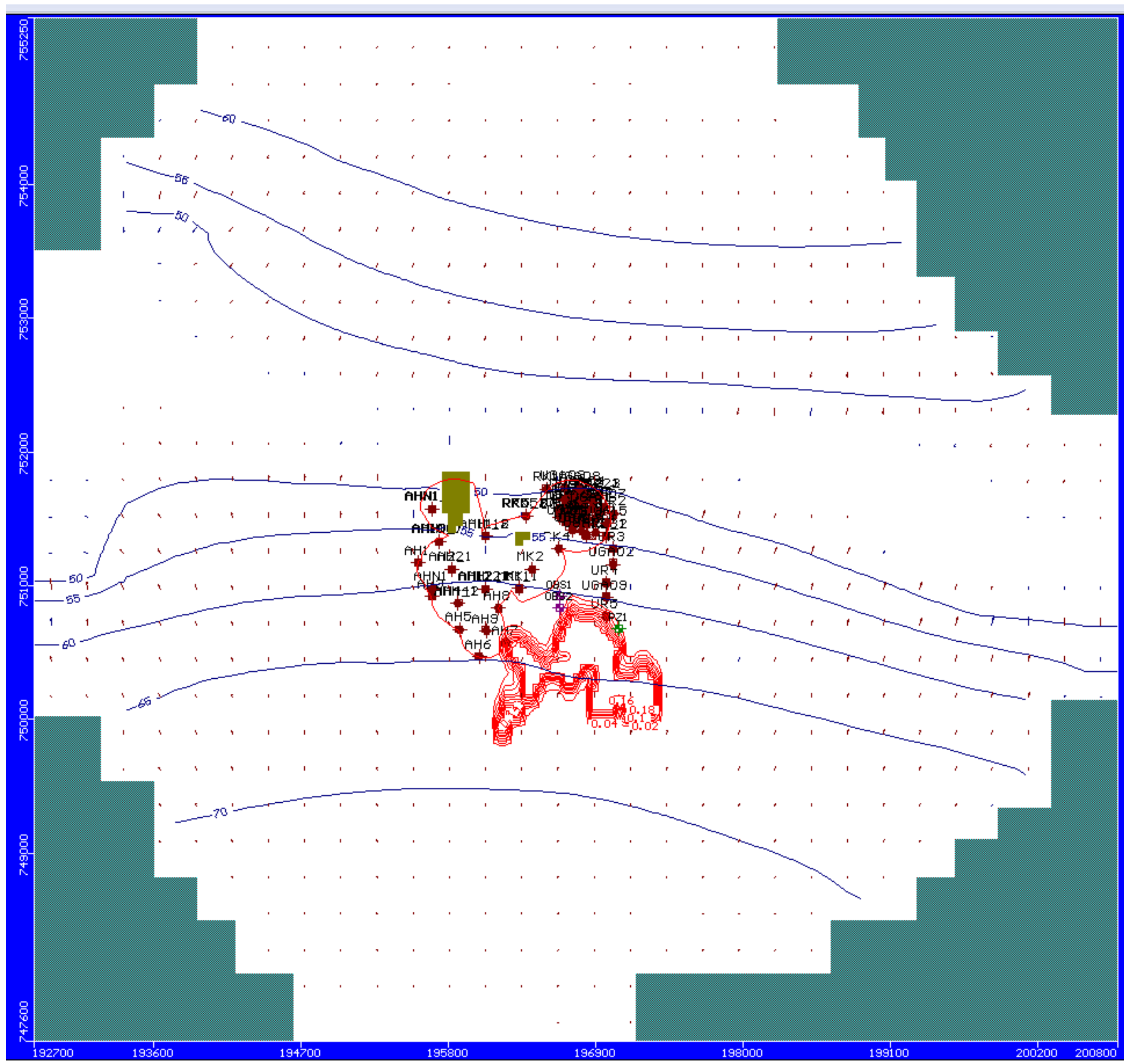

Figure c. Copper plume map after 13 years

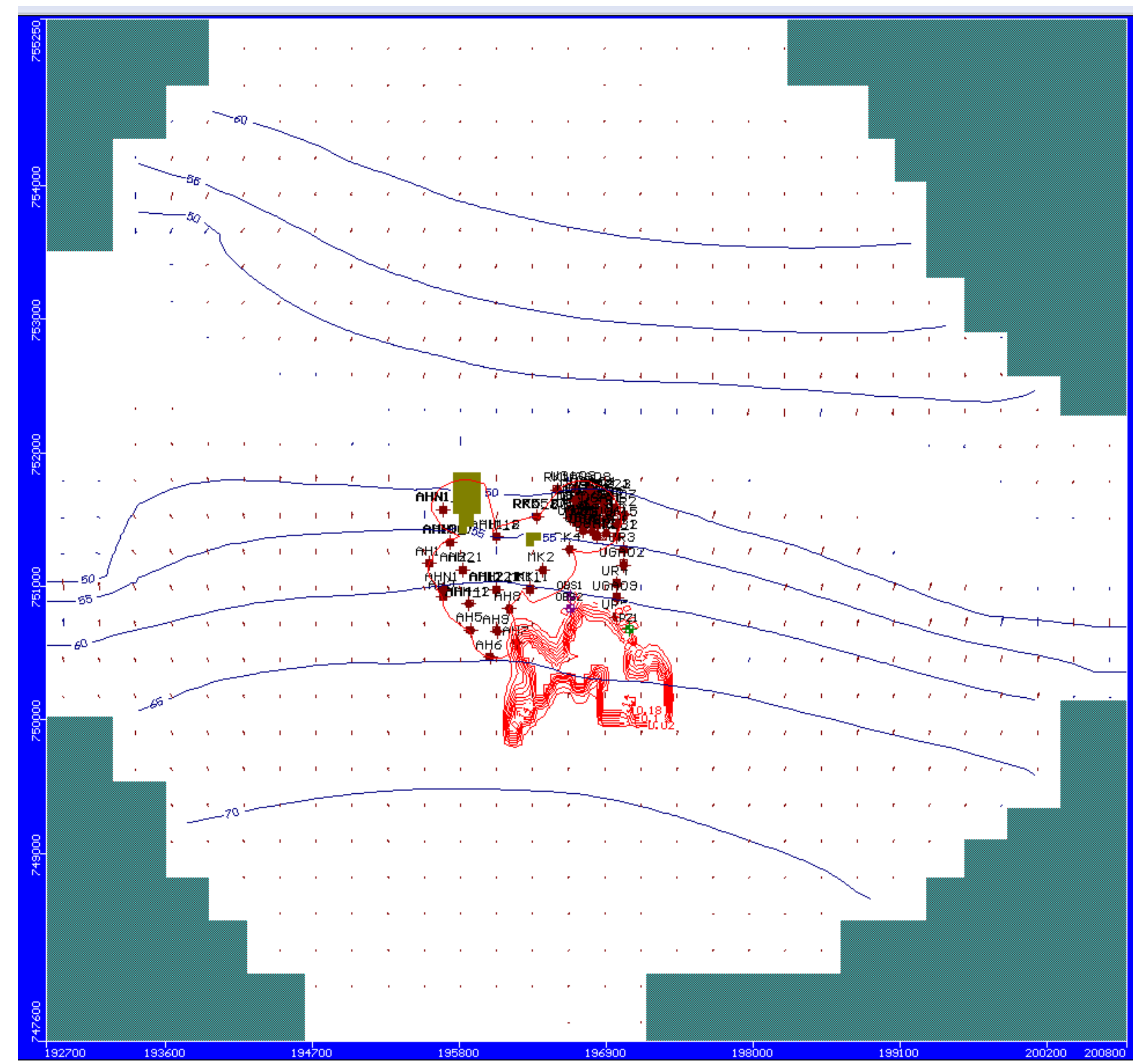

Figure d. Copper plume map after 18 years

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Figure 18 (cont.): Transient Simulation Results of a Continuous Injection of Copper in the Mine Water Pond Area at a Concentration of 0.19 mg/L

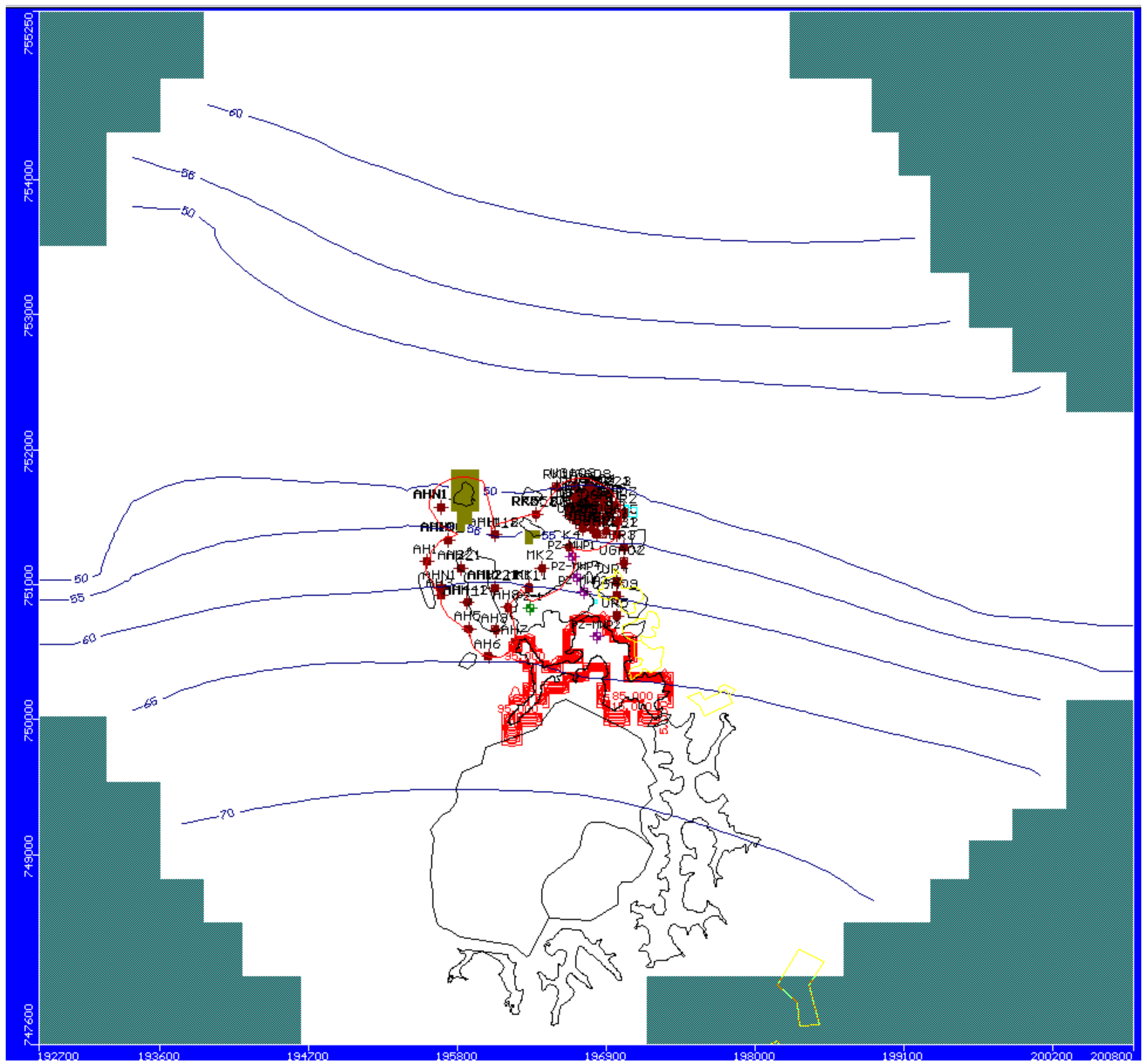

Figure a. Benzene plume map after 1 year

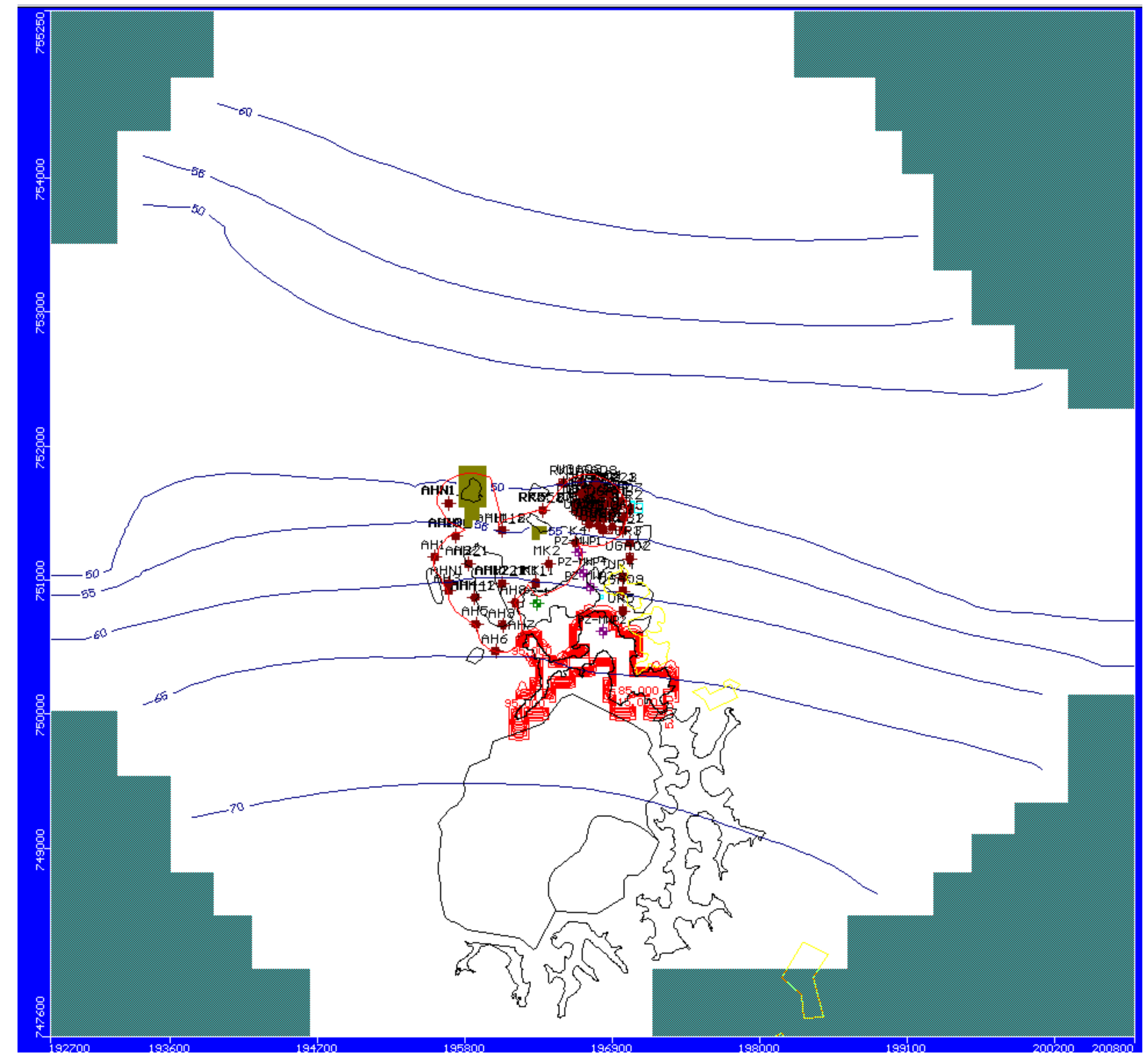

Figure b. Benzene plume map after 2 years

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Figure 19: Transient Simulation Results of 18 Yearly Injections of Benzene in the Mine Water Pond at a Concentration of 95 mg/L (12 hours per year)

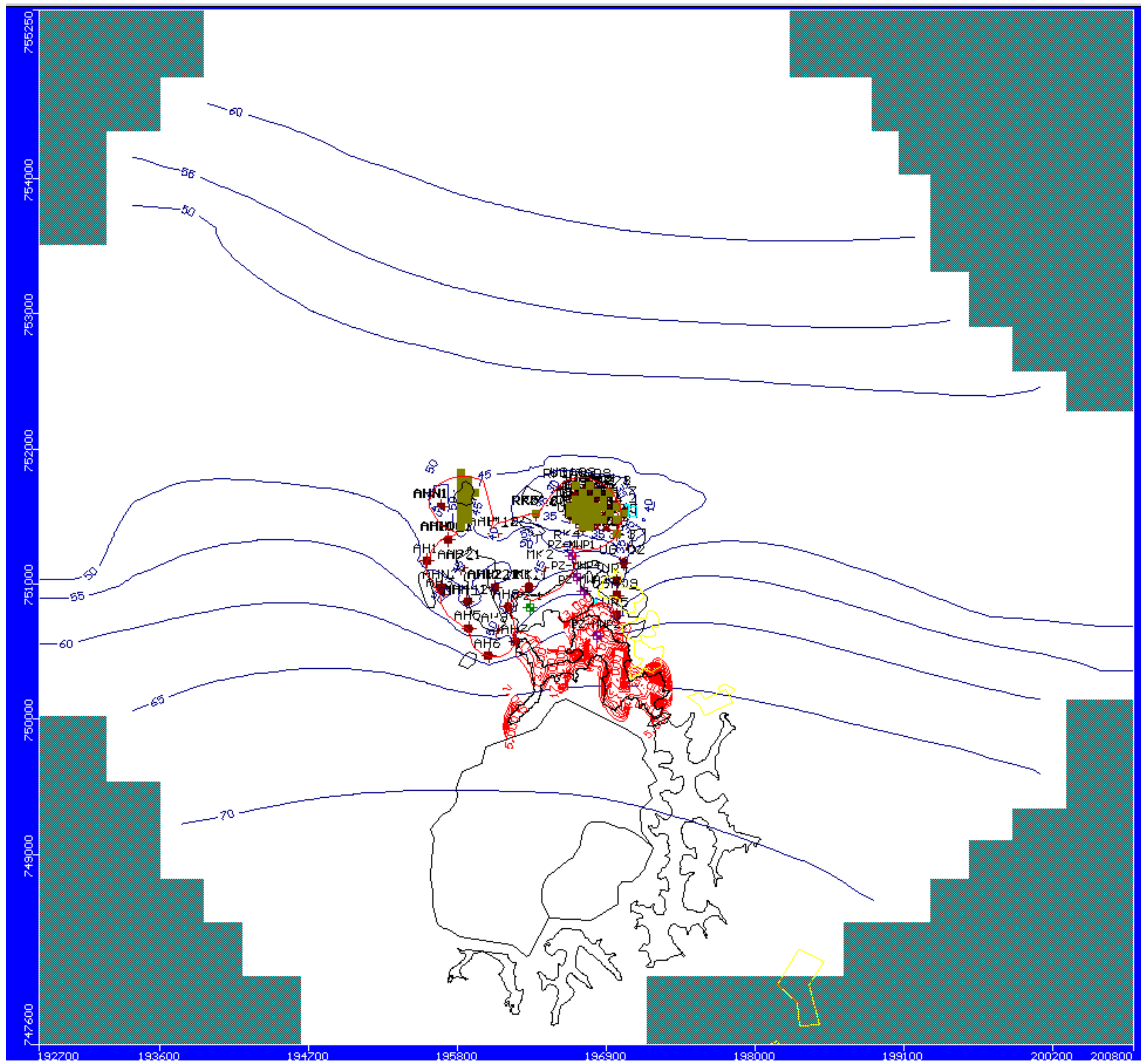

Figure c. Benzene plume map after 13 years

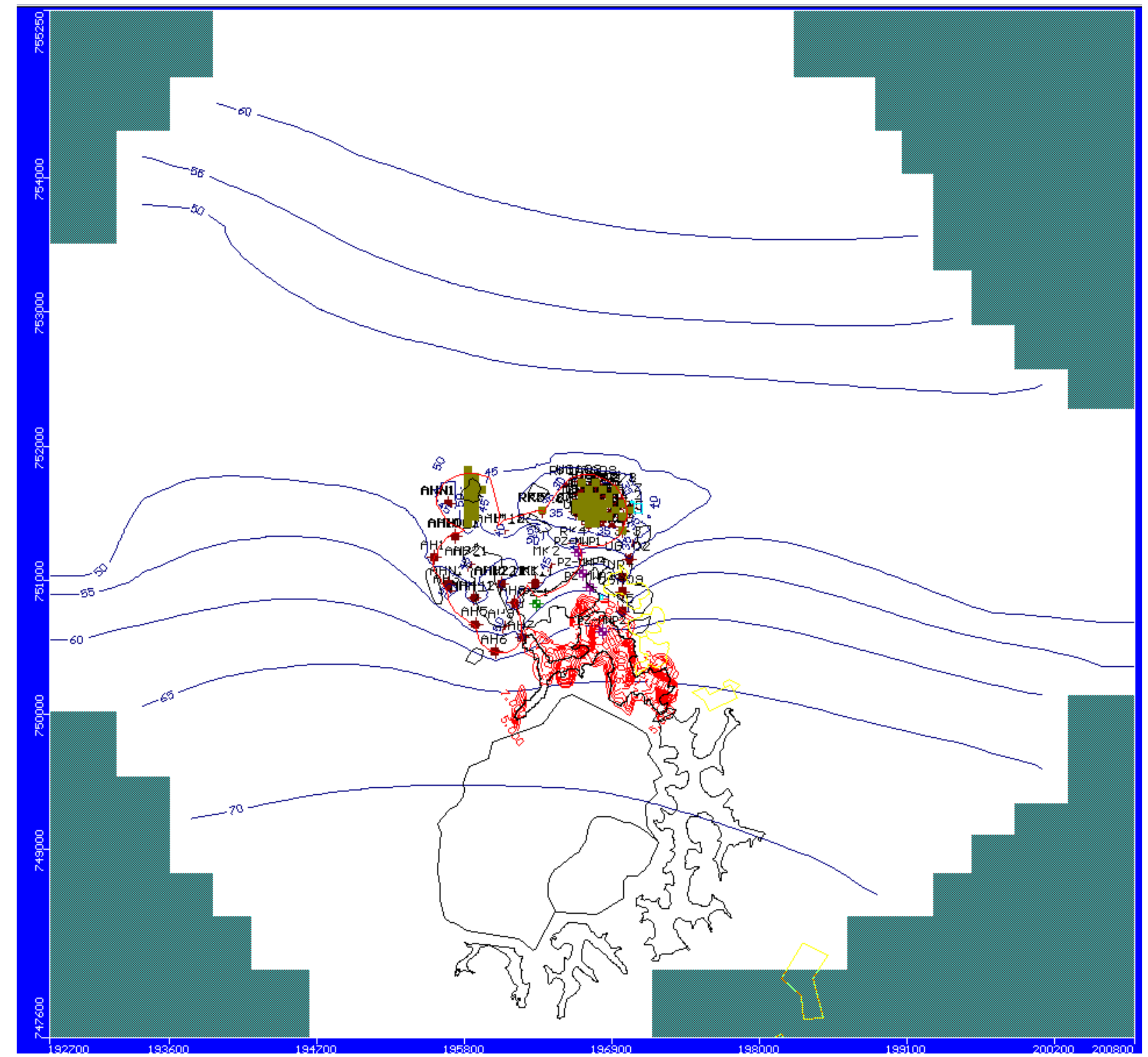

Figure d. Benzene plume map after 18 years

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Figure 19 (cont.): Transient Simulation Results of 18 Yearly Injections of Benzene in the Mine Water Pond at a Concentration of 95 mg/L (12 hours per year)