TETRA TECH

Appendix I

CPF Residue Hydro-Geochemical Assessment

Cesium Products Facility
Residue Dry Stack Infiltration Evaluation and Hydro-geochemical Assessment

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1.0 INTRODUCTION

The Cesium Products Facility (CPF) generates cesium-based chemical products from pollucite ore mined by the Tantalum Mining Corporation at the TANCO Mine (TANCO) located approximately 160 km northeast of Winnipeg, Manitoba (Figure 1-1). The TANCO mine has been in operation since 1969, mining a variety of rare minerals associated with a large pegmatite body.

The CPF includes the chemical plant, two CPF residue containment cells (Cells 1 and 2) and a residue stockpile comprised of solids removed from the containment cells. Cells 1 and 2 and the residue stockpile are located in the inactive Old Tailings Management Areas (TMA), northeast of the mine site. The Old TMA contains conventional tailings produced from the mining of tantalum and spodumene ores. The Old TMA covers an area of approximately 28 hectares and is approximately 1,000 meters (m) by 500 m wide. The containment cells are used for the clarification and settling of solids from the CPF process liquor. The clarified liquor is reclaimed from the cells for use in the process. The containment cells are used alternately, when one cell is filled with solids the discharge is moved to the other cell and the accumulated residue is removed and stockpiled.

1.1 Purpose and Objectives

To comply with regulatory re-licensing requirements, this investigation includes a hydrogeologic and geochemical assessment of the effects of the dry stack residue on groundwater within the Old TMA facility. Specific objectives include:

- Vadose analysis of infiltration through the residue dry stack,
- Hydro-geochemical assessment including:
  - Residue dry stack material and associated pore water,
  - Mechanisms for chemical transfer, and
  - Distribution of impacted wells.

1.2 Approach

To complete the project objectives, a review of historic and recent monitoring data has been completed. Data compiled from this review have been utilized in:

1. Mathematical modeling of residue dry stack infiltration using VADOSE/W;
2. Water quality spatial and graphical time trend-analysis; and,
3. Calculations to estimate chemical loading in groundwater, based on residue pore water quality and porosity and aquifer volume and water quality.

1.3 Data Gaps

The stacking timeline and progressive footprint of the primary and secondary residues dry stack areas were estimated from the available studies (UMA, 2001; SEACOR, 2004; and Wardrop, 2009). Limited surface water information was identified. Available data primarily reflects down-gradient water quality in toe seepage ponds adjacent to the Old TMA dykes (Wardrop, 2008).

FIGURE 1-1. PROJECT LOCATION, BERNIC LAKE, MANITOBA

Figure Source: Wardrop, 2009

2.0 HYDROGEOLOGY OF THE OLD TMA

The TANCO site has been the subject of several studies related to assessment of the potential effects of residue placement on groundwater in the Old TMA. These studies include Lakefield Research Limited (2000); Agassiz North (2001); UMA (2001); SEACOR (2004 and 2005); Wardrop (2009); and Solylo (2010).

Since 1998, 43 monitoring wells (Tables 2.1 and 2.2) have been installed in the Old TMA (Figure 2-1). Based on borehole logs, UMA (2001) described the hydrostratigraphy of the Old TMA to include tailings (comprising fine sand to silt sized sediment), interlayered organics and silt, silty clay, silty sand, sand and gravel, and bedrock. Bedrock was intersected in boreholes between 23.0 and 57.5 feet below ground surface and bedrock forms a bounding valley to the Old TMA facility.

UMA (2001) completed a hydrogeology study of the Old TMA and described the unconfined aquifer with saturation at depths between 0.6 and 3.1 m below the surface of the tailings. Aquifer gradients were calculated between 0.001 and 0.012. Groundwater divides were noted near the north end of the Old TMA with groundwater flow toward the East, West, and Main Dams; an updated potentiometric map by Wardrop (2009) indicates similar flow directions (Figure 2-1).

Average linear groundwater velocities were calculated (Wardrop, 2009) from gradients, slug test estimates of hydraulic conductivity, and porosity estimates, to be between 1.4 and 2.9 m/y. Based on aquifer properties, estimated annual seepage from the TMA was estimated to be in the range of 3,200 to 6,700 m^3/year, primarily through four key discharge locations (North Dam, East Dam, West Dam, and Main Dam) (Figure 2-1).

UMA's (2001) investigations formed the basis for recommended placement of residue dry stack on the Old TMA. Based on UMA's recommendations, the residue dry stacks were strategically located on groundwater divides in the northern part of the TMA (Figure 2-1). Nine of the monitoring wells (Table 2.1) within the TMA were constructed with nested piezometers screened directly below the water table, at the base of the aquifer, and within the underlying overburden immediately above bedrock.

Table 2.1. Nested Wells Completed within the Old TMA

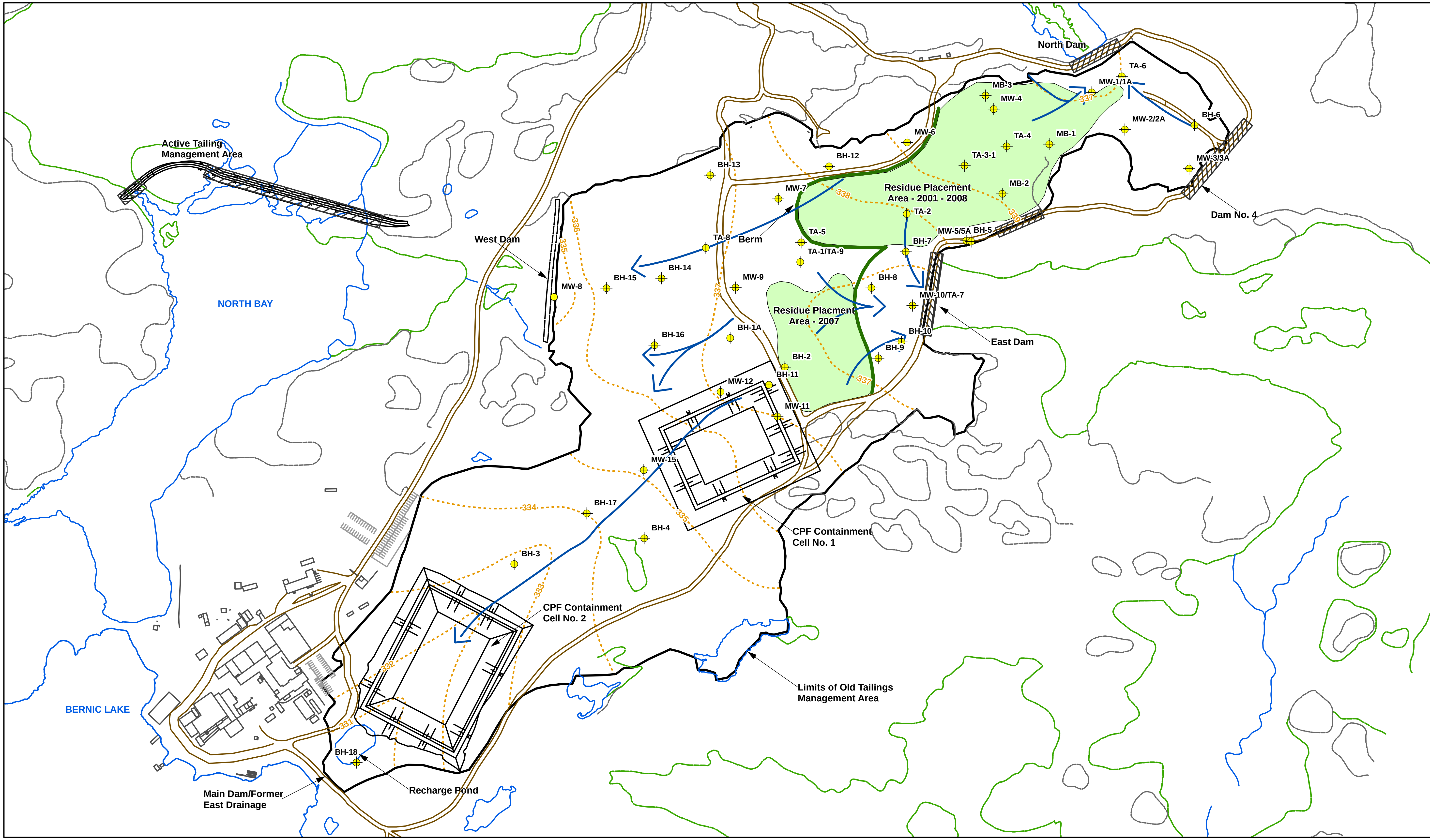
Well	Installed	Period of Record of Available Data	Screened Interval (1)
Nested Wells			
TA-1-1	2000	Jun-07 - Jun-08	Shallow
TA-1-2	2000	No Record Available	Deep
TA-1-3	2000	Jun-07 - Jun-08	Overburden
TA-2-1	2000	Oct-00 - Summer-07	Shallow
TA-2-2	2000	Oct-00 - Summer-07	Deep
TA-3-1	2000	Oct-00 - Summer-05	Shallow
TA-3-2	2000	Oct-00 - Summer-05	Deep
TA-3-3	2000	Oct-00 - Summer-05	Overburden
TA-4-1	2000	Oct-00 - Autumn-01	Shallow
TA-4-2	2000	Oct-00 - Autumn-01	Deep
TA-4-3	2000	Oct-00 - Autumn-01	Overburden
TA-5-1	Oct-02	Oct-02 - Summer-08	Shallow
TA-5-2	Oct-02	Oct-02 - Summer-08	Deep
TA-5-3	Oct-02	Oct-02 - Summer-08	Overburden
TA-6-1	Oct-02	Oct-02 - Present	Shallow
TA-6-2	Oct-02	Oct-02 - Present	Deep
TA-6-3	Oct-02	Oct-02 - Present	Overburden
TA-7-1	Jun-08	Jun-08 - Present	Shallow
TA-7-2	Jun-08	Jun-08 - Present	Deep
TA-7-3	Jun-08	Jun-08 - Present	Overburden
TA-8-1	Jun-08	Jun-08 - Present	Shallow
TA-8-2	Jun-08	Jun-08 - Present	Deep
TA-8-3	Jun-08	Jun-08 - Present	Overburden
TA-9-1	Jun-08	Jun-08 - Present	Shallow
TA-9-2	Jun-08	Jun-08 - Present	Deep
TA-9-3	Jun-08	Jun-08 - Present	Overburden

(1) Shallow: Screens placed just below the water table, Deep: Screened in the lower portion of the tailings above the clay liner, Overburden: Screened in the underlying overburden

Table 2.2. Single Wells Completed within the Old TMA

Well	Installed	Period of Record of Available Data	Screened Interval(1)
Single Wells			
Piezometer 4	2000	Oct-00 - July-01	Shallow
MW-1	2000	Oct-00 - July-01	Shallow
MW-1A	Oct-02	Oct-02 - Present	Shallow
MW-2	2000	Oct-00 - July-01	Shallow
MW-2A	Oct-02	Oct-02 - Present	Shallow
MW-3	2000	Oct-00 - July-01	Shallow
MW-3A	Oct-02	Oct-02 - Present	Shallow
MW-4	2000	Oct-00 - July-01	Shallow
MW-5	2000	Oct-00 - July-01	Shallow
MW-5A	Oct-02	Oct-02 - Present	Shallow
MW-6	2000	2000 - Present	Shallow
MW-7	2000	2000 - Present	Shallow
MW-8	2000	2000 - Present	Shallow
MW-9	2000	2000 - Present	Shallow
MW-10	2000	2000 - 2005	Shallow
BH-1	1998	1998 -2001	Shallow
BH-1A	2002	Oct-02 - Present	Shallow
BH-2	1998	1998 - 2007/8	Shallow
BH-3	1998	1998 - Present	Shallow
BH-4	1998	1998 - Present	Shallow
BH-5	Jun-08	Jun-08 - Present	Shallow
BH-6	Jun-08	Jun-08 - Present	Shallow
BH-7	Jun-08	Jun-08 - Present	Shallow
BH-8	Jun-08	Jun-08 - Present	Shallow
BH-9	Jun-08	Jun-08 - Present	Shallow
BH-10	Jun-08	Jun-08 - Present	Shallow
BH-11	Jun-08	Jun-08 - Present	Shallow
BH-12	Jun-08	Jun-08 - Present	Shallow
BH-13	Jun-08	Jun-08 - Present	Shallow
BH-14	Jun-08	Jun-08 - Present	Shallow
BH-15	Jun-08	Jun-08 - Present	Shallow
BH-16	Jun-08	Jun-08 - Present	Shallow
BH-17	Jun-08	Jun-08 - Present	Shallow
BH-18	Jun-08	Jun-08 - Present	Shallow

(1) Shallow: Screens placed just below the water table, Deep: Screened in the lower portion of the tailings above the clay liner, Overburden: Screened in the underlying overburden



LEGEND

- Monitoring Well
- Groundwater Flow Direction
- Dam
- Containment Area
- Road
- Infrastructure
- Water Feature
- Berm
- Parking Lot
- Groundwater Elevation Contour
- Limits of Old Tailings
- Residue Placement Area

0 50 100 200 Meters

N

Sources: Wardrop, 2009; Tetra Tech GIS, 2010.

FIGURE 2-1
POTENTIOMETRIC MAP

3.0 VADOSE ZONE INFILTRATION ANALYSIS

To assess infiltration through the unsaturated dry stack residue on the Old TMA tailings, a time-sequenced series of one-dimensional, finite element computer models were used. The models were created to simulate the time periods of and between residue placements. Once the maximum dry stack height was reached, the model was run for an additional 36 years to evaluate infiltration in the future.

VADOSE/W software was used for the modeling (GeoStudio, GEO-SLOPE, 2007). VADOSE/W allows the evaluation of hydrologic and temperature gradients in the saturated and unsaturated zones beneath the ground surface. VADOSE/W considers infiltration due to rainfall, snow melt, surface evaporation, runoff, and ponding of water. Additionally, daily temperature, solar radiation, and wind speed information is used by the model to determine the hydrologic and temperature gradients within the soils.

At the time of this analysis, each of Cell 1 and Cell 2 has been emptied of residue three times (Wardrop, 2008). The periods over which emptied were listed in a letter from Wardrop dated May 23, 2008 (Wardrop, 2008). These periods and the maximum dry stack height were the basis of the modeling scenarios. The maximum dry stack height, for stability reasons, was determined to be 10 meters. The residue volume placed from Cells 1 and 2 was 52,000 m^3 and 91,000 m^3, respectively, during each placement period.

Being one-dimensional, the models do not represent the actual deposition in the Old TMA from either Cell 1 or Cell 2. More defined dry stack placement rates at a specific location, and the increase in dry stack height over time was not available. Therefore, an approach was taken by modeling the volume of residue coming out of each cell and treating this volume as being placed separately. This is conservative because after each lift of dry stack residue placement, the period before the next lift placed is modeled. During this time the dry stack is subject to infiltration and the water within the dry stack is equilibrated according to the climate conditions. Table 3.1 presents the series of models that were completed. Figures 3-1 through 3-3 show the general model configurations for the model scenarios run for the times given for Cell 1.

3.1 Material Properties

Information gathered from the excavation of borings MB-2 (Solylo, 2010) and TA-3 (Agassiz North, 2001) indicates that the tailings in the TMA generally consist of fine grained sands with silt and minor amounts of clay. The dry stack residue was analyzed in the 2010 report by Solylo and consists of fine sands, feldspar minerals, mica, and minor amounts of clay. For the purposes of the modeling, the gradation analyses from UMA (2001) were used to determine the field capacity and wilting point of both the TMA tailings and the dry stack residue. The saturated hydraulic conductivity for the tailings was determined by UMA (2001). The hydraulic conductivity for the dry stack residue was estimated based on the data from the UMA (2001) report and visual examination of the core sections and additional data from Solylo (2010). The hydraulic soil parameters for the soils are summarized in Table 3.2.

Table 3.1. VADOSE/W Model Scenario for Infiltration through the Dry Stack Residue

Model No.	Cell No.	Model Description	Modeling Time Period	Height of Dry Stack (m)	Figure Showing Model Configuration
1	1	Residue placed from August 2001 through April 2002(1)	8/1/01 through 4/30/02	3.33	Figure 3-1
2	1	No new residue added	5/1/02 through 5/31/04	3.33	Figure 3-1
3	1	Residue placed from June 2004 through September 2004	6/1/04 through 9/30/04	6.67	Figure 3-2
4	1	No new residue added	10/1/04 through 5/31/06	6.67	Figure 3-2
5	1	Residue placed from June 2006 through August 2006	6/1/06 through 8/31/06	10	Figure 3-3
6	1	No new residue added	9/1/06 through 9/31/42	10	Figure 3-3
7	2	Residue placed from August 2002 through November 2002	8/1/02 through 11/31/02	3.33	Figure 3-1
8	2	No new residue added	12/1/02 through 4/30/05	3.33	Figure 3-1
9	2	Residue placed from May 2005 through September 2005	5/1/05 through 9/30/05	6.67	Figure 3-2
10	2	No new residue added	10/1/05 through 5/31/07	6.67	Figure 3-2
11	2	Residue placed from June 2007 through August 2007	6/1/07 through 8/31/07	10	Figure 3-3

(1) The 2008 report from Wardrop indicated that the residue was placed from April 2001 through spring 2002. April was chosen for modeling purposes as the end of the deposition period.

Table 3.2. Summary of Soil Parameters Used in the Infiltration Analyses

Soil Type	Saturated Hydraulic Conductivity	Saturated Volumetric Water Content	Volumetric Water Content at Field Capacity(3)	Volumetric Water Content at Wilting Point(3)
	(m/sec)	(vol./vol.) (2)	(vol./vol.) (2)	(vol./vol.) (2)
Dry Stack Residue	$2.5x10^{-5}$(1)	0.40	0.049	0.015
TMA Residue	$5.0x10^{-5}$(4)	0.40	0.046	0.012

(1) Average hydraulic conductivity from TA-1-1, TA-2-1, and TA-3-1 (UMA, 2001)
(2) Volumetric water content = volume of water / total volume of soil
(3) Estimated using Fredlund-Xing function in VADOSE (2007)
(4) Estimated based on core sections from Solylo (2010)

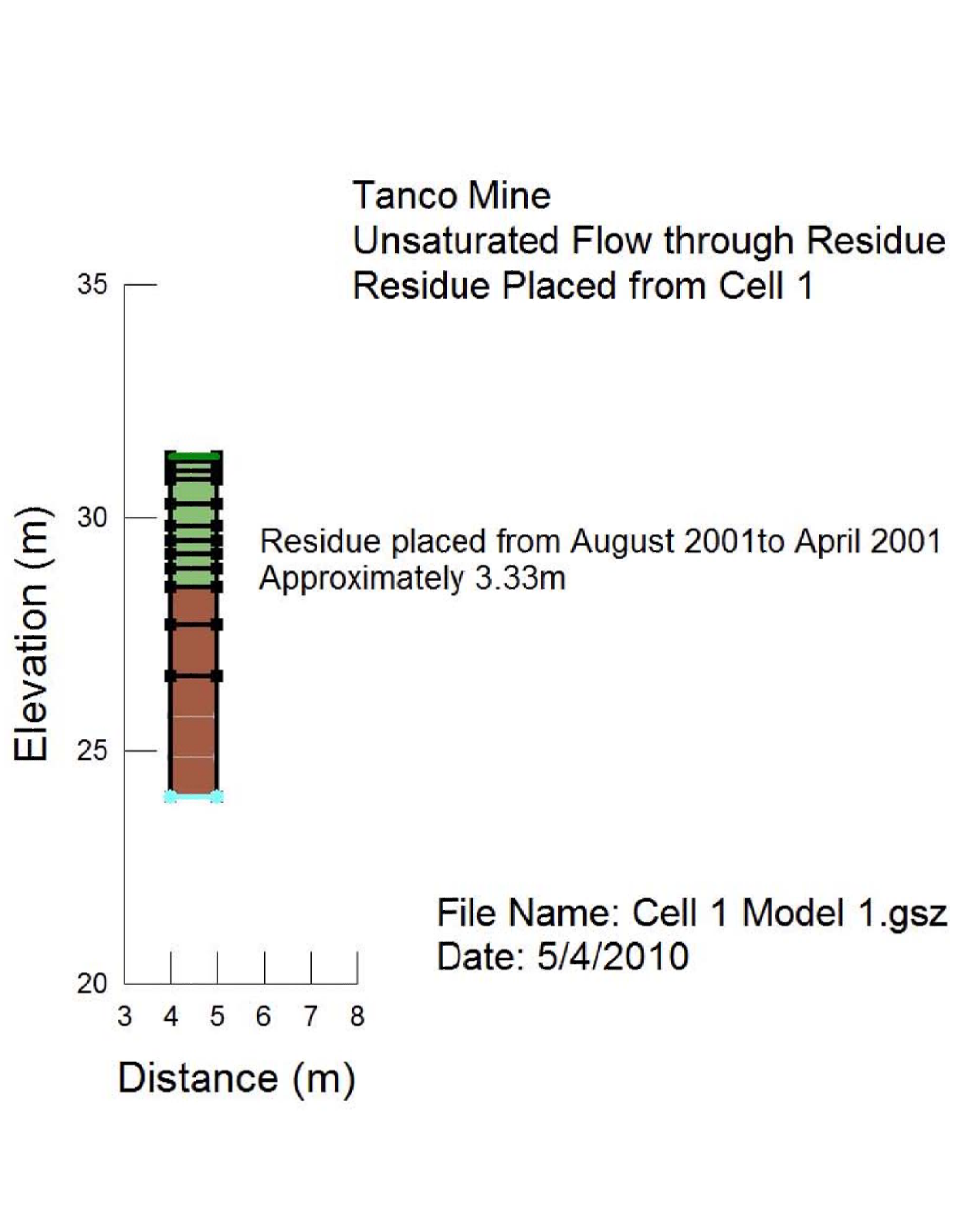


FIGURE 3-1.
GENERAL MODEL CONFIGURATION:
UNSATURATED FLOW MODEL 1

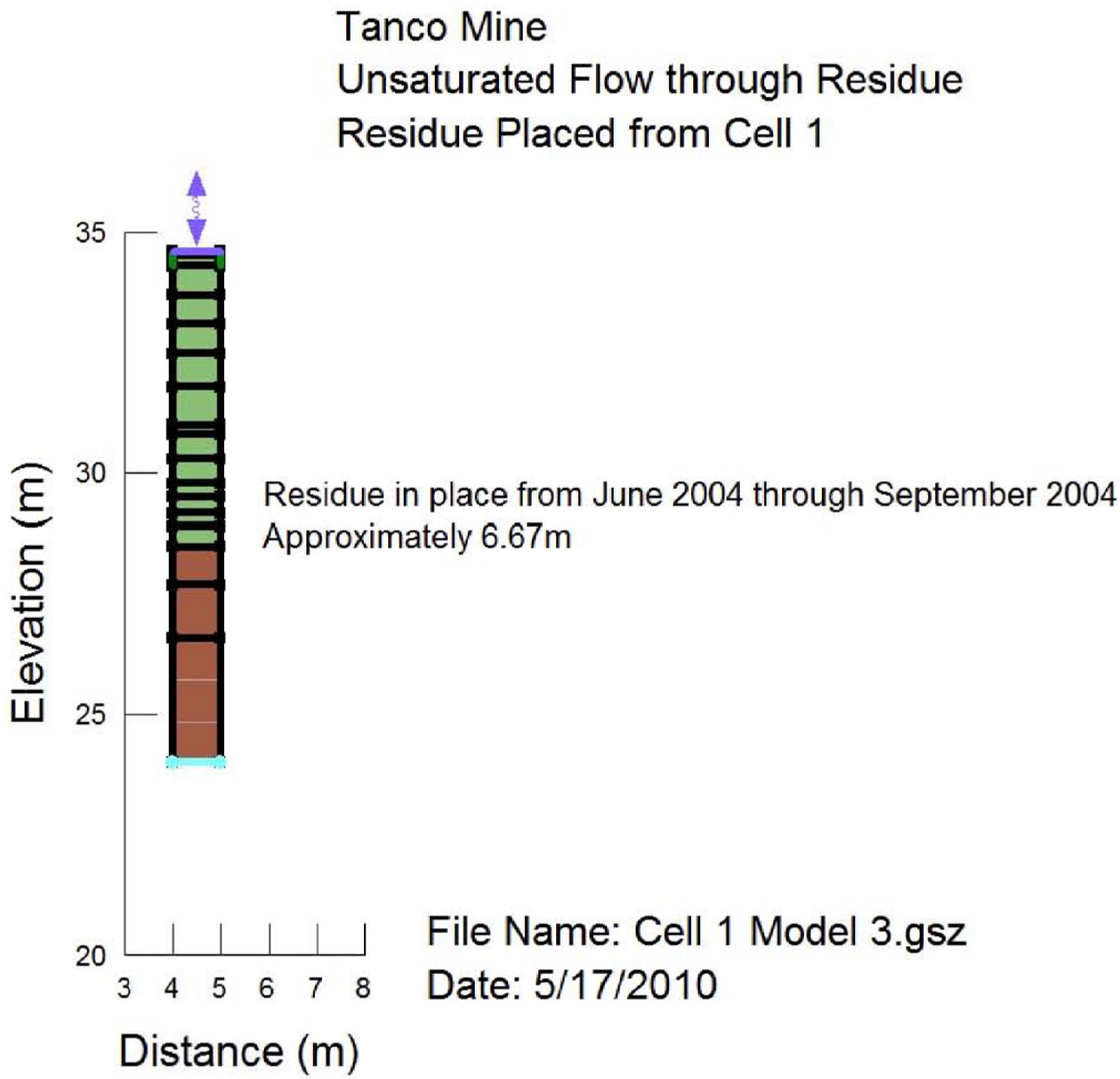


FIGURE 3-2.
GENERAL MODEL CONFIGURATION:
UNSATURATED FLOW MODEL 3

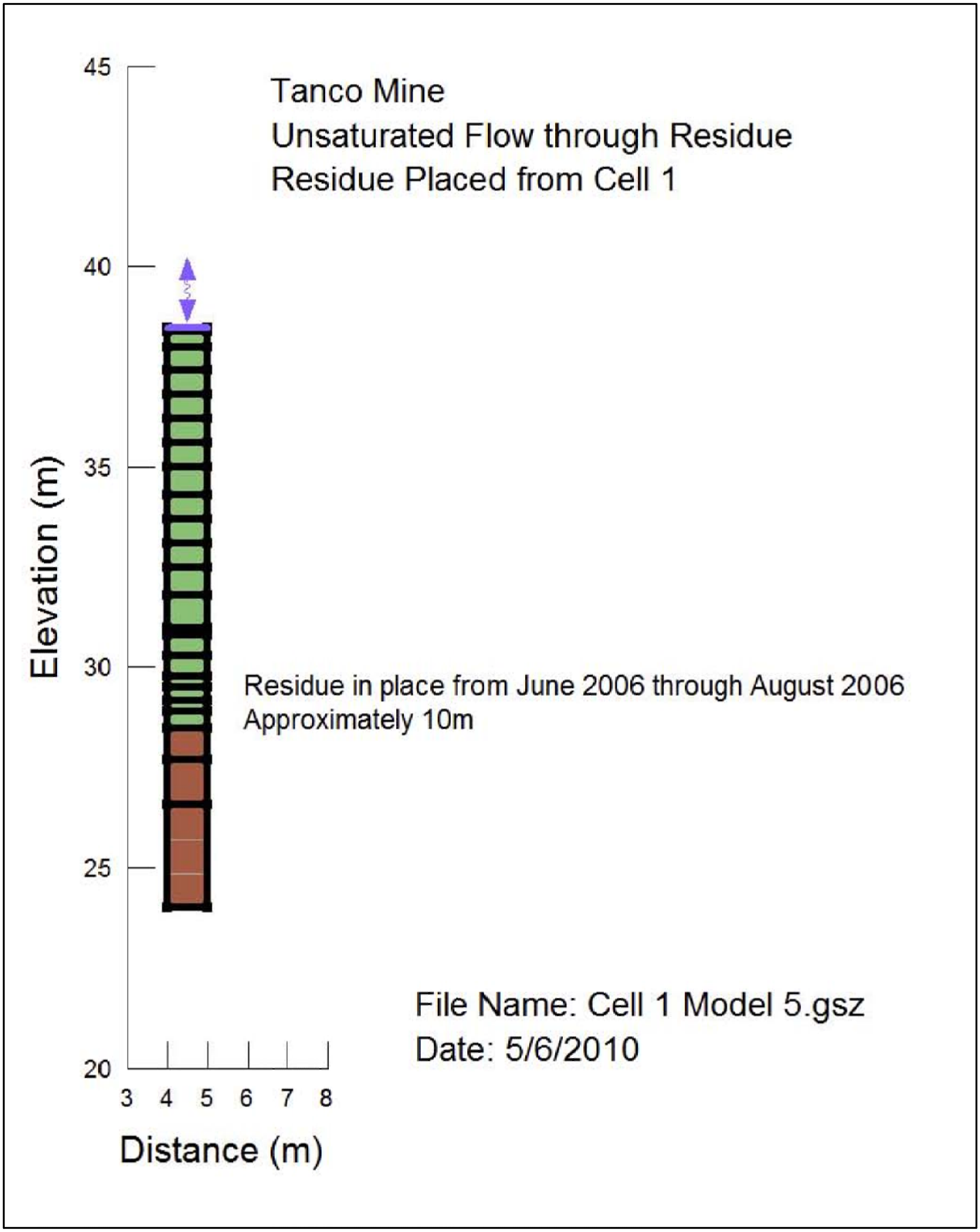


FIGURE 3-3.
GENERAL MODEL CONFIGURATION:
UNSATURATED FLOW MODEL 5

3.2 Climate Data

The climate data used in the model were obtained from two Environment Canada meteorological stations located in Pinawa and Bissett, Manitoba. Pinawa is located approximately 50 km southwest of the project site, and Bissett is approximately 60 km to the north. These stations were chosen because of their proximity to the project site, long period of record, and no more than three years of consecutive missing data, the strictest standard developed by Environment Canada (Environment Canada, 2008).

Data were assembled for the period of 2001 through 2007 using precipitation data from the Bissett station and wind speed and relative humidity from the Pinawa station. This period was chosen because it corresponds to the period that the residue from Cells 1 and 2 was emptied and placed in the old TMA. Because wind speed and relative humidity data from Pinawa station were not available until 2003, a typical year was generated using the available data by averaging individual days from the existing data. Actual evaporation is calculated by the model using positive and/or negative pore water conditions at the ground surface. The first six models for Cells 1 and 2 were run with climate data corresponding to the period over which the residue deposition took place. The climate data for the final models for each cell were derived by taking the 2001 through 2007 data and cycling it to create thirty-six years of climate data. In general, precipitation falls primarily as snow during the winter months, with the greatest snowfalls occurring in November, December, and January. Annual average precipitation ranges from 573 to 577 mm with overall levels of precipitation peaking in June.

3.3 Boundary Conditions

The elevation of the groundwater table in the vicinity of borings MB-2 (Solylo, 2010) and TA-3-3 (Agassiz North, 2001) was used as the boundary condition for the bottom of the model. In this area of the TMA, the groundwater table is approximately 1.4 m below the surface of the pre-placement tailings (UMA, 2001). The climate data were used as the boundary condition on the top of the column.

3.4 Model Verification

The model output shows the ground temperatures responding to the diurnal and seasonal temperature fluctuations. Model output indicates that the soil surface responds immediately to the air temperature, but there is a lag in response to temperature with increasing depth below the ground surface. Soil temperature also varies less with depth. The surface soil is exposed to the weather and experiences a wide range of temperatures. Deeper in the soil, the temperature fluctuates less, and the soil eventually reaches a constant temperature. Both of these phenomena have been demonstrated by numerous researchers. The VADOSE/W models for TANCO effectively demonstrate soil temperature fluctuations with both time and depth.

Figure 3-4 shows output from Model 8 with the infiltration into the surface at a point 0.1 m below ground surface and the precipitation plotted for a two year period. The infiltration is on the primary y-axis, and the precipitation is on the secondary y-axis. The largest amount of infiltration occurs at approximately the same time as the greatest precipitation close to the ground surface.

3.5 Results of Analyses

The model results are summarized in Table 3.3. The flow rate presented (Table 3.3) occurs at the interface of the residue and the tailings. A positive number indicates upward flow at the interface, and a negative number indicates downward flow at the interface.

Figure 3-5 presents the output for models 1 through 5. The infiltration out of the residue from the dry stack from Cell 1 is shown during the deposition period. For the first 3 models, the column is taking a small net amount of water from the tailings. Starting with the fourth model, a small net amount of water begins to seep into the tailings from the dry stack. Figure 3-6 presents the output for models 7 through 11. The infiltration out of the residue from the dry stack from Cell 2 is shown during the time period when it was placed.

The results show that when the dry stack residue was first placed in 2001 the amount of flow between the dry stack and the underlying tailings was very small. There is an uptake and release of water at the bottom of the dry stack from the tailings occurring due to capillarity. This accounts for part of the effluent out of the dry stack at the end of each model period; precipitation seeping through the dry stack accounts for the remainder. The amount of effluent leaving the dry stack fluctuates based on the modeling time period.

Table 3.3. Results of VADOSE/W Models for Residue Placed from Cell 1

Model No.	Average Flow out of Dry Stack Residue ($m/s/m^2$)	Model Description	Modeling Time Period	Total Effluent out of Dry Stack Residue (m^3/m^2)
1	7.97×10^{-9}	Residue placed from August 2001 through April 2002[1]	8/1/01 through 4/30/02	1.9×10^{-1}
2	1.33×10^{-8}	No new residue added	5/1/02 through 5/31/04	8.7×10^{-1}
3	6.54×10^{-8}	Residue placed from June 2004 through September 2004	6/1/04 through 9/30/04	3.9×10^{-3}
4	-1.78×10^{-8}	No new residue added	10/1/04 through 5/31/06	-9.4×10^{-1}
5	-1.66×10^{-7}	Residue placed from June 2006 through August 2006	6/1/06 through 8/31/06	-1.2×10^{-2}
6	-1.29×10^{-8}	No new residue added	9/1/06 through 9/31/42	-9.9
7	3.28×10^{-8}	Residue placed from August 2002 through November 2002	8/1/02 through 11/31/02	3.5×10^{-1}
8	1.4×10^{-8}	No new residue added	12/1/02 through 4/30/05	1.5
9	4.8×10^{-8}	Residue placed from May 2005 through September 2005	5/1/05 through 9/30/05	-6.4×10^{-1}
10	1.77×10^{-8}	No new residue added	10/1/05 through 5/31/07	-9.27×10^{-1}
11	-1.31×10^{-4}	Residue placed from June 2007 through August 2007	6/1/07 through 8/31/07	-2.6×10^{-1}

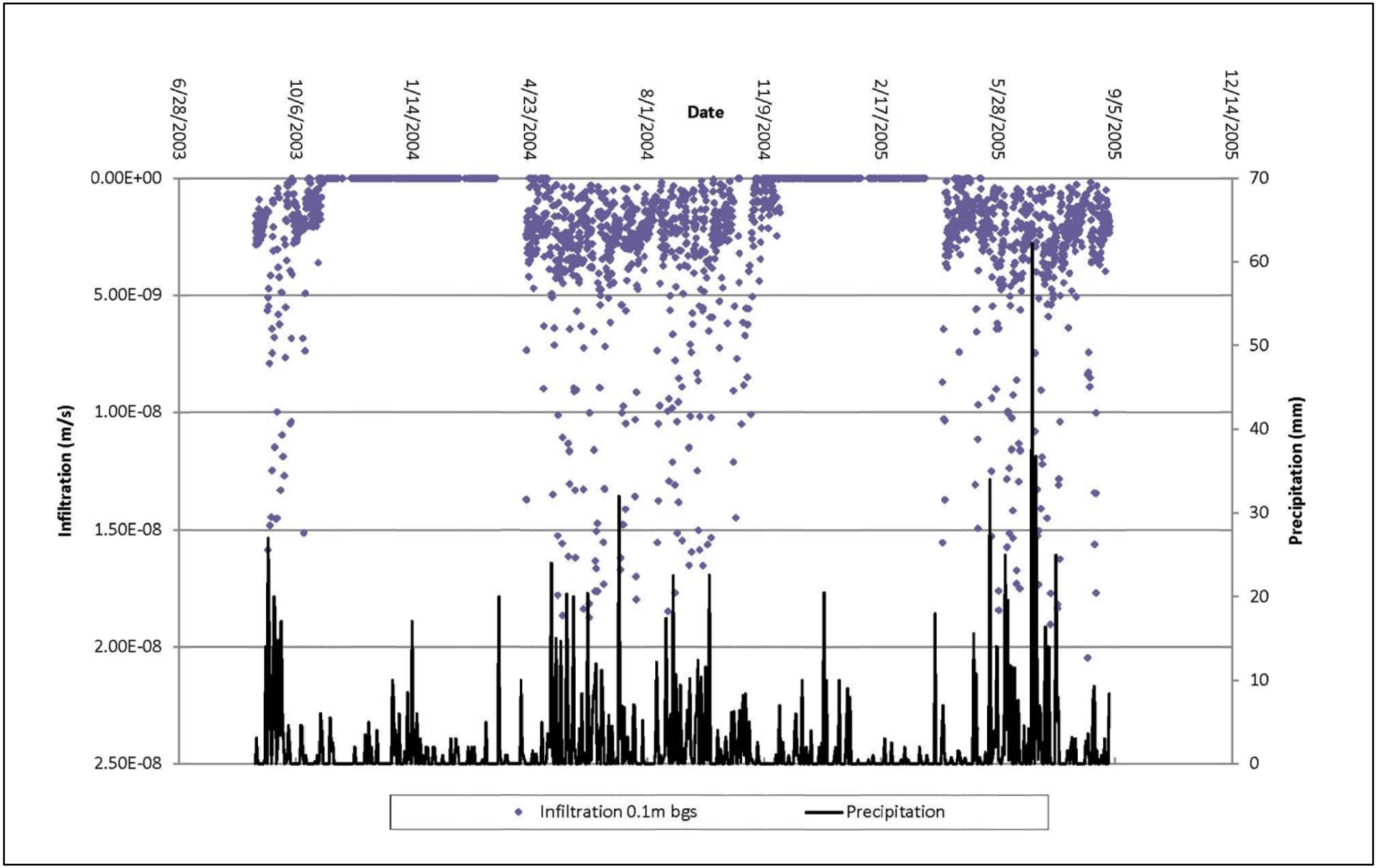


**FIGURE 3-4.
OUTPUT FOR MODEL 8: UNSATURATED
FLOW THROUGH RESIDUE PILE**

For the second case, the water content at various times during Model Run 5 (June 2006 through August 2006) were examined. Figure 3-8 shows the volumetric water content of the dry stack for this scenario. At the beginning of this model, the bottom of the dry stack is saturated. As the model progresses through time there is fluctuation of the water content within the dry stack at the surface responding to climate conditions, and there is a fluctuation of the water content within the dry stack at the interface between the dry stack residue and the tailings. This fluctuation is a draining and wetting between the dry stack and the tailings. There is flow occurring between the two layers; however, the amount of flow is small.

For the long term case, Model 6 was run after the final deposition of dry stack was placed in August of 2006 for an additional 36 years. The results of the long term analyses show that the amount of water exchanged between the dry stack residue and the tailings increases over time, but the residue does not convey a significant amount of water. In general, the dry stack residue acts as a cap for the TMA tailings where it is placed.

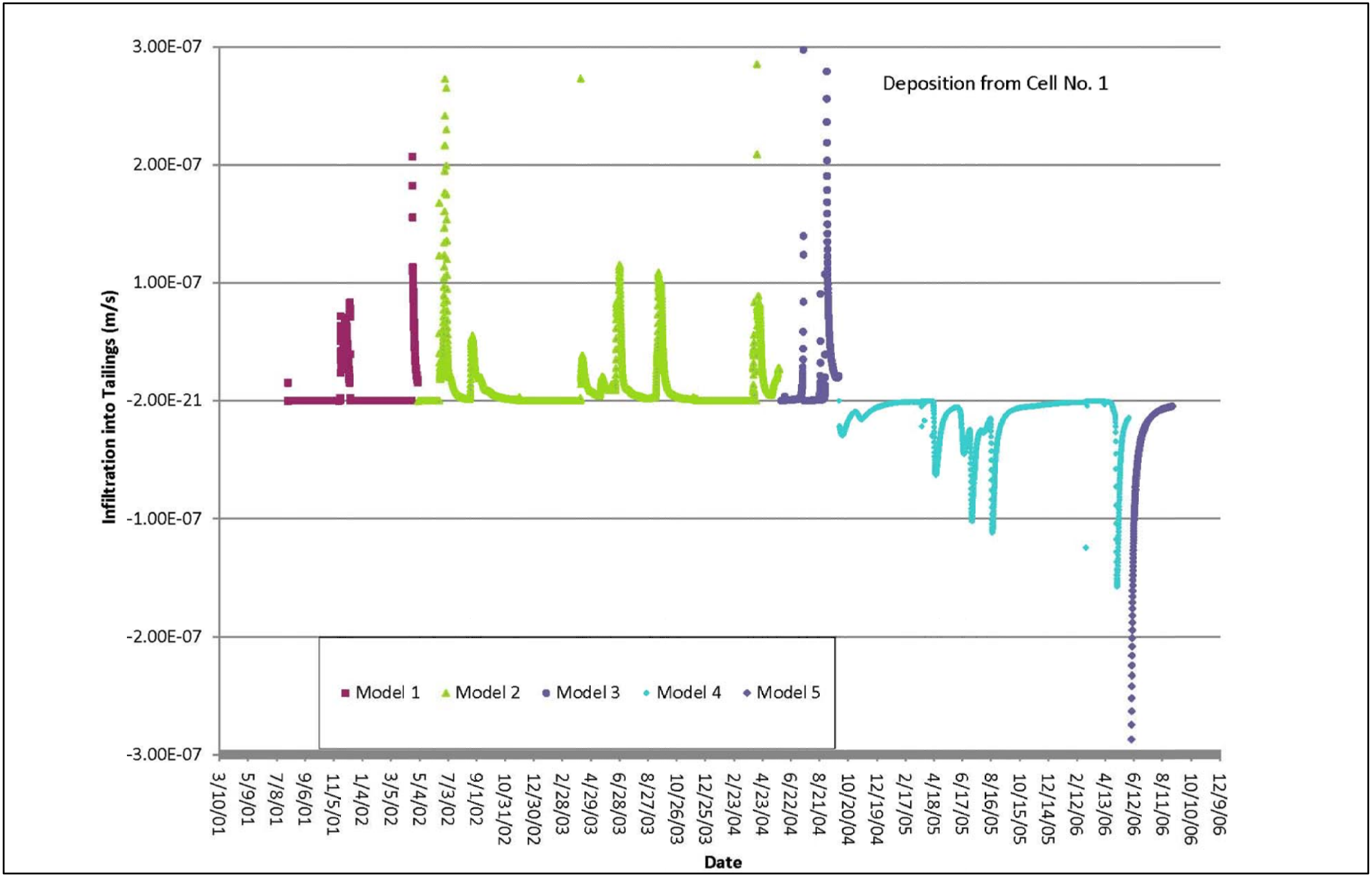


FIGURE 3-5.
OUTPUTS FOR MODELS 1 THROUGH 5:
UNSATURATED FLOW THROUGH RESIDUE PILE

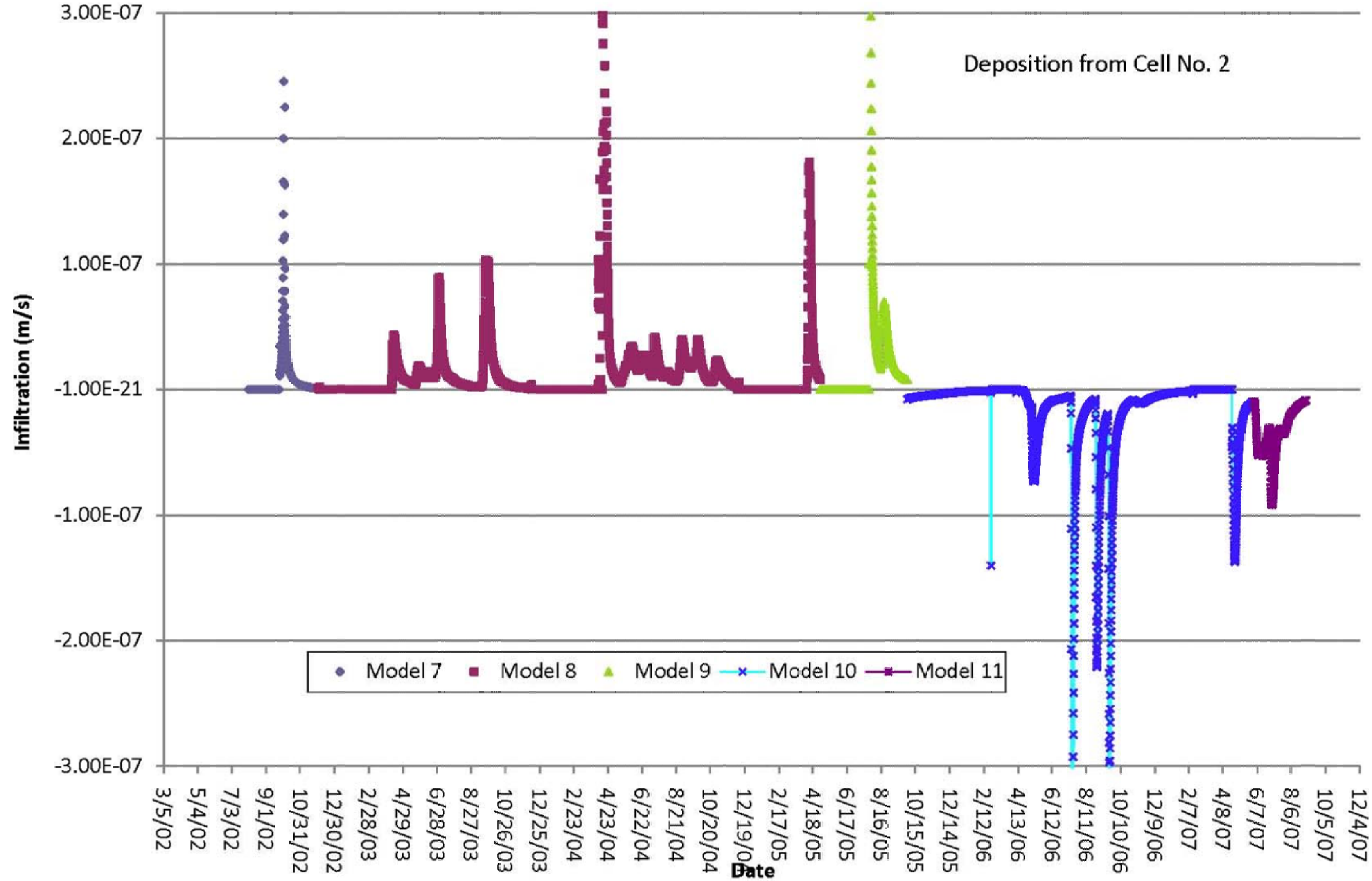


FIGURE 3-6.
OUTPUTS FOR MODELS 7 THROUGH 11:
UNSATURATED FLOW THROUGH RESIDUE PILE

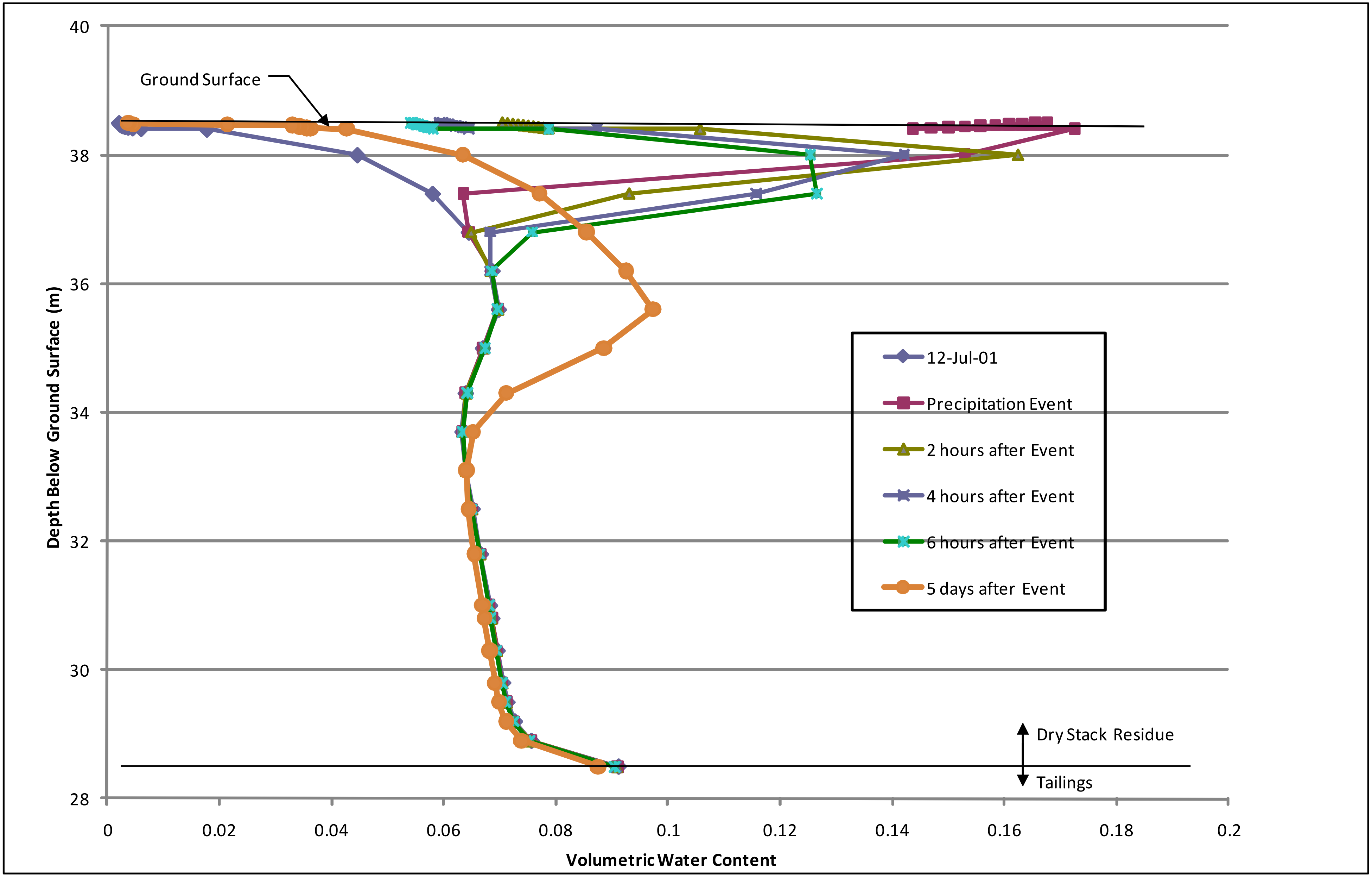


FIGURE 3-7.
VOLUMETRIC WATER CONTENT OF THE RESIDUE DRY STACK FOR MODEL 3

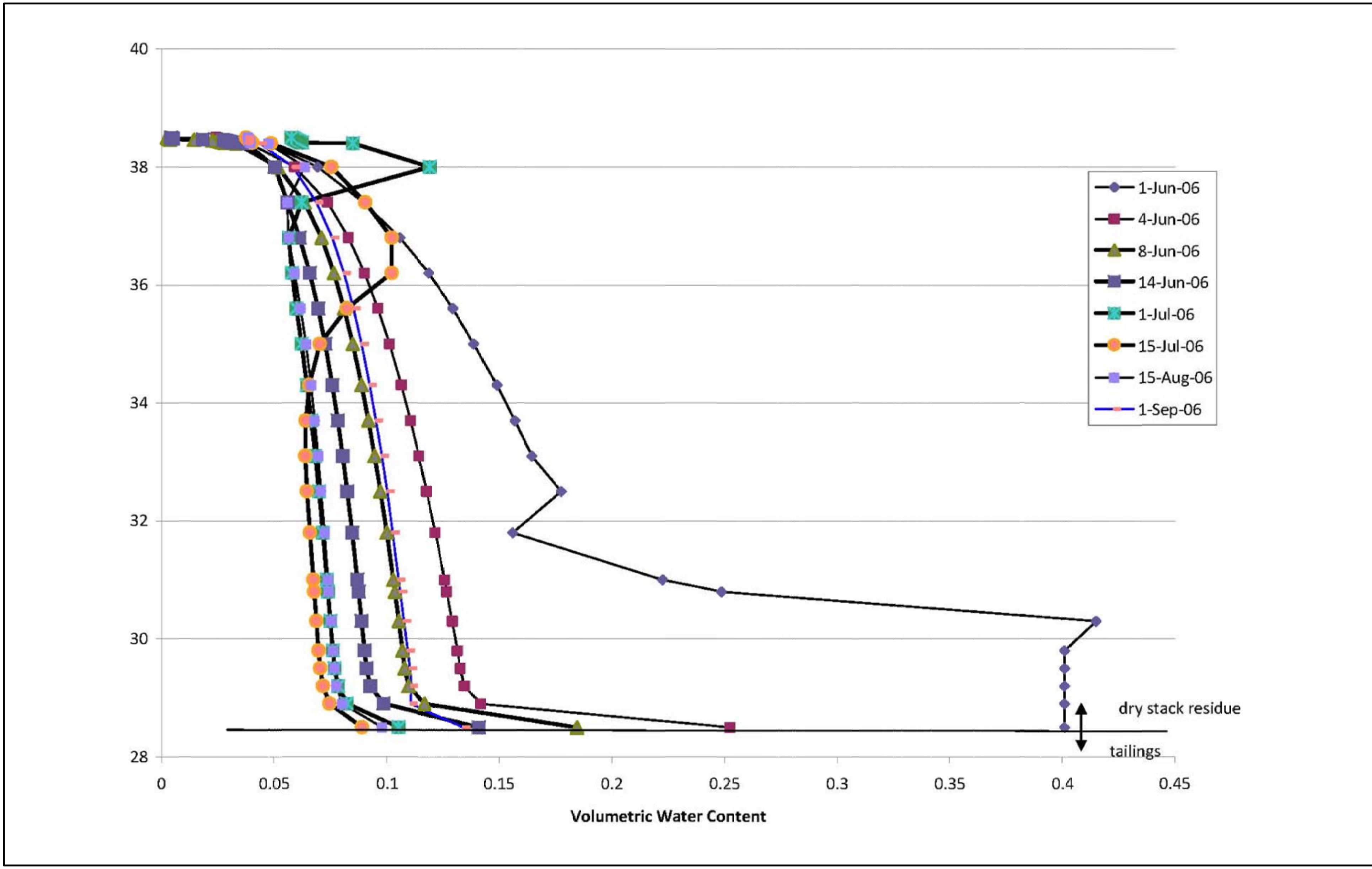


FIGURE 3-8.
VOLUMETRIC WATER CONTENT OF THE RESIDUE DRY STACK FOR MODEL 5

4.0 HYDRO-GEOCHEMICAL ASSESSMENT

Residue leachate migration through the old TMA is traced using the leachate signature which is characterized by elevated concentrations of six key parameters (conductivity, dissolved calcium and strontium, total cesium and rubidium, and sulphate). For brevity, the following discussion focuses on groundwater quality impacts as indicated by elevated concentrations of the signature parameters. A detailed characterization of the other parameters assessed prior to and following residue placement is provided elsewhere (e.g., SEACOR, 2004; Wardrop, 2008).

4.1 CPF Residue Mineralogy

UMA (2001) characterized the CPF residue as predominantly silt-sized particles with some fine sand and clay whereas Solylo (2010) indicates the CPF residue consists of fine sands, feldspar minerals, mica, and minor amounts of clay. Mineralogically, the residue consists primarily of gypsum, quartz and pollucite ore gangue with trace amounts of other sulphate and hydroxide compounds.

4.2 Water Quality Characterization

The Environmental Approval for residue placement within the old TMA required the investigation of residue properties, pre-placement baseline water quality characterization and continued groundwater quality monitoring within the old TMA to assess the influence of residue leachate on groundwater and potentially on receiving surface water. The concentrations of the leachate signature parameters identified during field and laboratory testing are summarized in Table 4.1.

Table 4.1. Summary of Field and Laboratory Characterization Data

Parameter	Units	Average Shallow Pre-placement Groundwater Quality	Shallow Impacted Well (TA-3-1, June 2005)	Stable Average 20-week Leach Testing	Average Residue Pore Water	Average Saturated Tailings Pore Water
Total Dissolved Solids (TDS)	mg/L	330	7930	2300 (conductivity)	-	-
Dissolved Calcium	mg/L	26.57	484	600	227	214
Sulphate	mg/L	8.61	3610	1500	3372	2501
Dissolved Strontium	mg/L	0.122	1.360	-	0.069	0.43
Total Cesium	mg/L	3.96	2530	25	38.4	1635
Total Rubidium	mg/L	1.41	20.6	-	38.4	28.6

Laboratory Testing on CPF Residue

Lakefield Research (2000) completed 20-week leach testing of residue samples from the CPF pilot plant to characterize the seepage produced by movement of water through the residue pile. During the first few weeks of testing, pore water showed elevated concentrations of calcium, sulphate, cesium, sodium, and several heavy metals. Following this initial flushing of the pore water in the samples, most parameters dropped close to or below the analytical reporting limits with the exception of calcium and sulphate which were released at a fairly constant rate throughout the test. The key finding of the leach testing is that the leachate signature is likely to be released from the residue upon rinsing with water.

The laboratory-based characterization of the residue was advanced by Solylo (2010) through the analysis of pore water quality associated with three boreholes (MB1, MB2 and MB3) cored through the residue pile and underlying tailings. Core samples were obtained by consecutive pushing and extracting of 1.22 m long high-density clear plastic rods into the residue/tailings. Pore water was extracted from each sample by applying a maximum of five tons of pressure using a hydraulic press. Solylo (2010) provided additional evidence that the leachate signature is present in the residue pore water as demonstrated by elevated levels of signature parameters with the exception of strontium which was low compared to the concentrations observed in the shallow impacted groundwater at TA-3.

As demonstrated in the laboratory testing described above (Lakefield, 2000; Solylo, 2010), the residue is capable of releasing the leachate signature constituents as a result of water infiltration.

4.3 Distribution of Impacted Wells

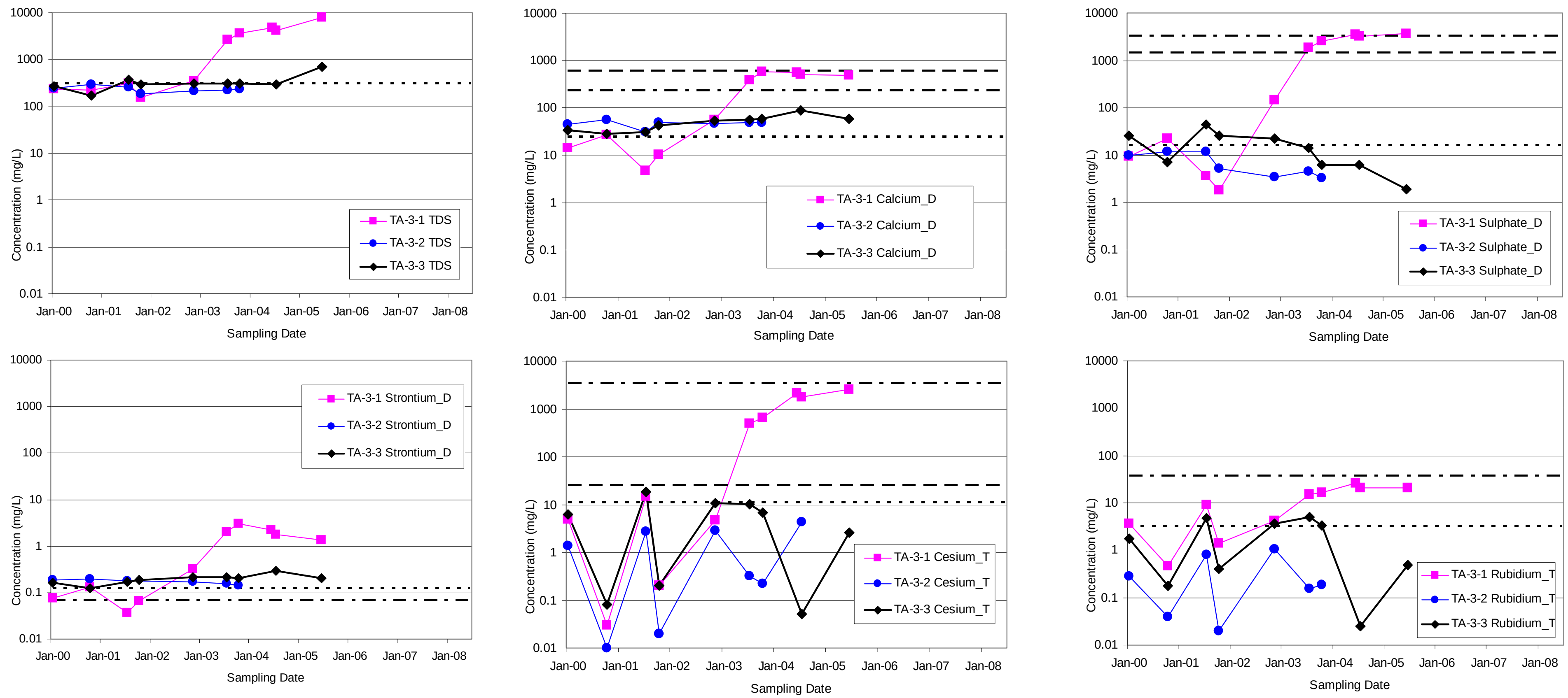
The baseline water quality assessment within the Old TMA aquifer was conducted by UMA (2001). A comparison of the average concentrations of leachate signature parameters before residue placement and subsequent groundwater quality monitoring confirms the Wardrop (2008) analysis that shallow groundwater quality within the old TMA has been altered by the residue placement beginning in approximately 2002-2003. Groundwater quality at the base of the tailings and in the overburden does not appear to be altered. This trend is best illustrated in TA-3, a nested well within the primary residue pile (Figure 4-1) with a period of record from October 2000 through June 2005. Initially groundwater quality from all three screened intervals within TA-3 was similar to the average baseline water quality; however, over time the concentrations of key leachate signature parameters in the shallow groundwater, specifically sulphate, rubidium and cesium, approach the pore water concentrations determined by Solylo (2010) and level-off. This trend was also evident in wells distal to the primary residue pile (e.g., MW-1/1A and TA-7), but concentrations were lower than observed directly beneath the pile.

In general, the leachate signature is less evident in wells farther from the residue placement areas. This is well illustrated (Figures 4-2 through 4-7) using proportionality symbol plots of the monitoring well network throughout the TMA.

4.4 Mechanisms for Chemical Transfer

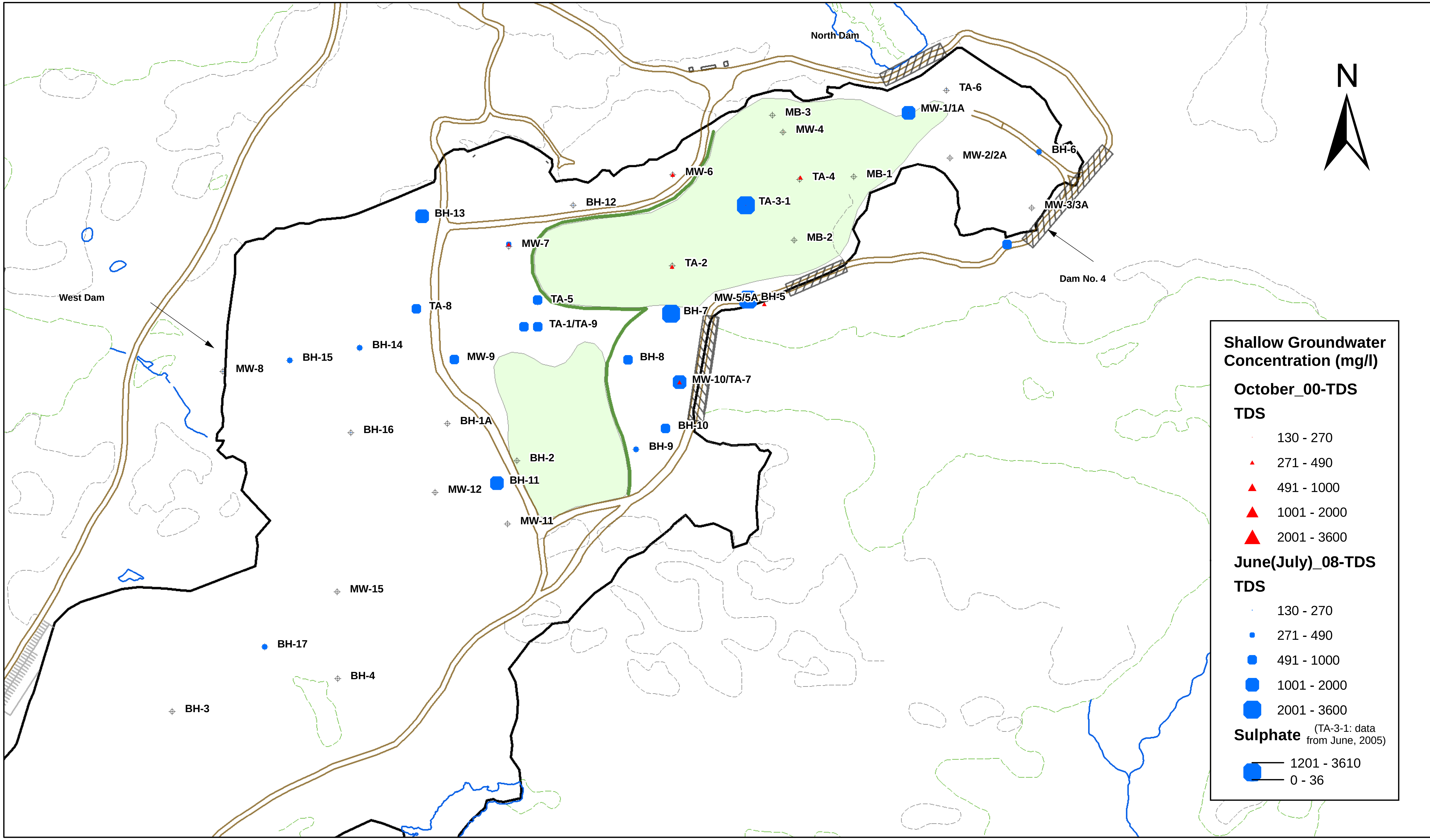
Three different release mechanisms are recognized to potentially account for the transfer of leachate signature parameters from the residue to the saturated tailings:

- Percolation of meteoric precipitation through the residue piles;
- Runoff of meteoric precipitation from the residue piles which infiltrates saturated tailings directly; and,
- Rinsing of the residue by water from the saturated tailings.



Initial sampling event is an inferred baseline value obtained from Wardrop (2008) and set to Jan-00 for illustration purposes.

Figure 4-1
Groundwater Quality Trend Analysis at Nested Well TA-3



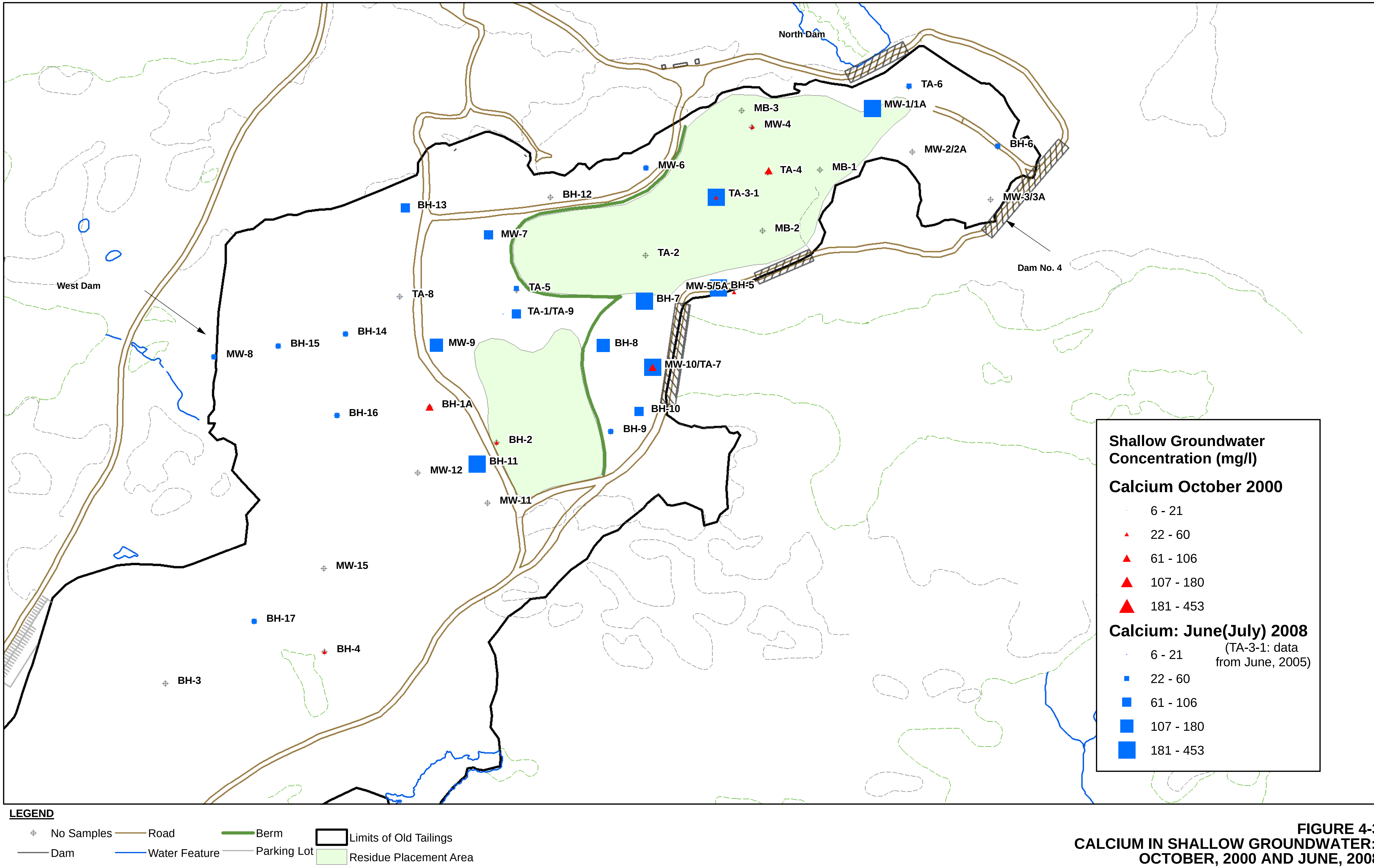
LEGEND

No Samples — Dam — Road — Water Feature — Infrastructure — Limits of Old Tailings — Residue Placement Area

Meters: 0 50 100 200

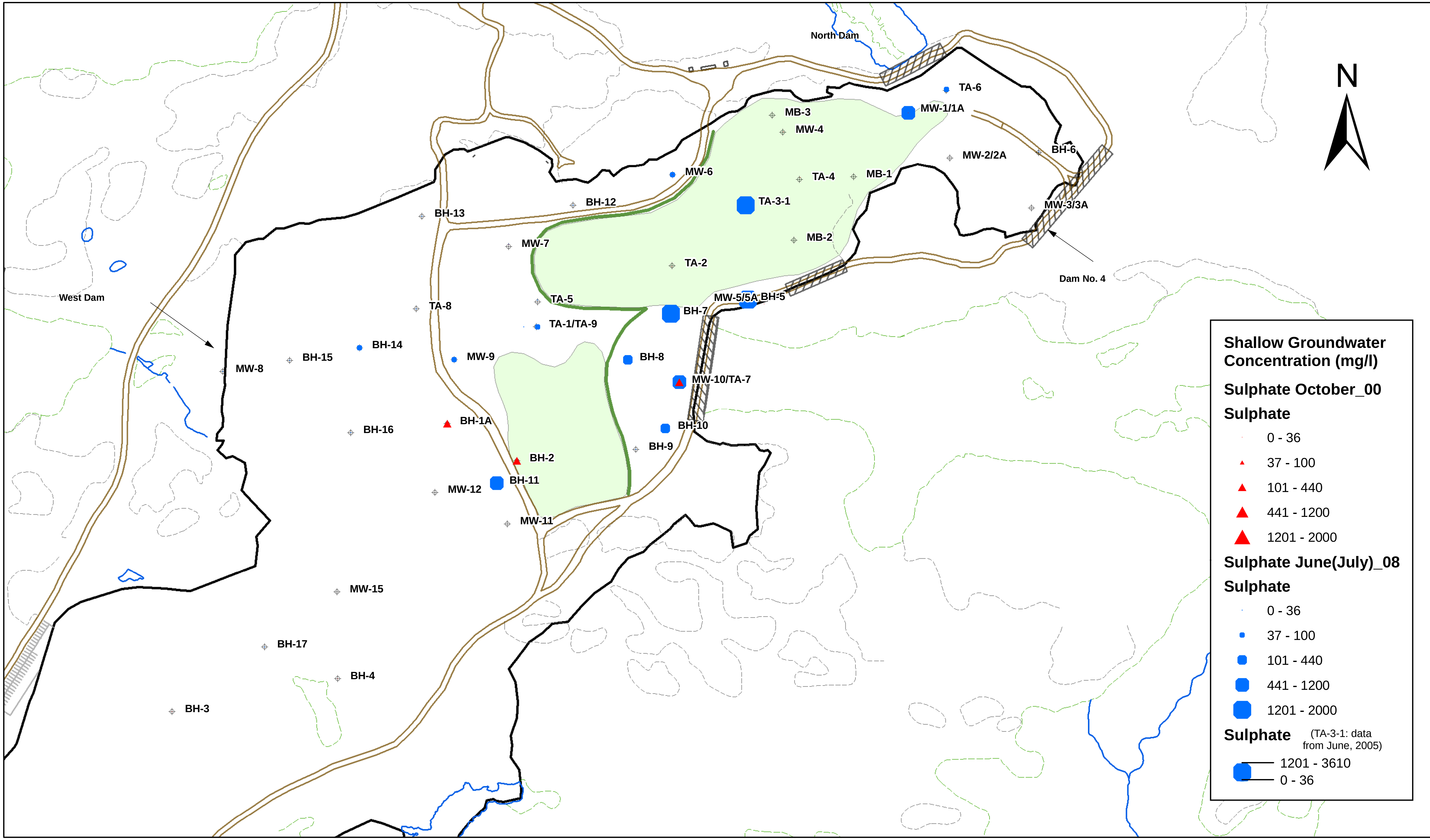
FIGURE 4-2
TDS IN SHALLOW GROUNDWATER: OCTOBER, 2000 AND JUNE, 2008

Sources: Wardrop, 2009; Tetra Tech GIS, 2010.



Sources: Wardrop, 2009; Tetra Tech GIS, 2010.

FIGURE 4-3
CALCIUM IN SHALLOW GROUNDWATER: OCTOBER, 2000 AND JUNE, 2008



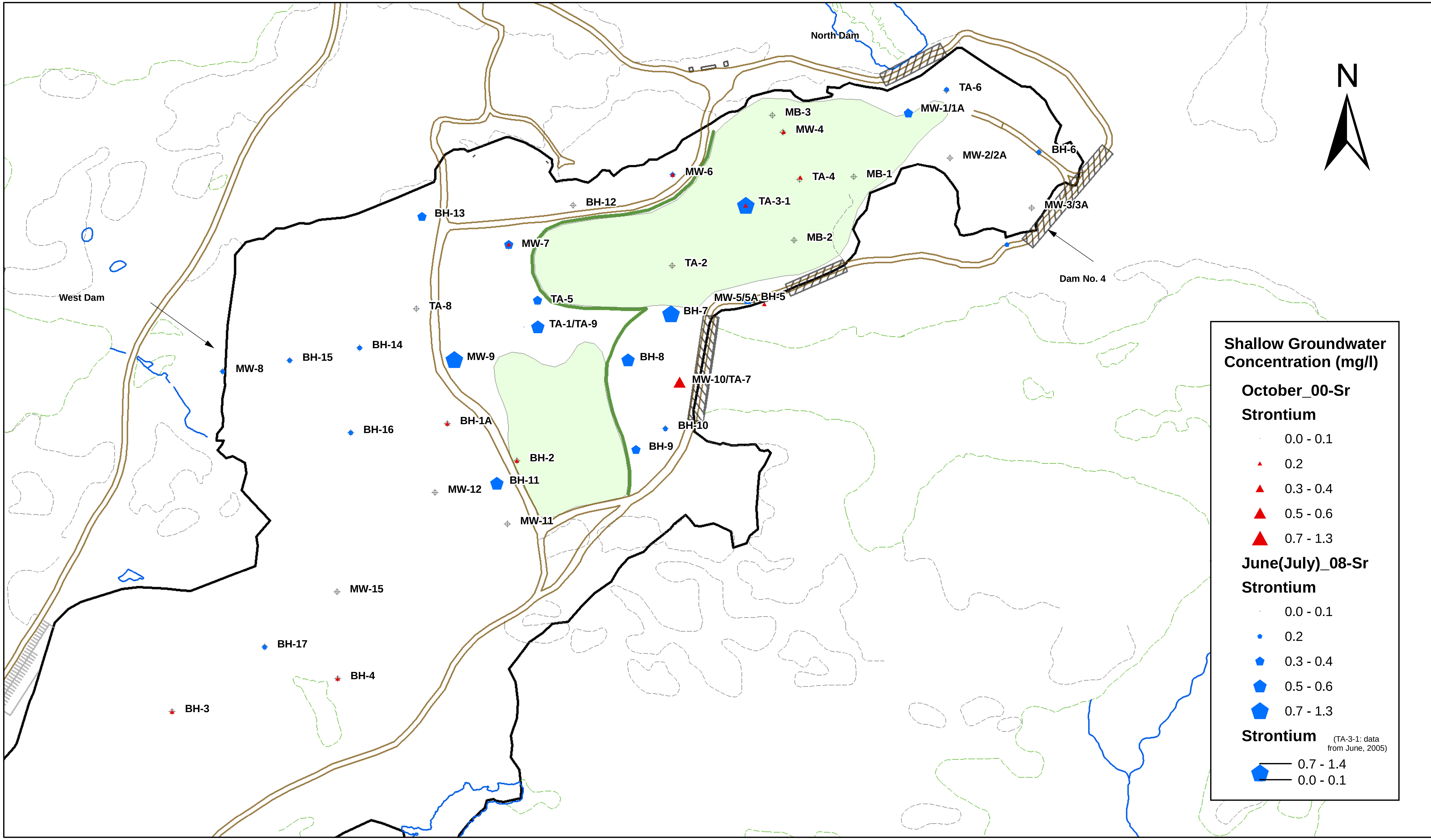
LEGEND

No Samples, Dam, Road, Water Feature, Infrastructure, Limits of Old Tailings, Residue Placement Area

Meters: 0, 50, 100, 200

FIGURE 4-4
SULPHATE IN SHALLOW GROUNDWATER: OCTOBER, 2000 AND JUNE, 2008

Sources: Wardrop, 2009; Tetra Tech GIS, 2010.



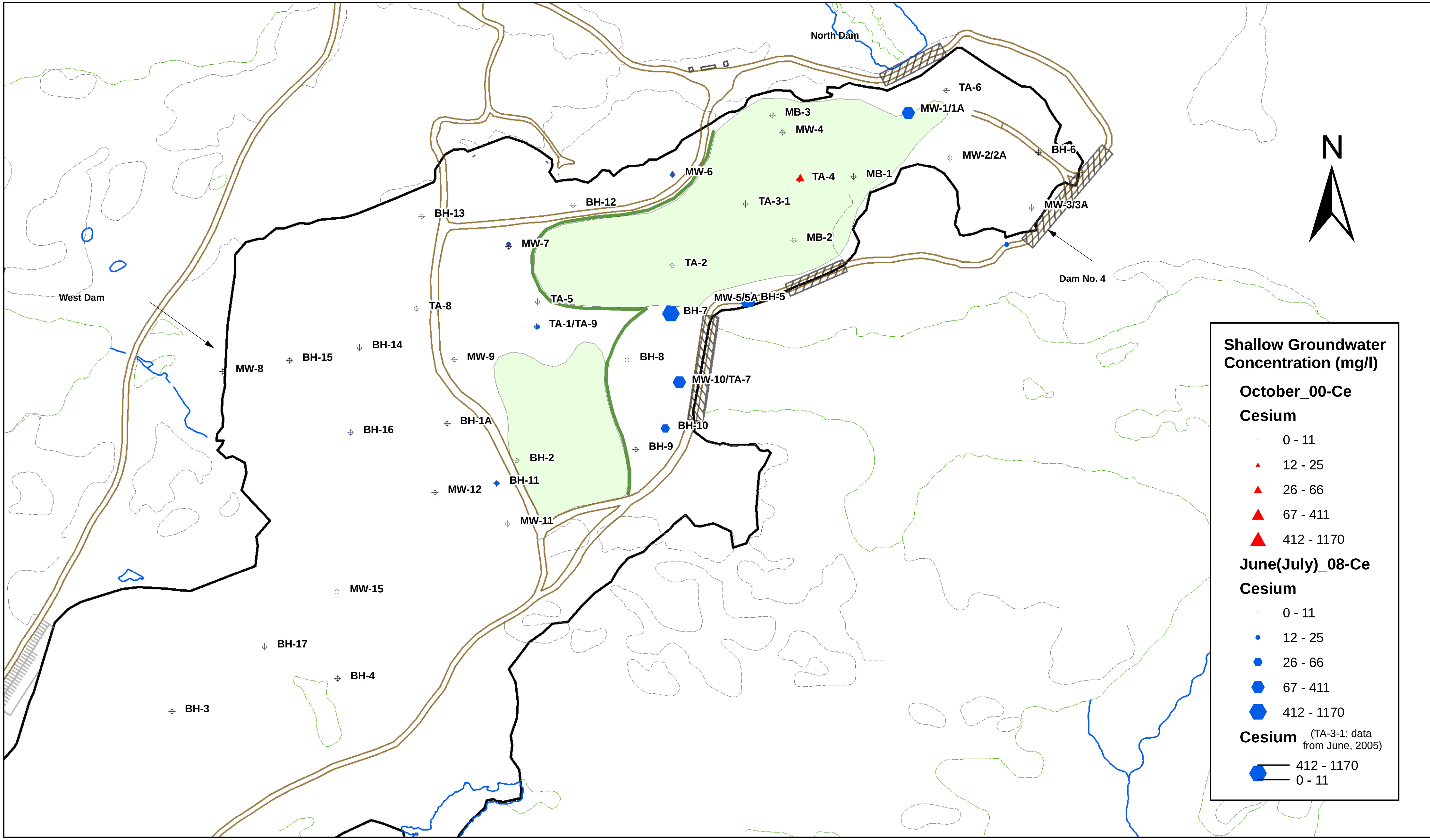
LEGEND

No Samples — Dam — Road — Water Feature — Infrastructure — Limits of Old Tailings — Residue Placement Area

Meters
0 50 100 200

FIGURE 4-5
STRONTIUM IN SHALLOW GROUNDWATER: OCTOBER, 2000 AND JUNE, 2008

Sources: Wardrop, 2009; Tetra Tech GIS, 2010.



LEGEND

No Samples; Dam; Road; Water Feature; Infrastructure; Limits of Old Tailings; Residue Placement Area

Meters: 0, 50, 100, 200

FIGURE 4-6
CESIUM IN SHALLOW GROUNDWATER: OCTOBER, 2000 AND JUNE, 2008

Sources: Wardrop, 2009; Tetra Tech GIS, 2010.

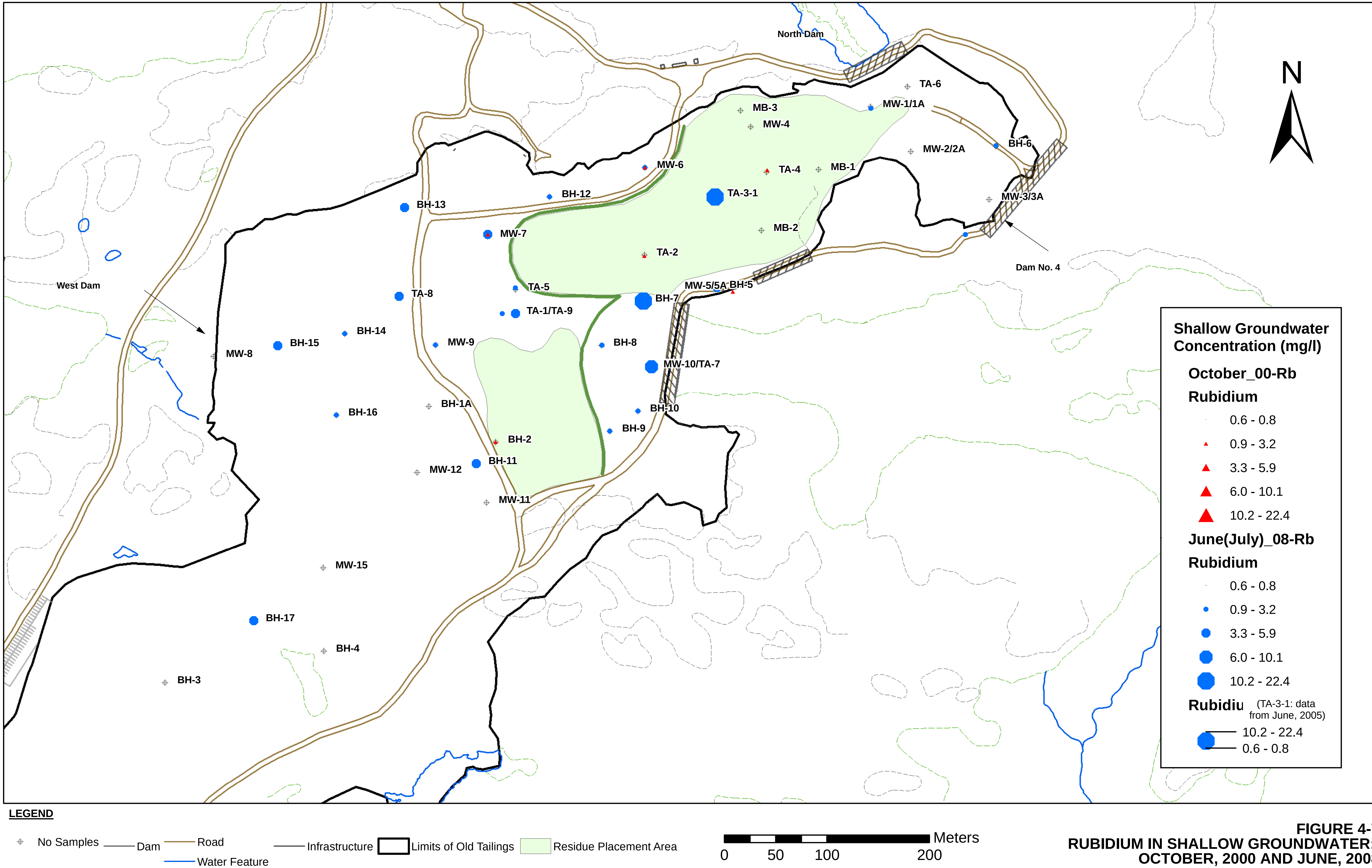


FIGURE 4-7
RUBIDIUM IN SHALLOW GROUNDWATER: OCTOBER, 2000 AND JUNE, 2008

Sources: Wardrop, 2009; Tetra Tech GIS, 2010.

4.4.1 Evaluation of Infiltration

The potential for infiltration of meteoric water through the residue to produce the observed leachate signature concentrations in saturated tailings may be made with a straightforward scoping calculation. Discharge from the base of the residue, at a selected chemical concentration, is mixed with a selected volume of saturated tailings water to estimate the resulting concentration increase. The calculation includes the following assumptions:

- A per unit (one m^2) column of residue that extends into the saturated tailings;
- The per unit area discharge from the residue into the saturated tailings is estimated at flow equal to 10^{-8} m/s based on vadose infiltration analysis (Section 3.5, Table 3.3);
- The residue pile is considered to behave under unsaturated, plug-flow conditions wherein a slug of water entering the top of the pile displaces an equivalent slug from the bottom;
- The residue discharge is blended with water in the first 3 m of saturated tailings, which is selected as the depth of the shallowest well screen in the representative TA-3 nested well;
- Porosity is estimated at 10%; calculated sensitivities are based on porosities of 5% and 15%;
- The chemical composition of the residue discharge is the average pore water chemistry reported by Solylo (2010) and provided in Table 4.1;
- A period for the calculation of one month, the approximate time required to replace the water in the m^2 column in the saturated tailings at a flow rate of 10 m/yr.

The results of the scoping calculation (Table 4.2) indicate an increase in signature parameter concentrations in the saturated tailings due to discharge from the residue pile; the increase is very small compared to that measured at TA-3. Notably, the highest residue signature concentrations reported for TA-1 in recent measurements (See Figures 4-2 through 4-7) are consistent with the average composition of saturated tailings pore water (see Table 4.1) reported by Solylo (2010). Therefore, discharge of infiltrating precipitation from the residue pile to saturated tailings does not appear to satisfactorily account for field observations. This mechanism does not satisfactorily explain present conditions and seems unlikely to present concern for the future.

Table 4.2. Hydro-geochemical Evaluation of Infiltration

Parameter	Concentrations (mg/l) in Old TMA Pore Water		
	at 5% porosity	@10% porosity	@15% porosity
Calcium	0.00	0.00	0.00
Sulphate	27.32	54.63	81.95
Strontium	0.00	0.00	0.00
Cesium	0.41	0.21	0.14
Rubidium	0.00	0.00	0.00

4.4.2 Evaluation of Residue Pile Surface Water Runoff

Evidence exists to indicate runoff of precipitation from the residue pile has contributed to the observed alteration of groundwater quality. Surface runoff likely travels a greater distance from the primary and secondary placement than groundwater for a comparable length of time. Thus, surface transport may have occurred in instances where notable increases in residue signature concentrations in groundwater at distances are unsupported by groundwater flow velocities.

Examples of residue leachate migration to greater distances than supported by groundwater flow are seen at TA-7 (near the East Dam) and MW-1 (near the North Dam) (Figures 4-2 through 4-7). Increases in leachate signature are documented to occur approximately one year following residue placement. Therefore, alterations of groundwater quality at distances greater than about 10 m from the residue placement area, as indicated at TA-7 and MW-1, suggests a surface transport mechanism. Runoff from the residue piles would appear to flow across the surface, pooling or otherwise infiltrating into the saturated tailings.

4.4.3 Evaluation of Residue Pile Rinsing by Groundwater

Saturated tailings directly beneath the primary residue pile contain significantly elevated leachate signature parameter concentrations as evidenced by TA-3. Given the inability of infiltration of precipitation to migrate through the residue to produce such concentrations (see Section 3.5), an alternative explanation is necessary.

Such explanation must entail a mechanism providing contact of groundwater within the Old TMA with residue that contains elevated signature parameters. While discharge from the residue pile would contain significantly elevated concentrations, the total mass of chemicals discharged is insufficient to account for concentrations in the underlying saturated tailings. Also, transport by surface runoff would disperse the signature away from the residue placement areas.

Two robust mechanisms for chemical transfer from the residue in the placement areas to the saturated tailings are evident and may include:

- Subsidence of the residue once placed on the saturated tailings, leading to direct rinsing of the residue; or,
- Uptake of saturated tailings groundwater by unsaturated residue (see Section 3.5) with subsequent re-release.

Notably, chemical loading from the residue pile to saturated tailings groundwater has been documented only to a depth of approximately 3 m within the shallowest samples of nested monitoring wells (e.g. TA-3-1). Saturated tailings pore water data (Solylo, 2010) indicate that effects extend deeper, to depths of approximately 12 m. It is not clear how Solylo's (2010) pore water data correlate with the freshwater rinse step in sequential extraction in the same report which suggest much shallower effects than 12 m. However, shallow data from TA-3 and Solylo (2010) are consistent with a chemical transfer mechanism that requires significant contact of the residue with water, probably from just under the footprint of the residue placement areas.

4.5 Site Conditions and Significant Effect Mechanism

As described, three mechanisms are noted by which transfer of chemical mass from the residue to the saturated tailings may occur. A mechanism involving discharge from the residue piles as a result of infiltration of meteoric precipitation fails to provide sufficient chemical mass to produce observed field effects. The effects observed at monitoring locations somewhat distal to the primary residue pile appear best supported by a surface runoff mechanism that transports leachate to locations too far to be accounted for by the relatively slow rate of groundwater flow. Flooding of the TA-7/MW-10 site has been noted (Wardrop, 2008) during 2005 and 2007 and may result in preferential surface water dispersion. To date, the most significantly altered saturated tailings water lies directly beneath the primary residue placement area and appears to be consistent with a rinsing of residue directly by saturated tailings water.

The elevated leachate signature concentrations associated with the primary residue placement area have not been observed to extend appreciably beyond the residue footprint. A hydrologic mechanism to support groundwater movement of chemical mass much beyond the residue pile is not apparent. As noted, the residue effectively acts as a cover, restricting recharge of precipitation to the saturated tailings. This effectively diminishes the hydrologic driving force to transport chemical mass. Indeed, the abundant recharge surrounding the recharge-depleted area under the residue results in the formation of a hydrologic barrier that restricts advective conveyance. The steep gradient between the low concentration (background) saturated tailings and the elevated concentrations beneath the residue supports diffusive movement of leachate; however, the magnitude of that movement would be quite small given the recharge occurring on the margin of the residue.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Several conclusions are evident from review of the TANCO TMA and residue dry stack area hydrology and monitoring water quality data and hydro-geochemical analysis based thereupon. These include:

- TMA groundwater quality has been significantly altered in selected monitoring wells as previously noted (Wardrop, 2008). These wells are generally located within the footprint of, or immediately peripheral to the residue pile.

- Effects in the Old TMA are restricted essentially to shallow groundwater (that near the water table); no (or rare) effects are evident within samples at the base of the aquifer or within the underlying overburden groundwater.

- Where elevated, most constituents increased in concentration sharply from approximately 2002 through 2003. These constituents often approximately level-off to an apparent maximum range and in some cases appear to decrease between approximately 2007 and 2008. This suggests that worst case water quality reflects pore water chemistry as observed to-date in affected wells. No mechanism is apparent for groundwater transport of affected waters.

- Analysis of infiltration of meteoric water through the residue dry stack indicates seepage is episodic and relatively minor compared to TMA groundwater volumes. As such, the effect on TMA groundwater quality from mixing is expected to be very minor and in most cases likely not detectable. Therefore, mixing of residue dry stack pore waters is likely not a significant mechanism driving effects on shallow groundwater quality.

- The vadose analysis suggests the residue dry stack acts overall as a hydrologic barrier cap over the footprint of the primary and secondary residue placement areas. As a cap, recharge to the underlying aquifer is prevented and no groundwater mound would develop. Through time, hydraulic gradients would flatten beneath the footprint and heads would progressively decrease; no mechanism of advective transport of pore water seepage or impacted groundwater is apparent.

- A rinse/re-saturation process may be responsible for effects on shallow groundwater quality within the residue dry stack area. This process may reflect periodic contact of residue pore water with TMA groundwater through subsidence of the pile. Re-saturation of the residue may occur through capillary action during extended dry periods.

- Surface water run-off may transport and disperse residue during major storm events in preferential directions based on topography. Accumulation of surface waters has been historically noted; such waters would infiltrate through the thin vadose zone and could result in lateral extension of effects on shallow groundwater.

Opportunities for future management of this transfer mechanism may include engineered surface grading of the residue pile in conjunction with placement of a suitable cover material to minimize precipitation contact with the residue. Due to the limited capacity of residue to conduct precipitation, such a cover design may not require resistance to infiltration so much as mechanical resistance to erosion. The closure plan for the residue dry stack includes the establishment of a vegetated cover on the dry stack and this should provide continuing management of precipitation contact with the residue.

To advance the hydro-geochemical analysis and further the understand mechanism(s) by which groundwater quality is affected within the old TMA, additional investigations would be required. These investigations may include:

1. Refinement of the infiltration model to account for dry stack placement history;
2. Evaluation of historic and current surface topography with regard to potential run-off towards impacted wells; and,
3. Sampling of ponded water from within the Old TMA following storm events to assess the quality of residue pile run-off.

6.0 REFERENCES

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