ATTACHMENT 2

Evaluation of Groundwater Flow Impacts on GWETS

This attachment provides a preliminary evaluation of potential groundwater flow impacts resulting from the proposed stormwater retention system. Currently, four retention basins are proposed to be used to collect stormwater from the Tronox facility. Two of the basins are located in the northern portion of RZ-D, one at the west corner (Northwest Basin) and one at the east corner (Northeast Basin). The third basin is the Beta Ditch, which was previously closed off to prevent stormwater discharge onto the TIMET Site. All three of these features have historically been used to contain and infiltrate stormwater runoff at the Tronox facility. Additionally, a fourth retention basin (Central Basin) is proposed in the central portion of the Facility. Based on the potential use of these basins, the possible effects of adding water to the groundwater system through the proposed stormwater retention system under the following scenarios were evaluated:

1. Controlled soil flushing of the entire Central Basin;
2. Infiltration of a ten-year rainfall event at the Northwest Basin, assuming runoff in the Central Basin drainage area is also diverted to the Northwest Basin; and
3. Infiltration of a hundred-year rainfall event at the Northwest Basin and at the Central Basin after flushing has been completed.

Central Basin Soil Flushing

This scenario assumes that the treatment system effluent or Lake Mead water is introduced into the basin at a controlled rate until sufficient water has been applied to flush the vadose zone. The feasibility of flushing the entire Central Basin will not be determined until after the planned pilot study, so only a preliminary evaluation of potential impacts to groundwater flow is presented. A more comprehensive evaluation may be performed after initial results of the flushing pilot study become available.

This preliminary evaluation was conducted using the recently developed and calibrated Tronox groundwater flow model (Appendix E of *Capture Zone Evaluation Report, Tronox LLC, Henderson, Nevada,* Northgate, December 10, 2010) based on the following parameters and assumptions:

- The two Central Basin sub-basins would be flushed sequentially.
- Water would be applied at a rate equivalent to 0.1 feet per day (ft/day), which would be approximately 70 gallons per minute (gpm) for the western sub-basin and somewhat less for the eastern sub-basin.
- A total of 1.5 pore volumes of water would be applied at the surface to flush each area (as specified in *Revised Work Plan to Evaluate In Situ Soil Flushing of Perchlorate-Impacted Soil, Tronox, LLC, Henderson, Nevada,* Northgate, November 12, 2010).

Sequential flushing was considered in this scenario to allow for a higher recharge rate without compromising capture at the interceptor well field (IWF). Because the western sub-basin is larger and extends beyond the western extent of the IWF/barrier wall, capture by the IWF during flushing of this sub-basin is more of a concern than capture during flushing of the eastern sub-basin. Therefore, for this preliminary evaluation, only flushing of the western sub-basin was modeled. The recharge rate of 0.1 ft/day was selected so that the water expected to be added to the groundwater system would be between approximately 70 gpm for the western sub-basin, based on expectations that this volume of additional water could be readily captured at the IWF. Based on this flow rate, and air-filled porosity of 35%, and an approximate groundwater depth of 24 feet, flushing 1.5 pore volumes is expected to take approximately four months for each sub-basin.

An initial modeling run using the current IWF well pumping rates was conducted for the steady-state condition with increased infiltration from soil flushing, and as expected the resultant IWF capture area was somewhat smaller than under current baseline conditions. However, with increased IWF pumping, the results shown on Figure 2-1 show that a capture area very similar to current baseline conditions can be achieved. For the model run depicted in Figure 2-1, pumping was increased such that most wells were extracting at the maximum rate possible without dewatering the model cell. The total increase in pumping across the well field was approximately 70 gpm, bringing the total IWF extraction rate to approximately 140 gpm. Because the model has not yet been calibrated for transient conditions, the recharge was modeled as a steady-state condition. This model very likely overestimates the effects on groundwater flow of the proposed flushing scenario, which is only four months in duration.

Northwest Basin Infiltration of "Combined" Ten-Year Rainfall Event

This scenario assumes that a ten-year storm event occurs within the next year while runoff that would normally flow into the Central Basin is being diverted to the Northwest Basin via the Beta Ditch. The total volume of stormwater that would be diverted to the Northwest Basin under this scenario has been calculated at approximately 9 million gallons based on drainage evaluations conducted by RCI Engineering (*Technical Drainage Study for Tronox Soil Remediation Treatment Basins*, October 2010). Based on the dimensions of the basin, the basin water depth associated with this "combined" ten-year rainfall event is approximately 7.2 ft.

To evaluate the potential effects of this retained rainfall on the underlying groundwater flow, we used the groundwater flow model with a steady-state recharge rate of 0.08 ft/day, or approximately 70 gpm distributed across the basin footprint. This recharge rate was selected as a reasonable approximation of the average rainwater discharge to groundwater based on the following factors:

1. Consideration of the wetting front velocity and transient recharge rates, which indicate:

    a) Maximum initial recharge rate to groundwater of 0.67 ft/day, based on an assumed 7.2 ft of retained water head in the basin (see Table 2-1 and Table 2-2); and,

    b) A five-day time for the wetting front to reach the water table and an eight-day time for the basin to be fully drained (Figure 2-2).

    Based on this, the initial recharge rate at five days would be expected to be significantly less than 0.67 ft/day (because significantly less than 7.2 ft of water will remain in basin), and the rate would be expected to drop off significantly as the basin empties and drainage of the infiltrated water in the vadose zone progresses.

2. A three month time period for the full collected rainwater volume captured in the Northwest Basin to reach groundwater, based on observations of water level recovery in monitoring wells adjacent to the recharge trench during periods of shutdown.

As shown on Figure 2-3, the Athens Road Well Field (AWF) capture under this steady-state simulation of rainwater discharge is similar to the baseline condition. Although somewhat more water is shown passing through the western half of the AWF under the rainwater discharge scenario, this assumes no increase to pumping rates in this area. Northgate plans to re-model this scenario with increased AWF pumping rates to confirm that current capture can be maintained. Figure 2-3 also shows greater groundwater bypass at the neighboring facility's (POSSM's) GWETS under the rainwater discharge scenario than under baseline conditions; however, this may be an artifact of the coarser model discretization for this off-site area.

Because this simulation is based on steady-state conditions and the rainfall infiltration is a transient event, this modeled simulation likely overestimates the impacts rainfall infiltration would have on groundwater flow. We note that all rain falling on the Tronox facility is already captured on-site and the proportion infiltrating into groundwater should not change significantly with the new retention pond system. The past five years of water level data for the facility in general, and specifically for monitoring wells near the Beta Ditch (which is unlined and captures/infiltrates significant rainwater), indicate only limited and localized increases in water levels in response to rainfall, and no clear evidence of changes in groundwater capture or extraction system flow rates.

Hundred-Year Rainfall Event

The "combined" ten-year rainfall volume described above slightly exceeds the hundred-year rainfall volume that is expected in the Northwest Basin, so no additional modeling analysis was conducted for this basin. For the Central Basin, the expected hundred-year rainwater event volume captured by the basin was calculated, and the potential impacts of this water on groundwater flow were qualitatively evaluated. The calculations indicate that the basin would initially contain about 5 feet of water (approximately 10 million gallons). Figure 2-2 plots the calculated wetting front depth versus time as well as the estimated time for the retention basin to fully drain. The methods and parameters used in calculating these values are discussed in the following section. As shown, these calculations indicate that the basin would be fully drained after five days while the wetting front would not reach the water table until after day seven. The maximum initial recharge rate at the groundwater table with five feet of water remaining in the basin is approximately 0.6 ft/day (Table 2-3); therefore, the actual rate would be significantly lower than this since the basin would be drained before the wetting front reaches the groundwater table.

Based on this preliminary analysis that indicates the hundred-year event rainwater would completely drain from the basin before reaching groundwater, the impact of the hundred-year rainfall event on groundwater flow is expected to be less than the impact from the flushing scenario described above, and therefore does not present a significant concern related to groundwater capture. In December 2010, approximately five feet of rainwater that had collected in the nearby Beta Ditch drained into the subsurface within three to four days, so it appears that the modeled drainage time for the planned Central Basin is reasonable. For the Central Basin, we also note that most of the leachable chemicals should be removed from the soil under the basin before a hundred-year event occurs, so the rainfall impacting groundwater would be expected to be significantly diluted in terms of Site chemicals of concern compared with the underlying groundwater.

Methodology for Calculating Infiltration Rates, Wetting Front, and Basin Drainage Time

The details of how infiltration rates, wetting front migration, and basin drainage times were calculated for the combined ten-year rainfall event in the Northwest Basin and the hundred-year rainfall event for the Central Basin are presented in this section.

Infiltration Rate and Wetting Front

The Green-Ampt equation (1911) was used to predict the infiltrating wetting front beneath the Central and the Northwest Basins and the time at which the water in the basins would drain. The cumulative infiltration as a function of time, t, is

$$z_f = \frac{K_s t}{\Delta\theta} - (h_f - h_0) ln\left[1 - \frac{z_f}{\Delta\theta(h_f - h_0)}\right] \quad (1)$$

Where h_f is the wetting front suction head, h_0 is the inlet head, z_f is the distance to the wetting front (positive upwards), $\Delta\theta$ is the increase in moisture content in the wetted zone, and K_s is the saturated hydraulic conductivity.

The wetting front suction head was calculated using an equation derived by Kao and Hunt (1996) that is a function of the soil permeability (k), water density (ρ) and surface tension (σ), the initial water saturation (S_i), $\Delta\theta$, and a dimensionless geometric factor, B, determined by Kao and Hunt (1996) to be 0.5:

$$h_f = -\frac{\sigma B^2 \Delta\theta}{2\rho g(1-S_i)^{3/2}\sqrt{k}} \qquad (2)$$

The infiltration rate as a function of depth can be calculated by taking the derivative of Equation 1:

$$q = -K_s\left[\frac{h_f - h_0 + z_f}{z_f}\right] \qquad (3)$$

The average saturated vertical hydraulic conductivity of Qal cores from the Tronox site is 0.9 ft/d. Air entrapment likely occurs during infiltration and to account for this effect, Bouwer (1964) suggests using one half of the saturated hydraulic conductivity to calculate infiltration. Therefore, a value of 0.45 ft/d was used for K_s to calculate the wetting front below the basins.

The Qal porosity and the moisture content at the Tronox site were also measured from cores. The average porosity is 0.4 and the average moisture content from cores obtain 9 feet to 15 feet below ground surface is 0.154. A summary of the measured Qal properties and literature values for the water properties used in the calculations are summarized in Table 2-1. For the calculations, the increase in moisture content during infiltration is 0.246, the difference between the porosity and the initial moisture content. The initial saturation is 0.385, obtained by dividing the moisture content by the porosity.

The storage volume for the Central and Northwestern Basins and the corresponding basin areas were obtained from the drainage study report for the Tronox soil remediation basins (RCI Engineering, 2010). The average height of the water in the basin was calculated by dividing the storage volume by the area of the basin. This height was used as h_0 to calculate the wetting front using Equation 1 and assumed to remain constant with time. In reality, h_0 decreases with time as the water in the basin drains. Using a constant value for h_0 results in a higher infiltration rate and therefore provides a more conservative value for the infiltration rate.

Tables 2-2 and 2-3 summarize the calculated infiltration rates and times for the wetting front to reach different depths for the Northwest and Central Basins, respectively.

Basin Drainage Time

The time for water to drain from the basins was estimated by first calculating the wetting front depth at which the volume of infiltrated water equals the storage volume of the basin, $V_{storage}$. This depth is:

$$z_f = \frac{V_{storage}}{\Delta\theta A_{basin}} \quad (4)$$

where A_{basin} is the basin area. If the depth calculated using Equation 4 is less than the groundwater depth, then the time for the basin to drain is calculated by inputting the depth calculated with Equation 4 into Equation 1. If this depth is greater than the groundwater table depth, then the time for the basin to drain, t_{drain}, is calculated by

$$t_{drain} = t_{GW\ table} + \frac{V_{remain}}{q_{GW\ table} A_{basin}} \quad (5)$$

where $t_{GW\ table}$ is the time corresponding the when the wetting front reaches the groundwater table using Equation 1, $q_{GW\ table}$ is the infiltration rate calculated using Equation 3 at the depth of the groundwater table, and the V_{remain} is the volume of water in the basin remaining after the wetting front reaches the groundwater table, calculated using the following equation:

$$V_{remain} = V_{storage} - (z_{f,GW\ table} \Delta\theta\, A_{basin}) \quad (6)$$

This calculation assumes that once the wetting front reaches the groundwater table, the infiltration rate remains constant at the value calculated using Equation 3 for the depth corresponding to the groundwater table, $z_{f,GW\ table}$.

REFERENCES

Bouwer, H. 1964, Unsaturated flow in groundwater hydraulics, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, 90 HY5, 121 – 127.

Green, W.H. and G.A. Ampt, 1911. Studies on soil physics, I, The flow of air and water through soils, *J. Agric. Sci.*, 4, 1-24.

Kao, C.S. and J.R. Hunt, 1996. Prediction of wetting front movement during one-dimensional infiltration into soils, *Water Resources Res.*, 32(1), 55-64.

RCI Engineering, 2010. Technical drainage study for Tronox soil remediation treatment basins. RCI Engineering, Las Vegas, NV, October 2010.

TABLES

FIGURES

TABLE 2-1

Summary of Parameters Used in Calculations

Parameter	Value	Units
moisture content	0.154	
porosity	0.4	
$\Delta\theta$	0.246	
S_i	0.385	
K_s, measured	0.9	ft/d
K_s, used in calculations	0.45	ft/d
μ	0.001	kg/(m s)
ρ	998.2	kg/m^3
g	9.81	m/s^2
k	3.22E-13	m^2
σ	0.073	N/m
B	0.5	
h_f	0.84	m
h_f	2.76	ft
NW Basin, Combined Ten-year Storm		
Area	169581	ft^2
Storage Volume	1219680	ft^3
Basin water height, h_0	7.2	ft
Basin drainage time	8.3	days
Central Basin, Hundred-Year Storm		
Area	268163	ft^2
Storage Volume	1295474.4	ft^3
Basin water height, h_0	4.8	ft
Basin drainage time	5.4	days

TABLE 2-2

Wetting Front and Infiltration Rates for Northwest Basin

NW Basin, Combined Ted-Year Storms			
z_f (ft)	q (ft/d)	t (d)	
0	0	0	
1	-4.93	0.03	
2	-2.69	0.10	
3	-1.94	0.21	
4	-1.57	0.35	
5	-1.35	0.52	
10	-0.90	1.68	
15	-0.75	3.20	
20	-0.67	4.94	GW Table

TABLE 2-3

Wetting Front and Infiltration rates for Central Basin

Central Basin, Hundred-Year Storm			
z_f (ft)	q (ft/d)	t (d)	
0	0	0	
1	-3.87	0.03	
2	-2.16	0.12	
3	-1.59	0.26	
4	-1.30	0.43	
5	-1.13	0.63	
10	-0.79	1.98	
15	-0.68	3.67	
20	-0.62	5.58	
24	-0.59	7.20	GW Table

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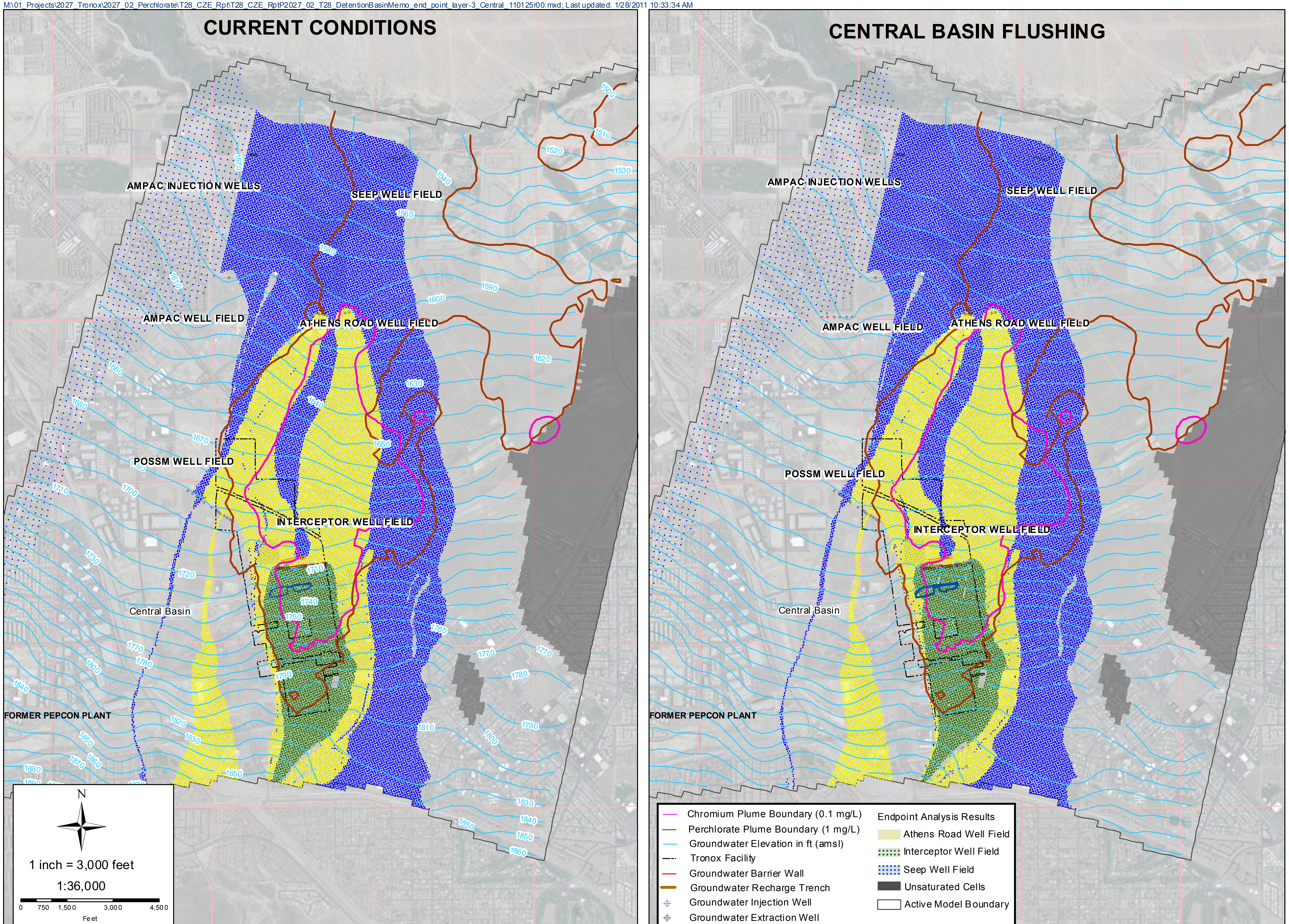

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TRONOX

NO:	DESCRIPTION:	DATE:	BY:

REVISIONS:

DESIGNED BY: | DRAWN BY: | CHECKED BY: | APPROVED BY:

SIMULATED GROUNDWATER FLOW FOR CENTRAL BASIN FLUSHING SCENARIO

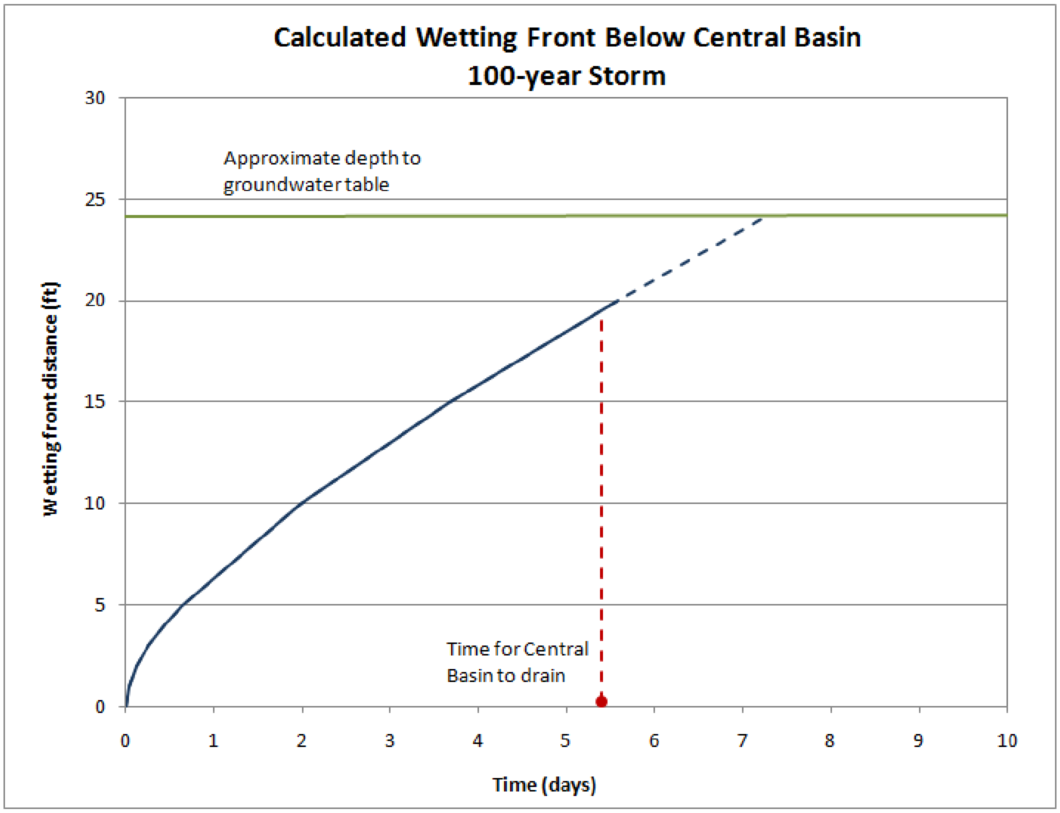
Retention Basin Memo
Tronox LLC
Henderson, Nevada

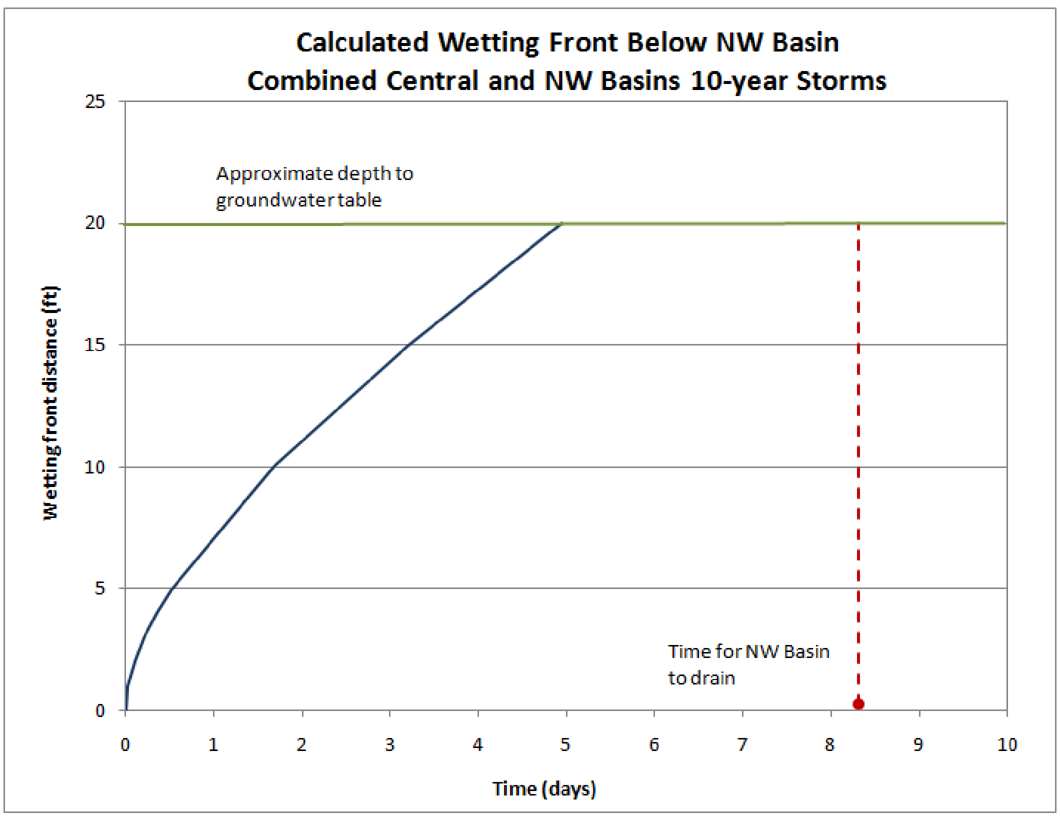
SCALE:
DATE: 12/10/10
PROJECT NUMBER: 2027.02 T28

FIGURE NUMBER:
2-1

SHEET NUMBER:
1

FIGURE 2-2
Wetting Front Graphs for Two Selected Rainfall Events





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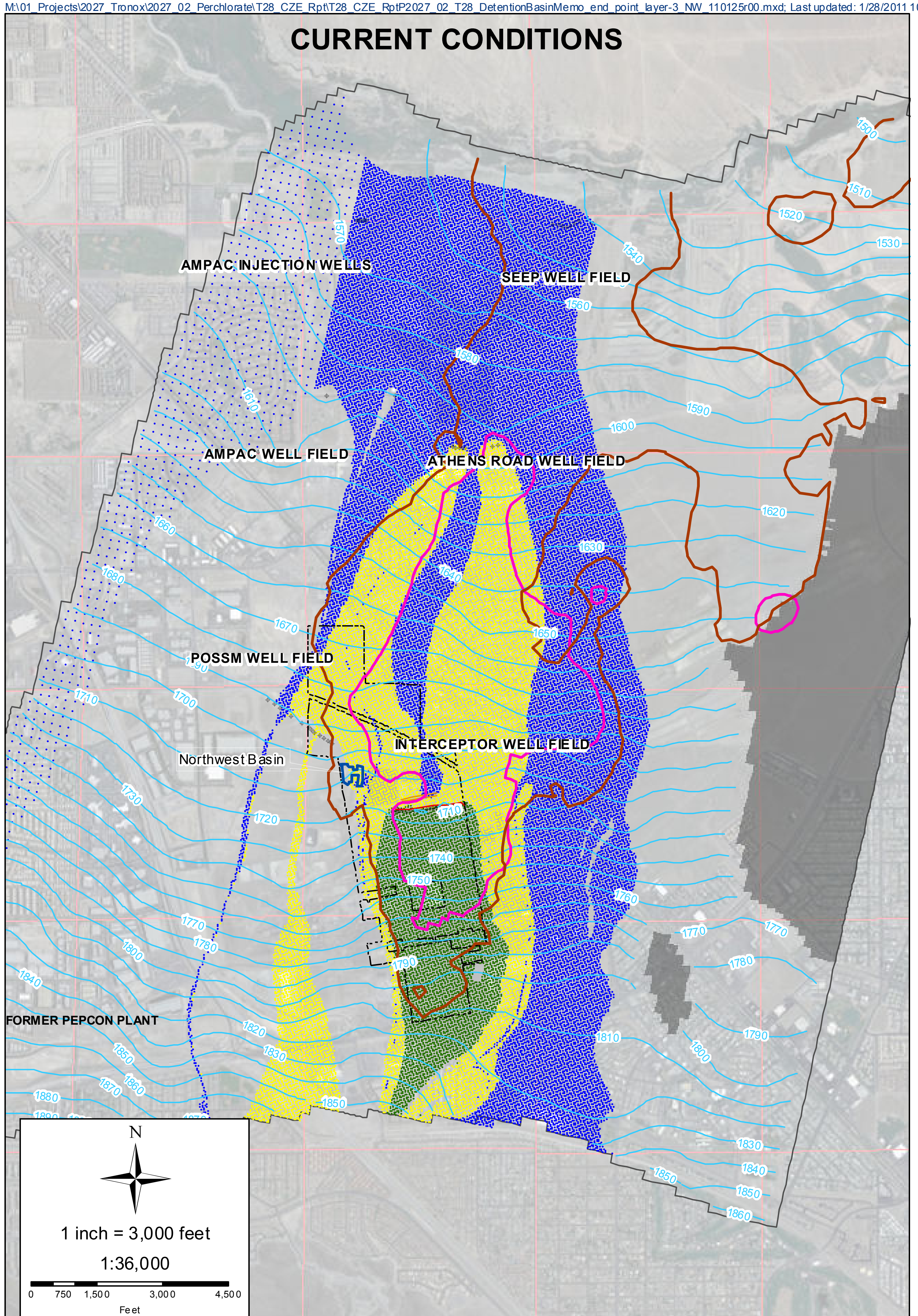

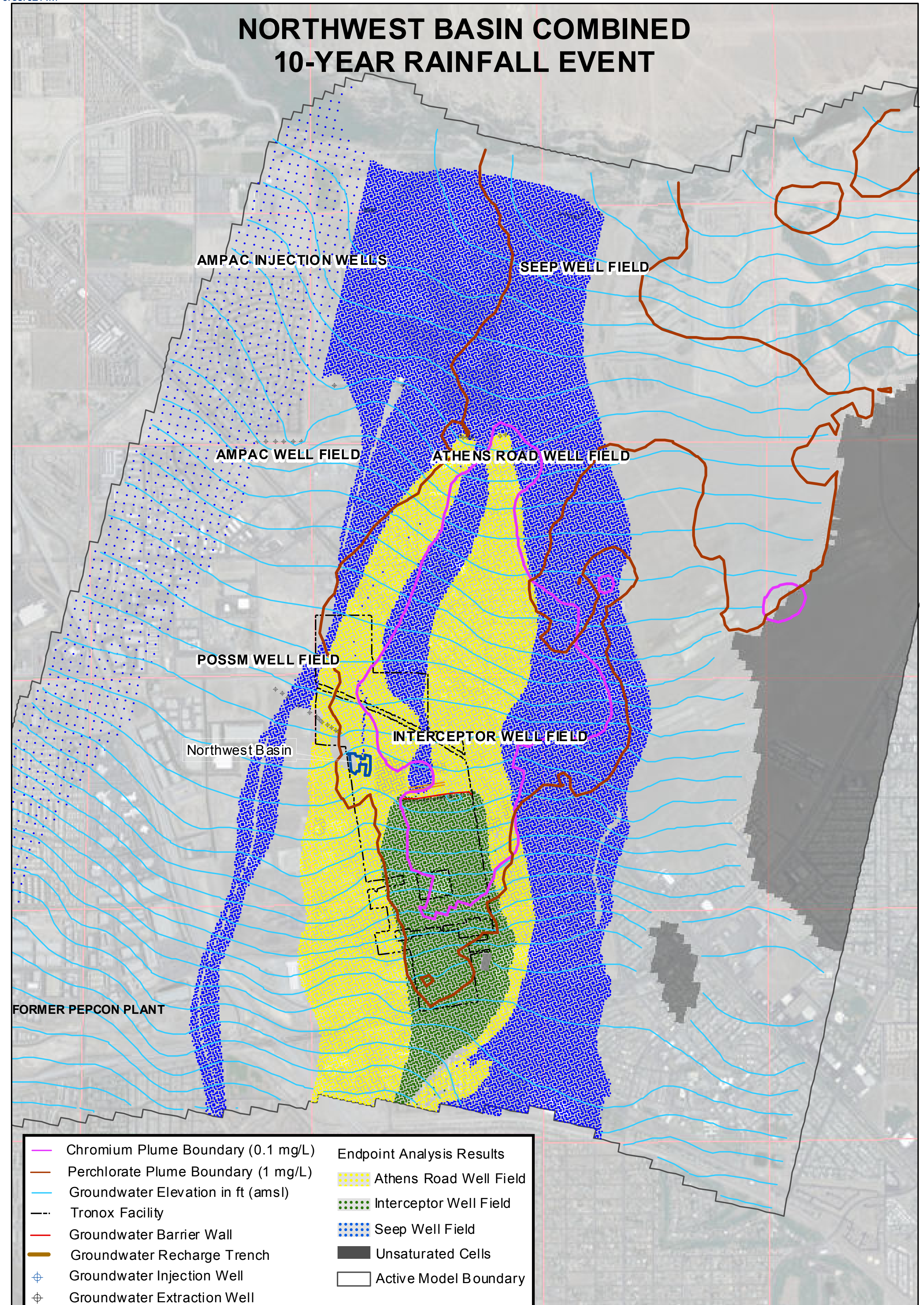

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CHECKED BY:
APPROVED BY:

SIMULATED GROUNDWATER FLOW FOR NORTHWEST BASIN COMBINED 10-YEAR RAINFALL EVENT SCENARIO

Retention Basin Memo
Tronox LLC
Henderson, Nevada

SCALE:	DATE:	PROJECT NUMBER:
1:36,000	12/10/10	2027.02 T28

FIGURE NUMBER:
2-3
SHEET NUMBER:
1