From: Deni Chambers, Northgate
Pascual Benito, Northgate

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To: Shannon Harbour, NDEP

RE: Technical Memorandum: Hydrogeologic Groundwater Model Inputs, Tronox Facility, Henderson, Nevada

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1.0 INTRODUCTION

Northgate Environmental Management, Inc. (Northgate) has prepared this summary of the hydrogeologic flow model inputs on behalf of Tronox LLC for the Tronox facility located in Henderson, Nevada (the Site; Figure 1). This document provides an update on the development of a three-dimensional, hydrogeological numerical model for the Site and surrounding areas (Figure 2), which is referred to in this document as the “Tronox groundwater flow model” or “Tronox model.” The model development effort follows the *Revised Hydrogeologic Modeling Work Plan* submitted by Tronox in June (Northgate, 2010c) and approved by the Nevada Department of Environmental Management (NDEP) in July 2010. As presented in the *Capture Zone Evaluation Work Plan* (Northgate, 2010b), this model will be a key tool for completing the revised capture zone evaluation being conducted for the Site in accordance with United States Environmental Protection Agency (USEPA) guidance (USEPA, 2008).

This model update is being provided to NDEP in the interest of getting feedback on assumptions, parameter definition, and methods prior to final development, calibration and predictive use of the model for the capture zone evaluation (CZE). The current schedule calls for submittal of the CZE report (of which the modeling report will be an appendix) in early December. To the extent possible, Tronox will incorporate any changes discussed and agreed upon with NDEP in the model prior to completing the CZE report.

The following information is provided in this model update, as described in more detail below:

- Table 1 which lists model input parameters and data sources,
- Figures 1 and 2 showing the site location and the general model domain,
- Figures 3 and 4 showing the interpolated contour map of Qal-UMCf contact, and the locations of paleo-channels,

- Figures 5 and 6 showing the developed three-dimensional lithologic layer model and fence diagrams,
- Figures 7-9 showing different views of the numerical model grid layers, and
- Figures 10-13 which show maps of model input parameters zones and boundary conditions.

2.0 NUMERICAL FLOW MODEL DEVELOPMENT

Numerical flow model development includes selecting the model domain extent; creating the model grid and designating the active grid cells; assigning appropriate boundary conditions along the top, bottom, and lateral faces of the model domain; assigning aquifer hydraulic parameters (e.g., hydraulic conductivity, porosity, storage coefficients) to adequately represent the known distribution of lithologic units at the Site; and assigning internal sinks and sources to account for infiltration, evapotranspiration, and pumping wells. The MODFLOW numerical flow model is being developed using Groundwater Vistas Version 5. The three-dimensional geology model and the finite-difference numerical grid layers were developed using GMS 6.0 (Groundwater Modeling System).

2.1 Model Domain Extent

The extent of the model domain is shown in Figure 2. The active area of the model domain is wedge-shaped, narrowing from south to north toward the Las Vegas Wash. From south to north, the model domain extends from south of Lake Mead Parkway to the Las Vegas Wash, approximately 20,000 feet (about 4 miles) in total length. Laterally (perpendicular to the regional groundwater flow direction), the model extends east and west of the Tronox Site to include the existing groundwater capture systems at the BMI and POSSM properties to the west and the proposed groundwater barrier trench and capture wells at the TIMET site to the east, in addition to the AMPAC extraction/injection and treatment systems to the northwest of the Tronox site. The extent of the model domain is sufficient to reflect the hydraulic features which may impact the evaluation of groundwater capture zones and future plume evolution, and to avoid having the lateral boundaries of the active domain intersect active sources and sinks. As described in Section 2.4.1 below, this regional domain is being modeled using a relatively coarse grid size with the objective of describing the overall groundwater flow domain. Much smaller "sub-domain" models in the vicinity of the Tronox well fields are being developed at a greater level of detail and spatial discretization for the purpose of capture zone evaluation.

In the vertical direction, the model domain extends into the Deep Water Bearing Zone, as defined by NDEP (2009). The bottom depths were determined in the early stages of model development based on evaluation of the distribution of depths of monitoring well screen intervals, and of the depths of observed perchlorate concentrations.

In general, the orientation of the model layers follows the dip angle of alluvial fan sediments and the general Site topography. The model grid axes are aligned as best as possible with the general geologic and geomorphic structures of the valley to allow modeling of the hydraulic conductivity as diagonal tensors.

2.2 Qal-UMCf Lithologic Contact Surface

A regional scale contour map of the elevation of the Qal-UMCf contact was developed based on interpolation of contact elevations from almost twelve-hundred groundwater wells and soil borings (see Figure 3). The two main sources of data for the elevation of the Qal-UMCf contact elevation were the "All_Wells" spreadsheet of well construction and lithology data that is maintained jointly by all The Companies, and the soil boring logs from the Tronox Phase A and B soil sampling events. Additional data were drawn from the 2003 hydrogeological database developed for the combined sites by the Desert Research Institute (DRI, 2003), soil boring logs from the 2008 BRC Deep Background Soil report (BRC, 2009), data from Plate 1 of the BRC Eastside Hydrogeologic Connectivity evaluation report (DBSA 2010a), as well as additional and or/updated data for BRC wells contained in Table 4 of the BMI Common Areas, 2009 Groundwater Monitoring Report (BRC, 2010b).

As part of a quality assurance (QA) screening process, the recorded ground surface elevations of the wells were compared with ground surface elevations interpolated from the digital elevation model. If the differences between the recorded and interpolated ground elevation were greater than 15 feet then these well records were reviewed in greater detail to determine if errors existed in the recorded elevations and the resulting elevations of UMCf contact. For the small subset of wells for which surveyed ground surface elevations were missing, but a recorded depth to UMCf contact existed, the digitial elevation model was used to generate an interpolated ground surface elevation, allowing for the calculation of the elevation of the UMCf contact.

As an additional QA check to flag wells with possible elevation errors, the recorded top-of-casing elevations were compared with the recorded or interpolated ground-surface elevations. This difference is equivalent to the well riser-height, which is generally between two to five feet. In instances in which the recorded top-of-casing elevations differed by more than 15 feet from the recorded or interpolated ground surface elevation, then the well construction logs were also reviewed to check for possible errors missed in the other screening. Depths to the UMCf contact were also compared with total hole depths to identify inconsistencies, such as a reported depth to the UMCf contact greater than the total hole depth. In these cases, the well logs were reviewed to identify corrected depths.

The method of ordinary kriging was then used to generate an initial interpolated grid (100x100ft grid cell size) of the UMCf/Qal contact. Elevation contours of this initial map were then used to identify UMCf contact elevation data points that appeared anomalously high to low compared to other surrounding data points. In these cases, the well lithology and construction logs were reviewed to identify and fix any possible errors in the data set.

A new interpolated contour map was then generated based on the corrected and reduced dataset using the ArcGIS Geostatistical Toolbox, also using a 100x100 feet cell size grid for interpolation. The method of ordinary kriging was used with a spatial correlation model that accounts for north-south trending anisotropy introduced by the paleo-channel network. The Qal-UMCf contact slopes northward towards the Wash, and both the ground surface topography and the regional potentiometric surface mirror this slope. The method of kriging assumes statistical stationarity (*i.e.*, that the mean of the data set is the same everywhere), and the presence of this regional slope in elevation violates this assumption. For this reason a de-trending option was used to remove the regional slope of the contact elevation surface prior to generating the spatial correlation model used for kriging. The generated contour map of the elevation of the UMCf contact is shown in Figure 3.

This new regional contour map was compared to an earlier contour map interpretation generated previously by Kerr-McGee (Plate 3; Kerr-McGeee,1998). While the earlier map did not cover the entire model domain and was based on an older, more limited dataset, the two interpretations are in relatively good agreement.

The interpolated contour map was also compared with the recent contour map interpretation by BRC (Plate 1; DBSA 2010a). While many of the major topographic features are consistent between the two interpretations, there are also differences that appear to be due to the use of slightly different data sets and to differences in the methods of interpolation used to generate the contours.

The differences in the interpreted contours of the contact have an impact on the interpretations of paleo-channel locations as compared to the channel locations identified in the two previous studies. This is shown in Figure 4, which will be discussed in more detail in the following Section 2.3.

2.3 Definition of Paleo-Channel Drainage Network

The paleo-channels are understood to represent a paleo-alluvial drainage network incised into the top of the UMCf. The paleo-drainage network was identified by analysis and interpretation of the topography of the Qal-UMCf contact surface. This analysis included the synthesis of multiple lines of evidence for determining the location of channels.

The lines of evidence used to delineate channel locations included the use of a GIS based watershed drainage-network delineation algorithm, previous interpretations of the locations of paleo-channels conducted by Tronox and the other Companies, consistency with hydrogeologic interpretation of the regional potentiometric surface for the Shallow Water Bearing Zone, consistency with the observed spatial distribution of perchlorate movement in the alluvial sediments, consultation with geophysical survey section reconstructions, as well as professional judgment.

As a starting point, the interpolated Qal-UMCf contact surface was converted into a digital elevation model and then the automated hydrology drainage-network delineation algorithm of the ArcGIS Spatial Analyst Toolbox was used to extract the drainage network of this “paleo-basin” (see Figure 4). It is recognized that automated network delineation tools based on interpolated surfaces have their own limitations. For this reason the algorithm derived channel network map was used as a starting point on which to overlay the other lines of evidence. The auto-delineated network channels were compared with earlier interpretations of the paleo-channel networks by other investigators (Plate 3 of Kerr-McGee, 1998; Plate 1 of DBSA 2010a). Comparison with previous interpretations of channel locations is also shown in Figure 4. Greater weight was placed on channel locations that were consistent with evidence of channelized flow visible in contoured potentiometric maps for the Shallow Water Bearing zone, and with the known spatial distribution of the perchlorate plume.

2.4 Domain Discretization

2.4.1 Horizontal Discretization

For the large-scale regional model meant to establish appropriate boundary conditions and flow parameters at the regional scale, a uniform horizontal grid cell size of 200 by 200 feet is being used, as shown in map view in Figure 2, and in three-dimensional view in Figure 7. This horizontal grid dimension is thought to be sufficiently small to represent spatial heterogeneity in aquifer hydraulic properties at the smallest scale over which differences in parameters can likely be defined with existing data. The smallest scale of heterogeneity that can likely be well-characterized within the model domain would be some fraction of the width of buried alluvial paleo-channels incised into the UMCf. This horizontal grid cell size is also consistent with the grid cell size used in the current calibrated BMI Common Areas groundwater model (DBSA 2008). Once the Site-wide regional model is fully calibrated, Groundwater Vista's Telescopic Mesh Refinement (TMR) will be used to run sub-models with finer discretization for focused areas of interest. The boundary conditions of the sub-models will be consistent with the Site-wide model. For steady state models, the TMR feature of the Groundwater Vista software allows both specified head, specified flux, or head dependent boundary conditions. At this stage Tronox plans to use specified head boundary conditions unless conditions are faced in actual development that warrant other forms of boundary conditions. It is noted that the TMR method supports only the use of specified head boundary conditions when used with transient models. Tronox is currently in the process of developing two sub-models (one each for IWF, and AWF, with possibility of a third for the SWF). The sub-domain models are currently being developed with grid cell size of 20 by 20 feet, an order of magnitude smaller than the regional model.

2.4.2 Vertical Discretization

The regional Site-wide model has been discretized vertically into six layers (see Figures 7 though 9). First a three-dimensional (3D) lithologic model of the site was developed based on the land surface topography and the interpolated Qal-UMCf contact (see Figures 5 and 6). The elevations for the tops of cells in the upper layer of the model grid were assigned based on the land surface elevations. The elevations for the cell elevation for the top of Layer 1 of the model were derived from a digital elevation model generated from the 5-foot contour interval topographic map data available from the Clark County GIS web-site.

The bottom elevation of the model grid is set at a surface 385 feet below the Qal-UMCf contact, maintaining the general regional slope of the contact surface.

Lithologic data sets from across the Tronox Site and neighboring sites were combined and used in constructing a map of the Qal-UMCf contact across the entire model domain, as described above in Section 2.2.

The 3D lithologic model was then mapped to the grid to define the layer elevations (Figures 7 and 8). One of the main goals of the flow model is to accurately model the potentiometric surface in the shallow Qal and near the Qal-UMCf contact. For this reason the model has a finer vertical discretization in the Qal and in the top most UMCf layer along the Qal-UMCf contact. The Qal has been divided into two layers, with the combined thickness of these layers ranging from 10 to 50 feet depending on the thickness of the alluvium (see Figures 7 though 9).

Another important goal is to adequately represent the upward vertical flow gradients that bring water from the UMCf into the Qal. For this reason, the UMCf has been divided into 4 layers. The top most UMCf layer (model Layer 3) was assigned a thickness closer to that of each of the two Qal layers (Layers 1 and 2). Generally speaking the layer thickness and layer depths were also chosen in order to represent the screened intervals of pumping wells as best as possible to provide sufficient vertical resolution for representing the vertical gradients in hydraulic head, and to allow for sufficient vertical and horizontal coverage of hydraulic head calibration points (i.e., monitoring well screened intervals) in each layer.

2.4.3 Temporal Discretization

Site-wide hydrographs and pumping data were examined over a period between 2006 through 2009 to determine whether a steady-state period for the model could be identified. We assumed that a difference in groundwater levels of less than 2 feet over a time period could be considered steady-state. Using this criterion, the period between August 2008 and March 2009 was selected as being representative of steady-state conditions.

Once the steady state flow model is fully calibrated, additional transient calibrations will be performed using data from pump tests if suitable data exist for the modeled period. Temporal discretization will be chosen to adequately simulate the transient tests.

2.5 Aquifer Hydraulic Parameters

Estimates for the hydraulic properties assigned to the model are based on field measurements (slug and pumping tests) of hydraulic parameters for locations within the model domain. Table 1a summarizes the values of hydraulic conductivities obtained from field data for the alluvium, Muddy Creek formation, paleo-channels, and the Las Vegas Wash alluvial deposits. The range of hydraulic conductivities for the alluvium and Muddy Creek formation was bounded using the harmonic and the arithmetic means of the data.

The hydraulic conductivities of Layers 1 and 2 of the model, representing the alluvium, are divided into 5 zones (Figure 10). Two zones represent the hydraulic conductivities of the alluvium, one on the west side and the other on the east side of the model. Two additional zones represent the paleo-channels on the east and west sides of the model domain. The locations of the paleo-channels were defined using the paleo-channel map developed as described in Section 2.3 (see Figure 3). The division of the zones into the east and west sides was based on the aquifer test data and on a previous groundwater model of the BMI site (DBSA, 2008). A fifth zone represents the alluvial deposits near the Las Vegas Wash. A single hydraulic conductivity zone is used for the Muddy Creek formation (Layers 4 through 6).

2.6 Boundary Conditions

Accurate modeling of the hydraulic head distribution and flow paths depends on appropriate definitions of boundary conditions, sources and sinks. The boundary conditions and sources/sinks fundamentally provide the driving forces for flow within the model and control the mass flux of water entering and leaving the model domain.

2.6.1 Top Boundary Conditions

2.6.1.1 Recharge

The water table is modeled as a flux boundary, based on the spatial distribution of recharge from precipitation, ponds, irrigation, and leaking utilities. Recharge is modeled using the MODFLOW Recharge package (Harbaugh et al., 2000). Different recharge zones were defined on the basis of land use as shown in Figure 11 and the values of recharge used in the model are summarized in Table 1b. Estimates of recharge rates for the developed areas (residential and industrial) and the Tuscany Golf Course are obtained from Basic Remediation Company's (BRC's) calibrated flow model for the BMI Lower and Upper Ponds Area (DBS&A, 2006; DBS&A, 2008). Infiltration rates for these areas will be adjusted as part of the model calibration process. The recharge rate for undeveloped areas is based on a USGS study (USGS, 2007) and remains fixed. Recharge rates for the Birding Preserve and Northern RIBs were obtained from the City of Henderson. The TIMET ponds are no longer active during the steady-state period chosen for calibration. The Tronox ponds are plastic lined ponds and the seepage rate used is comparable to the leakage rate for a HDPE geomembrane (Peggs, 2009). Groundwater recharge from AMPAC re-injection systems and the Tronox recharge trenches were modeled as internal sources as described later in Section 2.7.

2.6.1.2 Evapotranspiration

Evapotranspiration (ET) is simulated using the MODFLOW Evapotranspiration Package (Harbaugh et al., 2000). Estimates of ET_0 (0.011 ft/day) and the extinction depth (5 feet) are based on values from the calibrated BMI Upper and Lower Pond Area model (DBS&A, 2008). Locations where ET is simulated are based on a GIS map of the phreatophytes along the Las Vegas Wash that was obtained from Southern Nevada Water Authority (Figure 1c). Phreatophytes that were on the BMI site were removed at the end of 2007. Since our calibration period occurs after they were removed, ET in those areas is not included in our model.

2.6.2 Bottom Boundary Condition

The bottom boundary of the model represents the vertical inflow or outflow of water into or out of the deeper water bearing zone. Vertical flow for the different regions of the model domain was assessed by evaluating reports of neighboring sites and the vertical gradient data from the Tronox area. Flow from the bottom boundary is vertically upwards throughout most of the model domain except for the Northeast region where downward vertical gradients were observed. Based on the variability in vertical gradients measured in the deeper zone, the bottom boundary was divided into 7 reaches, or zones (Figure 13). A summary of these gradients for these different reaches is included in Table 1d. The General Head Boundary (GHB) was used along the bottom boundary to represent the vertical flow into and out of that boundary. Hydraulic conductances corresponding to each zone were calculated using the gradients and the estimated range of vertical hydraulic conductivities for the UMCf.

2.6.3 Lateral Boundary Conditions

2.6.3.1 Eastern and Western Edges

The eastern and western edges of active model domain have been chosen to coincide as closely as possible with observed streamlines. This allows the lateral boundaries to be treated as no-flow boundaries.

2.6.3.2 Mountain Block Recharge (Southern Edge)

Mountain block recharge to the basin sediments along the base of the McCullough Range, at the southern boundary of the model, will be treated as a specified flux boundary condition. Estimates of this mountain block recharge flux were based on estimates calculated using a water budget approach (see Table 1e). The MODFLOW Well package was used to simulate the flux across the southern boundary based on these recharge estimates.

2.6.3.3 Las Vegas Wash (Northern Edge)

The water surface elevation of the Las Vegas Wash was represented as constant head boundaries at the northern edge of the model. Information on the water surface elevation in the Wash was obtained from the Clark County Regional Flood District and the Southern Nevada Water Authority (see Table 1f). Linear interpolation between these data was used to assign constant head values to all the cells along the northern edge of the model.

2.7 Internal Sources and Sinks

2.7.1 Groundwater Pumping Wells

Pumping wells (including both extraction and injection wells) are being modeled using the MODFLOW Well Package (Harbaugh et al., 2000) based on pumping records available from Tronox, AMPAC, and POSSM. Table 1g gives a summary of the combined extraction/injection rates for each well field included in the model. Information on the top and bottom of the screened intervals of pumping wells was obtained from the "All_Wells" spreadsheet maintained by the Companies.

2.7.2 Groundwater Infiltration trenches

The Tronox groundwater infiltration trenches are simulated using the MODFLOW Recharge package. Average recharge rates (Table 1h) are based on the records for recharge pump flow rates during the identified steady-state period.

2.8 Tronox Groundwater Barrier Wall

The Tronox groundwater barrier wall in the IWF is being simulated with the MODFLOW Horizontal Flow Barrier (HFB) package (Harbaugh et al., 2000) applied to Layers 1-3, with an assigned hydraulic conductivity of 1×10^{-6} cm/sec based on recent laboratory analysis of wall material.

2.9 Initial Conditions

A steady state model has been developed for the objectives stated in the Work Plan (Northgate, 2010c).

2.10 Model Calibration

The purpose of the calibration process is to ensure that all hydrologic input parameters are made to best describe the target (observed) hydraulic heads and/or fluxes in the model domain within an acceptable degree of accuracy. Model calibration is currently in process using several hundred target calibration heads, based on a selection of observation well data distributed across the model domain and with screened intervals representative of all model layers. Hydraulic head observation points were chosen from a regional groundwater data set of the Shallow, Middle, and Deep Water Bearing Zones compiled from water level data available from the Tronox Site and the neighboring sites. An extensive QA/QC screening process was used to identify potential errors in recorded well coordinates and well construction data prior to assembling the final water elevation data set.

Calibration metrics from the preliminary calibration runs, including average error, average absolute error, root mean square error (RMSE), and one-to-one plots of predicted versus observed hydraulic heads indicate good agreement between the predicted and observed hydraulic heads. Preliminary calibration runs also indicate a good match between the spatial distribution of dry model cells in Layers 1-2 and maps of unsaturated alluvium regions for the modeled steady-state period.

2.11 Sensitivity Analysis

A sensitivity analysis is being conducted to identify which model input parameters (including aquifer hydraulic properties, boundary conditions, etc.) have the greatest effect on the predicted hydraulic heads and on any of the conclusions derived from the model. Sensitivities of the parameters are calculated during the auto-calibration runs and are currently being evaluated.

3.0 PREDICTIVE SIMULATIONS

3.1 Capture Zone Evaluation with Current Conditions

After the model has been calibrated and parameter sensitivity assessed, the model will be used to delineate capture zones for the IWF, AWF, and SWF under the latest operational conditions. This will be accomplished through particle tracking analysis using MODPATH and following USEPA guidance (USEPA, 2008). Particle tracking analysis will also be used to evaluate the pathway and timing for perchlorate migration from various locations and depths in the UMCf upward into the Qal.

3.2 Optimization of Groundwater Systems to Achieve Target Capture or Improve Efficiency

The results of the simulation described in Section 3.1 above will be presented to NDEP. Target capture zones for the Site well fields are in the process of being established with NDEP, and if the model simulations indicate that the agreed-upon target zones are not being met under current conditions, physical modifications will be simulated in the Tronox model to improve the efficiency with which the target capture is achieved.

4.0 DOCUMENTATION

All the modeling tasks presented above will be documented in a complete modeling summary and calibration report, submitted as an appendix to the full Capture Zone Evaluation Report. The report and electronic model input and output files will be provided to NDEP in draft form for review and comment prior to completion of the final report. The modeling documentation and report will be prepared in accordance with the ASTM Standard Guide D-5718. This modeling report will be an appendix to the capture zone evaluation report as described in *Capture Zone Evaluation Work Plan* (Northgate, 2010b).

5.0 SCHEDULE

As presented in the *Capture Zone Evaluation Work Plan* (Northgate, 2010a), the draft capture zone evaluation report is currently scheduled for submittal to NDEP in early December 2010, and the modeling report will be included as an appendix to that submittal.

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ATTACHMENTS

TABLE

1 Inputs for Regional Groundwater Model
   - a. Hydraulic Conductivities
   - b. Recharge
   - c. Evapotranspiration
   - d. Vertical Flow from Deep UMCf
   - e. Southern Boundary Condition
   - f. Northern Boundary Condition
   - g. Injection/Extraction Wells
   - h. Recharge Trench

FIGURES

1 Location Map
2 Numerical Model Domain
3 Contour Map of Qal-UMCf Contact Elevation and Paleo-Channels
4 Previous Paleo-Channel Network Interpretations
5 3-D Lithological Layer Block Model