MODELING OF GROUNDWATER INFLOW TO A LARGE OPEN-PIT IN LOW-PERMEABILITY MOUNTAINOUS TERRAIN[1]

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Abstract. A regional-scale three-dimensional model was developed using MODFLOW-SURFACT to delineate the capture zone and groundwater flow regime associated with a large open pit mine situated in low-permeability mountainous terrain. In low-permeability mountainous settings, local-scale flow systems often develop between elevated terrain and local drainages. Accurate representation of these flow systems through robust handling of recharge and seepage across the land surface interface proved critical in representing the true three-dimensional nature of the pit capture zone. The approach further allowed for more accurate representation of recharge, discharge, and the directions of groundwater flow associated with stockpiles near the pit. Modeling results indicate that the pre-stockpile surface topography largely controls the direction of flow of recharged groundwater near the pit and the nature and extent of the pit capture zone. The pit capture zone is herein defined as the surface area over which particles released at the water table report to the pit. The modeling results further indicate that deeper groundwater from a larger area also discharges into the pit. With greater depth, the influence of the local surface topography dissipates, and the influence of the hydraulic sink associated with the pit increases, resulting in a transition of groundwater flow controlled by local surface topography to groundwater flow controlled by the pit.

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Introduction

A three-dimensional groundwater flow model was developed to evaluate the groundwater flow system near the Santa Rita Pit, an open pit copper mine in southwestern New Mexico owned and operated by Chino Mines Company, a subsidiary of Phelps Dodge Corporation. The objectives included defining the nature and extent of the pit capture zone and the nature and directions of groundwater flow near mine facilities adjacent to the pit. The work was required to support closure planning and reclamation activities.

The Study Area (Fig. 1) is located in a transitional zone between the Colorado Plateau geographic province to the northeast and the Mexican Highland section of the Basin and Range Province to the southwest (Trauger, 1972). The mine is located within the northwest-southeast-trending Pinos Altos Range and Cobre Mountains. These mountains are roughly 21 km (13 miles) wide near the pit and are typified by locally steep relief with elevations of up to 2,600 meters above mean sea level (m amsl) (8,500 ft amsl). Ground elevations range from 2,000 to 2,400 m amsl (6,600 to 7,700 ft amsl) in the immediate vicinity of the pit. Hillslopes are steep north of the pit, ranging from 5 to 50 percent. The Cobre Mountains south of the pit are characterized by relatively rugged terrain, with local relief ranging from 3 to 5 percent on the ridge tops to 65 percent on hillsides.

Mining activity has greatly altered the surface topography of the immediate pit area termed the North Mine Area (NMA) (Fig. 2). The Santa Rita Pit is located at the historical headwaters of Whitewater and Santa Rita Creeks. Currently, the pit is approximately 3.2 km (2 miles) in diameter, and extends to a depth of over 450 m (1,500 ft) below the original land surface. Large leach and waste rock stockpiles composed of mined material cover the pre-mine topography around the perimeter of the pit (Fig. 2). Leach stockpiles are irrigated with acidic water on the surface to recover copper in solution at the down-stream toe of the stockpiles. In the case of the Main and South Lampbright Stockpiles, as much as 1,000 L/s (16,000 gpm) of leach solutions are recovered and processed at Chino's Solution Extraction – Electrowinning Plant to produce copper cathode.

Climate

The climate is semi-arid, exhibiting a wide range of daily and annual temperatures, and relatively low humidity (Parham et al., 1983). Over half of the annual precipitation of 44 cm (17.2 in) occurs during the summer in the form of short-duration and frequently intense thunderstorms. The average annual temperature is 12°C (54°F), and the maximum summer temperature may exceed 38°C (100°F). Available pan evaporation data indicate an annual average pan evaporation of approximately 191 cm (75 in). This equates to an annual open water evaporation rate of 135 cm (53 in) assuming a standard correction factor of 0.7.

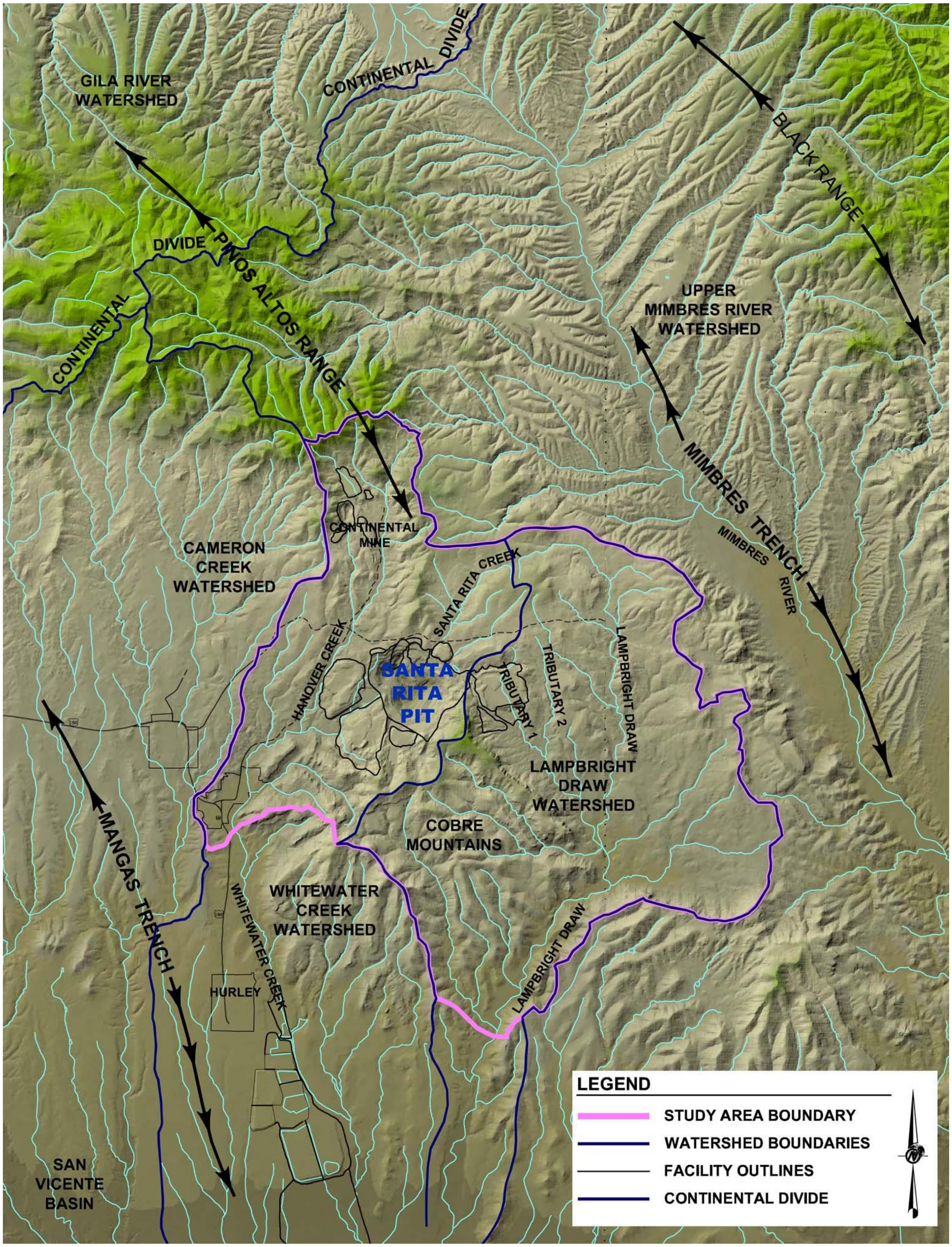

Figure 1. Chino Mine Study Area and regional setting.

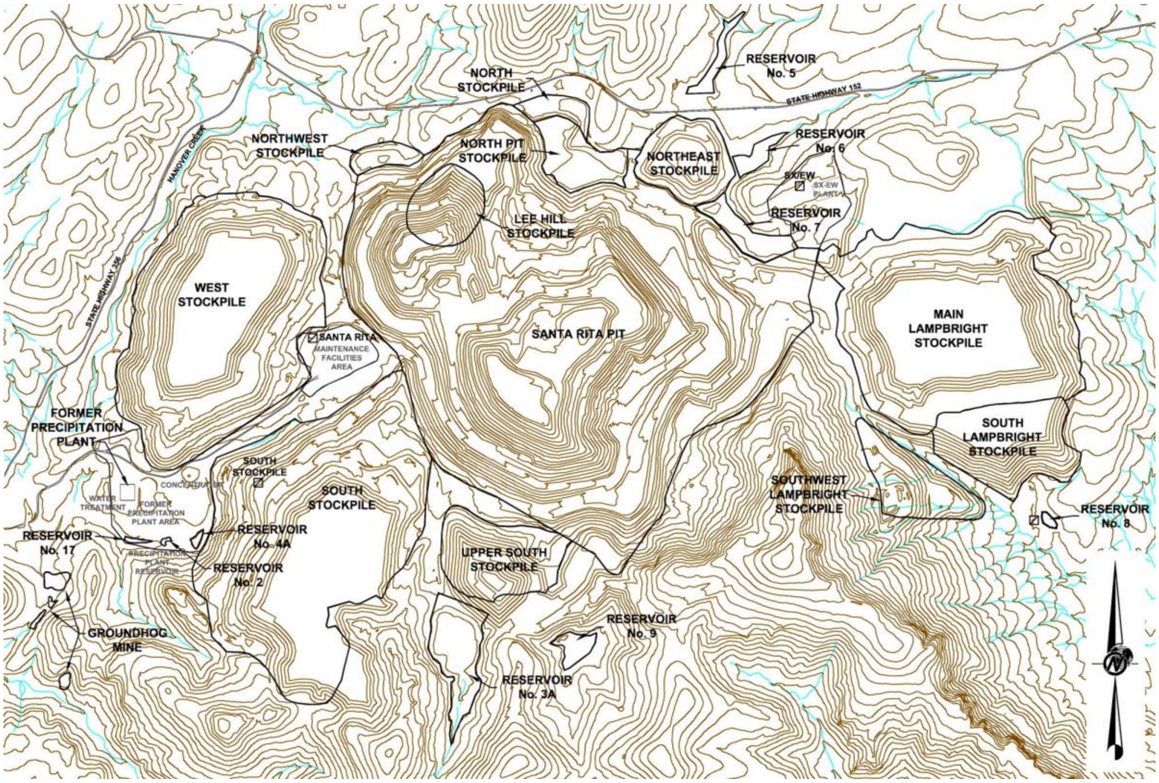

Figure 2. Chino Mine facilities map- North Mine Area.

Surface Hydrology

The Continental Divide is located 16 km (10 miles) north-northwest of the Santa Rita Pit. The Gila River and its tributaries drain the north side of the Continental Divide, and the Mimbres River and its tributaries drain the south side. The southwestern flank of the Pinos Altos Range and Cobre Maintains is drained by tributaries of the San Vicente Arroyo, which discharges into the Mimbres River several kilometers to the south of the Study Area. The northeastern flank is drained by the upper Mimbres River. The Study Area occurs entirely within the San Vicente drainage basin and is comprised of the upper drainage areas of Whitewater Creek and Lampbright Draw (Fig. 1).

Whitewater Creek drains a catchment area of approximately 148 km^2 (57 mi^2) and ranges in elevation from 1,600 to 2,300 m amsl (5,300 to 7,600 ft amsl). Major tributaries include Hanover Creek, which flanks the west side of the mine, and Santa Rita Creek, which occurs to the northeast of the pit. Intermittent flow is the major characteristic of Whitewater Creek and its associated tributaries. Flow is usually generated by runoff from short-duration thunderstorms during the summer. Storm response is rapid, and runoff may occur for only a few hours or days following a storm. Historical observations of limited periodic baseflow and the presence of seeps, wet soils, and evaporites along Hanover Creek near the mine indicate gaining conditions, although open water flow is rare (Golder, 1997).

Lampbright Draw, which drains the eastern portion of the Study Area, is dry throughout most of the year, flowing only during storm events. Tributary drainages referred to as Tributaries 1 and 2 occur within the immediate mine area (Fig. 1). The Lampbright Stockpiles occupy the headwaters of Tributary 1. Numerous seeps and springs have been observed along Tributaries 1 and 2 indicating gaining conditions.

Geology

Intrusive and extrusive igneous rocks, marine sediments, and continental deposits ranging in age from Precambrian to Holocene are present within the Study Area (Trauger, 1972). Precambrian granitic rocks are northwest of the pit. Marine sediments of Paleozoic (primarily limestone and dolomite) are exposed over a large area to the northeast of the pit along the crest of the Pinos Altos Range, extending to the southeast throughout much of the Lampbright drainage area. The Upper Cretaceous sedimentary rocks (sandstone, siltstone, shale, and minor shaley limestone) are exposed in the pit area. The Upper Cretaceous and Paleozoic rocks of the Study Area have been cut by numerous dikes, sills, and stocks of Upper Cretaceous/Lower Tertiary age. Post-mineralization, mid-Tertiary volcanic rocks overlie the southern and southeastern portions of the Study Area and probably initially covered the entire Study Area (Jones et al., 1967). Localized, thin alluvial deposits exist along the major drainages of the Study Area.

The major structural features of the Study Area are primarily related to the Late Cretaceous and Miocene intrusive activity. The major structural trend of the faults and dikes in the area is approximately north-northeast, which corresponds to the up-dip direction of the sedimentary units. Minor faults and dikes trend toward the northwest and east. The north-northeast-trending faults are generally high-angle normal faults dipping steeply eastward to nearly vertical.

Hydrogeology

Hydrostratigraphy

Despite the diverse geology of the Study Area, a detailed evaluation of the available hydraulic testing information indicates that the geometric mean of the hydraulic conductivity of nearly all of the rock types falls within a fairly narrow range, between 3.5×10^{-6} and 3.5×10^{-4} cm/s (0.01 and 1 ft/d) (Golder, 2005). Alluvium is an exception. Although few data exist for alluvium, it is expected to be considerably more permeable than the other rock types. Volcanic rocks are another exception as they appear, on average, to be less permeable than the other rock types, possibly on the order of 10 to 100 times. Geologic units with apparent similar hydraulic properties were grouped into hydrostratigraphic units for modeling purposes. These hydrostratigraphic units include Alluvium, Volcanic Bedrock, Igneous Plutonic Bedrock (including adjacent sedimentary units in places), and Sedimentary Bedrock.

An array of underground workings exists along the western and northern flanks of the Santa Rita Pit, extending northward to the Continental Mine where additional underground workings are present. The interconnected array of underground workings provides conduits for groundwater flow. These high permeability features were incorporated into the model by defining hydraulic conductivity cells with values several orders of magnitude higher than the surrounding bedrock.

The stockpiles were not included as a hydrostratigraphic unit and were not directly incorporated into the model. Recharge from infiltration through stockpiles, however, is accounted for in the numerical model by applying it directly to the underlying bedrock. Given the complex geologic conditions, the selection and grouping of geologic units into hydrostratigraphic units are not straightforward. As such, the consequences associated with the choice of hydrostratigraphic units and the range of assumed hydraulic properties assigned to each was evaluated as part of a sensitivity analysis.

Groundwater Occurrence, Flow Directions, and Boundaries

Figure 3 shows the current configuration of the water table (uppermost water) in the NMA. The water table elevations in this area range from over 1,980 m amsl (6,500 ft amsl) north and south of the pit to approximately 1,600 m amsl (5,200 ft amsl) at the bottom of the pit. Corresponding depths to groundwater range from over 150 m (500 ft) below ground surface beneath the ridges and elevated terrain, to near ground surface along the major drainages of Hanover/Whitewater Creek and Lampbright Draw (Tributaries 1 and 2) and within the Santa Rita Pit. The interpreted horizontal directions of groundwater flow are shown on Figure 3. The primary area of groundwater discharge in the NMA is the Santa Rita Pit. The pit acts as a hydraulic sink, capturing groundwater flowing from all directions. Outside of the pit capture zone, groundwater flows toward and discharges to Hanover/Whitewater Creek and the Lampbright Draw tributaries.

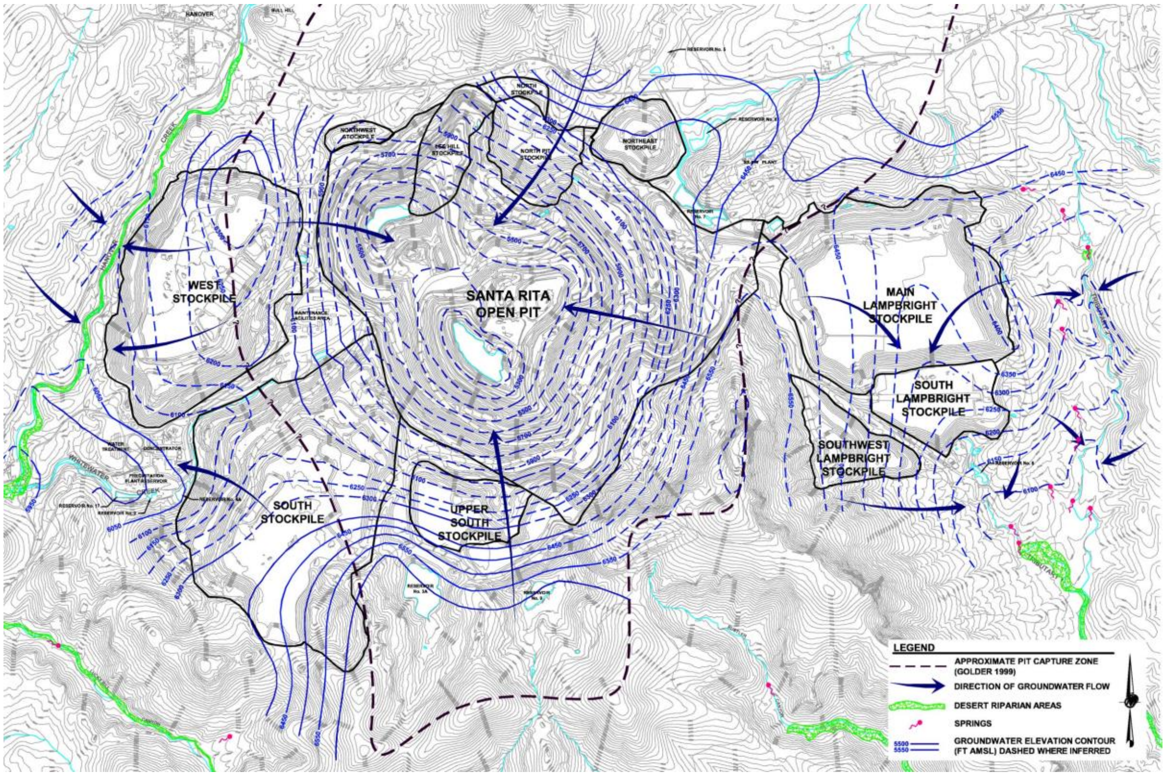

Figure 3. Groundwater elevations and directions of flow near the Santa Rita pit.

Outside of the NMA, groundwater level data are relatively sparse, limited to monitoring wells in the Continental Mine area (Fig. 1) and to domestic and livestock watering wells. The combined datasets indicate that hydraulic heads within the Study Area range from approximately 2,100 m amsl (7,000 ft amsl) to less than 1,600 m amsl (5,200 ft amsl) (Fig. 4). The higher hydraulic heads occur in recharge areas located in the elevated terrain, such as to the north along the crest of the Pinos Altos Range and to the south in the Cobre Mountains. The lower hydraulic heads occur in discharge areas along the major drainages and tributaries of Hanover/Whitewater Creek and Lampbright Draw, and within and near the Santa Rita Pit where sumps remove inflowing groundwater.

The data further indicate the presence of groundwater divides coincident with the major surface watershed divides between the Lampbright Draw and the upper Mimbres River watershed to the east and north, and between the Whitewater Creek watershed and Cameron Creek watershed to the west (Fig. 1 and 4). These watershed divides and coincident groundwater divides were used to define the area of the groundwater flow model (Study Area as depicted on Fig. 1). The northern and western boundaries of the model were later extended outward to coincide with surface drainages when the sensitivity analysis indicated that the original boundaries were too close as depicted on Fig. 4 (due to the presence of underground workings north and west of the pit).

Study Area Groundwater Budget

The Study Area occupies an area of approximately 210 km^2 (81 mi^2). Of this area, stockpiles cover a total surface area of 9 km^2 (3.3 mi^2), and the Santa Rita Pit and slopes cover approximately 6.5 km^2 (2.5 mi^2). The water balance for the Study Area includes all sources of groundwater recharge, groundwater extraction, and natural discharge (e.g., baseflow to drainages). Groundwater is recharged via infiltration from precipitation, stockpile seepage, and reservoir seepage. Groundwater discharge occurs via evapotranspiration, discharge to the Santa Rita Pit, extraction by wells, and downgradient groundwater flow. Previous estimates of average recharge in the Study Area from a collaboration of investigators range from 1.3 to 2.5 cm (0.5 to 1 in) per year, which equates to a total groundwater flux of 4,730 to 9,460 liters per minute (Lpm) (1,250 to 2,500 gpm) over the entire Study Area. Discharges within the Study Area include pit inflow estimated from 1,140 to 1,670 Lpm (300 to 440 gpm); extraction from wells estimated from 380 to 570 Lpm (100 to 150 gpm); and downgradient outflow through the alluvium of Whitewater Creek and Lampbright Draw, roughly estimated using Darcy’s Law in the range of 190 to 570 Lpm (50 to 150 gpm). The remaining quantity of groundwater, calculated as the difference between the other water balance components at between 1,320 and 7,150 Lpm (350 to 1,890 gpm), is believed to be discharged from the Study Area primarily as evapotranspiration.

On an areal basis, the quantity of groundwater removed by evapotranspiration is small, equal to approximately 6.3 to 34 Lpm/km^2 (4.3 to 23 gpm/mi^2). Assuming a maximum evapotranspiration rate of 135 cm (53 in) per year (equal to the estimated annual open water evaporation), all of this water could be removed via evapotranspiration from a minimum area of 0.5 to 3 km^2 (0.2 to 1.2 mi^2) or approximately 0.25 and 1.5 percent of the total Study Area. The actual area where the water table is at or near land surface within the Study Area is substantially greater. As such, removal of a large component of water via evapotranspiration in this semi-arid setting without having significant observable surface water discharge is deemed reasonable. The presence of evaporite deposits locally along the major drainages, as noted earlier, provides evidence of groundwater evaporation in discharges areas.

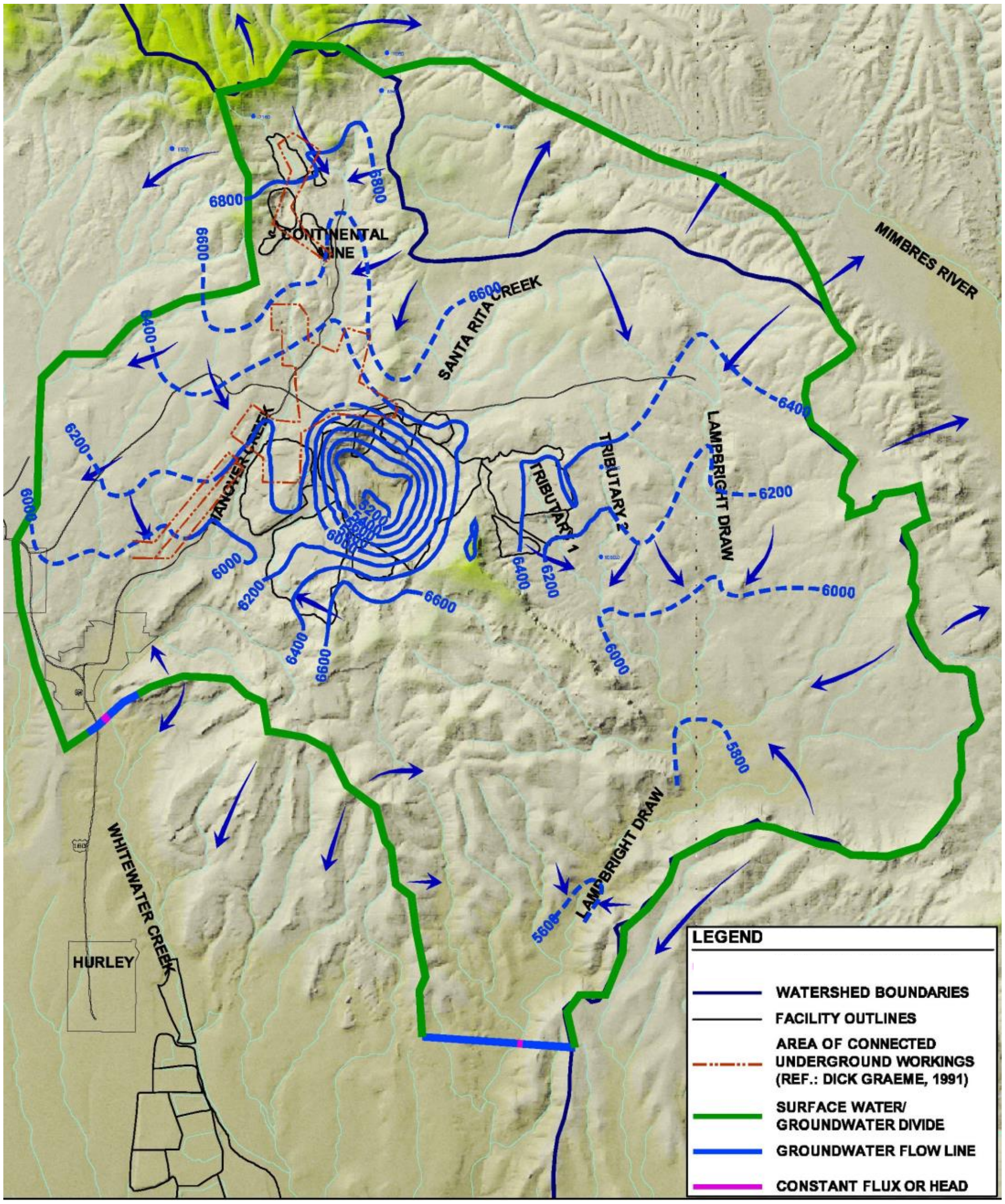

Figure 4. Chino Mine Study Area groundwater elevations, directions of flow, and model boundary conditions.

Conceptual Model Key Concepts

The key concepts of the Study Area groundwater system conceptual model used to construct the numerical groundwater model, and subsequently tested via numerical simulation and sensitivity analysis, are summarized as follows:

- The Study Area consists of generally low hydraulic conductivity bedrock in an area of pronounced local relief. It is therefore likely that groundwater flow is predominantly controlled by local- to intermediate-scale systems, linking recharge in topographically higher areas to discharge within adjacent or nearby topographically lower areas, as described in Freeze and Cherry (1979).

- As a result of local recharge and discharge, groundwater divides occur approximately beneath the major surface water divides. As shown on Fig. 4, the presence of these groundwater divides largely delineates the areal extent of the groundwater system of interest.
- Boundaries of the numerical model were chosen to reflect the geometry of the groundwater system as described above. The boundaries around the perimeter of the model were chosen to conform to groundwater divides present beneath the major surface water divides. Other limited portions of the model boundary were chosen to coincide with inferred streamlines.
- The groundwater system within the Study Area is largely recharged via infiltration of precipitation. Other sources of recharge include seepage from stockpiles and reservoirs. Most of the groundwater recharge subsequently discharges internally either to the land surface (where it is removed by evapotranspiration), to the Santa Rita Pit, or to extraction wells. The remaining recharged groundwater flows downgradient along Whitewater Creek and Lampbright Draw out of the Study Area.
- Groundwater within the Study Area flows horizontally from elevated terrain toward the major drainages and the Santa Rita Pit, as shown on Fig. 4. Vertical groundwater flow is generally downward beneath the elevated terrain where the groundwater is recharged and upward beneath the drainages and the pit where groundwater is discharged.

Numerical Model

A steady-state model was constructed to represent the Study Area groundwater system. A steady-state model was deemed appropriate because of relatively constant water level elevations in most of the wells (seasonal fluctuations are generally on the order of a meter to no more than a few meters), and a lack of observed drawdown due to dewatering of the pit. MODFLOW-SURFACT, an advanced version of the widely used and accepted modeling software MODFLOW, was used along with the processing package Groundwater Vistas to model the Study Area (ESI, 1996; McDonald and Harbaugh, 1988; and Waterloo Hydrologic, 1996). MODFLOW-SURFACT incorporates variably saturated modeling capabilities to allow for more accurate representation of the water table, a more robust recharge package that allows for the reduction of recharge to the subsurface if water levels reach land surface, and the ability to represent seepage face conditions to accurately track discharge of groundwater when the water table intersects the land surface. These enhancements are of particular use because of the shallow water table that occurs within the Study Area and the associated discharge that occurs to the land surface.

Model Grid and Boundary Conditions

The numerical model encompasses the area of the Santa Rita Pit and the mine facilities, and extends outward covering a large region around the mine totaling 246 km^2 (95 mi^2). The active model area has a grid spacing of approximately 150 m (500 ft). The base of the model was set to a uniform elevation of 671 m amsl (2,200 ft amsl) to ensure a minimum model thickness of approximately 914 m (3,000 ft). The top surface of the model was defined by pre-mining surface topography. Model Layer 1 was set to be 15 m (50 ft) thick. Model Layers 2 through 10 were divided such that the shallower layers are thinner than the deeper layers; this allows greater resolution of the shallow flow system where recharge and discharge occur. The average thicknesses of model layers 2 and 3 were 50 m (160 ft), layers 4 and 5 were 65 m (220 ft), layer 6 was 140 (460 ft), layers 7 and 8 were 220 m (730 ft) , and layers 9 and 10 were 210 m (690 ft). The model grid was rotated 30 degrees to the northeast to align the grid with the regional structural trend and the regional dip and hypothesized primary axis of horizontal hydraulic conductivity of the sedimentary geologic units.

Hydraulic conductivity was assigned to model cells based on well logs and geologic maps to represent the four hydrostratigraphic units described earlier. The assigned hydraulic conductivity zones for model layer 1 which has all four hydrostratigraphic units are shown on Fig. 5. The hydraulic conductivity zones for the other model layers are similar, varying by the vertical extent to which they are defined (Table 1).

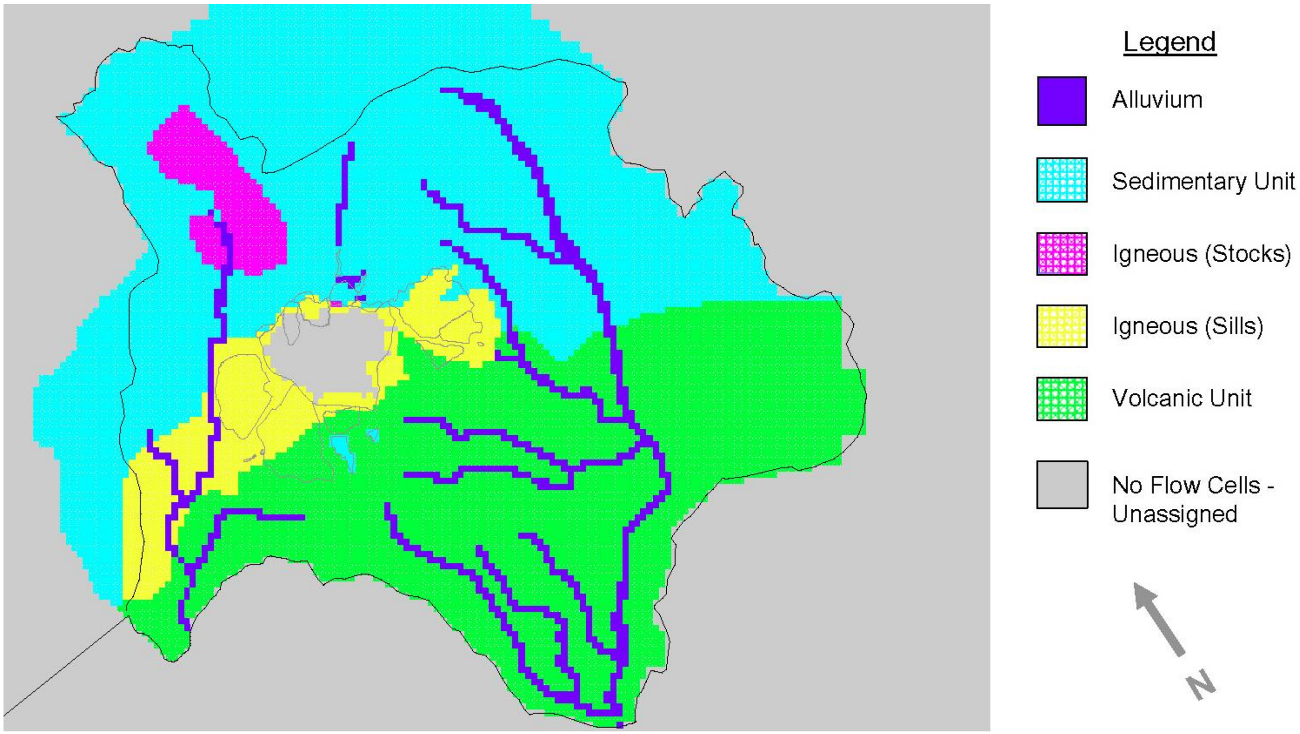

Figure 5. Defined layer 1 hydrostratigraphic units

The boundary conditions assigned to the perimeter of the modeled area are shown on Fig. 4. Most of the model area perimeter coincides with approximate locations of groundwater divides or stream channels. Both are represented numerically as “no-flow” boundaries, as groundwater diverges from a groundwater divide and converges toward the stream channels, but in neither case does groundwater cross from one side to the other. To fully enclose the model, the concept of streamlines was used along small lengths of the model perimeter to establish no-flow boundaries along the downstream ends of Lampbright Draw and Whitewater Creek from the local ridges (groundwater divides) to the creek channels. The downstream ends of the alluvial stream channels of Whitewater Creek and Lampbright Draw were represented by a "constant head" boundary condition to allow groundwater to discharge from the modeled area through the stream alluvium that is confined to these relatively narrow stream channels (estimated at approximately 15 m [500 ft] wide).

Table 1. Vertical extent of modeled hydrostratigraphic units

Hydrostratigraphic Unit	Hydraulic Conductivity	Simulated in Model Layer:
Alluvium	Kx = 1x10^{-3} cm/s (3 ft/d); Kz = 1x10^{-4} cm/s (3 x 10^{-1} ft/d)	1
Volcanic Bedrock	Kx = Kz = 2x10^{-7} cm/s (6 x 10^{-4}	1 through 5
Igneous Plutonic	Kx = Kz = 1.7x10^{-6} cm/s (5 x 10^{-}	1 through 10
Sedimentary Bedrock	Kx = 1x10^{5} cm/s (3 x 10^{-2} ft/d); Kz = 1x10^{-7} cm/s (3 x 10^{-4} ft/d)	1 through 10

Kx = Horizontal hydraulic conductivity; Ky = Vertical hydraulic conductivity

Boundary conditions applied to the top surface area of the model include recharge, seepage face, evapotranspiration, and general head boundaries. Areal recharge was applied to the top layer of the model in two zones: background recharge and recharge beneath the stockpiles. Background recharge was applied at 4 cm/yr (1.5 in/yr), and recharge beneath the stockpiles was applied at 8 cm/yr (3 in/yr). In effect, these values are the maximums per unit area, as MODFLOW-SURFACT reduces or eliminates recharge in certain areas (e.g., discharge areas) to prevent the water table from rising above land surface, or in the case of the stockpiles, the original land surface beneath them. The hydraulic conductivity of the stockpiles is several orders of magnitude higher than the average underlying bedrock hydraulic conductivity; consequently, ponding of water in the stockpiles is generally minimal. A seepage face boundary condition was automatically applied to cells where the hydraulic head is above the prescribed land surface elevation. Such conditions occur along the major drainages and within the pit. An evapotranspiration boundary condition was applied along the major drainages of Hanover Creek, Lampbright Draw, and portions of Tributaries 1 and 2. Infiltration from mine water reservoirs within the NMA was addressed using a general head boundary condition.

Calibration and Sensitivity Analysis Results

A conventional trial-and-error approach was used to calibrate the model. To achieve calibration, hydraulic conductivity and other input model parameter values were varied until a reasonable match was obtained between the model-calculated groundwater levels and the observed groundwater levels. Calibration was evaluated by the match of the simulated hydraulic heads to observed groundwater levels at the calibration targets (Table 2), the overall shape of the groundwater level contours (Fig. 6), and model-calculated water budget components, particularly groundwater inflow to the pit (Table 3). The sensitivity of the model results to each input parameter was evaluated with a comprehensive sensitivity analysis (Golder, 2005).

Table 2. Statistical analysis of model calibration

Number of Observation Points	152
Minimum (absolute) Residual	0.33 m (1.1 ft)
Maximum (absolute) Residual	75 m (247.8 ft)
Mean Error	-14.5 m (-48 ft)
Mean (absolute) Residual	17 m (57 ft)
Root Mean Squared (RMS) Error	22 m (73 ft)
%RMS	5.3

Table 3. Calibrated model water balance.

	Model Calculated Values		Estimated Values
	Total Model Area (Lpm)	Rate Per Unit Area (cm/yr)	
Inflows			
Recharge	10,000 (2,645 gpm)		
Background	9350 (2,470 gpm)	2 (0.82 in/yr)	1.3 2.5 cm/yr (0.5 - 1.0 in/yr)
Stockpile infiltration	658 (175 gpm)	3.8 (1.5 in/yr)	3.8 – 5 cm/yr (1.5 - 2 in/yr[3])
Reservoirs	182 (48 gpm)		840 Lpm (222 gpm)
Outflows			
Seeps/Springs*	5,325 (1,407 gpm)		
ET**	3,198 (845 gpm)	135 (53 in/yr)	73 – 292 cm/yr (28 – 115 in/yr)
Downgradient groundwater flow	11 (3 gpm)		190 Lpm (50 gpm)
Discharge to Pit	1,600 (425 gpm)		1,135 Lpm (300 gpm) 1,658 Lpm (438 gpm)

* Land surface discharge assumed to be removed via evapotranspiration.

** Evapotranspiration explicitly assigned to model cells.

From the model calibration and sensitivity analysis, the structure of the model and model parameters appear appropriate and reasonable. Model calculated horizontal groundwater flow directions converge at the drainages and pit, and generally replicate the observed groundwater level contours (Fig. 6). The calibrated model shows groundwater recharge occurring in the elevated terrain and discharge occurring within and along the nearby local drainages consistent with the conceptual model of groundwater flow in the Study Area. The values used for the hydrostratigraphic units compare well to the hydraulic test results. A distinct vertical anisotropy of the sedimentary hydrostratigraphic unit was required for calibration, consistent with its pervasive layered nature. However, no horizontal anisotropy aligned with the regional structural trend and regional dip of the sedimentary units (30 degrees to the northeast) was required for calibration, indicating that these features do not enhance hydraulic conductivity on the regional scale. In addition to the above, the calibrated average rates of background recharge from precipitation (2 cm/yr) (0.8 in/yr) and recharge to bedrock from infiltration beneath the stockpiles (4 cm/yr) (1.5 in/yr) are consistent with previous estimates (Golder, 1999).

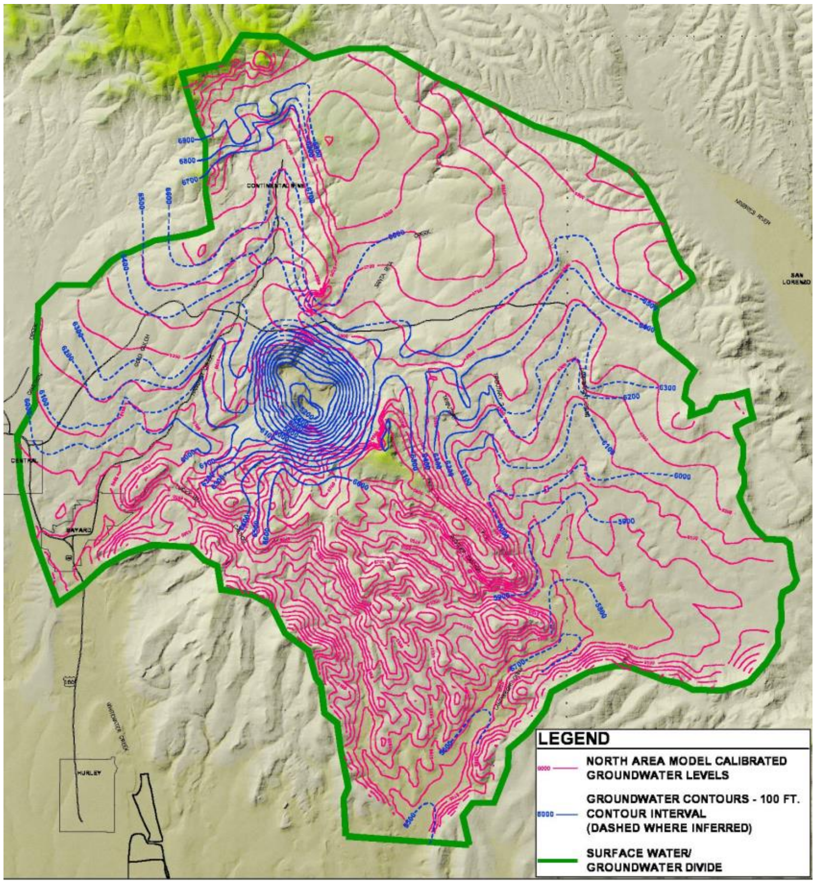

Figure 6. Calibrated and measured hydraulic head contours

One item of note in Table 2, is the mean error of -14.5 m (-48 ft), that reflects an overall negative bias (an overall slight over-prediction of hydraulic heads over the model domain). This apparent bias is due, in large part, to the relatively coarse model grid (150 m) and the relative steep relief of the land surface. Drainages where discharge occurs are typically deeply incised, and are below the elevations of the cells used to represent these areas. Consequently, model-calculated hydraulic heads in these discharge areas are systematically somewhat greater than the actual hydraulic heads. The impacts of this bias, however, are negligible on the overall behavior and representation of the groundwater flow system of the Study Area

An important outcome of the sensitivity analysis was the observation that the model-calculated hydraulic heads were not particularly sensitive to the hydrologic parameter values. The model was sensitive to global changes in hydraulic conductivity values as expected, but relatively insensitive to assumed regional heterogeneity or the geometry of the hydrostratigraphic units, as well as to the other assigned model inputs. The relative insensitivity of the model to these parameters is believed to reveal a key characteristic of the groundwater system: the importance of the land surface topography as a key boundary condition that in turn dominates the behavior of the groundwater system by controlling the locations of recharge and discharge areas.

Simulation Results

Pit Capture Zone and Groundwater Flow Near the Pit and Stockpiles

Groundwater flow paths from points of recharge to points of discharge near the pit were evaluated using MODPATH, a particle tracking routine that uses MODFLOW results (Pollock, 1994). The surface area over which particles released at the water table report to the pit was mapped and defined as the "pit capture zone." The pit capture zone (shaded area) shown on Fig. 7 extends several miles to the north in the direction of the regional topographic divide (The full extent of the pit capture zone to the north was not mapped because the focus was on the open pit and nearby mine facilities). The pit is capturing groundwater naturally flowing downgradient to the south-southwest from the regional topographic (and groundwater) divide. The extent of the pit capture zone to the east, west, and south, however, is largely controlled by the local pre-stockpile topographic conditions. Groundwater recharge either flows toward and into the pit or away from the pit and into local drainages, depending on the geometry of the local surface topography relative to the pit. This finding is a key result of the modeling study and is consistent with the conceptual model of the dominance of local groundwater flow systems in this type of setting.

The Lampbright Stockpiles, located east of the pit, was constructed in the north-south-oriented drainage of Tributary 1. Recharge applied to the buried bedrock ridges along the east and west sides of the stockpiles infiltrates to the water table and flows toward the center of the stockpiles. Here, the water table intersects the original pre-stockpile land surface, and groundwater discharges into the overlying stockpile materials along the original channel of Tributary 1. This is shown schematically on Fig. 8. As a result of this pattern of localized groundwater flow, nearly all of the groundwater recharged within the footprint of the stockpile surfaces within the stockpile and exits at the toe of the stockpile where it is collected. Similarly, on the west and south sides of the pit, recharged groundwater generally travels short distances as dictated by the local pre-stockpile topography. Groundwater discharges either to the pit, or if outside of the pit capture zone, as surface water along the perimeter of the stockpiles where it is collected via a series of collection sumps, or to the creek channels where it is removed via evapotranspiration.

The hypothesis that local surface topography acts as a dominant control on the groundwater flow system was further tested during a sensitivity analysis by evaluating the sensitivity of the pit capture zone to the model assumptions. This was done by comparing the shift in the location of the pit capture zone along transects extending to the east, west, and south from the pit. The results indicate that the pit capture zone is not sensitive to the model input parameters. These shallow flow paths, which are of primary concern with regard to transport of impacted groundwater, are controlled primarily by the land surface boundary condition (recharge and discharge across the land surface). The results of this analysis provide further confidence that the modeled shallow groundwater flow paths discussed in the preceding section are reasonably accurate at the level of resolution possible for a regional-scale model.

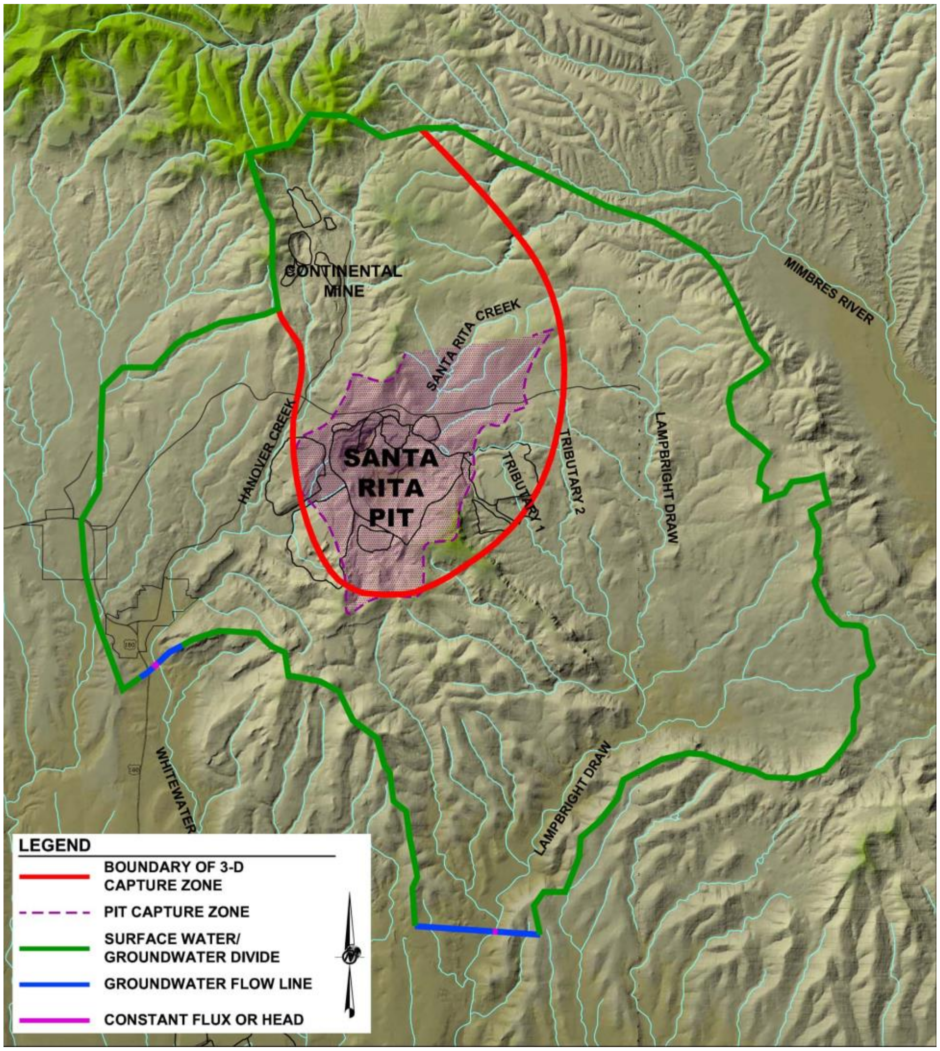

Figure 7. Santa Rita pit capture zone and boundary of three-dimensional capture zone.

Three-dimensional Capture Zone

In addition to the forward tracking of particles placed at the water table beneath the stockpiles and near the pit, particles were also tracked backward from the pit walls and bottom to the original points of recharge at the water table. The traces of these particles define the three-dimensional nature of the flow system that discharges into the pit. This zone is herein referred to as the "three-dimensional capture zone."

The surface projection of the three-dimensional capture zone (red line on Fig. 7) extends well outside of the pit capture zone as defined and discussed earlier. This illustrates that deeper groundwater well outside of the pit capture zone flows toward and into the pit, whereas the fate of shallower groundwater recharged near the pit is controlled by the local pre-stockpile topography (except in the regional upgradient direction). This is further illustrated schematically on Fig. 8. The shaded area represents the cross sectional nature of the three-dimensional pit capture zone at this location. The surface exposure of the shaded area represents the pit capture zone as noted on the figure. The groundwater comprising the portion of the three-dimensional capture zone that extents outside of the pit capture zone is recharged from areas upgradient to the north of the pit, beyond the mapped area of the pit capture zone (Fig. 7).

The sensitivity of the three-dimensional capture zone to the model assumptions was evaluated similarly to the sensitivity analysis undertaken to determine the importance of local surface topography on the shallow groundwater flow system and pit capture zone. The results show that the geometry of the deeper flow system comprising the three-dimensional capture zone is much more sensitive to assumed ranges of model input parameters, especially hydraulic conductivity and anisotropy. The geometry of the deeper flow system is also probably sensitive to the presence of the underground workings, although, this was not evaluated in detail.

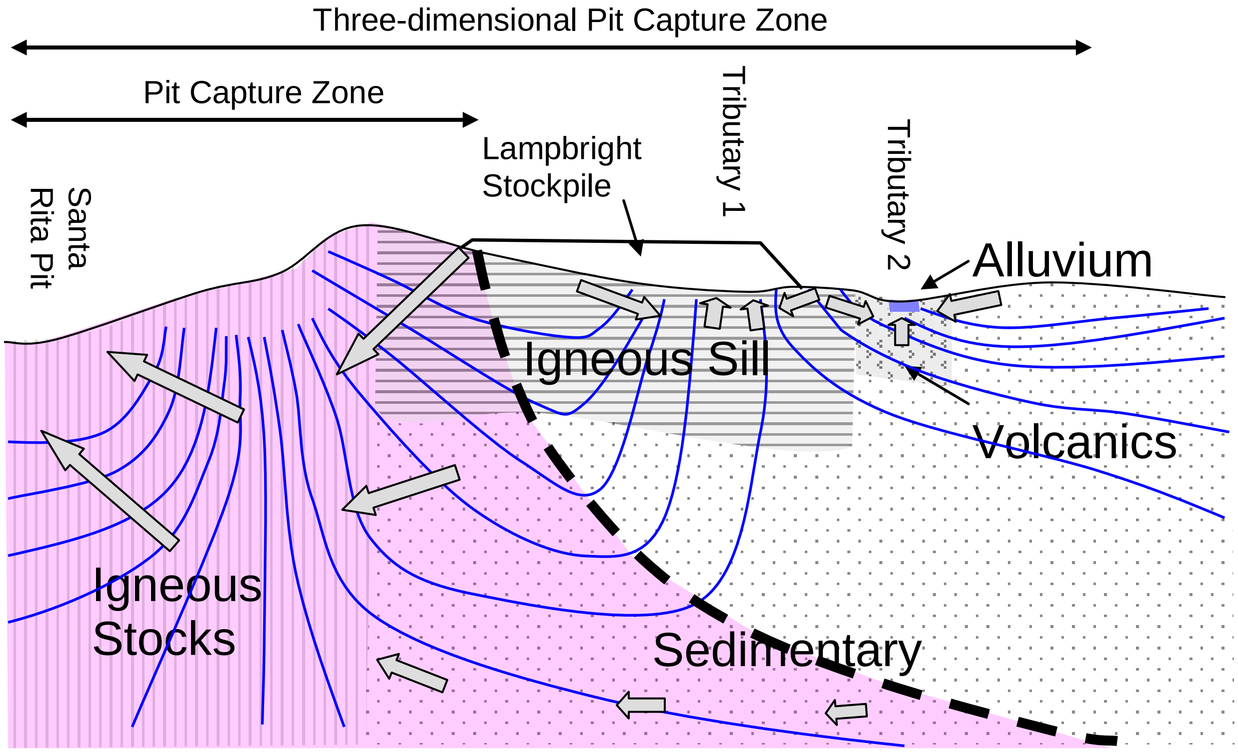

Figure 8. Schematic cross section of lithology and groundwater flow through the Lampbright Stockpile.

Conclusions

Reliable representation of recharge and seepage across the land surface is necessary to model groundwater flow systems and open mine pits in low-permeability, mountainous terrain. In such settings, local-scale groundwater flow systems generally dominate over intermediate- and regional-scale groundwater flow systems as defined by Toth (1963). Groundwater predominately recharges along local ridges and elevated terrain, and predominantly discharges to local drainages and lower terrain where the water table is intersected. The key characteristic of this type of system is the occurrence of a shallow water table in the local drainages that in turn provides a location for groundwater to discharge locally. In higher permeability settings, in contrast, the water table may be much deeper. In this latter case, there may be no local area for groundwater to discharge, preventing the formation of local-scale groundwater flow systems.

As a result of the local-scale nature of the groundwater flow system, the pre-stockpile surface topography largely controls the direction of flow of recharged groundwater near the pit. Groundwater recharge near the pit either flows toward and into the pit or away from the pit and into local drainages, depending on the geometry of the local surface topography relative to the pit. The pit capture zone is consequently largely controlled by local topography in the immediate vicinity of the pit. Furthermore, as indicated by the results of the sensitivity analysis, the pit capture zone is influenced to a lesser degree by other characteristics of the hydrogeologic system, such as recharge and hydraulic conductivity distribution.

Although the pit capture zone, as herein defined, near the pit is controlled by local pre-stockpile topography, the modeling results indicate that deeper groundwater from a larger area discharges into the pit. With greater depth, the influence (hydraulic gradient) of the local surface topography dissipates, and the influence of the hydraulic sink associated with the pit increases, resulting in a transition of groundwater flow controlled by local surface topography to groundwater flow controlled by the pit. The results are analogous to the transition between local groundwater flow systems and intermediate groundwater flow systems, as characterized by Toth (1963). The differences noted here between the pit capture zone and the three dimensional characteristics of the groundwater flow system that reports to the pit illustrates the importance of employing three-dimensional modeling techniques over two-dimensional plan-view or cross-sectional modeling techniques to represent groundwater flow systems in this type of setting.

References

Chino Mines Company, 1995. *Administrative Order on Consent Investigation Area Remedial Investigation Background Report.* Chino Mine Investigation Area. Prepared for New Mexico Environment Department. October 5, 1995.

Environmental Simulations, Inc. (ESI), 1996. *Groundwater Vistas* Version 4.18, Copyright 1996-2005, Environmental Simulations, Inc.

Freeze R.A, and J.A. Cherry, 1979. *Groundwater.* Prentice-Hall, Inc. Publishers.

Golder, 1997. *Draft DP-526 Remedial Hydrogeologic Investigations, Volume I Hydrogeology and Engineering Design*.

Golder, 1999. *Comprehensive Groundwater Characterization Study, Phase 3 Report, Volumes 1 and 2, Chino Mines Company*. January 1999.

Golder, 2005. *Report on North Mine Area Groundwater Flow Model: Chino Mine, New Mexico*. January 2005.

Jones, W.R., R.M Hernon, and S.L. Moore, 1967. *General Geology of Santa Rita Quadrangle Grant County, New Mexico*. Geological Survey Prof. Paper 555.

McDonald and Harbaugh, 1988. *A modular three-dimensional finite-difference ground-water flow model.* Technical report, U.S. Geol. Survey, Reston, VA.

Parham, T.L., R. Paetzold, and G.E. Souders, 1983. *Soil Survey of Grant County, New Mexico, Central and Southern Parts.* U.S. Department of Agriculture, Soil Conservation Service. 216p.

Pollock, D.W., 1994. *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A Particle Tracking Post-processing Package for MODFLOW.* U.S. Geological Survey Open-file Report 94-464, 6ch.

Toth, J.1963. A Theoretical analysis of groundwater flow in small drainage basins. J. Geophys. Res., 68, pp. 4795-4812. http://dx.doi.org/10.1029/JZ068i016p04795.

Trauger, F.D., 1972. *Water Resources and General Geology of Grant County, New Mexico.* New Mexico State Bureau of Mines and Mineral Resources Hydrologic Report 2, 211p.

Waterloo Hydrogeologic, 1998. *MODFLOW-SURFACT software (version 2.1), Overview: Installation, Registration, and Running Procedures*.