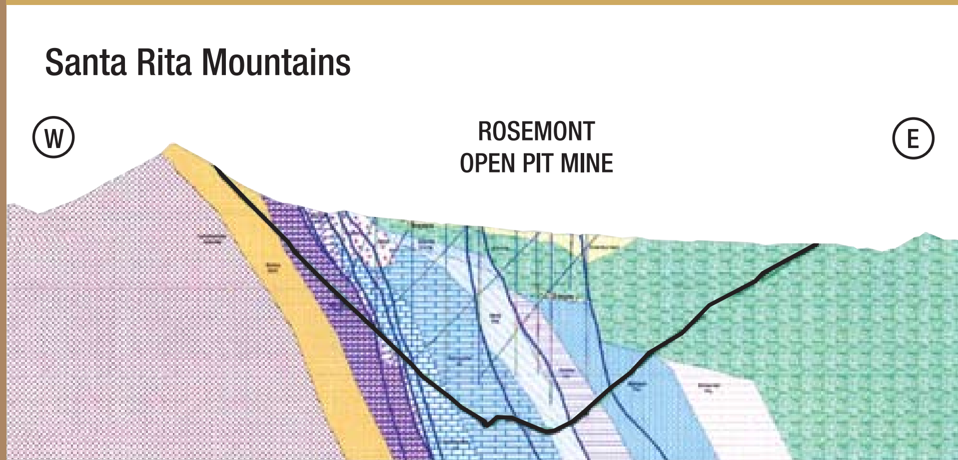
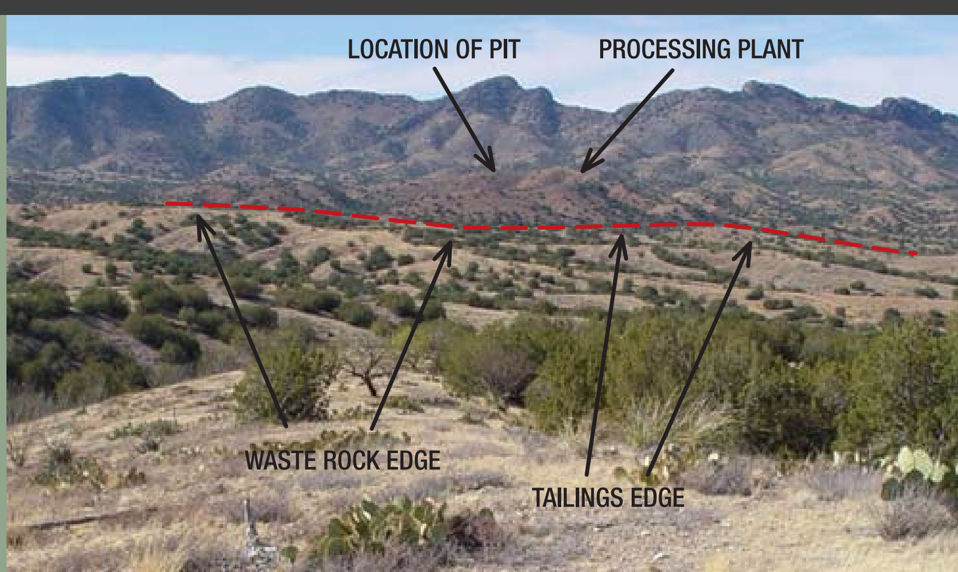
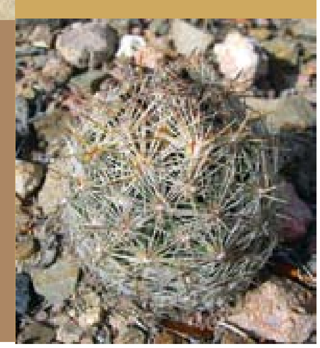


Groundwater Model of the
SANTA RITA ROSEMONT PROJECT SITE





Front cover imagery credits:

Top: Geological cross-section through Santa Rita Range. By Pima County graphics, based on information by Augusta Resources.

Center: View from Highway 83 by Julia Fonseca, with annotations based on Forest Service Congressional briefing material dated February 16, 2007.

Bottom: Flower from the Rosemont project area by Nancy Zierenberg, 2008. Cactus from the Rosemont project area by Julia Fonseca, 2006.

Hydrogeology of the Santa Rita Rosemont Project Site Numerical Groundwater Modeling of the Conceptual Flow Model and Effects of the Construction of the Proposed Open Pit

April 2008

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Executive Summary

The Augusta Resources Corporation proposes to construct the Rosemont Mine project in the northern Santa Rita Mountains. The proposed open pit would cover about 700 acres. Full construction of the proposed pit would require 20 years. Large open pits can affect both ground and surface water by dewatering, diverting surface water, and capturing runoff. Even if the groundwater inflows are not substantial enough to require a large system of dewatering wells, the proposed pit will lower the water table and cause inflows similar to pumping a large diameter well.

Recharge to the site is a combination of diffuse recharge to bedrock and recharge from the ephemeral channel deposits. There is also mountain front recharge north of the site where Davidson Canyon discharges onto the Cienega Creek alluvial basin. Groundwater flows to the east-northeast through bedrock where it discharges from the site as underflow through the bedrock or as flow to Cienega Creek. ET from riparian vegetation within the project area is from the perched, ephemeral aquifers in the channel deposits rather than from the regional aquifer. The proposed open pit would lower the regional aquifer water table by up to 2000 feet within the pit area and cause a drawdown cone and groundwater to discharge into the pit. Drawdown is the amount that a water table lowers due to development from its predevelopment level. In three dimensions around a well, the drawdown shape often takes the shape of an inverted cone. The drawdown cone would change the water table for a significant distance from the pit and affect groundwater flows throughout nearby watersheds.

This study reports on the development of a reconnaissance level numerical groundwater model of the Davidson Canyon and Cienega Creek watersheds. The model domain, the watershed, and aquifers to be simulated, is represented numerically with a three-dimensional structure of cells among which groundwater flow can occur. Model cell size was selected to balance water balance calculation efficiency with accuracy. The grid must be sufficiently detailed to parameterize the geologic formations and simulate flow among levels and to springs but it must not be too detailed. Six layers represent the changing aquifer material with depth. The upper three layers were unconfined and the lower layers were confined. The aquifer formations were represented using the parameter zone method of MODFLOW to specify conductivity and storage properties.

Three types of boundary conditions were used to model the rates of groundwater movement through the system. Recharge approximating 1.5 in/y over one-third of the domain was a specified flux boundary condition. General head boundaries simulated underflow from Davidson Canyon and Cienega Creek above the Narrows. Drain boundaries, head-controlled flux boundaries, modeled the discharge to Cienega Creek which approximated the measured flow near the Narrows on Cienega Creek. Evapotranspiration boundaries, a head-controlled flux boundary, modeled the evapotranspiration from riparian vegetation in Cienega Creek. Drain boundaries were also used to represent the lowering pit levels.

Calibration included balancing the simulated heads with observed heads in various wells in the watersheds and the fluxes estimated through the system for steady state conditions.

Storage properties were based on textbook values due to the lack of transient calibration data. The model accurately simulates the conceptual flow model developed for the area and fits observed data.

The proposed project would cause extensive drawdown near the proposed pit. Low transmissivity causes a steep gradient near the proposed pit. The pit would be excavated to and the potentiometric surface lowered 2000 feet to about 3100 feet at the pit. Drawdown expands downgradient from the mine slowly due to faults and low conductivity. Within 100 years from the end of mining, significant drawdown will have expanded several miles downgradient from and to the southeast of proposed pit. Any spring within the drawdown could potentially be affected. After 8000 years, when the entire study area has reached close to steady state conditions, there is extensive drawdown throughout Davidson Canyon that reaches significantly in the Cienega watershed as well.

The project would lower the water table near the groundwater divide southeast of the pit up to 20 feet. Up to 20 af/y of groundwater would be diverted from the Cienega Creek watershed to the Davidson Canyon watershed and the proposed pit.

Two aspects of the study area limit the amount of water withdrawn for dewatering and the expansion of the dewatering cone. The steepness of the terrain and low transmissivity limits the rate that drawdown expands Davidson Canyon. The pit would capture most of the recharge from the watershed above the proposed pit, but the small area upgradient of the pit limits the inflow to the pit to 600 af/y. This diversion of groundwater would eventually affect underflow from the model and discharge to Cienega Creek, but the time frame is long. Discharge from Davidson Canyon, groundwater flow through the cross-section at the downstream boundary of the canyon, begins to decrease after about 400 years and ultimately decreases about 16% within 6000 years. This also reflects the potential effect on Davidson Springs.

The proposed project would occur within the upstream portion of Davidson Canyon watershed. The pit will capture all runoff from within and above the pit area. Most of this runoff would otherwise leave the study area without infiltrating and become mountain front recharge into alluvial basin north of the Davidson Spring area. This analysis has not estimated the runoff to be captured, but it could be substantial considering the recharge estimate is 1.5 in/y in an area with approximately 20 in/y of precipitation. The mountain front recharge captured by the pit could be several times the diffuse recharge in mountain block. This could have a significant impact on downstream baseflow because Davidson Canyon provides approximately 20% of the baseflow in Cienega Creek.

If the storage properties of the aquifer were significantly less than modeled herein because aquifers are significantly less fractured and yield significantly less water than assumed, the effects of this project could be spread over a larger area more quickly. The flux intercepted by the project would increase because the drawdown near the proposed pit would expand and capture more recharge. Discharge from the Davidson springs and Cienega Creek would be reduced by a few percent.

The report also includes recommendations for data that must be collected prior to completing environmental analyses for the proposed project. These include surface and groundwater monitoring and pump tests. Additionally, there are several types of mitigation which should also be implemented. These include long-term monitoring and the construction of diversions to prevent the capture of runoff.

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Introduction

The Augusta Resources Corporation proposes to construct the Rosemont Mine project in the northern Santa Rita Mountains (Figure 1). It would affect up to 4415 acres of Coronado National Forest, state and private land with an open pit, tailings disposal areas and waste rock (Westland 2007). The proposed open pit would cover about 700 acres and ancillary facilities would affect an additional 250 acres and the tailings/waste rock and leach pad would cover 2895 acres (Westland 2007, pages 9-11). Full construction of the proposed pit would require 19 years.

Large mining projects such as proposed by Augusta can affect both ground and surface water by dewatering pits, diverting surface water, capturing runoff, covering areas with tailings which may decrease the recharge and contaminate the groundwater, and by developing process water. Even if the groundwater inflows are not substantial enough to require a large system of dewatering wells, the proposed pit will lower the water table and cause inflows similar to pumping a large diameter well. The lowering of the water table is a drawdown, the amount that a water table lowers due to development from its predevelopment level. In three dimensions around a well, the drawdown shape often takes the shape of an inverted cone and is often referred to as a drawdown cone.

The analysis in this report estimates the potential effects of constructing the proposed open pit on the groundwater flow of the site and downstream watersheds in Davidson Canyon and Cienega Creek. It builds on the report by Myers (2007), who considered the conceptual flow model and estimated the water balance for the watersheds. Myers (2007) discussed how the mine would affect the hydrology by intercepting groundwater flow. This report does not address changes in surface water flow due to the pit capturing runoff which could change recharge downstream from the site.

Myers (2007) also determined the steady state water balance including an estimate of recharge to and discharge from the system. To estimate the potential effects of constructing the proposed pit on the water balance of the area, a reconnaissance-level groundwater model of the Davidson Canyon and Cienega Creek watersheds was developed to simulate the conceptual model. The model attempts to accurately simulate flows through the basins in steady state mode. The model is then used to predict the effects of dewatering the proposed open pit on the water balance of the two valleys. This report primarily discusses the development of and predictions made with that groundwater model. Additionally, the report uses model fluxes to address the concerns of Davis (2007) about the development of a pit lake within the proposed pit.

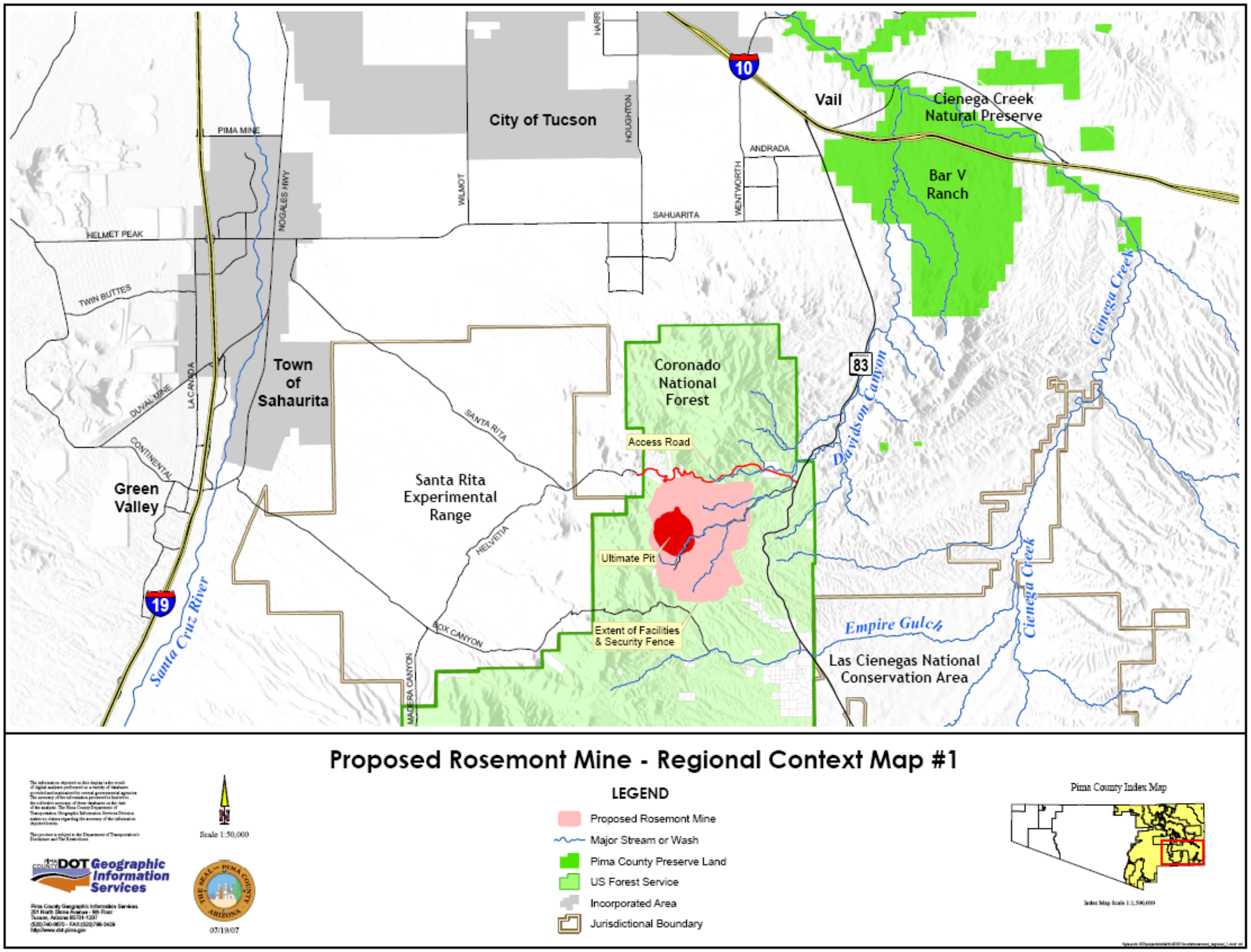

Figure 1: Regional site map for the Proposed Rosemont Mine

Basic Hydrogeology at the Rosemont Project Area

Geologic Formations

The proposed Rosemont Ranch project lies in the headwaters of Davidson Canyon on the east side of the Santa Rita Mountains. Davidson Canyon is a tributary subbasin of the larger Cienega Creek watershed. The study area therefore is Davidson Canyon and Cienega Creek watershed above the Narrows (Figure 2). Discharge from Davidson Canyon, further downstream from the study area, is about 20% of the baseflow in Cienega Creek (PAG 2003).

The topographic divides of the Santa Rita Mountains and Whetstone Mountains form the northwest and southeast boundary of the study area, respectively. The northeast boundary coincides with the mountain front of the Davidson Canyon and Cienega Creek watershed, roughly coinciding with Davidson Spring and the Cienega Creek Narrows. The southwest boundary is the topographic divide between Cienega Creek and Sonoita Creek.

The Santa Rita Mountains are part of the basin and range province that covers most of Arizona southwest of the Mogollon Rim. They are located 45 miles southeast of Tucson. The ridgeline consists of formations dipping steeply eastward consisting of a metamorphic core complex flanked by Paleozoic and Mesozoic-aged metamorphic carapaces of mostly sedimentary rock including carbonates, shales, and limestone (Wardrop 2005). The Rosemont Ranch area is within an east-facing mountain-block watershed. The Mesozoic and Paleozoic sedimentary rocks, which predominate the bedrock geology of the area, are complexly fractured by northwest and northeast trending fractures (Harshbarger and Hargis 1976). Myers (2007) includes maps of the geology.

The watershed consists of three aquifers – bedrock, alluvium and basin fill (Harshbarger and Hargis 1976). The bedrock is the primary regional aquifer within the mountains; it discharges to alluvium (and springs) downgradient of the project area near the outlet of Davidson Canyon.

The bedrock aquifer is fracture controlled and possibly confined. The predominant outcrop in the mine area is the Willow Canyon formation which Harshbarger and Hargis (1976) describe as arkosic sandstone, conglomeratic sandstone, mudstone, and silt limestone. This formation ranges from 200 to about 1500 feet thick within the mine pit outline; east of the mine pit, the thickness increases to more than 3000 feet (WLR 2007). The Willow Canyon formation primarily controls the hydrogeology east of the proposed project. Montgomery (2007) drilled four wells within the area of the proposed pit. The well logs primarily indicate Willow Creek formation to a depth up to 1500 feet.

The west side of the study area consists of Paleozoic rocks in the Santa Rita Mountains (Drewes 1971 and 1976), with water at various levels (Harshbarger and Hargis 1976, page 32). Drillers indicated the water level fluctuated, primarily by rising, as they encountered new fractures. The aquifer is confined and fracture-controlled producing a moderate amount of water (Harshbarger and Hargis 1976).

Harshbarger and Hargis (1976) suggested that recharge west of the topographic divide may contribute to spring flow high on the east side of the divide, but geologic cross-sections (WLR 2007) do not reveal stratigraphy which would be conducive to flow under the topographic divide (Myers 2007). However, if the percolating high elevation recharge follows the dip, it may flow deeply prior to discharging from the watershed. An upward vertical gradient observed in wells drilled into the bedrock (Harshbarger and Hargis 1976, Montgomery 2007) reflects this.

Small alluvial aquifers occur in the ephemeral drainages such as Schofield Canyon or Wasp Canyon, but any water in them is perched above the regional aquifer. While describing them as an aquifer, Harshbarger and Hargis (1976) indicate that water levels in wells that intersect the alluvium are at or below the bedrock interface. Ephemeral channels are important for recharge, but the alluvial aquifers may be perched by the bedrock or by the clay and silt layers and ephemeral due to the infrequent runoff events, ET from riparian vegetation, and drainage to underlying bedrock.

There is also a basin fill aquifer southeast of the project site in the Cienega Creek watershed upstream of the Narrows (Harshbarger and Hargis 1976). In this report, the distinction will be made between the Davidson watershed and this upper Cienega Creek watershed. This basin fill aquifer southeast of the proposed mining site may be connected to aquifers in the project watershed and be affected by the proposed open pit. The extent of and impacts to this connection caused by the proposed mine is a subject of this project.

Groundwater Flow

Myers (2007) determined groundwater contours for the Davidson Canyon watershed. The extent of this mapping was increased for this report. Well levels for all of the wells maintained by the U.S. Geological Survey for the watershed were downloaded (Appendix 1, http://waterdata.usgs.gov/az/nwis/gw/). Only a few are within the domain of the Phase 1 analysis, and those did not have a well depth specified. The US Geological Survey (USGS) monitors many wells within the Cienega Creek watershed, above the Narrows, in the south part of the Santa Rita Mountains south of Box Canyon, and in the north part of the Whetstone Mountains near watershed boundary (Plate 1).

Groundwater contours developed for Phase 1 were extended across the Cienega Creek watershed and Davidson Canyon (Plate 1) to provide a basis for the conceptual model and steady state calibration for the groundwater modeling. Contours were drawn manually based on the observed water levels. The location of contours chosen in some areas required professional judgment. First, they were drawn without considering topography. Then they were adjusted to reflect topography if appropriate, a process which was most necessary for the shallow contours. Two wells located in the downstream portion of Davidson Gulch, D-18-16 24BDC1 and 2, are located in the same quarter-quarter section and screened at less than 100 feet but their static water levels differed by about 20 feet. An average was used for this location with the name D-18-16 24BDC

The groundwater divide south of the Rosemont project identified in Phase 1 exists because the water levels in both the shallow (<300 feet) and deeper wells become lower south of the divide (Plate 1). The general flow direction is northeastward to the narrows and the likely groundwater evapotranspiration (ET) discharge point. Near the mountains and upgradient portions of the Cienega watershed, groundwater contours based on shallow wells are slightly higher than that at depth. This reflects the gradient which drives recharge. The exception occurs where an upward gradient from depth to the surface occurs in the lower portions of the Cienega Creek basin. This upward gradient drives groundwater to discharge into the creek and to the phreatophytes along the creek. There is about 20 to 40 feet of difference in water levels. At least three wells monitored by the USGS in the discharge portion of Cienega Creek were flowing, reflecting the pressure observed at depth (Appendix 1); these are near Cienega Creek where the shallow well levels are close to the groundwater surface.

In certain areas, one or more wells were located in close proximity. Substantial differences in water level among those wells could indicate a vertical gradient or that the wells screen different material or represent fractures or other isolated saturated zones. For example, static water levels differ by about 100 feet between wells D-20-16 02AAB and D-20-16 02AAA, but there is only about 100 feet difference in depth. The water level in the former fits the trend throughout the area better and was used for this analysis. Although the material screened is not noted, that for the later well is volcanic rock which indicates the deeper well may not be hydraulically connected to the overlying alluvium.

Conceptual Model of Flow at the Rosemont Ranch

The project area and the portions of Davidson Canyon and Cienega Creek watershed, above the Narrows, are essentially mountain block watersheds (Wilson and Guan 2004). The mountain front is the area at which the streams discharge from the mountains and intermountain basins into the broader Cienega Creek alluvial basin north of the Whetstone, Empire and Santa Rita Mountain ranges.

The basic conceptual groundwater flow model for the entire study area is that precipitation recharges in the mountain block and through ephemeral channel bottoms and discharges to springs and streams where structural controls force the flow to the surface. Myers (2007) estimated recharge over the entire area to be about 0.5 in/y. Because it would be concentrated on the mountainous third of the watershed, he estimated that about 1.5 in/y would occur there and the remaining two-thirds of the watershed would have little recharge. Because the study area is above the mountain front, and because substantial amounts of runoff flow through the Narrows and likely recharge further downstream, the recharge rate may be lower than determined for a model of the basin fill north of the project area by Anderson et al (1992).

The discharge includes the seepage to Cienega Creek, caused by the Narrows through which the creek and groundwater flows (Roudebush 1996). Myers (2007) used an estimate of this discharge to estimate the recharge rates in the basin above the Narrows. The flow then may become secondary recharge on the alluvium north of the mountains. Additional discharge from the area includes underflow through the cross-section beneath Davidson Canyon, between the Santa Rita Mountains and Empire Mountains, and through the section beneath the Cienega Creek Narrows (Myers 2007). Mountain front recharge would occur northeast off of the study site as runoff infiltrates the alluvium.

In this conceptual model, riparian vegetation in ephemeral channels (PAGWP 2006) is not a discharge from the regional aquifer because it transpires water from the channel deposits. This ET is an abstraction from the channel deposits and prevents water that otherwise would become recharge to the bedrock aquifer from doing so.

Groundwater flows from recharge to discharge zones at a rate which depends on the aquifer transmissivity and gradient. Because of the dominance of bedrock, most flow would be through fractures. Most studies suggest that the fractures are very tight and that conductivity would be low (Harshbarger and Hargis 1976, Hargis and Montgomery 1982). Most wells completed in this formation produce poorly, less than 30 gpm, but Hargis and Montgomery (1982) suggested that wells up to 100 gpm could be constructed. They report that well D-18-16-29cda, located near Rosemont Junction, was pump-tested in 1963 at 64 gpm and with 480-foot drawdown. The specific capacity equaled 0.13 gpm/ft. A recent study (Montgomery 2007) that included detailed well logs and pump tests for four new wells within the area of the proposed pit confirmed that most of the bedrock has a low conductivity (Table 1). One of the four wells had a significantly higher transmissivity and very rapid recovery, but considered over the 820-foot screen length the conductivity is just 4.4 ft/d, a value that is representative of a fracture zone. The pump test was 24 hours long at an average rate of 50 gpm. The total groundwater volume pumped was 9625 ft^3 which is insufficient to adequately stress a small, high-conductivity zone. The pump test may not have stressed the entire fracture zone. Therefore, the high transmissivity determined at PC-1 (Montgomery 2007) may not be representative of large portions of the bedrock aquifer. More wells should be drilled and pump tests performed to better define the fractured nature of the bedrock near the proposed pit.

Table 1: Transmissivity Values for Pump Tests in Montgomery (2007) Converted to Hydraulic Conductivity Based on Screen Length

Well	**Calculated Transmissivity (gpd/ft)**	**Converted Transmissivity (ft^2/d)**	**Screen Length (ft)**	**Hydraulic Conductivity (ft/d)**
PC-1	27,000	3609	820	4.4
PC-2	350	46.8	1303	0.036
PC-3	25	3.3	1160	0.0029
PC-4	10	1.32	1300	0.001

In summary, recharge to the site is a combination of diffuse recharge to bedrock and recharge from the ephemeral channel deposits. Groundwater flows to the east-northeast through low-transmissivity bedrock where it discharges from the site as underflow through the bedrock, predominantly through the Willow Canyon formation. ET from riparian vegetation within the project area is from the perched, ephemeral aquifers in the channel deposits rather than from the regional aquifer. The proposed open pit would lower the regional aquifer water table by up to 2000 feet within the pit area. This would cause a drawdown cone and groundwater to discharge into the pit. Because of the pit depth, this drawdown cone will change the water table for a significant distance from the pit, including potentially the basin fill aquifer southeast of the site in the Cienega Creek watershed. Fractures may increase temporarily the flow to the pit as excavation reaches unanticipated fracture zones.

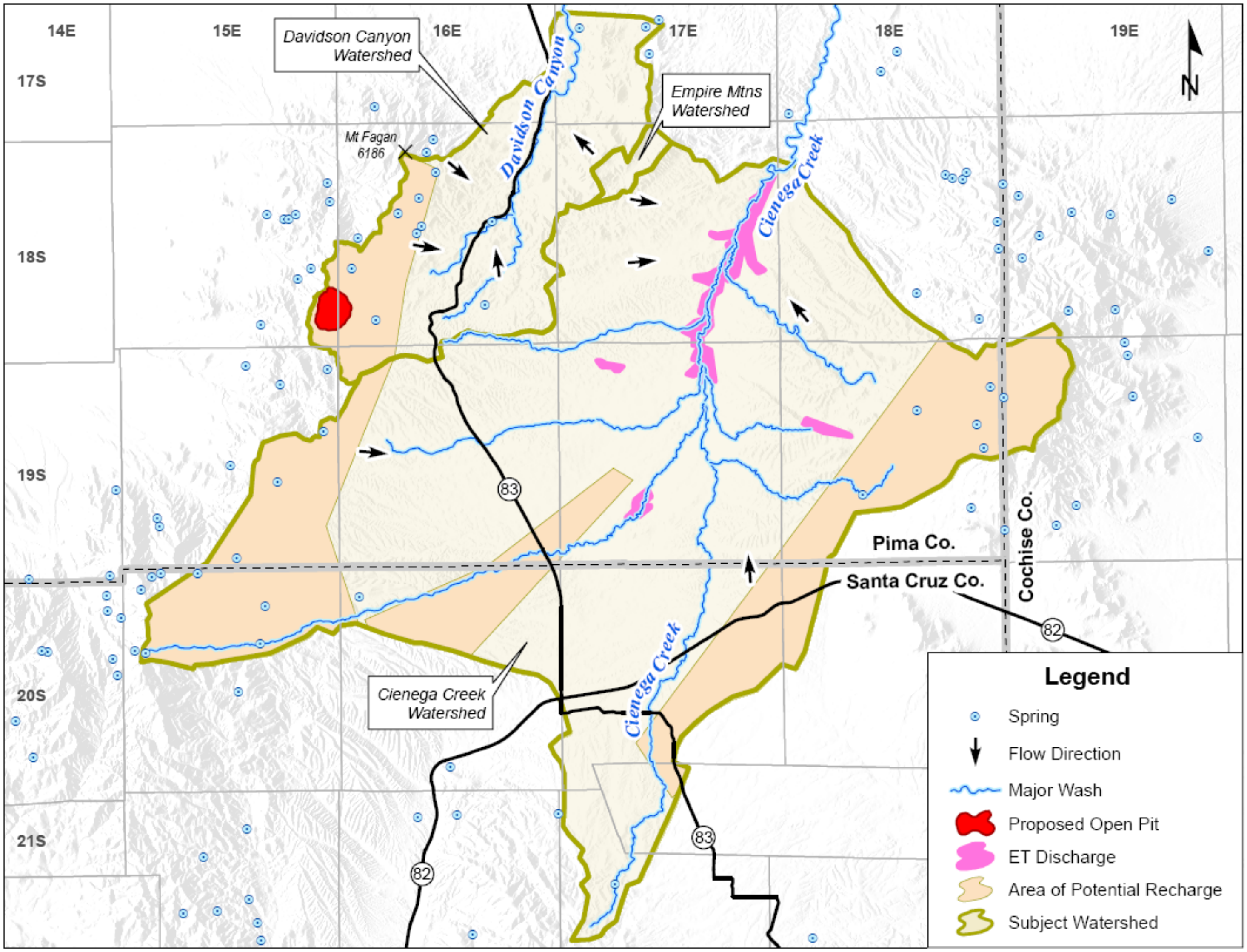

Figure 2: General project area for the Davidson Canyon and Cienega Creek watershed including the conceptual flow model. Arrows indicate the general direction of flow based on the potentiometric surface shown in Plate 1.

Groundwater Modeling of the Project Area and Proposed Open Pit

The conceptual flow model described above was numerically modeled using a MODFLOW-2000 (Harbaugh et al 2000). MODFLOW-2000 is the 2000 edition of the popular MODFLOW (MacDonald and Harbaugh 1988) code. MODFLOW uses a block-centered finite difference approach to balancing the flows between model cells in three-dimensional space. Quantifying preliminary estimates of the effect of the proposed project on flows from the domain near Davidson Spring, the Narrows and to the Cienega Creek channel above the Narrows and the change in the potentiometric surface is a primary objective of this modeling effort.

Model Structure

The model domain, the watershed and aquifers to be simulated, is represented numerically with a structure of cells among which groundwater flow can occur; a three-dimensional model has more than one layer so that groundwater flow can be vertical, among layers. The model simulates flow among the cells and reaches a solution when the water balance among all cells balances. The domain of interest here is the watershed directly affected by the proposed Rosemont project, the Davidson Canyon watershed downstream to Davidson Spring, and the Cienega Creek watershed above the Narrows (Figure 2). The southwestern boundary is the topographic ridge of the Santa Rita Mountains which coincides with a groundwater divide.

The model is completed at a reconnaissance level of detail which reflects its exploratory nature. Detailed flow analysis is not appropriate but the model is sufficiently accurate to simulate the observed heads and fluxes. Future predictions completed with the model will be accurate but imprecise because of the paucity of data with which to fine-tune the conceptual model or the parameters (Bredehoeft 2005). Thus, the two problems being considered are the determination of a basic understanding of the flow system and a prediction of what will occur if a stress caused by the proposed mine is added to the system (Reilly and Harbaugh 2004).

Cell size is selected to balance water balance calculation efficiency with accuracy. Cells must be small enough to parameterize the geologic formations and simulate flow among levels and to springs but must not be too small because of cost. Parsimony was a guiding principle because too much detail can provide a false sense of accuracy in the simulation. Areas near the proposed pit and near the discharge site on Cienega Creek had smaller cells to improve the calculations at those points (Figure 3). The shape of the drawdown immediately adjacent to the proposed pit will be affected by small scale hydrologic features which are not adequately represented in the model, or even known. However, the coarse drawdown caused by the proposed pit, more than 2000 feet from the pre-development water table, can be accurately simulated with respect to the regional aquifer with relatively coarse cells.

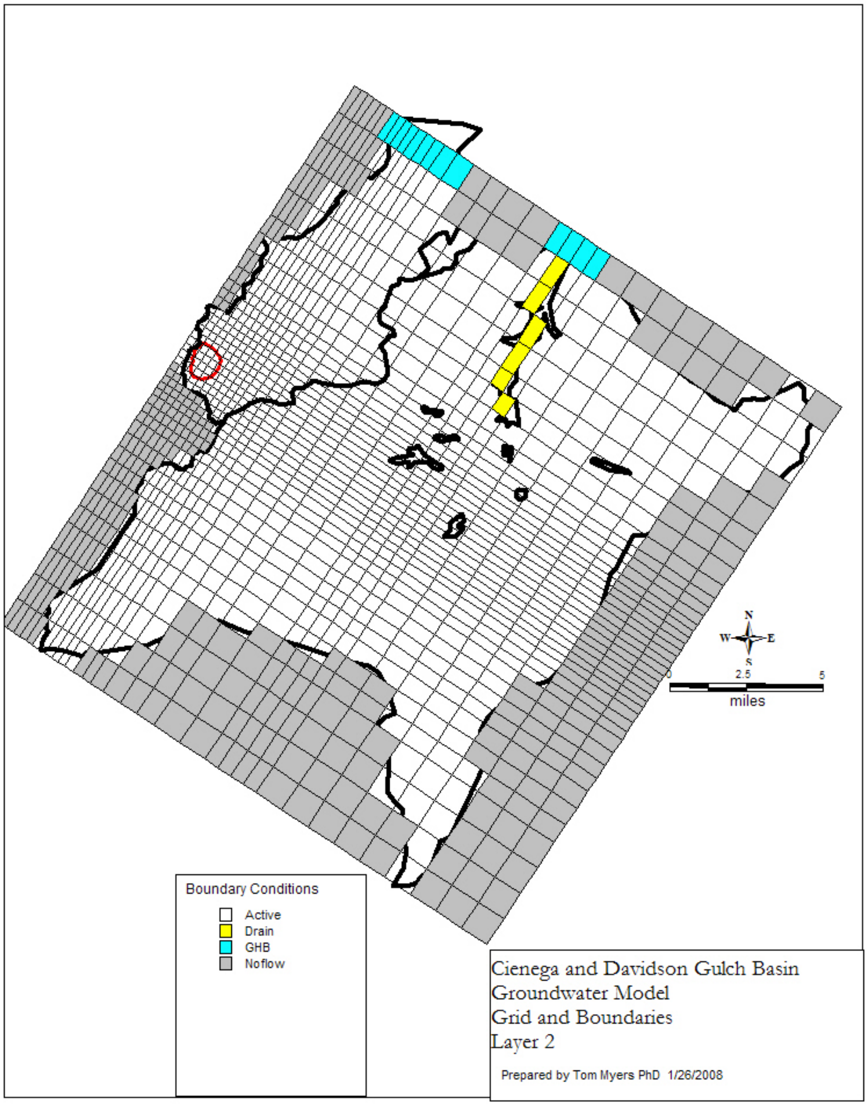

Figure 3: Grid and boundary conditions for the Cienega and Davidson Canyon groundwater model, layer 2. Near the pit, the cells are 1320 feet square and increase to 5280 feet square at locations where stress is not expected to cause sharp change in the head. The column spacing telescopes to 2620 feet near the Cienega Creek channel to improve the modeling of the discharge from that creek and the evapotranspiration near the creek. The general head boundaries (GHB) model underflow from the model domain northeastward. The drain cells model discharge to Cienega Creek.

Six model layers were used to simulate vertical flow through the model domain. Layer 1 was unconfined, layers 2 and 3 were transitional between confined and unconfined, and the lower layers were confined. Layer thicknesses were set as follows. The ground elevation for each model cell was determined from topographic maps, except that the highest elevation is 6000 feet; it is not necessary to specify layer one elevations because evapotranspiration is not being modeled in the mountain areas. Transmissivity would be the product of the hydraulic conductivity and saturated thickness regardless of the specified top of layer. The bottom of the first layer was set initially so that the thickness equaled 300 feet. However, this created transitions in bottom elevation from cell to cell which were more than the thickness. This does not cause computational problems, but layer 1 in the upper elevations would have likely been dry. Therefore, the bottom elevation of layer 1 was smoothed at elevations that, prior to any modeling simulations occurred, were low enough to be saturated. The thickness exceeded 300 feet only in the mountains where the formations dip steeply and similar hydraulic conditions can be assumed for the thickness. Layers 2 and 3 were set 300 feet thick by subtracting 300 from the bottom elevation of the layer above it. Layer 4 is 600 feet thick. The bottom of layer 5 is 2100 feet which resulted in a thickness ranging from 400 to 2000 feet. The bottom elevation of layer 6 is 1000 feet.

Hydraulic Parameter Zones

The parameter zone method of MODFLOW was used to specify the hydrogeologic properties of the geologic formations. Areas of similar material were given the same zone so that the properties could be specified for the entire zone. The formations were as described in the Arizona state geology map (Hirschberg and Pitts 2000) with additional information from Drewes (1971, 1976) and Finnel (1972) (Table 2 and Figure 4).

Table 2: Hydrogeologic Parameter Zone and Geologic Formation (Hirschberg and Pitts 2000). Initial conductivity values are specified.

Zone[1]	**Form.**	**Description**[2]	**K_h (ft/d)**	**K_v (ft/d)**
1	Ocs	Sedimentary rocks	15	7.5
2	Qts	Sedimentary deposits and conglomerate. Consists of loosely to firmly consolidated gravel, sand, and silt, local clay, gypsum, marl, limestone, diatomite, and some intercalated basalt flows and felsic tuff beds.	10	5
3	Ks	Sedimentary and volcanic rocks	1	.1
4	Kvs	Sedimentary and volcanic rocks	1	
5	Tvi	Volcanic rocks	1	.1
6	Pnu	Naco Group Upper formation: includes Rainvalley formation, Concha limestone and Scherrer formation	20	10
7	TKg	Intrusive rocks	.01	.001
8	PZs	Paleozoic sedimentary rocks undivided	1	.1
9	TKr	Volcanic rocks	1	.5
10	pCgr	Intrusive rocks	.001	.0001
11	MZv	Mesozoic volcanic rocks	1	.5

The west side of the study area consists of intrusive rocks (Drewes 1976). Both a site visit (Myers 2007) and detailed projected mapping (WLR 2007) show these formations as almost vertical, with fractures running into the formation. These fractures likely percolate meteoric water to the regional water table as recharge. The Empire quadrangle geologic map indicates the Willow Canyon formation is as much as 3500 feet thick to the northeast of the proposed project (Finnel 1972). Additionally, wells in the Cienega Creek drainage are completed in volcanic rocks under the Qts. This appears to be an extension of Ks or hydrogeologically similar material, such as Kvs (or Kw). Also, the Pima County project area geology map (Johnson and Fergus 2007) shows Tg under Barrel Canyon. Finnel (1972) also shows these outcrops extending onto the ridge east of Barrel Canyon. These outcrops are not shown at the scale of the Pima County geology map. These outcrops suggest an intrusive underlying the ridge and the Qts east of that canyon. These factors influenced the location and parameterization of zones 2 and 3.

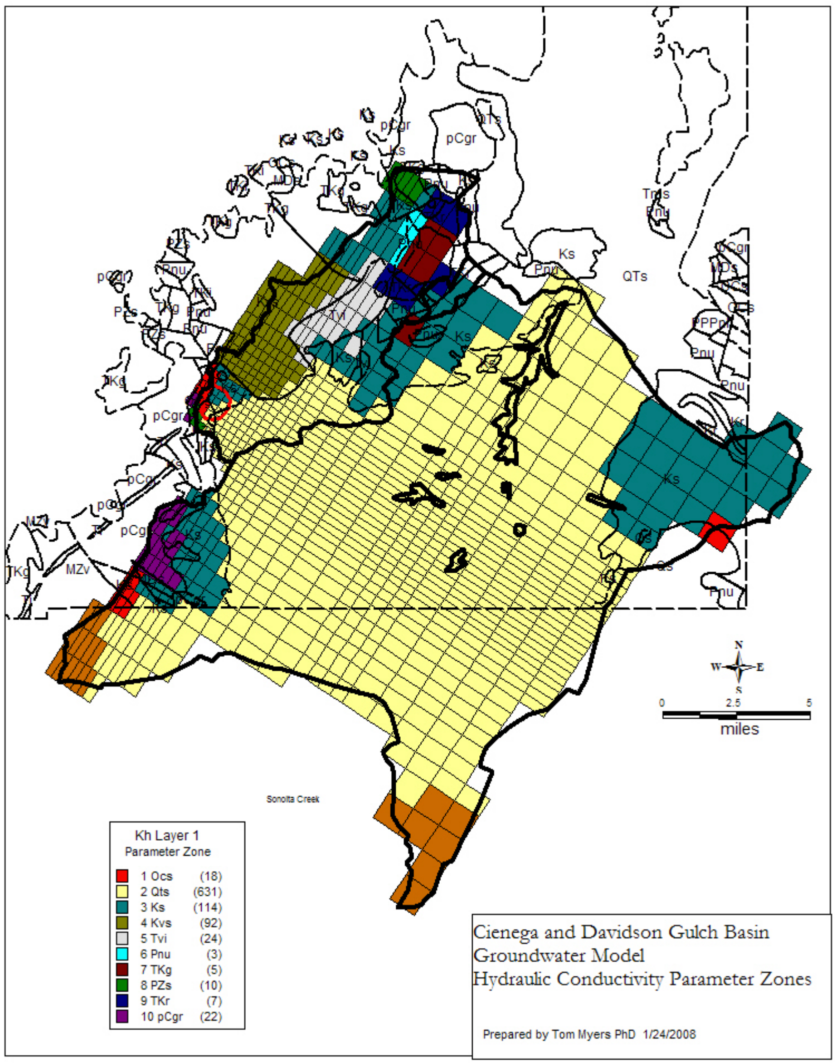

Figure 4: Layer 1 hydraulic parameter zones for the Cienega Creek and Davidson Canyon groundwater model and the geologic formations from Hirschberg and Pitts (2000). See Figure 3 for a description of the grid.

Boundary Conditions

Boundary conditions constrain the model by providing flux and controlling the heads. The inflow to the model is exclusively provided by specified flux, recharge boundaries (Figure 5). Outflow from the model occurs through head-dependent flux boundaries, including the MODFLOW general head boundary (GHB), drain boundary and ET boundary (Figures 3 and 5). GHBs simulate this underflow from the domain through the outlet from Davidson Canyon and through the bedrock under the Cienega Creek Narrows.

Myers (2007) estimated average recharge to the basin above the Narrows on Cienega Creek to be about 1.5 in/y over the mountainous 1/3rd of the area. The total recharge applied to the model over six recharge zones is about 6800 af/y, of which about 5800 af/y is applied to the Cienega Creek portion of the watershed. The amount applied to Davidson Canyon watershed is higher than discussed in Myers (2007) because a larger portion of that watershed is included, including the Empire Mountains and the ridgeline along the Santa Rita's north of the project area. Recharge is a flux to the model specified among five parameter zones (Figure 5). The rates for each zone were adjusted during calibration as discussed below.

Discharge from Davidson Canyon, modeled with a GHB, was estimated to be about 650 af/y (Myers 2007). The conductivity associated with this discharge was 0.31 ft/d, assuming the cross-section at the confluence of McCleary Wash and Barrel Canyon is 1 mile wide by 2000 feet thick (WLR 2007), and the gradient is 0.024. This is consistent with the conductivity values determined for sedimentary bedrock in the Santa Cruz model completed by Nelson (2007). This value was used for determining the conductance in the GHB at the outlet from Davidson Canyon (Figure 3). Also, although the GHB does not directly model the spring flow, changes in flux from the GHB would indicate potential changes to the spring.

GHBs also model underflow from the Cienega watershed through the Narrows. Myers (2007) assumed most of this flow surfaced to Cienega Creek as indicated by groundwater contours. The GHB in the deeper layers have a specified groundwater elevation 80 feet higher than the GHB in layer 1. The conductance and elevations were balanced during calibration so that the boundary did not inadvertently add water to the model. Conductance was also set so that the effect of the boundary would be to force most flow to surface to the drains.

Discharge to the reach of Cienega Creek just above the Narrows was modeled using the drain boundary in MODFLOW-2000. The drain cells were specified in layer 2 because the discharge from this area is from deep bedrock due to an upward gradient (see the contours in Plate 1). If the drains had been specified in layer 1, a head drop would have occurred across the model cell and there would have been little head remaining to drive flow from the drain. This model technique is similar to that used by Prudic et al (1995) for modeling discharge from carbonate springs which discharge to the surface.

Several areas in the Cienega watershed discharge groundwater as ET. Being a steady state model, the ET was specified to be 0.0011 ft/d, or 0.4 ft/y. This is less than the actual rate expected for the phreatophytes in the area (Myers 2007) because it represents a rate for the entire cell rather than just a portion of the cell. The extinction depth was 50 feet.

The southwest and northeast boundaries are topographic divides and modeled as no flow boundaries which prevent flow across the boundary. The southeast boundary is a much lower topographic divide, but is also modeled as no flow even though the geology would be conducive to flow. The likely groundwater divide would prevent cross-boundary flow unless a stress changes the groundwater levels, an outcome which is unlikely because it is too far from the proposed pit to be affected by drawdown.

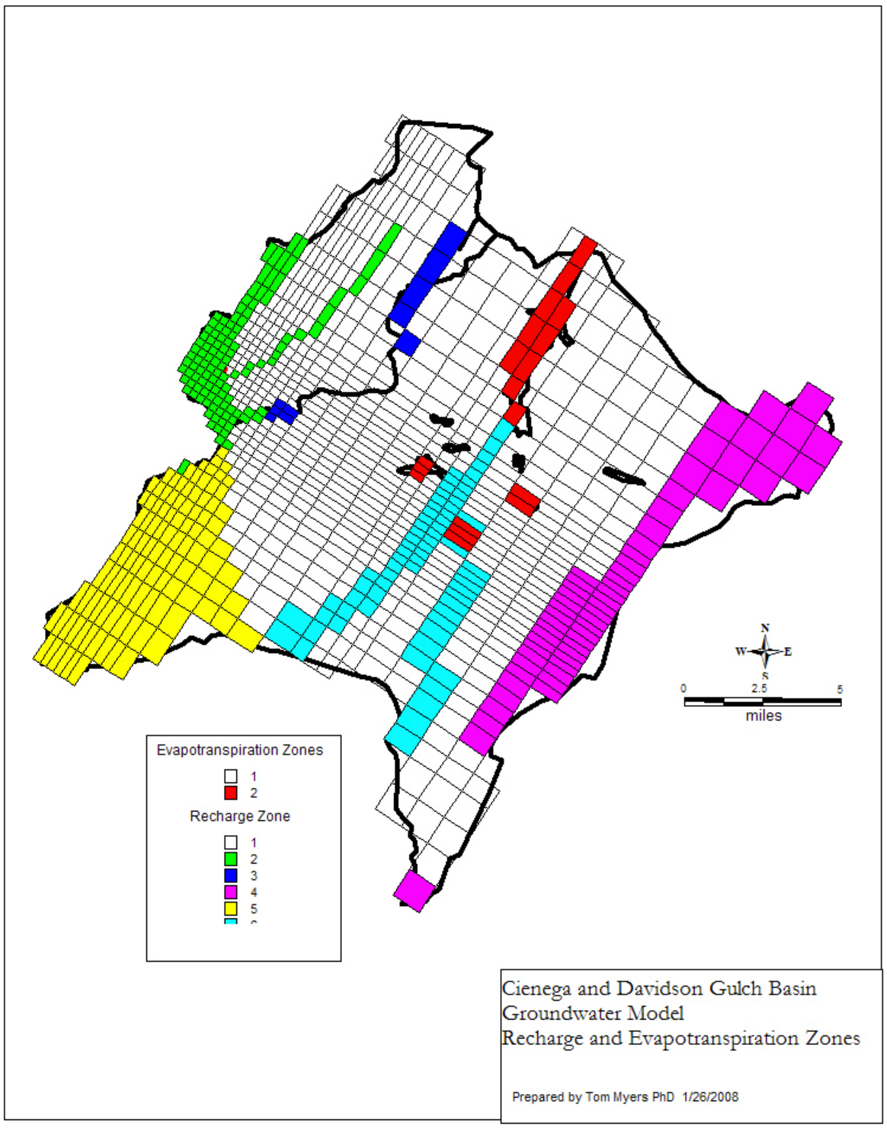

Figure 5: Recharge and evapotranspiration boundaries for the Cienega and Davidson Canyon groundwater model. See Figure 3 for a description of the grid.

Faults are not technically a boundary condition within MODFLOW-2000, but are rather a means of specifying low conductance between cells based on a wall or fault that is much thinner than the width of the cells. Hirschberg and Pitts (2000) show a large fault north and northeast of the Rosemont area, between the Kvs and Ks formations. The large drop in head apparent between the Rosemont pit area, around 5000 ft msl, and in the formation beneath the Davidson Canyon, near 3750 ft msl, indicates a large gradient through the area. A fault was added to the model ½ mile northeast of the pit area to increase the head drop beyond that which could reasonably be simulated with the conductivity parameters zones.

Steady State Calibration

Steady state calibration is the process of adjusting model parameters and specified fluxes, under steady state conditions, so that the modeled heads approximate observed heads and that modeled fluxes approximate observed or estimated fluxes. Hydraulic conductivity and drain conductance values were adjusted to minimize the head residuals. Initial calibration was completed using trial and error. Then, the calibration routine within MODFLOW-2000 (Hill et al 2000) was used to complete the calibration. Initially, the parameters were tested for sensitivity because modeling with parameters that are not sensitive often leads to convergence difficulties (Hill 1998).

Perched or highly fractured systems may cause high residuals because the observation wells may be completed in an aquifer system different from that being modeled. If the connection between the monitored fracture system and the regional flow system is poor, the data obtained from the monitoring well may be useless or worse, misleading. This may be the case with wells D-18-16_01BCC and _13BAA which have observations more than 250 feet below other nearby wells as contoured (Plate 1). Well D-17-17 31ADD is shallow and on a terrace above Davidson Canyon, near a spring which is apparently a perched source. Well D-18-18 33CAD, in the fan below the Whetstone Mountains and on the edge of the model domain, has an observed water level several hundred feet above the water table expected from surrounding wells. Matching the heads in those wells would require an unrealistic conceptual model of local flow in the vicinity of the wells. In the downstream end of Davidson Canyon, it would cause the modeled head to be far below the observed levels in springs such as Davidson Spring. Because water levels in these wells were outside of the domain being modeled, the wells were not used for calibration.

After these obvious high outliers were removed, the parameter estimation routine resulted in a good fit for about 90% of the observation wells, but about twelve remaining wells had high residuals. Most were in layer 1 and at high elevation. Five of them were in a dry area of layer 1 and were therefore not being useful for calibration. For further calibration, these wells were also dropped from use for the same reason as just described: they were mostly in perched systems.

Recharge was tested for sensitivity because the areal average was 1.5 in/y over about 1/3rd of the domain. In reality, recharge would vary significantly more than that. The recharge area was divided into five zones (Figure 5) which initially had the same rate. After initial trial and error adjustment of conductivity rates and adding several parameter zones (31, 41, and 71) to allow for transitions of properties within a given formation, recharge sensitivity was tested using the MODFLOW-2000 sensitivity routine. Zone 6, simulating recharge through stream bottoms in the Cienega basin, was least sensitive; because it simulates recharge through the stream alluvium and riparian zone, the rate spread over a model cell would be low and was therefore decreased to 0.0001 ft/d. This rate decreased the overall recharge to the model, therefore another model run was used to verify that zones 2 and 5 were most sensitive. During this simulation, the parameter estimation routine made the rate through zone 4 negative; therefore it was also set to 0.0001 ft/d. Parameter estimation doubled the rate in zone 5, so it was set to 0.0006 ft/d but still tested for sensitivity. The total recharge equaled about 6800 af/y to the model domain.

The most sensitive parameters are the horizontal hydraulic conductivity for zones 2, 3, 4, 5, 6 and 9 and the vertical hydraulic conductivity in zone 4 (Figure 6). Using a series of sensitivity analyses with just these parameters, the hydraulic conductivity parameters were adjusted to minimize the sum of squared residual.

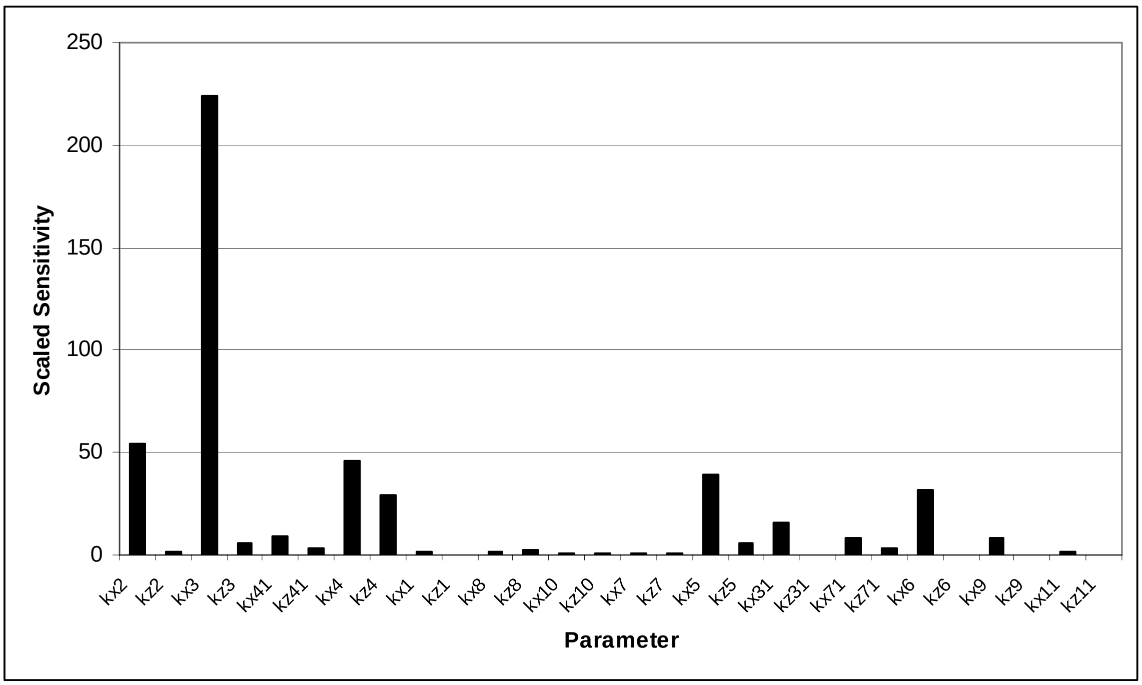

Figure 6: Sensitivity analysis of hydraulic conductivity parameters for the Cienega Creek and Davidson Canyon groundwater model.

The conductivity parameter values were adjusted through a series of parameter estimation routines (Hill et al 2000). After each adjustment, parameter sensitivity was considered to determine whether the parameters remained sensitive. Calibration ended when the sum of residuals squared stopped decreasing significantly for each new model run. The final SSR was 25,700, a decrease from the SSR resulting from trial and error calibration of about 1,600,000. The final mean, standard deviation and variance was -4.85, 49.7 and 2470, respectively. Based on variance, none of the specific layers had a significantly higher variation (Table 3), with all of the layers having statistics similar to that of the overall data set. The scatter plot shows a good fit with no tendency for higher or lower residuals with the observation level (Figure 7).

Table 3: Statistics of the residuals for each model layer.

	Layer 1		***Layer 2***		***Layer 3***		***Layer 4***		***Layer 5***	
	Obs	Res	Obs	Res	Obs	Res	Obs	Res	Obs	Res
Mean (ft msl)	4558	3	4669	-26	4590	14	4614	-5	5007	14
Std Err (ft)	31	8	32	9	47	9	55	13	53	17
Median (ft msl)	4598	5	4704	-26	4587	20	4581	-1	5031	32
Std Dev (ft)	189	52	179	49	176	33	218	52	119	37
Var (ft^2)	35762	2675	32057	2406	31060	1085	47694	2686	14126	1406
Skew	-0.6	-0.6	-0.3	0.2	-0.1	-0.6	0.9	-0.7	-0.3	-0.9
Range (ft)	864	199	749	208	576	115	855	207	290	93
Min (ft msl)	4070	-119	4279	-119	4321	-52	4307	-135	4854	-42
Max (ft msl)	4934	80	5028	89	4897	62	5162	72	5143	50
Count	38	38	31	31	14	14	16	16	5	5

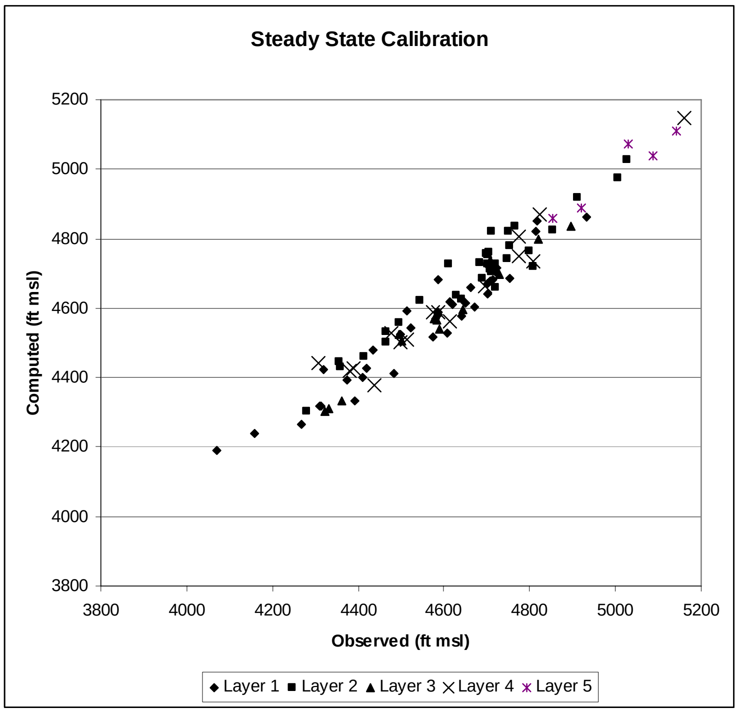

Figure 7: Scatter plot of computed and observed groundwater levels for the Cienega Creek and Davidson Canyon groundwater model.

The residual mean/median in layer 2 was negative (Table 3) which reflects a tendency for the model to predict water levels that are slightly high for that layer; the tendency for layer 3 is opposite that. The tendency for residuals to be either positive or negative as a function of layer suggests the vertical gradient differs slightly from the observed. The primary location of these tendencies among layers is the lower end of Davidson Canyon (Figure 2) where there is converging underflow from the Santa Rita Mountains and Empire Mountains. It could be due to seasonal changes in the shallower wells not observed in the deeper wells. The magnitude of the variation from 0 is small compared to the almost 750 and 550-foot head ranges in layers 2 and 3, respectively, and indicates the trend will cause little error in the simulations.

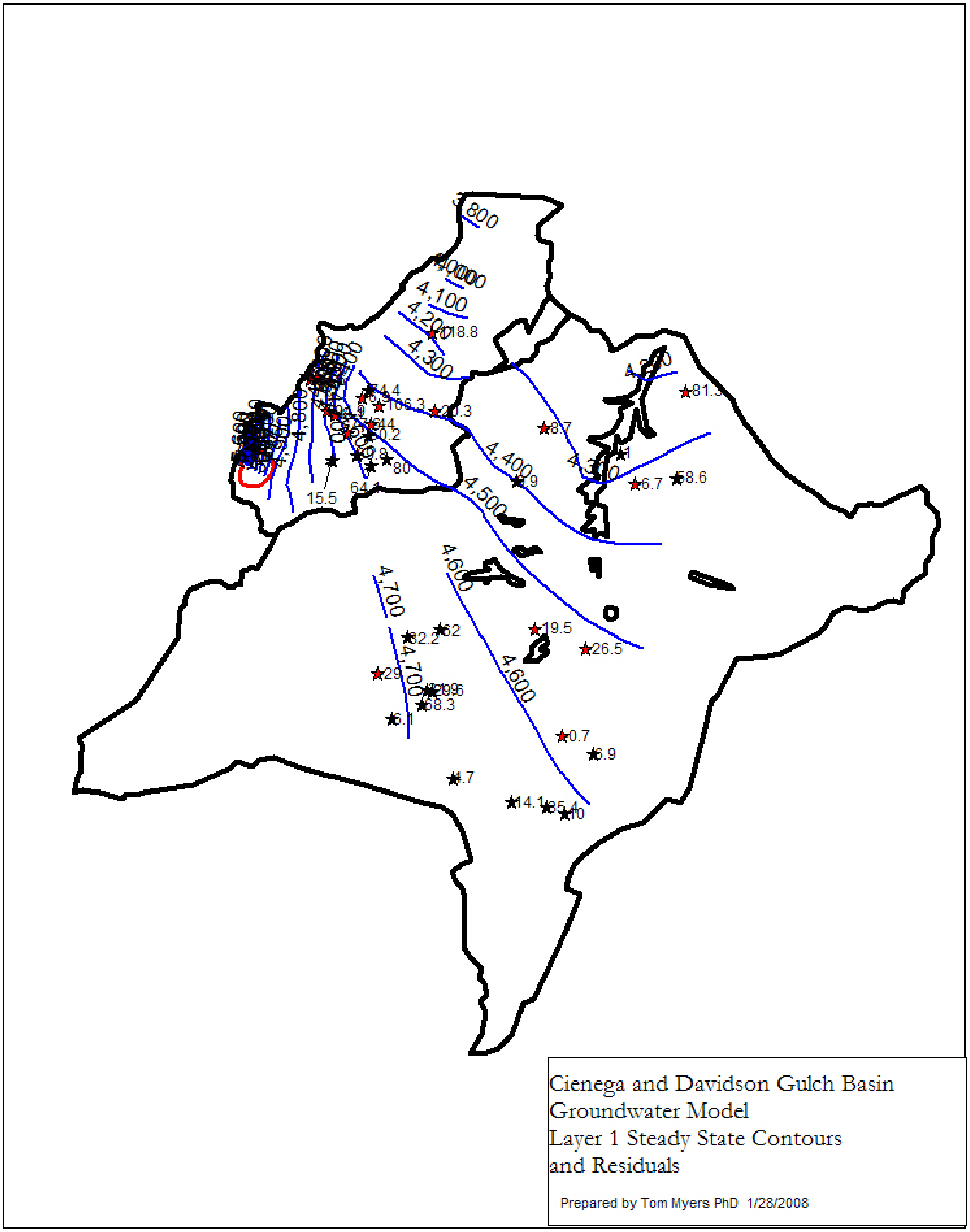

Figure 8: Steady state groundwater contours and residuals for layer 1, Cienega Creek and Davidson Canyon groundwater model. Red stars represent negative residuals where computed value is less than the observed value.

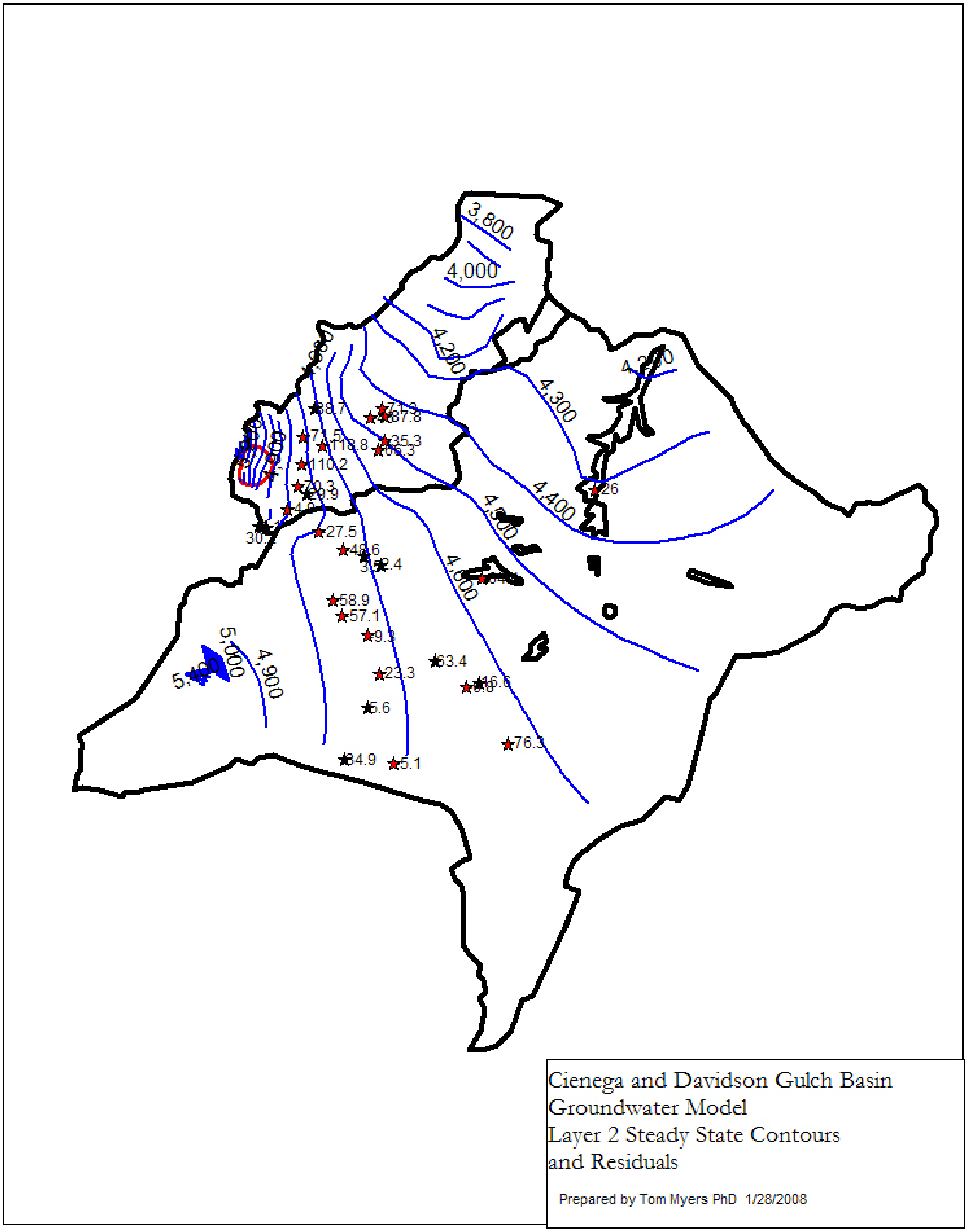

Figure 9: Steady state groundwater contours and residuals for layer 2, Cienega Creek and Davidson Canyon groundwater model. Red stars represent negative residuals where computed value is less than the observed value.

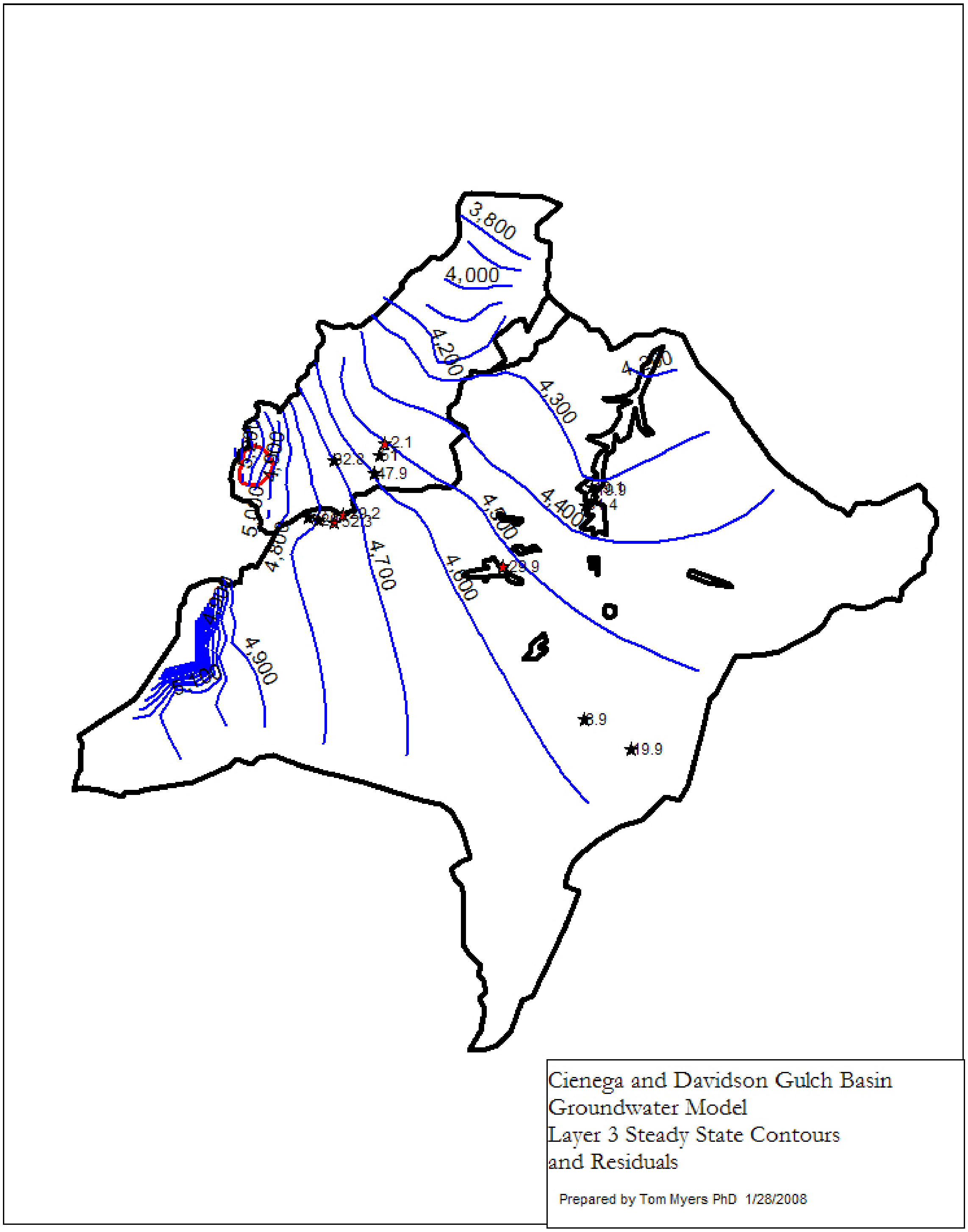

Figure 10: Steady state groundwater contours and residuals for layer 3, Cienega Creek and Davidson Canyon groundwater model. Red stars represent negative residuals where computed value is less than the observed value.

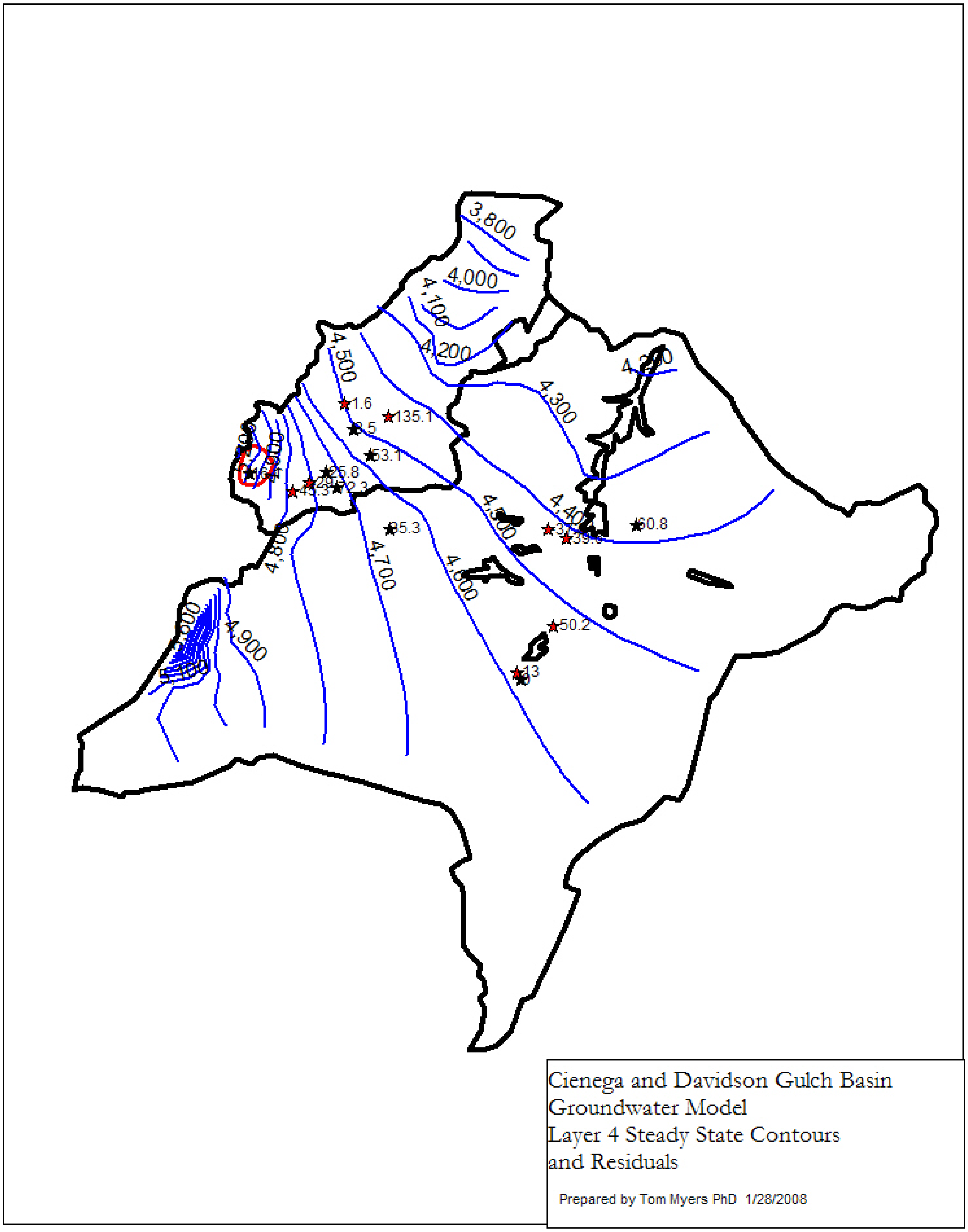

Figure 11: Steady state groundwater contours and residuals for layer 4, Cienega Creek and Davidson Canyon groundwater model. Red stars represent negative residuals where computed value is less than the observed value.

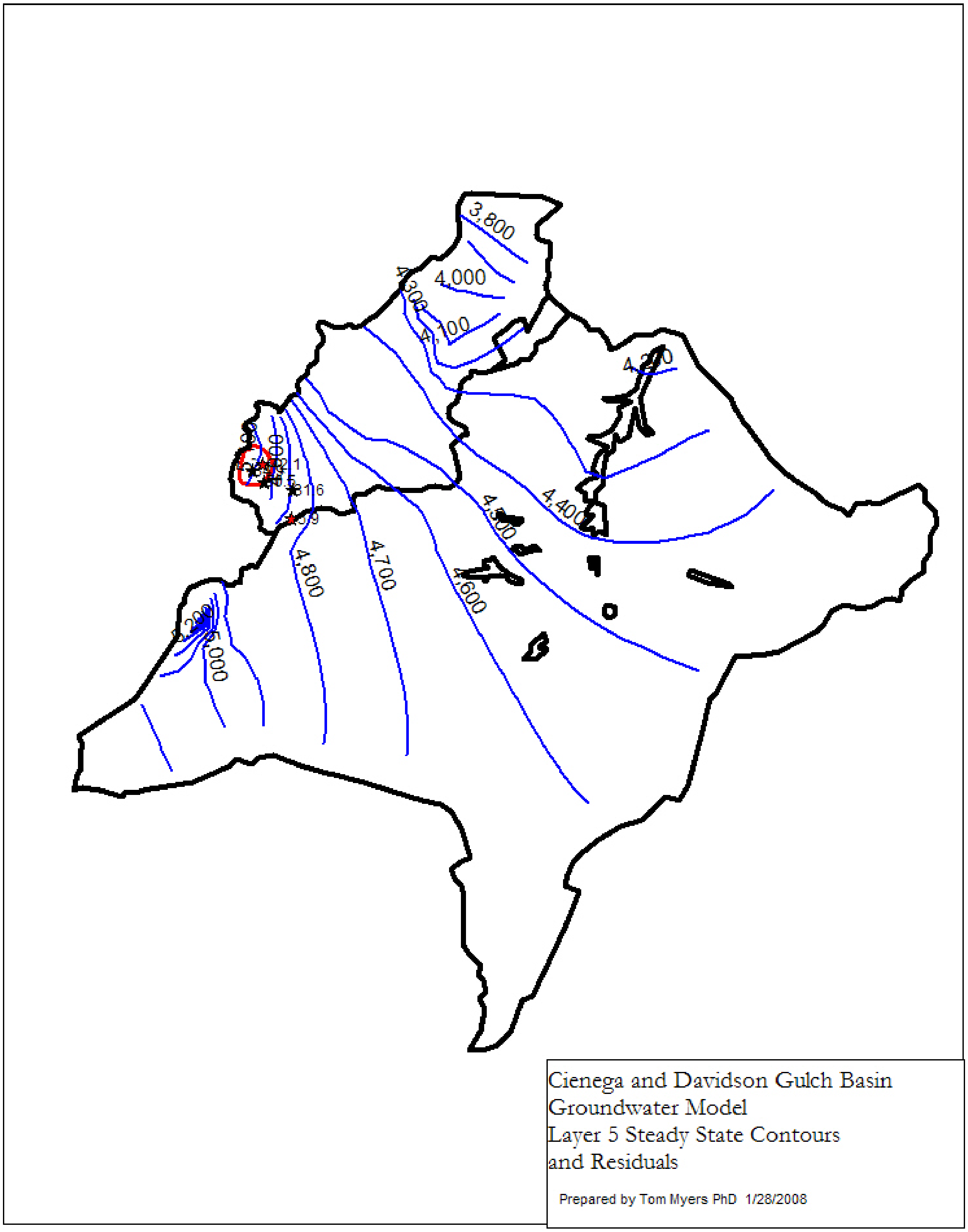

Figure 12: Steady state groundwater contours and residuals for layer 5, Cienega Creek and Davidson Canyon groundwater model. Red stars represent negative residuals where computed value is less than the observed value.

Head values in the mountains, both in the south near Mt. Wrightson and in and west/northwest of the proposed pit, reflect a recharge scenario (Figures 8 through 12). The head levels in the upper layers, which are not unsaturated, are several hundred feet higher than in the lower layers. The low conductivity at the point of recharge influences the mound. In the area of the proposed pit, the water levels correspond within tens of feet with observed values. A cross-section through the pit also shows the vertical gradient (Figure 13). South along the Santa Rita Mountains, the water level in upper layers exceeds 6000 ft msl but is several hundred feet lower in deeper layers (Figure 14).

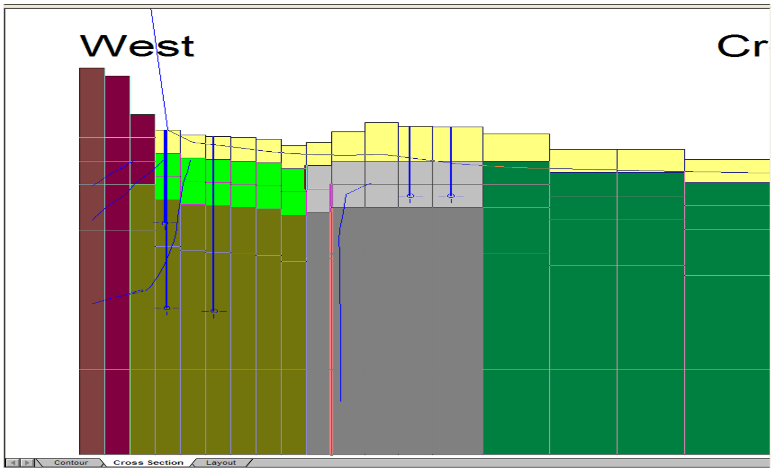

Figure 13: Screen capture of a cross-section through row 20 at the proposed pit. Water level contours show vertical gradient. The cells are 1320 feet wide on the west and increase to 5280 feet wide on the east.

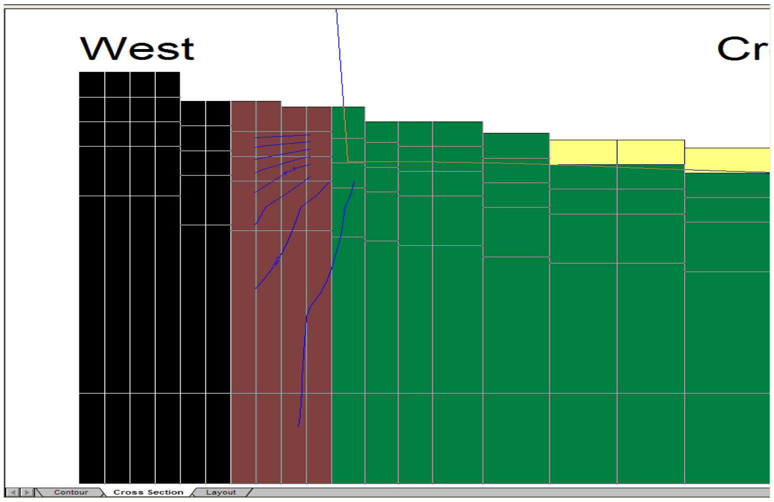

Figure 14: Screen capture of vertical cross-section through row 34 southwest of the proposed pit showing a vertical gradient of several hundreds of feet between layers. The cells are 1320 feet wide on the west and increase to 5280 feet wide on the east.

The steady state contours developed with this groundwater model all show flow to the north and northwest (Figures 8 through 14). A groundwater divide coincides with the topographic ridge between the Davidson Canyon and Cienega Creek watershed. Just south of the proposed open pit, the groundwater ridges about 50 feet. Further north, near the Empire Mountains, the groundwater ridges about 100 to 150 feet above the level in the surrounding valleys. Flow converges on Davidson Canyon but water levels remain below the ground surface, as they should because there is no discharge from the regional aquifer. Flow also converges on Cienega Creek where the water levels reach the ground surface, as they must, and discharge to the drain cells and ET boundaries. The steady state contours and flow direction confirms the model accurately simulates the conceptual flow model for the model domain.

Steady State Water Balance

It is essential that groundwater fluxes balance appropriately for the model to be considered calibrated. More than 4000 af/y discharges to the drain cells simulating Cienega Creek and about 1200 af/y discharge to ET in the Cienega Creek watershed. The total is almost 5500 af/y which is just 300 af/y less than estimated by Myers (2007). Interflow through the bedrock beneath the Narrows approximates 500 af/y which, when summed with the discharge and ET, indicates the recharge to the Cienega Creek watershed is about 6000 af/y.

Approximately 850 af/y discharges north from the Davidson Canyon area. This exceeds by 200 af/y Myers' (2007) estimate for interflow but also includes additional recharge occurring on the Empire Mountains. The relatively accurate breakdown of flux among watersheds is due to the accuracy of the sensitivity analysis that had been completed on recharge to the system.

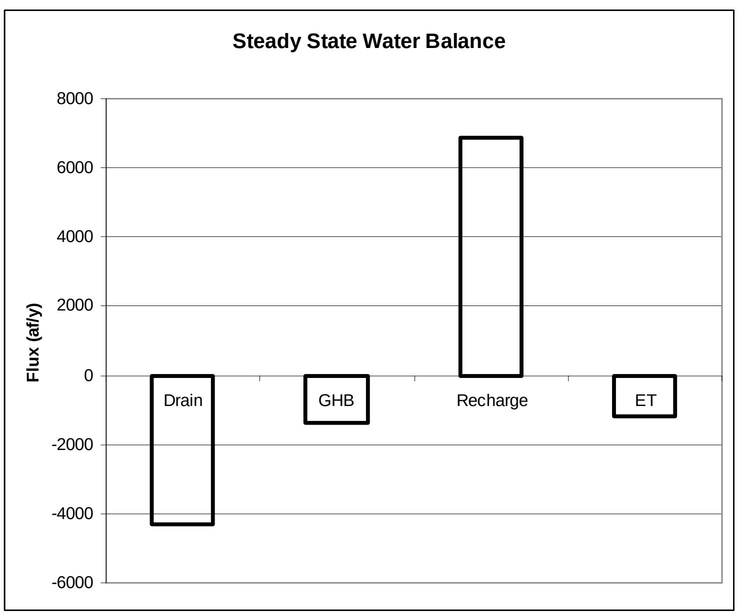

Figure 15: Groundwater model fluxes for the steady state water balance, Cienega Creek and Davidson Canyon groundwater model.

Parameter Values

Table 4 shows the final calibrated hydraulic conductivity values. There was no data for transient calibration, therefore the storage parameters were set based on textbook values (Anderson and Woessner 1992). The specific storage values are similar to those determined for low permeability sandstone by Pool and Dickinson (2007). Montgomery (2007) (Table 4) found the storage coefficients determined from drawdown at wells PC-2 and PC-4 are $8x10^{-4}$ and $2x10^{-4}$, respectively. They are not directly comparable to the specific storage values used for this analysis because they are storativity and therefore depend on the aquifer thickness, which is unknown. Screen thickness is an inappropriate substitute for aquifer thickness because it could result in a specific storage that is three orders of magnitude off. A sensitivity analysis to the selected values was tested as part of the analysis.

Table 4: Final calibrated hydraulic parameters including horizontal and vertical conductivity (K_h and K_v), storativity (S_s), and specific yield (S_y). Figure 4 shows the parameter zones for layer 1.

Zone	K_h (ft/d)	K_v (ft/d)	S_s (ft^{-1})	S_y
1	0.002	0.0001	0.000011	0.27
2	0.4496	0.02	0.000021	0.21
3	0.4567	0.5797	0.000011	0.27
4	0.038	0.000608	0.000011	0.27
5	0.8021	0.01	0.000011	0.21
6	0.23	0.04	0.000011	0.14
7	0.000119	0.00001	0.000001	0.26
8	0.001	0.0001	0.000011	0.21
9	1.521	0.08	0.000011	0.21
10	0.002	0.0001	0.000001	0.26
11	0.4	0.08	0.000011	0.21
21	0.4	0.04	0.000021	0.21
31	0.01958	0.02	0.000011	0.27
41	0.001839	0.0011	0.000011	0.27
71	0.0243	0.001	0.000001	0.26

Transient Modeling

The model simulation was taken to 120 years. The time frame was based on the first 20 years representing development of the pit, as described below, with a 100-year post-development period. Each year was one stress period, 365 days with 20 time steps and a 1.2 multiplier. The 21^{st} stress period was 100 years (36500 days) with 40 time steps and the same multiplier. The MODFLOW program wrote output every 5 time steps which for the first 20 years was at 15, 51, 141 and 365 days for each year (0.04, 0.14, 0.39 and 1.0 years, respectively). The multiplier causes the time steps to be shorter at the beginning of the stress period, when the model applies the new stress, and to lengthen throughout the period. After running the 120-year scenario, the model was also run for an 8000-year post-development period to determine the time to steady state and what the water levels and fluxes would be at steady state. The 8000-year period had 80 time steps and a 1.06 multiplier to decrease the time-step length and avoid problems with non-convergence that occurred in the last several time steps of the 8000-year period.

Simulation of Mine Development Plan

The pit development as described in the July 2007 plan of operations (Westland 2007) was imposed on the model as described in this section. The plan is not very specific, but it describes seven phases over 20 years and postulates a constant mining rate at 27,375 ktons/year of sulfide ore and about 117,000 ktons/yr of total rock (Westland 2007, Table 2). For modeling the impacts of pit development, the most important aspect is the depth and area of the pit at specific time periods. The plan of operations includes pit configurations at 5, 10, 15 and 20 years, respectively, but these figures do not specify mining phases. The pit bottom will be 4250 ft msl after five years and will bottom at 3150 ft msl. The total area at ground surface will be about 700 acres and the pit bottom will be about 300 acres.

Westland (2007, Figure 2-3-3 through 2-3-7) shows the development of the open pit. The first several phases remove more overburden, hence the large strip ratio (Westland 2007, Table 2), which disturbs almost the entire pit area after five years (Westland 2007, Figure 2-3-3). Mining deepens the pit over the next 15 years; the figures show almost a constant rate of deepening.

The groundwater level in the pit area slopes from about 5400 to 5000 ft msl. The bottom elevation of model layer 1 in the pit ranges from 5100 to 4800 ft msl, from west to east. The bottom elevation of layers 2, 3, 4, 5 and 6 ranges from 4800 to 4600, 4500 to 4300, 3900 to 3700, 2100 to 2100, and 1000 to 1000 ft msl, respectively. The pit therefore will be excavated and lower the water table through layers 1 through 4 and into layer 5. The bottom layer will not be affected by having the potentiometric surface drawn into the layer by pit excavation.

The preferred modeling technique for lowering the water level below a given level in a layer is to use a drain boundary. Drain boundaries have been used to simulate the construction and dewatering of mine shafts (Cox 1998), coal-bed methane fields (Myers 2006), in addition to their common use for modeling springs and discharge to streams (Anderson and Woessner 1992). A drain boundary obviates the need to specify a pumping rate if dewatering wells were used. Because the inflow is dispersed around the perimeter of the pit and is expected to be low, a system of dewatering wells may not be necessary. It is possible that a specific fracture zone will be pumped until it stops producing groundwater. For initial modeling, drain cells will remove the amount of water necessary to lower the water table.

The potentiometric surface for a drain is specified at the beginning of each stress period and the conductance was set to draw sufficient water from the model domain to lower the potentiometric surface to the specified level by the end of the period. The drains remove from storage the water necessary to lower the water level to the specified level, including the water that within the pit that is being excavated. The drain flux is a function of the gradient, or the difference in water level in the cell and specified for the drain, and the conductance of the drain. For the cells within the pit, the conductance must allow the entire layer to be drained.

The water level in the drains simulating the pit development will be set at 4250 ft msl after five years and 3150 after 20 years based on the plan of operations. Water levels specified for other years will require assumptions. It will be assumed that the water table within the pit area will be reached during the second year, therefore the drain level was set at 5000 feet at the beginning of the second year. The water level was assumed to vary linearly between years 2, 5 and 20 (Table 4). The number of drain cells will also vary with layer, with 14 cells in layer 1 decreasing to 7 cells in layer 5 (Table 5), approximating 300 acres; of the initial 14 drain cells in layer 1, cells were removed from the east side of the drain with depth to simulate the smaller pit surface area at deeper depths. The drain cells become active only once the excavation reaches the layer, not just when it drops below the potentiometric surface within the layer; this is because it is possible for confined conditions under the pit bottom to cause pressure in the deeper layers and for there to be vertical flow from layers beneath the pit to the pit. These assumptions adequately represent the development of the pit, especially because the actual mining rate will vary based on mineral values.

Table 5: Specified layer bottom and drain cell elevations by year or stress period which represents the level to which the pit would be excavated. All elevations ft msl.

Year	Period	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Layer Bottom		4800	4600	4300	3700	2100
2	1	5000				
3	2	4800	4750	4750		
4	3	4800	4600	4500		
5	4	4800	4600	4300	4250	
6	5	4800	4600	4300	4176	
7	6	4800	4600	4300	4100	
8	7	4800	4600	4300	4030	
9	8	4800	4600	4300	3960	
10	9	4800	4600	4300	3880	
11	10	4800	4600	4300	3810	
12	11	4800	4600	4300	3740	
13	12	4800	4600	4300	3700	3660
14	13	4800	4600	4300	3700	3590
15	14	4800	4600	4300	3700	3520
16	15	4800	4600	4300	3700	3440
17	16	4800	4600	4300	3700	3370
18	17	4800	4600	4300	3700	3300
19	18	4800	4600	4300	3700	3220
	19	4800	4600	4300	3700	3150
Number of pit drain cells per layer.		14	12	10	8	7

The layer bottom elevation is the deepest layer within the pit. The minimum drain elevation is the bottom elevation in a specific cell.

Seven locations were chosen to monitor the potentiometric surface during the transient simulation of mine development (Figure 16). Two of them, Rosemont Pit and West Side

Rosemont Pit, were within the pit to monitor the water level during excavation. Downgradient Rosemont Pit was about ¾ mile north of east from the pit. Davidson Canyon monitoring site was about three miles downstream the canyon from the proposed pit. The Watershed Divide side was on the divide between Davidson Canyon and Cienega Creek watershed about 1.2 miles southeast of the pit. Empire Mountains monitoring sites was on the divide in the south end of the Empire Mountains. Cienega Creek monitoring site was in Cienega Creek.

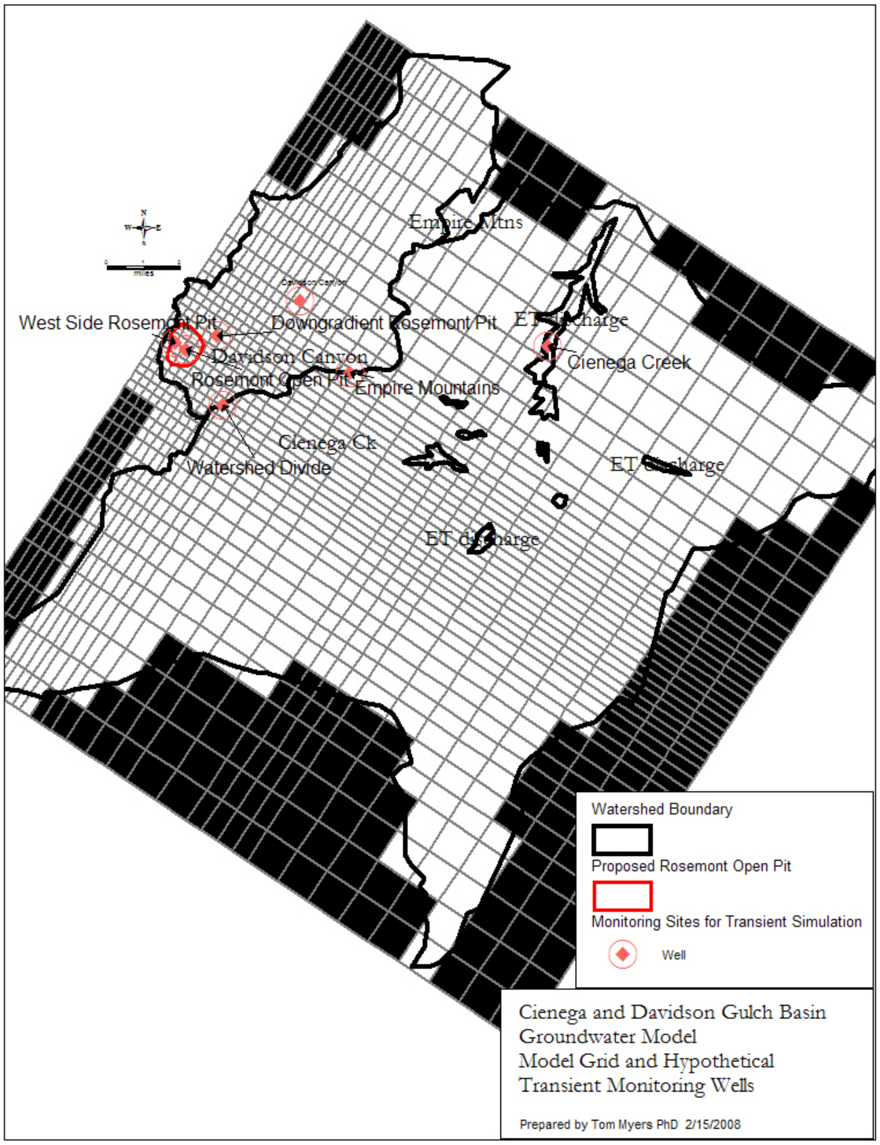

Figure 16: Sites used to monitor the transient simulations. See Figure 3 for a description of the grid.

Simulated Results of Mine Development

Drawdown Within and Flux to the Excavated Pit

Modeled drawdown within the pit occurs as rapidly as excavation reaches saturated material. As designed, drawdown within the pit reaches the level specified by the end of the year the level is specified for within the drain cell (Figures 17 and 18). Water level hydrographs within the pit become horizontal at the elevation of the bottom of the layer once the layer has been completely excavated and desaturated. The Figure 17 monitoring point lies east of the deepest point in the pit, therefore the hydrograph for layer 5 does not reach the pit bottom (Figure 17). At year 20, the level 5 hydrograph is at about 3700 ft msl after which it decreases to 3500 ft msl by about year 80. This point is within 2000 feet of the east face of the proposed pit at a deep level. The hydrograph for the monitoring point on the west side of the proposed pit, which is near the deepest portion of the pit, in layers 4 and 5 reaches the excavated level (Figure 18).

Layer 6 is below the pit and water levels at points under the pit reflect an upward gradient driving flow into the pit. From the beginning of mining to year 120 in layer 6, the potentiometric surface beneath the pit drops from about 5200 to 4300 ft msl (Figures 17 and 18) which is many hundreds of feet higher than the excavated level in layer 5. Once the pit has been excavated into layer 5, flux into the pit from layer 6 begins (Figure 19). It peaked at about 87 af/y 2.5 years after construction ended after which the potentiometric surface beneath the pit continued to lower (Figures 17 and 18) while that within the pit equals the pit bottom elevation (Figure 18).

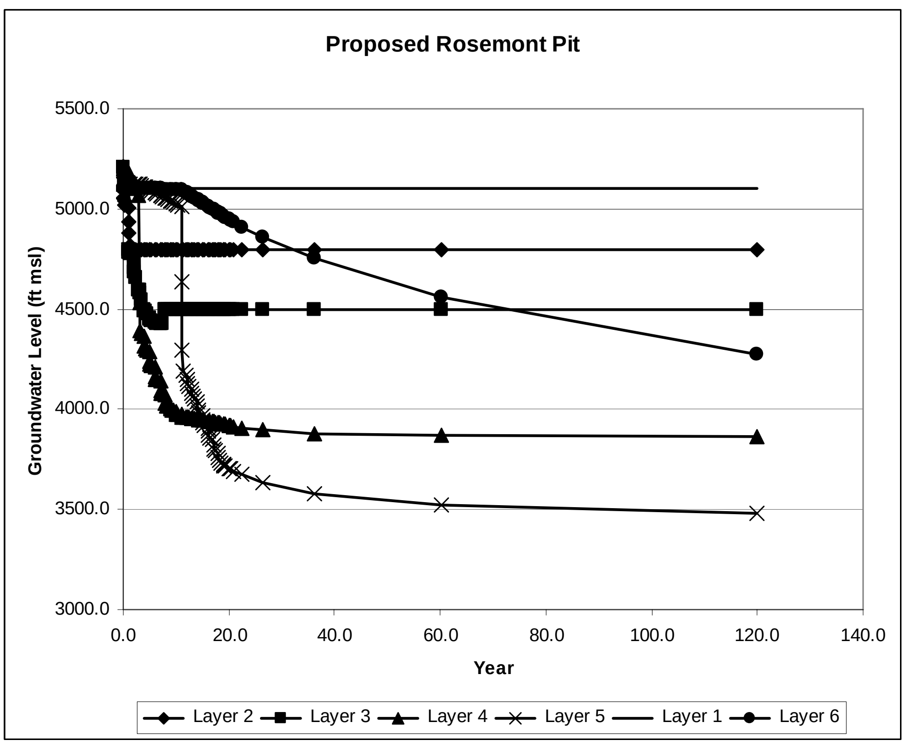

Figure 17: Water levels in various model layers in the proposed open pit. See Figure 16 for the location of the monitoring point.

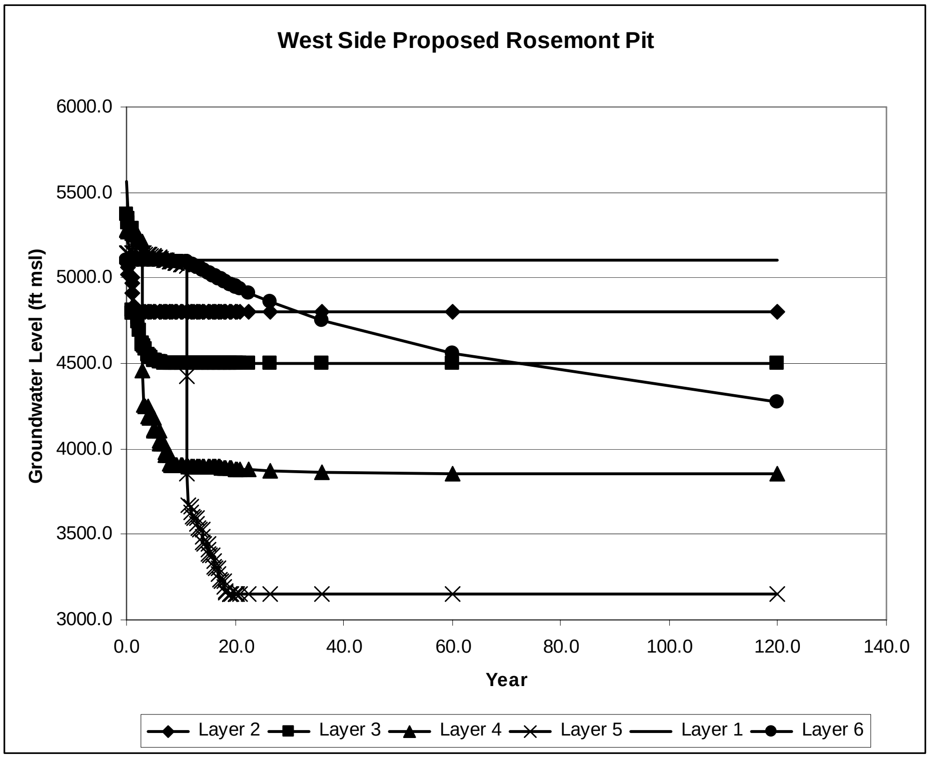

Figure 18: Water levels in various model layers near west side of the proposed open pit. See Figure 16 for the location of the monitoring point.

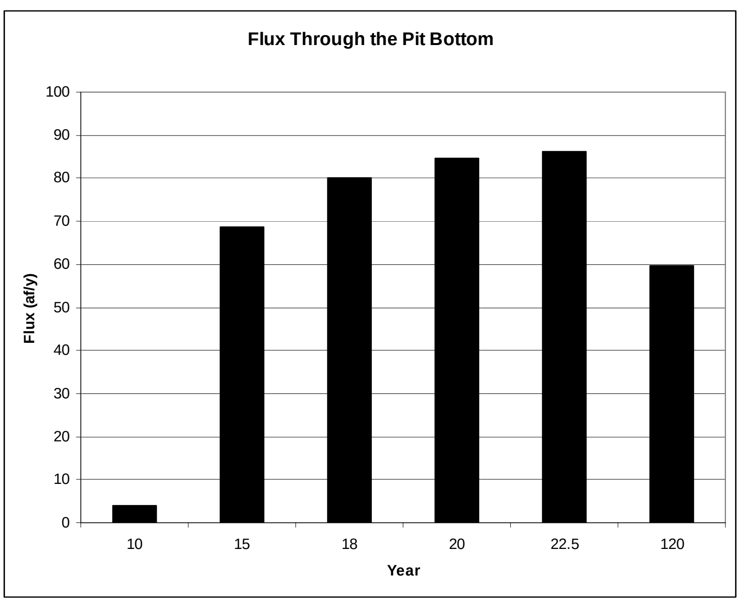

Figure 19: Flux (af/y) from layer 6 to layer 5 through 16 cells corresponding with the proposed open pit.

Initially the dewatering rates were very high (Figures 20 and 21) because they represent the extraction of saturated overburden in model layer 1. Similar results occur at the beginning of other years as layers transition from confined to unconfined and dewatering drains of the water from the media within the mine. In reality most of this water would be removed by excavation as reflected by the amount removed from storage as a proportion of the entire modeled discharge from the drains (Figure 22). It is not dewatering pumpage, although there could be a temporary disposal or discharge problem; the operator may need to establish temporary dewatering wells in fracture traces such as those found by Montgomery (2007). The high groundwater volume removed is, however, a deficit created in the groundwater system, but one that will never be refilled unless a pit lake forms. Over the long term, it is groundwater that may no longer flow to the outlet of the basin.

Groundwater that would be intercepted from the flow system would be drawn from the area surrounding the pit and from recharge that would have occurred within the pit. Initially, most of the flow from the area surrounding the pit to the pit is from the north and south with just a small proportion from the east and west (Figure 23). At the end of year 1, total inflow is a little less than 200 af/y and recharge is a little less then half of that. After the first ten years, inflow approximates 250 af/y. Flow from the east and west increased the most (Figure 23). Between years ten and fifteen, inflow to the pit doubles to about 500 af/y with most of the additional inflow from the west and north (Figure 23). This reflects the pit excavation reaching layer 5 and additional inflow from that layer (Figure 21). Combined with recharge of about 80 af/y, the pit has begun to capture all of the recharge in the upper portion of the Davidson Canyon watershed (580 af/y according to Myers (2007)).

The amount of water removed by drain cells representing the pit initially exceeded the inflow from around the pit by more than an order of magnitude (compare Figures 22 and 23) and represents the removed of storage within the pit. Once the pit excavation reaches deeper layers after ten or more years, drainage of storage decreases substantially and the inflow exceeds the amount removed from storage by a larger proportion (Figure 23).

There will be three long-term sources of flow into the pit after construction ceases. A substantial flow into the pit from below, approximating 87 af/y, will continue essentially into perpetuity (Figure 19). The inflow from the sides will peak at about 580 af/y, or most of the recharge in the upper portion of Davidson Canyon. Together, the total inflow will approximate 670 af/y. Spread across 300 acres expected to be the pit bottom, the rate is about 2.3 ft/y which is substantially less than the evaporation rate at this latitude and elevation. The expected inflow rate combined with rainfall and runoff from within the pit will support only a seasonal pit lake. Low points or sumps in the bottom of the pit will collect inflow and rainfall within the pit and possibly form deeper ponds with a small enough surface area to last through the dry seasonal periods. Water would not likely seep from the pit to degrade nearby groundwater because the gradient would be towards the pit.

Total inflow decreased by a quarter between year 20 and year 120. Decrease in inflow from the west is about 80 percent of the total decrease (Figure 23). This reflects the proximity of the western basin boundary in that the groundwater is drained within the time period. The steady inflow from the west reflects the pit intercepting the recharge between the pit and the ridgeline no flow boundary. Inflow from the north and south had decreased just slightly which reflects the expansion of drawdown in those directions. Inflow from the east increased almost 50 percent because of the expanding drawdown in that direction.

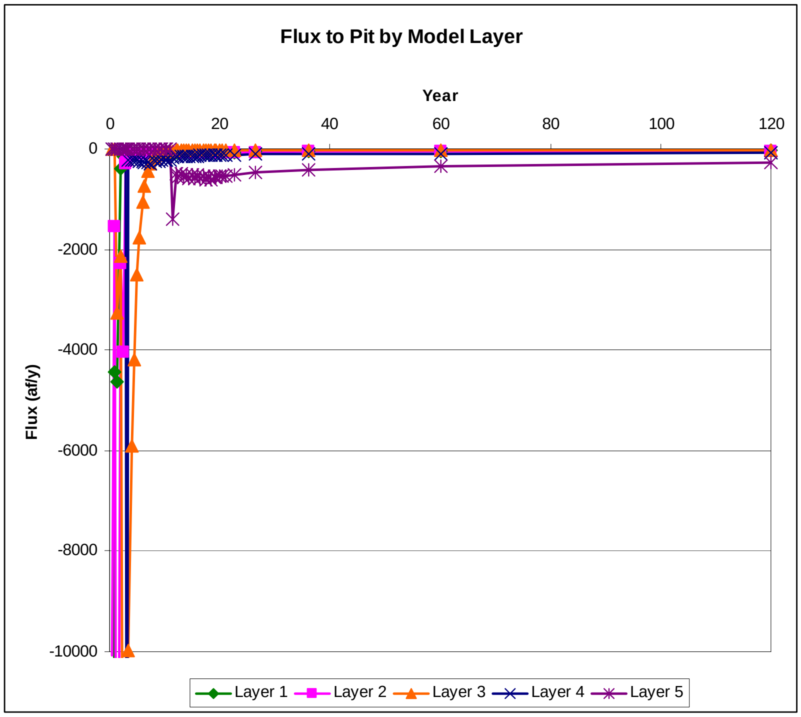

Figure 20: Flux (af/y) from the drain cells representing the pit, by layer.

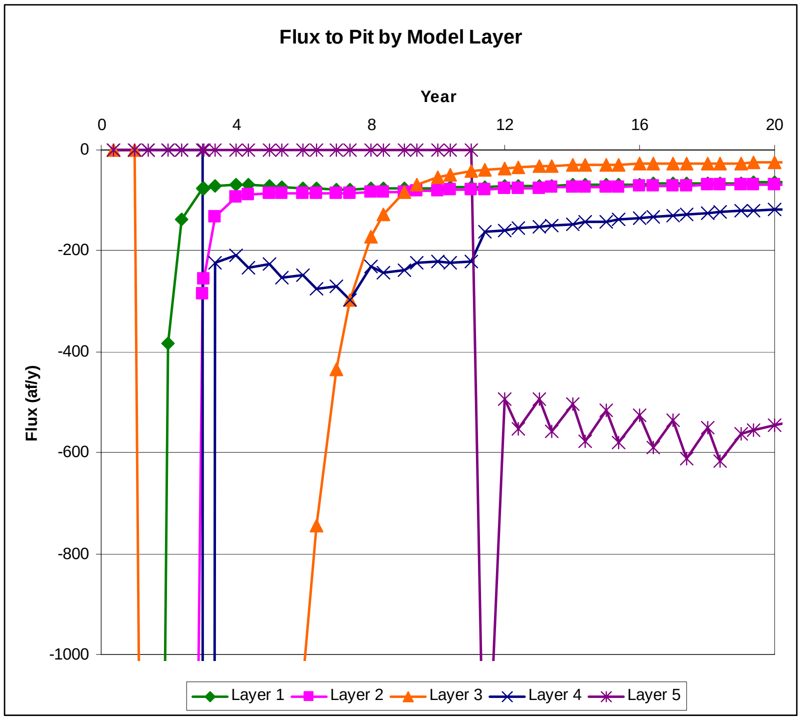

Figure 21: Flux (af/y) from the drain cells representing the pit, by layer. (detail of first 20 years)

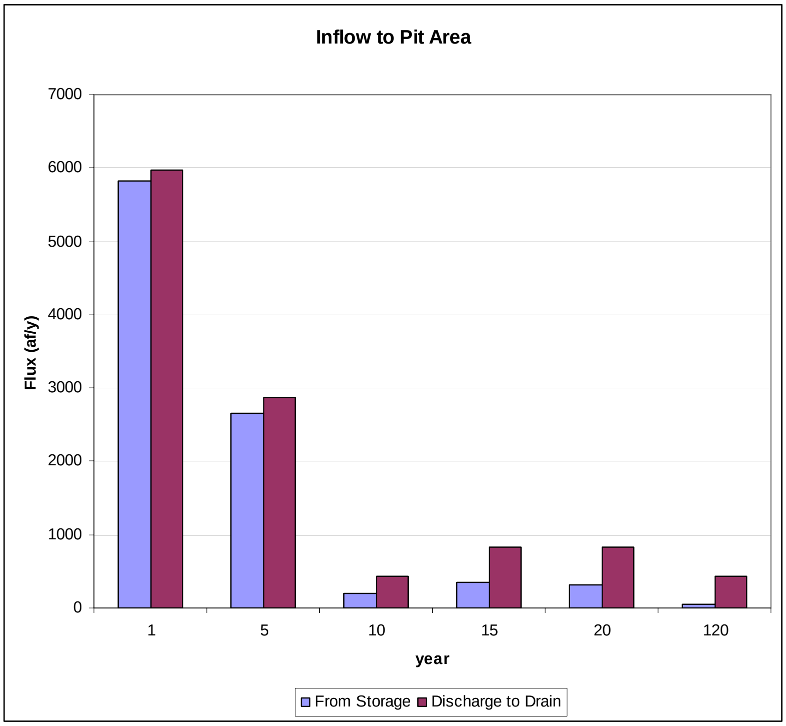

Figure 22: Inflow (af/y) to the pit from storage or from discharge to pit.

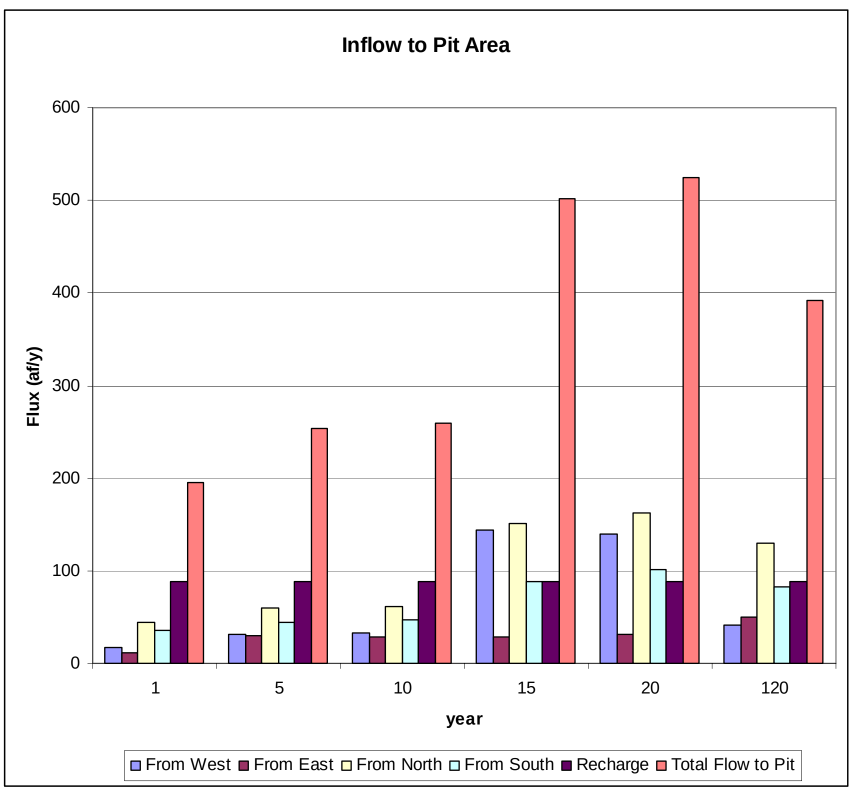

Figure 23: Inflow (af/y) to the pit by direction for select model years.

Drawdown and Flux Near the Proposed Pit

Drawdown due to excavating the pit expands in all directions from the pit (Figures 24 through 27). The maximum drawdown presented on the maps is 140 feet because near the pit the drawdown is as much as 1400 feet which is too steep to show on these maps. Figures 25 through 27 also show the zero-drawdown contour that lies closest to the pit. It is most important in layer 2 because any drawdown could affect spring flow.

In layers 1 and 2, the drawdown initially expands most obviously to the southeast (Figures 24 and 25). Within the pit area, layers 1 and 2 are dry by year 10. After 20 years, the 20-foot drawdown is about a mile southeast of the pit in layer 1 and about 1 ¼ miles in layer 2 (Figures 24 and 25). After 120 years, the 20-foot drawdown expanded to almost 2 miles from the pit in layers 1 and 2 (Figures 24 and 25).

The drawdown in layers 4 and 5 is very well defined with a steep gradient near the edge of the cone during the first 20 years (Figures 26 and 27). This reflects the control provided by the fault northeast of the pit. The fault was modeled as an impedance (Kh=0.0001 ft/d for 100 feet based on calibration), not a barrier. The apparent boundary is about ½ mile northeast of the pit. In both areas, drawdown less than 100 feet expands to the southeast up to 0.6 and 0.8 miles after 10 and 20 years in layer 4, respectively (Figure 26). After 120 years, drawdown has expanded through the fault. The 20-foot drawdown has expanded about 1.5 miles to the northeast and southeast and about 1 mile to the east.

After 10 years, the drawdown in layer 5 reflects the fact that the excavation had not yet reached the layer (Figure 27a). After 20 years, the layer had been excavated and the steep gradient in the drawdown contours is apparent as the potentiometric surface had dropped from almost 5000 to 3100 ft msl. Between 20 and 120 years, the drawdown has expanded through the fault and to the east and southeast (Figure 27c). The expansion to the east is similar to that in layer 4. Drawdown to the east of south direction is more substantial than in layer 4 indicating that more groundwater flowing to Cienega basin is captured in layer 5.

Layer 2 is most appropriate for considering springs because it represents bedrock regional flow near any discharge to springs. Springs were not directly modeled because none had a significant flow rate compared to the overall water budget and because their connections with the regional aquifer are uncertain. Unless they are perched, any perennial spring within the drawdown of the pit, as represented by the zero drawdown contour, would likely be affected because the lowered water table would change the gradient controlling discharge.

The drawdown caused by the pit also propagates to the west, draining the bedrock to the topographic divide which was the no-flow model boundary. The steeply east-dipping low-permeability geologic formations forming the crest indicate there would be little hydraulic connectivity under the crest. As on the east side, the high elevation springs west of the ridge would likely be perched. Drawdown caused by construction of the proposed will not likely affect these springs, but it is possible. Lower elevation springs near the mountain front on the west side may discharge from the regional aquifer, but there are at least three bedrock formations dipping to the east that would prevent a connection through the mountain range. However, there should be a plan to monitor the flow from these springs as will be described below.

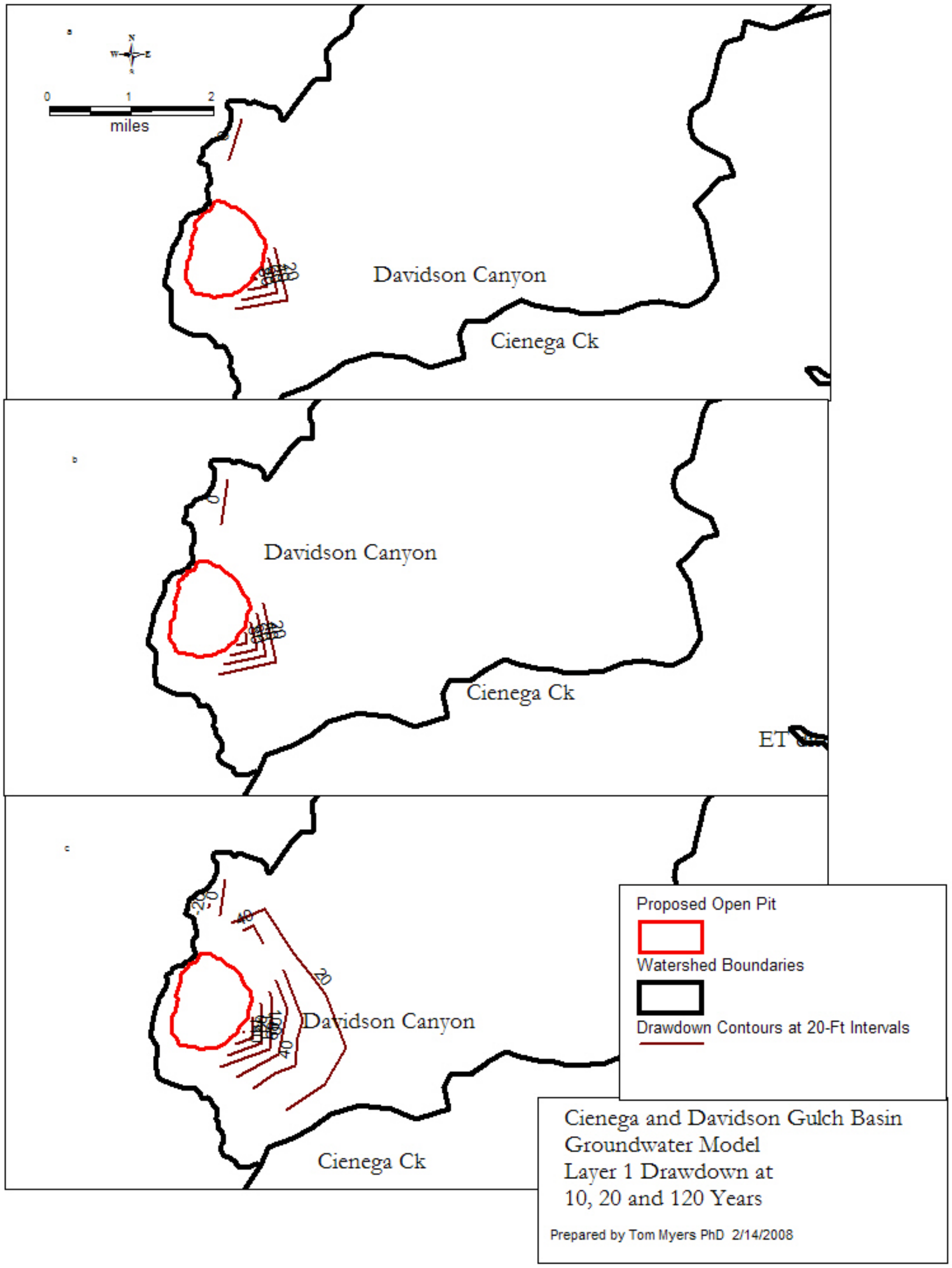

Figure 24: Drawdown in model layer 1 for years 10 (a), 20 (b), and 120 (c). Drawdown contours at 20-foot intervals. The maps show only up to the 140-ft drawdown; much higher drawdown occurs in and near the proposed pit.

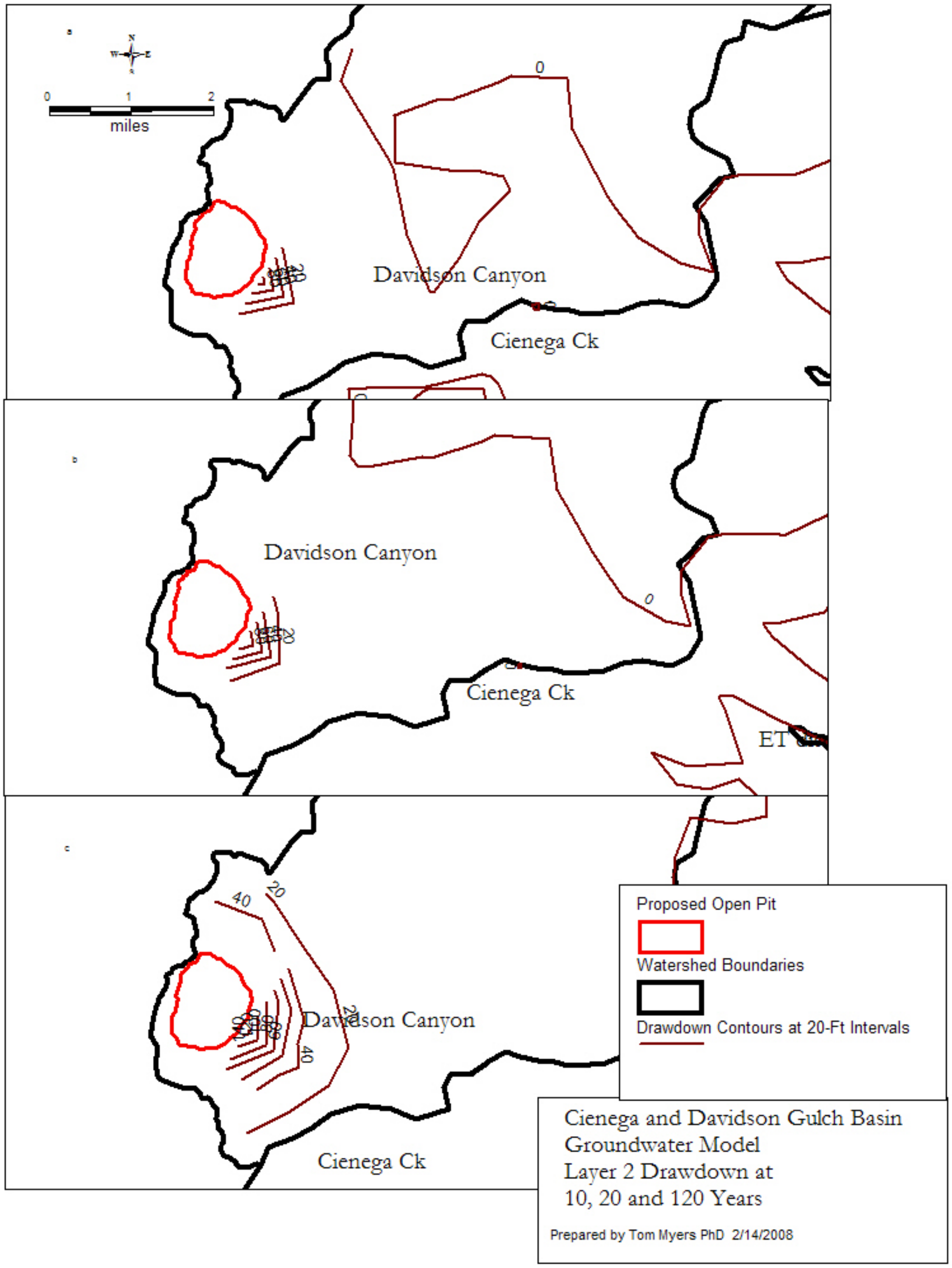

Figure 25: Drawdown in model layer 2 for years 10 (a), 20 (b), and 120 (c). Drawdown contours at 20-foot intervals. The maps show only up to the 140-ft drawdown; much higher drawdown occurs in and near the proposed pit.

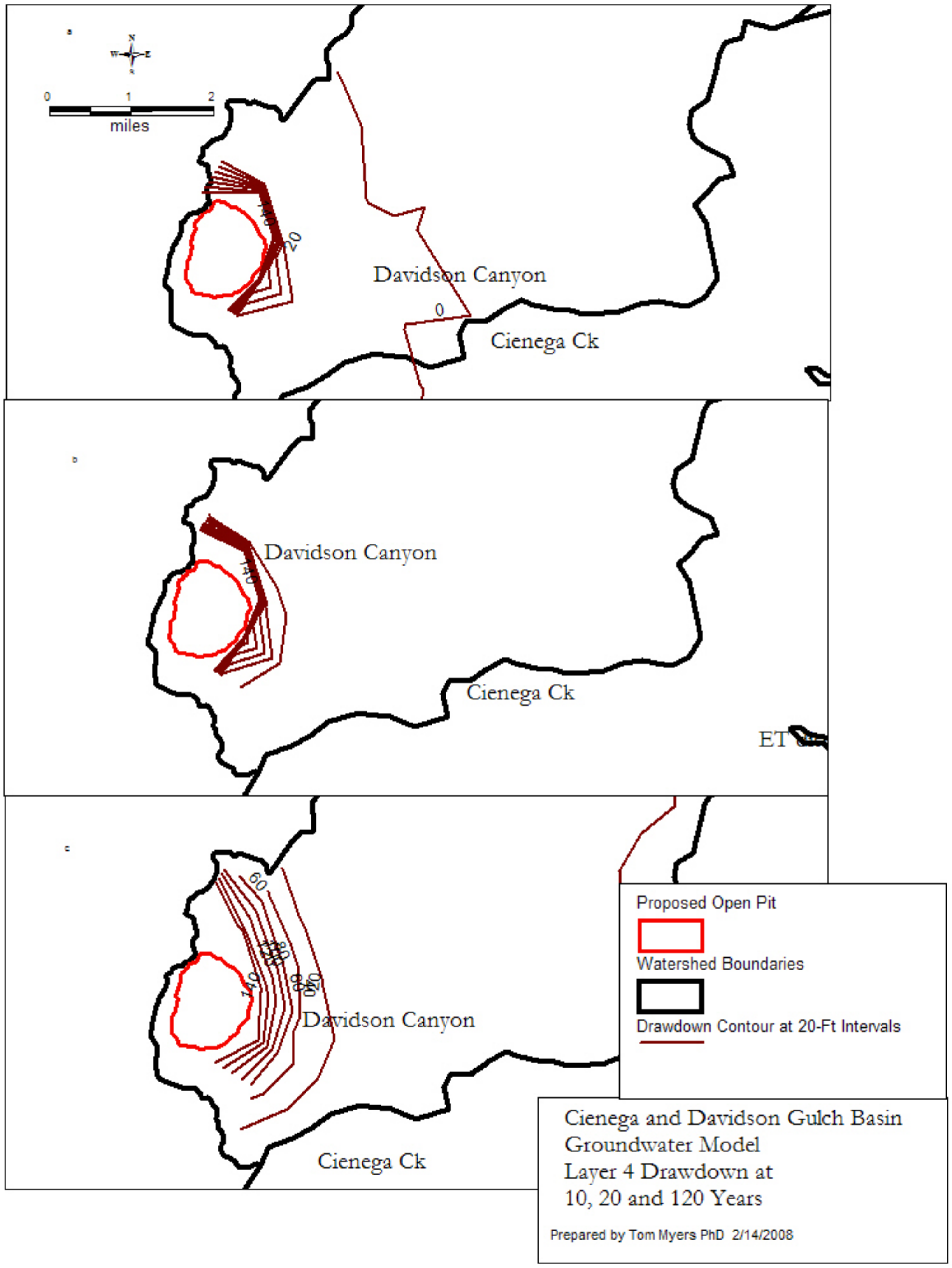

Figure 26: Drawdown in model layer 4 for years 10 (a), 20 (b), and 120 (c). Drawdown contours at 20-foot intervals. The maps show only up to the 140-ft drawdown; much higher drawdown occurs in and near the proposed pit. The zero drawdown is not shown in b because it is not well defined.

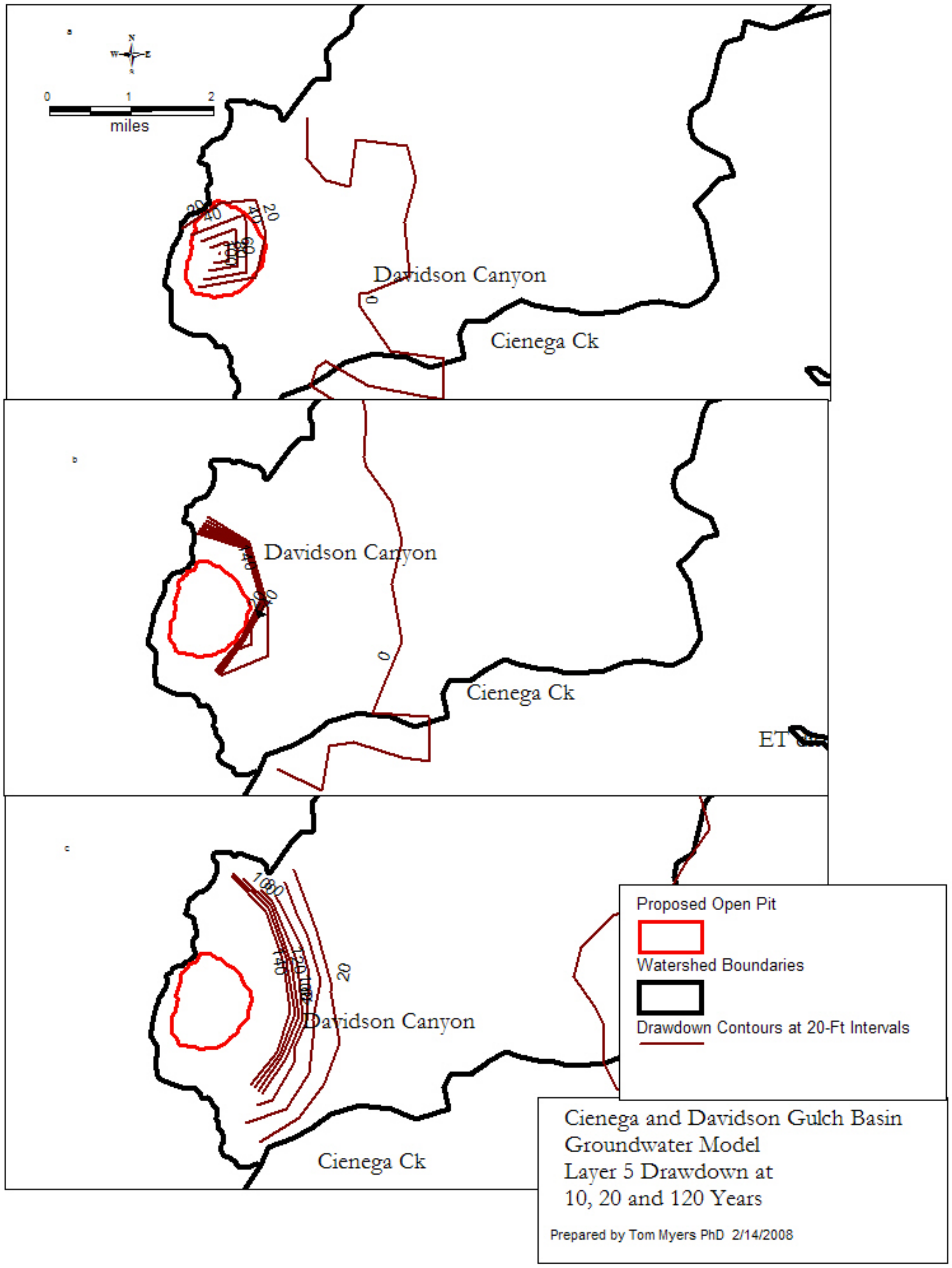

Figure 27: Drawdown in model layer 5 for years 10 (a), 20 (b), and 120 (c). Drawdown contours at 20-foot intervals. The maps show only up to the 140-ft drawdown; much higher drawdown occurs in and near the proposed pit.

Drawdown and Flux Throughout the Davidson Canyon and Cienega Creek Watershed

Groundwater levels at the divide between Davidson Canyon and Cienega Creek decrease with time in all layers (Figure 28). In layer 3, the groundwater levels begin to decrease almost immediately, although that decrease is just a couple of feet. In layers 2, 4 and 5, the decrease does not begin for at least 20 years. The differing lag times reflect the differing transmissivities among layers. The apparent vertical gradient reflects recharge on the divide. The potentiometric surface in the upper layers decreases more, but only by a few feet, than in the deeper layers. In all layers, the decrease is less than 10 feet.

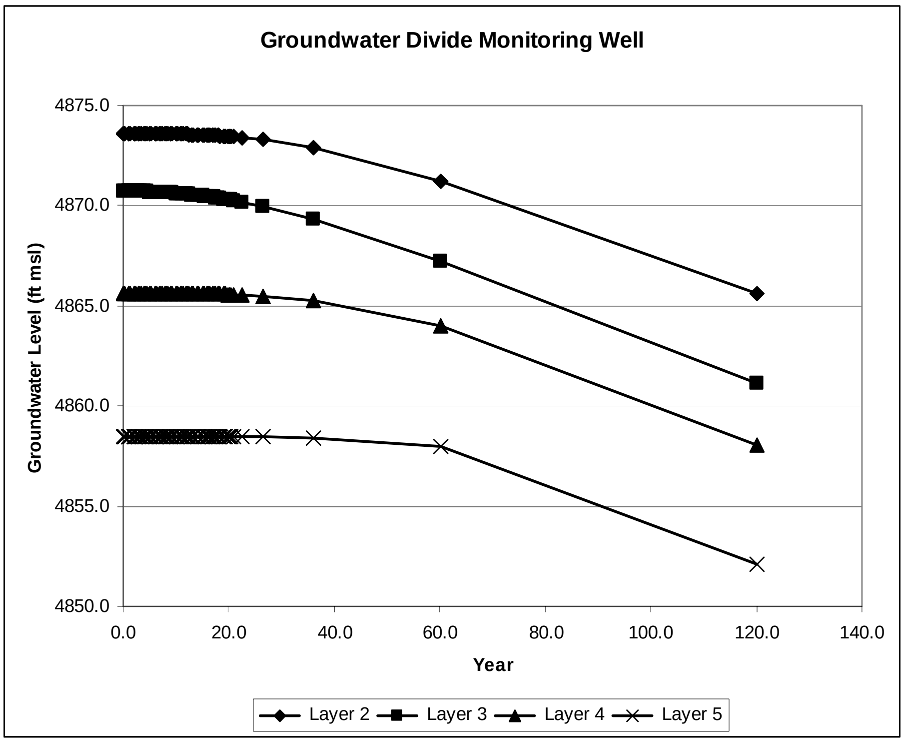

Figure 28: Water levels in a hypothetical monitoring well on the divide between Davidson and Cienega Creek watersheds.

One concern of this potential project is whether it will capture flow from Davidson Canyon to Cienega Creek watershed (Myers 2007). Groundwater flow through a cross-section, approximately 3.2 miles long, along the topographic divide from the ridge of the Santa Rita Mountains, just west of the Watershed Divide monitoring point, and the Empire Mountains monitoring point (Figure 16), decreased from an initial 70 af/y inflow from Davidson to Cienega Creek watershed to 65 and 51 af/y after 20 and 120 years, respectively. The proposed pit will decrease the water budget of the Cienega Creek watershed by approximately 20 af/y within 120 years.

Simulation to Steady State Conditions

Conditions had not reached steady state within the initial 120 year study period. Some of the monitoring points had not even been impacted by drawdown from the proposed pit. Therefore, the period after pit construction, period 21, was extended to 8000 years from the initial 100 year period to consider the time to steady state and potential ultimate effects of the project.

The drawdown cone extends through much of the Davidson Canyon watershed after 8000 years. Compared with Figures 24 through 27, the drawdown cone encompasses a much larger portion of the watershed (Figure 29). This indicates the system reaches steady state very slowly according to distance from the proposed pit (Figures 30a through 30f). After 8000 years, the drawdown expands significantly into the Cienega Creek watershed as well.

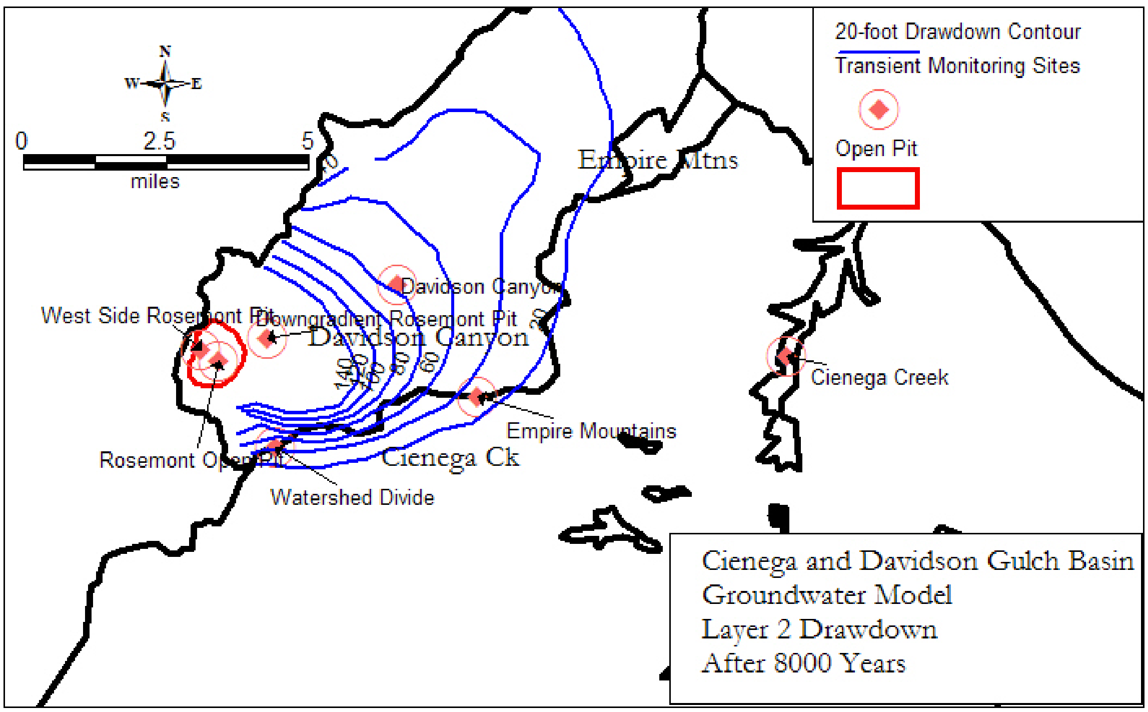

Figure 29: Drawdown cone in model layer 2 8000 years after the end of mining. The contours represent a steady-state condition in most locations.

Water levels at the monitoring points (Figure 29) that began to be affected almost immediately, such as the groundwater divide monitoring well and a point downgradient from the pit (Figure 30 a, c) continued to decrease until steady state was reached after 4000 years. The Davidson Canyon Downstream monitoring point (Figure 30d) began to exhibit drawdown commencing at about 150 years and approached steady state at about 6000 years. Other points, such as the groundwater divide in the Empire Mountains and the outlet from Davidson Canyon (Figures 30b, f), were not affected for from 500 to 1000 years, but then the level lowered for until approaching steady state in about year 6000. Water levels near Cienega Creek decreased less than a foot in several thousand years, with the deepest layer exhibiting the most change

(Figure 30e). Layer 1, not shown, had water level decreases of just 0.3 feet. The slow response and small change on Cienega Creek corresponds to the fact that the monitoring point monitors water levels near the primary ET discharge point in the Cienega Creek watershed. The water level in layer 1 can only change in response to a change in ET discharge from the watershed which is primarily controlled by recharge within the Cienega watershed. Most of the loss of inflow across the divide between the watersheds is reflected in a decrease in ET discharge near Cienega Creek.

Both the amount of water level decrease, the time to water levels begin to change, and the time to steady state reflect the distance the monitoring point being considered is from the pit. For example, water levels at the groundwater divide near the Empire Mountains (Figure 30b) decreased just half as much as those nearer the pit (Figure 30a). The time until the maximum drawdown occurs in the Empire Mountains is thousands of years longer as well. The lag between the two points in Davidson Canyon (Figure 30 d, f) reflects the drawdown cone expanding down the watershed from the proposed pit. Eventually most of the springs in the watershed could be at risk from declining groundwater levels.

Discharge hydrographs from around the model domain also reflect the magnitude and time to steady state for changing water levels in the model domain (Figure 31). Discharge from Davidson Canyon, groundwater flow through cross-section leaving the canyon, begins to decrease at about 400 years; it ultimately decreases about 16% within 6000 years (Figure 31). Total discharge to Cienega Creek, which is a summation of discharge to the drain boundaries and to ET at the creek, begins to decrease after about 1000 years but its total decrease is just 1% within an additional 5000 years at which point the discharge becomes steady (Figure 31). The Davidson Canyon discharge is therefore the dominant discharge from the model domain, except for the discharge to the proposed pit during the first few years, which has been discussed above. After 120 years, discharge to the pit is about 430 af/y which decreases for about 6000 years when discharge to the pit stabilizes at approximately 281 af/y (Figure 31). The decrease in discharge to the pit reflects the depletion of groundwater storage around the pit area. The gradient toward the pit decreases as a result.

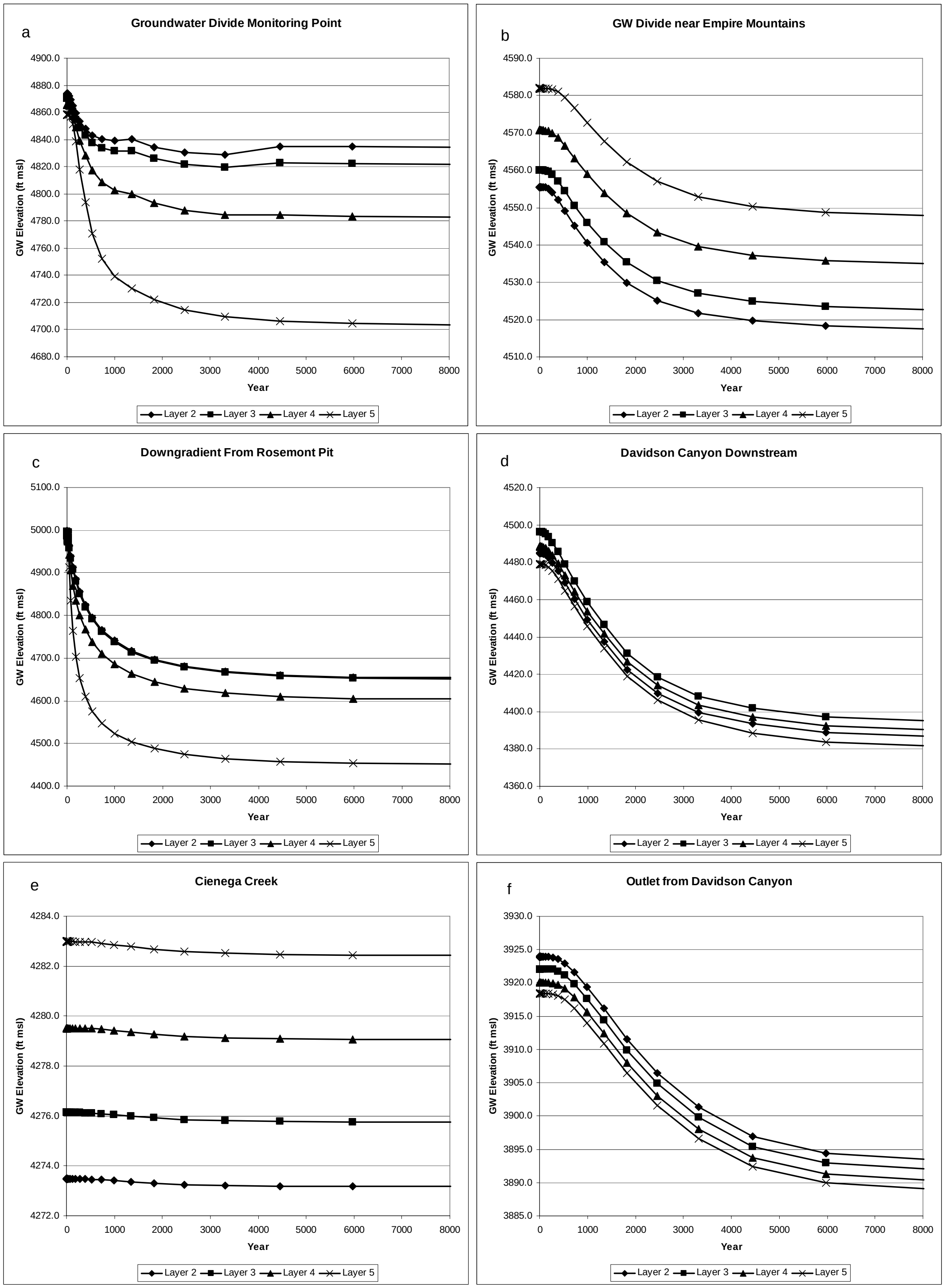

Figure 30: Water level hydrographs for six points for 8020 years from the start of construction. The monitoring points are: (a) groundwater divide south of the pit, (b) groundwater divide near the Empire Mountains, (c) downgradient from the pit, (d) Davidson Canyon, (e) Cienega Creek, and (f) model outlet from Davidson Canyon. See Figure 16 for the location of the monitoring points.

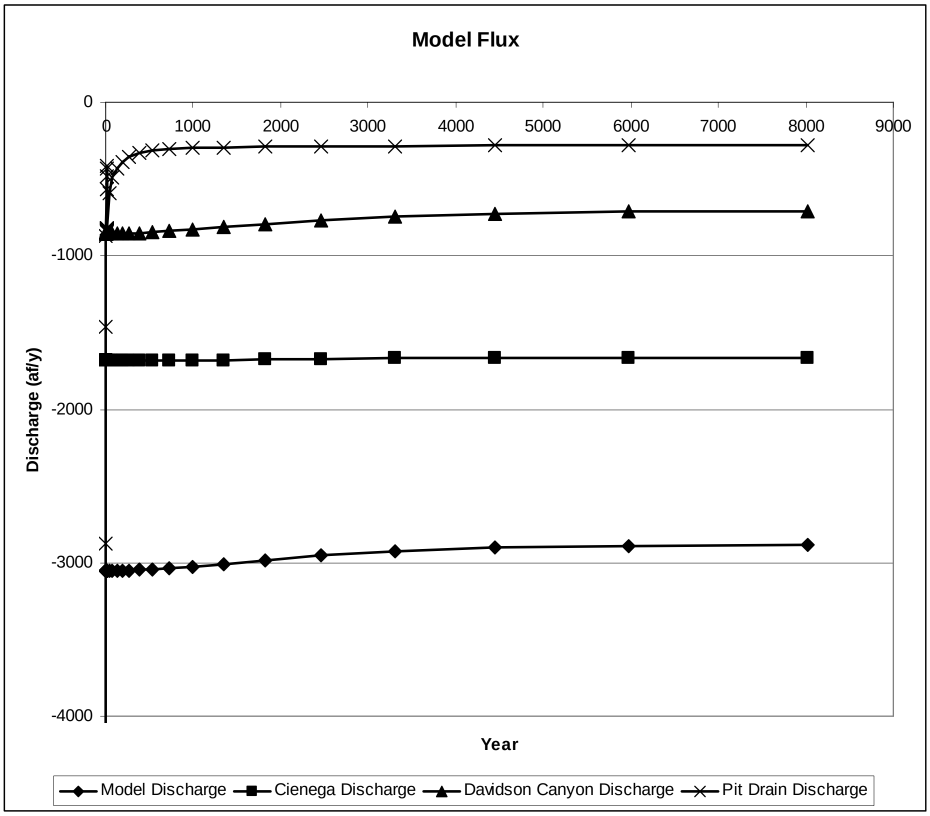

Figure 31: Discharge hydrographs for the model domain, discharge to Cienega Creek and riparian area, and discharge to the proposed open pit.

Sensitivity of the Transient Model

The storage coefficients were not calibrated, therefore there is significant uncertainty associated with them. For example, Pool and Dickinson (2007) found lower specific yield values for crystalline rock and low permeability sandstone bounding the basin fill of the San Pedro River than used herein. Lower specific yields would cause the effects due to pumping to expand more than predicted herein.

To test uncertainty in the storage coefficients, the model results were considered for the scenarios of storage coefficients being 20% high and lower and two orders of magnitude lower. The last scenario is considered an outlier and represents the scenario in which significantly less fracturing has occurred than otherwise appears to be represented by the geological studies and well pump tests (Drewes 1971 and 1976; Hargis and Montgomery 1982, Harshbarger and Hargis 1976, Montgomery 2007).

The 20% variation affected water levels under the pit, up to plus or minus 100 feet (Figure 31), because much of the inflow to the pit comes from below. Pit inflow changed up to plus or minus 20 af/y due to the change in gradient. With extremely low storage coefficients, the water levels reached about 3900 ft msl, which is much lower than for the other scenarios, very quickly which indicates that decreased storage coefficients would cause the system to come to equilibrium sooner.

Downstream of the proposed pit in Davidson Canyon, the 20% variation caused a one to two foot variation in the groundwater levels (Figure 32). The extreme scenario caused about a 15-foot difference. On the divide between watersheds, a 20% storage coefficient increase caused a 2-foot drawdown decrease and a 20% decrease caused a 3-foot drawdown increase (Figure 33). The two order of magnitude decrease caused a 22-foot drawdown decrease.

Based on the transient sensitivity scenarios, if selected storage coefficients are relatively close to the assumed values, the model predictions are accurate. If the aquifers are significantly less fractured and yield significantly less water than assumed, then the effects of this project could be spread over a larger area more quickly. The flux intercepted by the project would increase because the drawdown near the proposed pit would expand and capture more recharge.

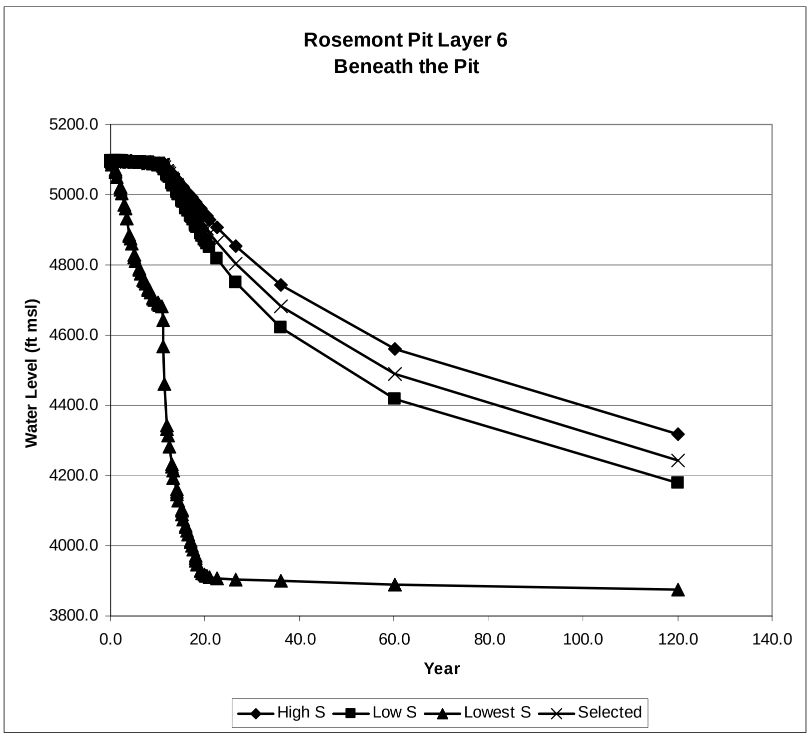

Figure 32: Water level hydrograph for a monitoring point in layer 6 under the pit for the storage coefficient sensitivity analysis.

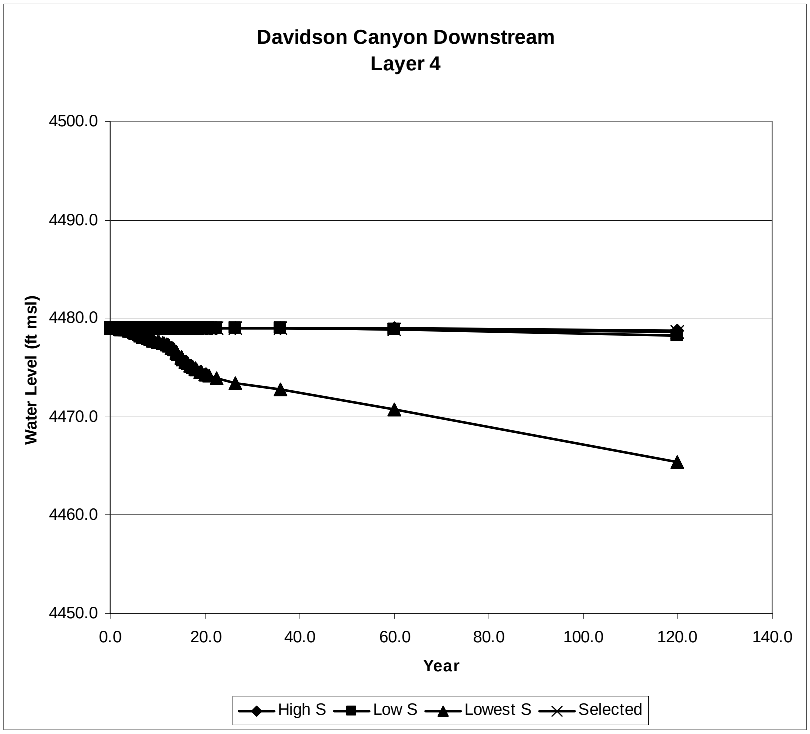

Figure 33: Water level hydrograph for a monitoring point in layer 4 downstream in Davidson Canyon from the pit for the storage coefficient sensitivity analysis.

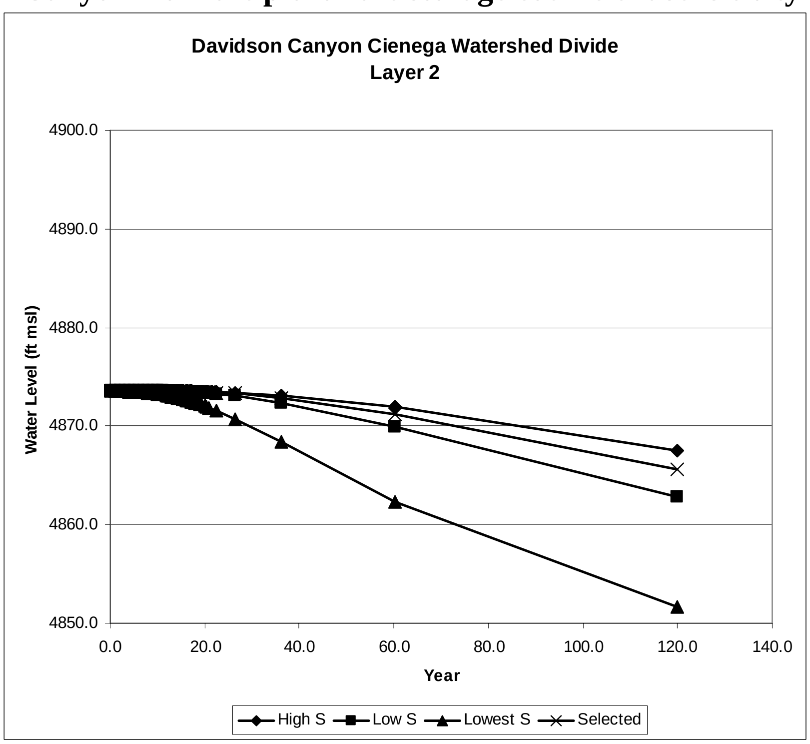

Figure 34: Water level hydrograph for a monitoring point in layer 2 on the watershed divide between Davidson Canyon and Cienega watershed for the storage coefficient sensitivity analysis.

Conclusion

This study reports on the development of a reconnaissance level numerical groundwater model of the Davidson Canyon and Cienega Creek watersheds. The model accurately implements the conceptual groundwater flow model of the area and estimates the effects of constructing an open pit mine in the headwaters of the Davidson Canyon watershed on the east side of the Santa Rita Mountains.

The proposed project would cause extensive drawdown near the proposed pit. Low transmissivity causes a steep gradient near the proposed pit. The pit would be excavated to and the potentiometric surface lowered 2000 feet to about 3100 feet at the pit. Drawdown expands downgradient from the mine slowly due to faults and low conductivity. Within 100 years from the end of mining, significant drawdown will have expanded several miles downgradient from and to the southeast of proposed pit. Any spring within the drawdown could potentially be affected. After 8000 years, when the entire study area has reached close to steady state conditions, there is extensive drawdown throughout Davidson Canyon that reaches significantly in the Cienega watershed as well.

Two aspects of the study area limit the amount of water withdrawn for dewatering and the expansion of the dewatering cone. The steepness of the terrain and low transmissivity limits the rate that drawdown expands Davidson Canyon. The pit would capture most of the recharge from the watershed above the proposed pit, but the small area upgradient of the pit limits the inflow to the pit to 600 af/y. This diversion of groundwater would eventually affect underflow from the model and discharge Cienega Creek, but the time frame is long. Discharge from Davidson Canyon, groundwater flow through the cross-section at the downstream boundary of the canyon, begins to decrease after about 400 years and ultimately decreases about 16% within 6000 years. This also reflects the potential effect on Davidson Springs.

If the storage coefficients of the aquifer were significantly less than modeled herein because aquifers are significantly less fractured and yield significantly less water than assumed, the effects of this project could be spread over a larger area more quickly. The flux intercepted by the project would increase because the drawdown near the proposed pit would expand and capture more recharge. Discharge from the Davidson springs and Cienega Creek would be reduced by a few percent.

The pit will not contain a large pit lake after mining ceases, but seasonal ponding could occur and result in small pit lakes in low points on the bottom of the pit. The evaporation rate exceeds the average groundwater inflow rate, which is about 2.3 ft/y assuming a 300 acre pit bottom. Rainfall and runoff within the pit would contribute to the seasonal formation of a pit lake and low points or sumps in the bottom of the pit could collect inflow and possibly form deeper ponds. Water would not likely seep from the pit to degrade nearby groundwater because the gradient would be towards the pit.

The proposed project would occur within the upstream portion of Davidson Canyon watershed. The pit will capture all runoff from within and above the pit area. Most of this runoff would otherwise leave the study area without infiltrating and become mountain front recharge into alluvial basin north of Davidson Spring. This analysis has not estimated the runoff to be captured, but it could be substantial considering the recharge estimate is 1.5 in/y in an area with approximately 20 in/y of precipitation. The mountain front recharge captured by the pit could be several times the diffuse recharge in mountain block. This could have a significant impact on downstream baseflow in Cienega Creek.

Recommendations

The study completed herein suffers from a lack of hydrogeologic data of the watershed but it demonstrated there could be a substantial impact to the groundwater system. This lack will also hinder any analysis completed for an environmental impact statement. The lack of data includes an understanding of the influence of fractures in the Davidson Canyon watershed and of faulting east and northeast of the proposed project on flows. There is also a significant lack of data concerning recharge in the Davidson Canyon watershed. The following are recommendations for future data collection and analysis prior to permitting the project and several mitigations necessary to decrease the impacts of the project, if it is approved.

1. The project proponent should install and operate several surface water gaging stations along Davidson Canyon downstream of the project area so that recharge from the channel can be estimated. This data should be collected for several years prior to permitting the mine so that the effect of diverting runoff from the channel on recharge can be estimated.

2. There should be a diversion around the proposed pit so that it does not capture runoff. The diversion should be lined to prevent infiltration and interflow to the pit.

3. Additional pump tests should be performed prior to completion of studies for a draft environmental impact statement. All nearby wells and springs should be monitored for water level changes. The following are specific recommendations for the pump tests.

   a. The tests should last longer than one day. A minimum of 72 hours is necessary but wells that produce significant yields should be pumped until nearby observation wells respond. If the wells do not respond, additional observation wells should be installed to determine from where the pumped well is drawing flow.
   b. The project proponent should install additional monitoring wells for the pump tests. A specific number is difficult to estimate, but the variability in results from Montgomery (2007) indicates a substantial number, more than four, is necessary.
   c. The pump tests should be designed to test pumping from specific layers by screening the wells over the target layer rather than over the entire depth of the well.
   d. The observation wells should also have multilevel completions so that water levels in different formations and fracture zones can be monitored for connectivity.
   e. The data from the pump tests as described may not lend itself to normal aquifer test methods due to the complexity of the aquifers. To adequately determine the properties resulting from these tests, a detailed groundwater model of pit area should be constructed and calibrated with the pump test results.

4. The wells used for the pump tests should have stable isotope (oxygen, hydrogen) data and other geochemical data collected to determine whether they monitor water from different sources. These geochemical tests should also include nearby springs, including those near the project area, Davidson Spring, and the flow seeping into Cienega Creek.

5. It is uncertain whether the springs within the Davidson Canyon watershed discharge from perched or regional aquifers. The project proponent should complete tritium tests on the flow from the springs in sufficient time to report the results in the draft EIS. Tritium levels can help interpret recency of recharge. Obtaining radiocarbon dates for the spring discharge would also help to determine whether they would be affected by pit drawdown.

6. There are many small springs within the drawdown cone of the proposed pit. There are also springs on the west side of the Santa Rita Mountains above the level of the pit bottom. All could be affected by drawdown from the proposed pit. The discharge from them should be monitored seasonally during mine operation to determine whether the pit affects the flow from the springs. There should also be a plan to mitigate the loss of flow that does not include pumping water near the spring to replace the flow. The monitoring and mitigation plan should provide for at least 100 years of at least annual monitoring beyond the completion of mining because drawdown will continue to expand.

7. During mine operation, aquifer response should be monitored over the groundwater divide into the Cienega basin to determine whether the response is consistent with the model.

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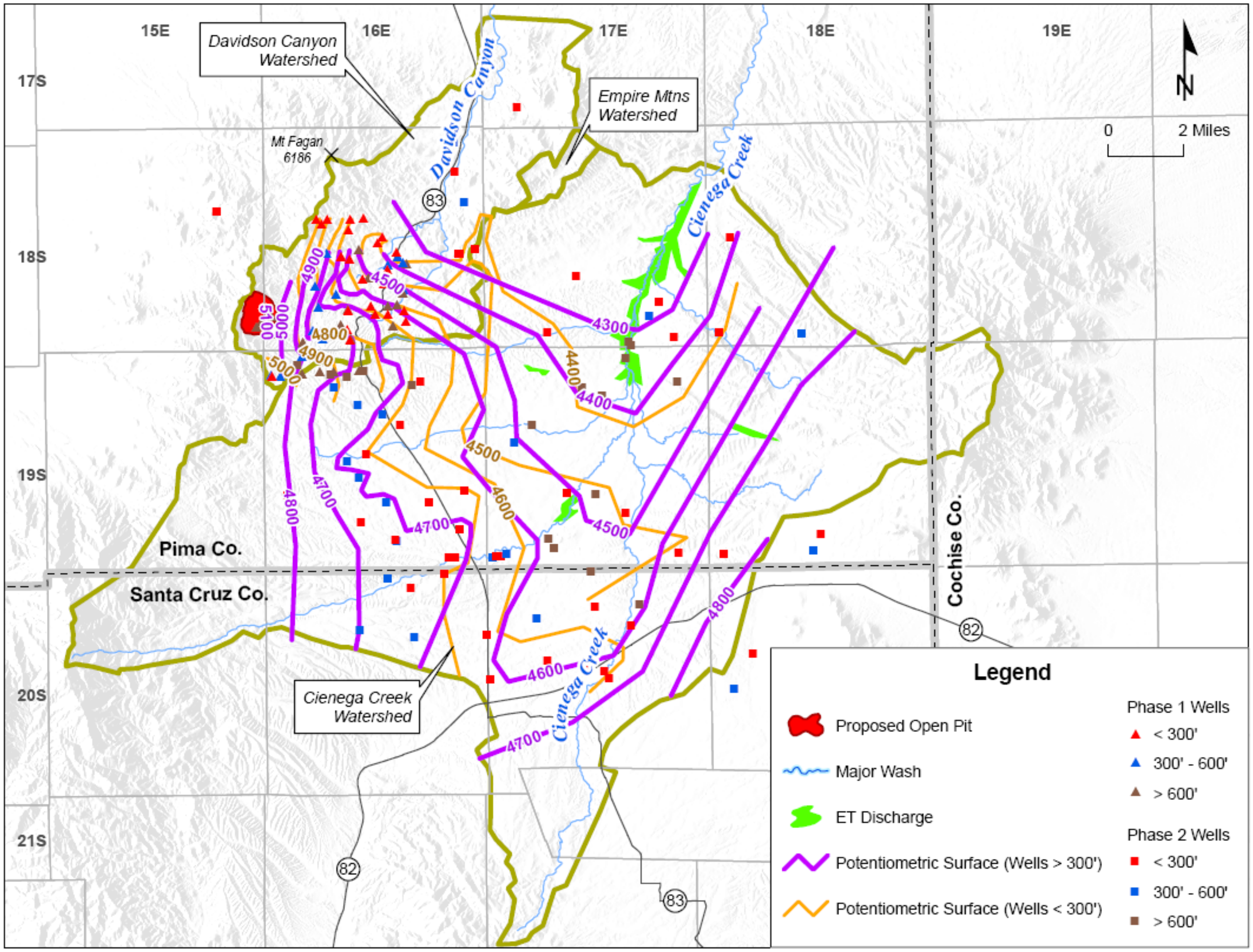

Plate 1: Groundwater contours for the Davidson Canyon/Cienega Creek watershed project area. Contours are for shallow wells and deep wells (greater than 300 feet). The map also shows the location of the monitoring wells.

Appendix 1: Groundwater well locations, elevations and water levels as used in this analysis (http://waterdata.usgs.gov/az/nwis/gw/).

Well ID	Latitude	Longitude	Ground Surface Elev (ft msl)	Aquifer	Well Depth (ft)	First Level Reading	Most Recent Level Read	Number of observation	Average SWL (ft)	Avg SWL Elev (ft msl)
D-20-18 19ACB	31.6834	-110.544	4837		368	3/17/1982	12/16/1987	2	0	4837
D-20-17 22ABB	31.6862	-110.595	4768		0	3/23/1982	3/23/1982	1	141.8	4626.2
D-20-18 21BBB	31.6868	-110.52	4872		0	7/24/1978	7/24/1978	1	0	4872
D-20-18 20AAA	31.687	-110.521	4852		160	3/17/1982	12/15/1987	2	0	4852
D-20-17 15CDC	31.6884	-110.601	4720		200	3/23/1982	12/16/1987	2	99.5	4620.5
D-20-17 18CCC	31.6884	-110.655	4850		150	3/19/1982	3/19/1982	1	182.2	4667.8
D-20-18 17DDA	31.6898	-110.521	4872		0	11/8/1972	11/8/1972	1	0	4872
D-20-17 15CCA	31.6909	-110.603	4693	120VLCC	140	12/11/1952	11/29/1954	8	97.2	4595.8
D-20-17 16DCA	31.6915	-110.61	4731		194	3/24/1982	12/15/1987	2	81	4650
D-20-17 17ACC	31.6954	-110.629	4730		125	3/19/1982	3/19/1982	1	88.76	4641.24
D-20-18 17BCB	31.6973	-110.535	4802		248	3/17/1982	11/6/2001	16	0	4802
D-20-17 14ADB	31.699	-110.573	4750		0	3/23/1982	3/23/1982	1	203.1	4546.9
D-20-16 10DDA	31.7051	-110.689	5100		500	11/5/1981	11/5/1981	1	393	4707
D-20-16 12DDA	31.7056	-110.656	4825		210	11/8/1949	12/15/1987	29	162.5	4662.5
D-20-16 09DBB1	31.7084	-110.714	5200		540	4/1/1941	4/1/1941	1	400	4800
D-20-17 10DAB	31.709	-110.591	4621		139	11/6/1972	12/15/1987	3	34	4587
D-20-17 07ADD	31.7095	-110.639	4771		0	3/19/1982	12/15/1987	2	122	4649
D-20-16 11ADA	31.7118	-110.675	4919		0	11/6/1972	11/5/1981	2	189.9	4729.1
D-20-17 08BDB	31.712	-110.633	4650	120VLCC	400	4/1/1964	4/1/1964	1	106	4544
D-20-17 09AAA	31.7162	-110.607	4655		100	3/19/1982	3/19/1982	1	69.14	4585.86
D-20-17 11BBB	31.7165	-110.586	4615		0	3/17/1972	12/16/1987	3	40.4	4574.6
D-20-17 02CCC	31.717	-110.586	4625	120VLCC	755	5/22/1970	5/22/1970	1	40	4585
D-20-18 05DAB	31.7223	-110.523	4900		0	10/19/1960	12/15/1987	3	52.2	4847.8
D-20-16 03DAA	31.7245	-110.691	4910	120VLCC	250	11/6/1981	11/6/1981	1	186.3	4723.7
D-20-18 05ACD	31.7251	-110.526	4870	BASEMENT	0	8/3/1978	3/25/1982	2	14.6	4855.4
D-20-16 02AAA	31.7301	-110.675	4800	120VLCC	205	9/24/1941	11/4/1981	2	112.4	4687.6
D-20-16 03BAC	31.7284	-110.701	4935	120VLCC	450	1941-09-00	9/1/1941	2	186.5	4748.5

D-20-16 02AAB	31.7298	-110.675	4827		35	11/4/1981	11/4/1981	1	73.7	4753.3
D-20-17 04AAC	31.7304	-110.608	4623		700	3/24/1982	12/16/1987	2	45	4578
D-19-17 31CBD2	31.7362	-110.653	4662		553	11/5/1981	11/5/1981	1	32.3	4629.7
D-19-16 36CB	31.7362	-110.67	4725	120VLCC	175	9/20/1941	9/20/1941	1	23.83	4701.17
D-19-16 35DAD	31.7362	-110.673	4740		143	9/20/1941	12/16/1987	3	31.5	4708.5
D-19-17 31CA 1	31.7365	-110.548	4750	120VLCC	180	4/15/1941	4/15/1941	1	40.67	4709.33
D-19-16 35DAA	31.7365	-110.673	4749	120VLCC	0	11/6/1972	11/6/1972	1	30	4719
D-19-17 31CA 2	31.7368	-110.649	4635	120VLCC	42	4/15/1941	4/15/1941	1	38.38	4596.62
D-19-17 31CBD1	31.7368	-110.651	4660		200	11/5/1981	11/5/1981	1	40.3	4619.7
D-19-17 36CBA	31.737	-110.568	4645		240	3/25/1982	12/7/1993	9	130.7	4514.3
D-19-18 33DAB	31.7373	-110.507	4950		354	2/1/1952	2/1/1952	1	0	4950
D-19-17 31CAA	31.7373	-110.647	4655		550	11/5/1981	11/5/1981	1	14.3	4640.7
D-19-17 32ADC	31.7395	-110.625	4600		1150	3/1/1972	3/1/1972	1	12	4588
D-19-16 35BC	31.7401	-110.687	4800	120VLCC	0	1941-09-00	9/1/1941	2	69.22	4730.78
D-19-16 34ABC2	31.7429	-110.697	4830		500	11/4/1981	11/4/1981	1	127.8	4702.2
D-19-17 32ABD	31.7431	-110.628	4602		1165	3/24/1982	12/16/1987	2	28	4574
D-19-16 34BBD	31.7431	-110.705	4875		0	11/6/1972	11/4/1981	2	191	4684
D-19-18 33AAA1	31.7437	-110.504	4977		0	11/6/1972	11/6/1972	1	0	4977
D-19-16 34ABC1	31.7437	-110.697	4830		212	11/4/1981	11/4/1981	1	131.9	4698.1
D-19-18 33AAA2	31.7439	-110.504	4975	112BSFLU	250	6/5/1996	6/27/1996	2	0	4975
D-19-16 25CDC	31.7473	-110.668	4818		300	11/4/1981	11/4/1981	1	96.8	4721.2
D-19-16 28DBC	31.7504	-110.713	4956		275	3/29/1982	12/16/1987	2	227.8	4728.2
D-19-16 25CAA	31.7526	-110.665	4790	120VLCC	0	11/13/1972	11/13/1972	1	105.1	4684.9
D-19-17 27DBA	31.7531	-110.592	4530		60	3/24/1982	3/24/1982	1	32	4498
D-19-17 28ACB	31.7562	-110.612	4545		0	3/24/1982	12/10/1987	2	32.7	4512.3
D-19-16 26BAD	31.7579	-110.682	4867		256	3/24/1982	12/10/1987	2	153.5	4713.5
D-19-16 27BAC	31.7584	-110.701	4955		336	3/29/1982	12/16/1987	2	235.5	4719.5
D-19-17 21DDD	31.7604	-110.606	4522		1480	3/24/1982	12/10/1987	2	43.2	4478.8
D-19-17 21CCD	31.7612	-110.619	4536		117	3/24/1982	12/10/1987	2	11.8	4524.2
D-19-16 19DC	31.7612	-110.746	5200	120VLCC	24	9/24/1941	9/24/1941	1	22.1	5177.9
D-19-16 24CDA	31.7623	-110.666	4804		203	3/24/1982	12/11/1987	2	102	4702

D-19-16 21ACC	31.7679	-110.714	5082		510	3/29/1982	12/16/1987	2	383.7	4698.3
D-19-16 21BAB	31.7745	-110.719	4985		375	3/30/1982	3/30/1982	1	281.4	4703.6
D-19-16 16DDB	31.7773	-110.71	4931		260	3/29/1982	12/14/1987	2	228.5	4702.5
D-19-16 18CCA	31.7779	-110.753	5160		0	11/9/1972	11/9/1972	1	54.8	5105.2
D-19-17 18DAB	31.7812	-110.643	4645	120VLCC	350	11/9/1973	11/9/1973	1	150	4495
D-19-16 14BDD	31.7826	-110.682	4805		0	3/25/1982	12/11/1987	2	98	4707
D-19-17 14ADD	31.7829	-110.571	4523		0	11/10/1972	12/10/1987	3	134	4389
D-19-16 17BDB	31.7843	-110.735	5080	120VLCC	0	11/9/1972	11/9/1972	1	209.1	4870.9
D-19-17 15BCA	31.7845	-110.601	4505		0	3/24/1982	12/10/1987	2	74.5	4430.5
D-19-17 16ACA	31.7854	-110.61	4465		0	3/24/1982	12/10/1987	2	26.3	4438.7
D-19-18 17BAD	31.787	-110.531	4667		0	3/25/1982	12/10/1987	2	46.2	4620.8
D-19-16 15ABA	31.7884	-110.695	4900		300	1/30/1952	11/6/2001	55	210	4690
D-19-17 17BBD	31.7876	-110.635	4539	120VLCC	845	6/1/1971	11/28/2000	12	-29	4568
D-19-16 10CCA	31.7926	-110.703	4997		386	3/25/1982	12/15/1987	2	287.2	4709.8
D-19-16 09DBB	31.7962	-110.714	5040		404	3/29/1982	12/15/1987	2	356.6	4683.4
D-19-17 10BCD	31.799	-110.602	4415		1250	3/24/1982	12/8/1987	2	34.1	4380.9
D-19-17 08BCB	31.7959	-110.637	4592		0	11/10/1972	12/9/1987	3	120	4472
D-19-17 12AAB	31.802	-110.557	4539		0	3/25/1982	12/10/1987	2	159.7	4379.3
D-19-17 09ABB	31.8023	-110.611	4440		1285	3/24/1982	12/8/1987	2	50.8	4389.2
D-19-16 08AAA	31.8034	-110.725	5160		554	3/29/1982	12/15/1987	2	407	4753
D-19-17 01CCD	31.804	-110.568	4450		1293	3/25/1982	12/10/1987	2	12	4438
D-19-17 03DDD	31.804	-110.589	4357		0	3/24/1982	12/8/1987	2	4.8	4352.2
D-19-16 11BBB	31.804	-110.689	4942		1510	3/24/1982	12/11/1987	2	245.2	4696.8
D-19-16 02CCD	31.8054	-110.685	4890		285	11/10/1972	12/11/1987	3	199	4691
D-19-16 04CDB	31.8073	-110.719	5320		825	3/29/1982	3/29/1982	1	617	4703
D-19-16 05DAC	31.8084	-110.726	5290		700	3/29/1982	3/29/1982	1	471.1	4818.9
D-19-16 04DBD	31.8095	-110.711	5115		700	3/29/1982	12/11/1987	2	406.7	4708.3
D-19-16 06ADD	31.812	-110.741	5130		905	3/29/1982	3/29/1982	1	497.3	4632.7
D-19-17 03ADB	31.8137	-110.591	4355		749	4/8/1970	6/15/1982	2	-8	4363
D-19-15 01AAA	31.8162	-110.758	5360		0	3/31/1982	3/31/1982	1	178.4	5181.6
D-18-16 32CCC	31.8168	-110.74	4959		0	3/31/1982	3/31/1982	1	51.96	4907.04
D-18-17 34DDD	31.8184	-110.589	4330	120VLCC	640	11/14/1972	11/14/1972	1	0	4330
D-18-16 31CCC2	31.8187	-110.754	5416		0	3/31/1982	3/31/1982	1	236.7	5179.3
D-18-16 31CCC1	31.819	-110.755	5416		0	3/31/1982	3/31/1982	1	243.4	5172.6
D-18-17 34DDA	31.8198	-110.59	4321	120VLCC	607	2/16/1972	2/16/1972	1	0	4321

D-18-16 32CCB	31.8204	-110.737	4921		0	3/31/1981	12/14/1987	3	67	4854
D-18-17 36CBC	31.8218	-110.569	4442		180	11/14/1972	11/6/2001	17	129.4	4312.6
D-18-18 33CAD	31.8223	-110.511	4791		590	3/24/1982	12/9/1987	2	118.3	4672.7
D-18-18 31CAC	31.8231	-110.549	4460		230	11/14/1972	12/9/1987	3	68	4392
D-18-17 32DBA	31.824	-110.627	4520		226	11/13/1972	11/6/2001	17	109	4411
D-18-17 34BDC	31.8268	-110.599	4370		0	3/24/1982	12/8/1987	2	60	4310
D-18-17 33ADA	31.827	-110.607	4438		0	3/24/1982	12/8/1987	2	92.8	4345.2
D-18-16 34BDA	31.8287	-110.696	4760		0	3/31/1982	12/15/1987	2	130.2	4629.8
D-18-17 35BAD	31.8298	-110.58	4305		554	3/24/1982	12/8/1987	2	26.3	4278.7
D-18-17 26DCA	31.8356	-110.576	4305		154	11/14/1972	12/9/1987	3	36.8	4268.2
D-18-18 30DCB	31.8356	-110.543	4429		0	1951-03-00	3/1/1951	2	72.44	4356.56
D-18-17 25CD	31.8343	-110.565	4350	120VLCC	0	3/1/1951	3/1/1951	1	25.95	4324.05
D-18-16 27CDB3	31.8354	-110.7	4720	120VLCC	0	3/31/1982	3/31/1982	1	101.4	4618.6
D-18-18 29ACC	31.8395	-110.527	4530		0	3/24/1982	12/9/1987	2	147	4383
D-18-17 28BAA	31.8459	-110.613	4378		120	3/24/1982	12/9/1987	2	69	4309
D-18-16 21DDC	31.8468	-110.71	4550		0	3/31/1982	12/14/1987	2	36	4514
D-18-18 20DAD2	31.8506	-110.521	4560		0	3/24/1982	12/9/1987	2	209	4351
D-18-16 22DBC	31.8509	-110.697	4508		0	3/31/1982	12/14/1987	2	76.7	4431.3
D-18-16 24BDC1	31.8551	-110.666	4390		22	3/31/1982	12/14/1987	2	5.8	4384.2
D-18-16 24BDC2	31.8551	-110.667	4395		98	3/31/1982	3/31/1982	1	32.02	4362.98
D-18-16 24ADB	31.8568	-110.66	4560		70	3/31/1982	12/14/1987	2	35	4525
D-18-16 21ACB	31.8568	-110.713	4546		0	3/31/1982	12/15/1987	2	47.8	4498.2
D-18-18 19ABB	31.8604	-110.543	4290		240	11/14/1972	12/9/1987	3	130.6	4159.4
D-18-15 14AAC1	31.8729	-110.777	4200	120VLCC	203	5/28/1971	5/28/1971	1	30	4170
D-18-15 14AAC2	31.8729	-110.777	4200	120VLCC	230	6/3/1971	6/3/1971	1	60	4140
D-18-16 13BAA	31.8754	-110.664	4280	120VLCC	545	6/14/1972	6/14/1972	1	200	4080
D-18-16 12BBD	31.8873	-110.668	4089		116	11/7/1972	4/1/1982	2	19.2	4069.8
D-18-16 01BCC	31.8985	-110.669	4120	112BSFL	500	12/6/1997	6/20/1998	4	383.6	3736.4
D-18-17 02AAC	31.9006	-110.574	4232		0	12/23/1981	12/4/1987	2	63.4	4168.6
D-17-17 31ADD	31.9123	-110.64	4160	120VLCC	112	6/12/1973	6/12/1973	1	53.36	4106.64
D-17-17 34ADB	31.9148	-110.59	4286		0	12/23/1981	12/4/1987	2	29.3	4256.7
D-17-17 36BAC	31.9154	-110.564	4203		0	12/23/1981	12/4/1987	2	158.2	4044.8