Technical Memorandum
Review of the Proposed Rosemont Ranch Mine
Hydrogeologic Analysis and Groundwater Model

Prepared for Pima County and Pima County Regional Flood Control District

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1. INTRODUCTION

The mining company, Rosemont Copper, has recently submitted two studies, completed by Errol L. Montgomery and Associate (M&A), to support its environmental analysis for its proposed mine. This review is of the following documents:


An additional supporting document was also reviewed because it provided substantial information used for the GMR.


The MODFLOW-SURFACT computer input files and Groundwater Vistas (GWVistas) files were also made available for review. There were three file sets available, including SteadyState, Trans_DRN, and Trans_LAK. The first is the final steady state model run, the second is the transient simulation during pit development, and the third is a simulation of pit lake development. Output files were not included, except that the file SteadyState.hds, provided as initial conditions for the Trans_DRN model runs, was the result of the steady state simulation. The files were used to examine details of the modeling not described within the reports. As described within the review, the files were converted to MODFLOW and simulations run to develop the water balances discussed herein.

2. SUMMARY AND RECOMMENDATIONS

2.1 Summary

The general conceptual flow model proposed by M&A for the Rosemont groundwater model is accurate with a few exceptions. The hydrogeologic units are properly determined, but the parameter zoning has errors or areas that require better justification. Conductivity along Davidson Canyon was too high. Formations in the lower portion of and just below the proposed pit had high conductivity but the formation just outside of
the pit zone had very low conductivity. This caused unusual flow paths near the pit, minimized the dewatering rates, and decreased the rate and extent that dewatering impacts spread away from the pit. Potential fault or fracture controlled flow pathways between the pit area and Davidson Canyon were not included.

Recharge was estimated with an inappropriate method using improper input, but the overall estimate was close to previous estimates. Recharge distribution around the project did not consider geology, topography, or potential recharge from washes. Overall discharge estimates, including ET were accurate.

The modeler used the MODFLOW-SURFACT code, which was apparently adequate but shown in this review to be unnecessary. The model boundaries were not set on no-flow barriers such as groundwater divides or flow lines and were too far from the project area. Too much area that would not be affected by the mine was simulated. Too many layers were used, especially at depth. The conductivity of the four lower layers was so low that there was almost no flow among the layers.

Head-controlled flux boundaries surrounded the entire domain, so there was little control on the location of flow entering and leaving the domain. No flux boundaries were used as targets for the calibration. Groundwater/surface water interactions were simulated using wells, an unusual method which forces water to or from the aquifer at a point without regard to the water level or whether it is high enough for ET and without regard for mounding. Doing this does not assist in the calibration of the conductivity zones near the streams.

The calibration showed some bias toward underpredicting head levels near the pit and in Davidson Canyon. Residuals were also much larger and positive at high and negative at low water levels. The model parameterization was not unique because it was not constrained for flux from the model domain. The targets for calibration should include flux targets from the two primary interbasin discharge points — Davidson Canyon and the Cienega Creek Narrows.

Simulation of mine dewatering was accurate with the DRAIN cell method, but the low conductivity zones near the pit in the layers 5 through 7 limited the rate. The simulation of the pit lake had errors but it is uncertain whether those errors would decrease the predicted size of the pit lake. The pit lake is the biggest difference between this model and that proposed by Myers (2008); Myers assumed a pit lake would not form because of evaporation, but he had also assumed a much larger pit bottom. The pit lake simulation herein did not account for evaporation from either the side walls below seeps or from shallow groundwater.

The biggest impacts caused by the mine would be in the pit lake formation phase because drawdown will expand for a period as the pit lake forms. The full extent of drawdown depends significantly on the ultimate depth of the pit lake. A larger lake will cause less downstream drawdown. The ultimate pit lake size is probably between that predicted here and the no pit lake scenario assumed by Myers (2008) because the bottom pit area
will be larger than assumed in this model and because there are several sources of evaporation which will decrease the inflow to the pit lake.

The model was run for just 100 years, and did not approach equilibrium. The model as presented also does not fully consider the long-term impacts of the mining activities because it was not run to equilibrium.

There were errors in the interpretation of the long-term pump test. One is that overlapping drawdown cones caused by pumping five wells at a time would have confounded the analytic results. The second is that the aquifer thicknesses were calculated incorrectly which would result in an improper conversion of transmissivity to conductivity.

2.2 Recommendations

The model boundaries should coincide with topographic and groundwater divides or with low conductivity bedrock and flux boundaries should coincide with points where breaks in the bedrock control the location of most interbasin flow. These boundaries allow for a specified flux boundary, no flow, and head-controlled flux boundaries at which the flux can be targeted which allows better control over the fluxes in and out of the model.

New recharge estimates should be completed using a water balance estimate on the site. Recharge should be distributed according to the site geology and topography. Simulation of dewatering and lake infill should consider the changes in recharge that would occur due to areas below the pit being covered in tails and leach pads. Groundwater/surface water interactions should be simulated with evapotranspiration boundaries and DRAIN cells using the drain return routine, which allows the water lost from the domain at one point to be returned at another. In this case, the water discharging to Cienega Creek above the Narrows could return to the domain below the Narrow as secondary recharge.

Spring data, including chemistry and isotopes, should be analyzed to determine their source and risk to dewatering. They are too small to directly simulate in the model, but all of the springs discharging from bedrock but within the drawdown should be listed as being likely to go dry.

The parameter zones forming a high conductivity "donut hole" within the low conductivity lower layers in the pit area and through Davidson Canyon and the low conductivity rock west of the pit should be re-conceptualized and re-parameterized so that simulated water levels better match the observed. It should include potential flow pathways (and barriers) due to faulting between the pit and Davidson Canyon. This would include higher conductivity cells coincident with preferential flow paths and also fault boundaries to slow the flow. Kh/Kv was very limited in the model and should be allowed to vary in a recalibration.

Parameterization was completed using the PEST parameter estimation routine. This method is commonly used and acceptable for use in this model if used properly, but there...
is insufficient description of its use provided in the GMR. The GMR should better
describe the methodology including the parameter ranges, correlations used in the
routine, weights given to observations, and which parameters were allowed to vary at the
same time.

The modeler should recalibrate the model considering the following factors which were
not considered in the original calibration:

- Model uniqueness
- Water balance controls
- Weight on the head observations
- Better description of and use of prior information from pump tests

Simulation with the LAK2 package must be redone with appropriate coding for
evaporation, precipitation, and runoff. Specifically, the package should be run with the
22 in/y rainfall rate on the pit lake surface, 50 in/y evaporation from the pit lake and
surrounding surface, and a proper runoff factor for rainfall reaching the pit walls.
Additional evaporation of groundwater inflow on the pit walls and shallow groundwater
beneath the pit walls must be considered in the pit lake water balance. The modeler
should consider whether recharge would occur through the pit walls and whether less
runoff would be appropriate.

The model should be run to equilibrium to consider the long-term impacts of constructing
the mine. The substantial uncertainty around the estimate should be bracketed, not used
as an excuse to not consider the future.

Parameters from the long-term pump test should not be used in the modeling effort as
presented in the report. However, the data from the long-term pump test should be used
in the existing model with improvements as recommended in this review as a transient
calibration or in a more detailed model of the pump test area to estimate new transient
parameters.

After recalibration, re-conceptualization and corrections noted above, the GMR should
present water-level data for the entire domain that shows the effects of the pit excavation.
The GMR needs water-level elevation contour maps at the 20-year, 50-year, 100-year and
beyond to show the changes in gradient over time. The 1-foot, 10-foot and 100 foot water
level decline contour maps are insufficient to conceptualize gradient changes over time.

2.3 Report Layout

The GMR presents the groundwater model developed for the proposed Rosemont open
pit. It mixes the development of the data analysis, conceptual model description, and
numerical model development. The review occurs in three primary sections. This first
cconcerns the conceptual flow model and aspects of the report that would normally be
discussed under that topic are included. These are hydrogeologic setting and water
balance. The second section concerns aspects of the numerical model development and
calibration. The third concerns the predictive model runs for mine development and pit lake formation.

3. ASPECTS OF THE CONCEPTUAL FLOW MODEL

3.1 Hydrogeological Units

The geological formations are grouped into hydrogeological units for modeling purposes. Because similar formations have similar hydrogeologic properties, grouping them is appropriate (GMR, section 4.3, p. 12-17). General rock types usually have different properties and can be segregated a priori. Intrusive rocks are usually treated as impermeable unless they are fractured. Sedimentary rocks vary in permeability based on age and rock type; intermediate groups often result in several groups of sedimentary rocks. Basin fill rocks vary due to cementation and depth due to compression. Dividing the basin fill deposits into three units, QTg, QTg1, and QTg2, was appropriate.

3.2 Faults/Fracturing

The groundwater model does not specifically model faults using the HFB (horizontal flow barrier) package. The GMR indicates there is not enough hydrologic data to adequately characterize any specific fault with respect to its flow characteristics. The report mentions that in many locations faults and fractures could be the primary flow pathways. Faults could also impede flow and affect the groundwater level in areas. Because there is not sufficient hydrologic data concerning the faults and fractures, they were not modeled. This may not have been appropriate. There are locations where faults may help increase the groundwater levels, such as in Davidson Canyon.

3.3 Groundwater Levels and Flow Directions

The groundwater contour map (GMR Figure 22) combines all of the c70 wells and piezometers on the site. It does not consider different well depths as was done by Myers (2007). Because of the different aquifer properties and to consider vertical gradients around the site, the groundwater contour map should be redone to consider water levels at different depths beneath the ground surface. The HAR mentions that most wells in the pit area show a downward gradient which could be shown in a set of groundwater maps at different levels.

M&A noted “data indicate that recent groundwater levels are generally higher than in 1975. Because precipitation in 1975 was generally much lower than average, groundwater recharge was probably also lower than average” (GMR, page 22). This is a good observation and also indicates that recharge varies annually.

3.4 Groundwater Recharge

The Anderson (1995) method should not be used to estimate recharge for the Cienega Creek basin. As noted by Myers (2007, p. 21):

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The Anderson et al (1992) method for estimating mountain-front recharge is not applicable at the Rosemont project area because the project area is within the mountain block. Mountain front recharge occurs where channels exit from the mountains and empty onto a broader valley and likely an alluvial fan. Even at the point where Barrel Canyon discharges into the next downstream valley, the equation would not apply because the area is too small and out of the range of data used by Anderson et al. Most specifically, Anderson et al’s equation estimates mountain front recharge to a valley fill basin, not ephemeral channel recharge to a regional bedrock aquifer.

The method is inappropriate for use here for two additional reasons.

- The method is for mountain-front recharge to a larger basin, not to estimate distributed recharge in a mountain block which better describes the basin at the Rosemont project. “The regression equation should not be applied to small watersheds and should not be used for isolated areas” (Anderson et al, 1992).
- The regression equation uses a precipitation estimate as input. It is necessary to use precipitation estimates from the same source to stay within assumptions used to define the regression equation. PRISM, the method used by M&A, may have higher or lower estimates than the method used by Anderson (1995), but the discharge used in the relationship would be the same. The Nevada State Engineer recently rejected uses of the similar Maxey-Eakin recharge estimation method, a very similar method used throughout the Great Basin, based on estimating basinwide recharge efficiencies based on precipitation zones, that are not based on the same precipitation maps used to derive the coefficients.

Recharge should be estimated by completing a water balance for the local area, similar to Myers (2007 and 2009). Recharge to a basin equals the discharge from that aquifer, in steady state, therefore a simple technique to estimate the recharge is to estimate groundwater discharge, a flux which is easier to measure (as flow from a spring, seeps to a stream, or GWET from a wetland, riparian, or other phreatophyte zone). M&A did appropriately limit the recharge to the upper Cienega basin to the discharge within that basin, but should have determined a recharge rate estimate based on the measured discharge and applied it to the remaining model domain.

### 3.5 Groundwater Discharge

The groundwater model report discussed evapotranspiration (ET) but does not distinguish between ET and groundwater ET (GWET), the difference being that ET may be satisfied with groundwater from all sources including groundwater as represented by GWET. The rates (page 28) are large enough to be ET rates, especially the bare soil rate (2.0 ft/y). However, the overall amounts of GWET from the three basins are appropriate, with the

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\(^1\) NV State Engineer Ruling 5726, In the Matter of Applications ... For the Spring Valley Hydrographic Basin...  
Myers: Review of Hydrogeologic Analysis and Groundwater Model of the Proposed Rosemont Ranch Mine
values for the upper Cienega basin being similar to those predicted by Myers (2008) after considering the breakdown between GWET and discharge.

M&A did not include local groundwater pumping in the model (pages 29 and 30), which is appropriate due to the reasons provided.

The discussion of springs as discharge from the groundwater system is very brief. M&A notes that most of the twenty springs they monitored were either dry or just wet spots on the ground. Five springs, Deering, Rosemont, MC-1, Helvetia, and Questa, had “sustained baseflow during the study period” (GMR, p. 7). M&A lists three factors which could cause the springs which can be summarized as follows:

- They are perched and flow only in response to recent precipitation.
- They discharge from deep bedrock.
- They discharge from bedrock constrictions.

The list is correct, as far as it goes, but there is no assessment as to whether dewatering drawdown will affect these springs.

Drawdown can affect a spring if it lowers the water levels or potentiometric surface below the ground level or decreases the gradient driving the discharge from the spring. Perched springs would likely not be affected by the mine unless they are directly excavated. Drawdown would affect and likely quickly dry those springs which discharge from deep bedrock because the potentiometric surface would drop quickly due to the very low storage coefficient in a confined bedrock aquifer. Springs caused by bedrock constrictions are phreatic meaning the saturated water table intersects the ground surface causing a discharge. Water levels would drop slower because the storage coefficient is a specific yield; the drawdown would mostly likely affect the gradient causing the discharge rather than quickly drying the spring.

There is substantial information provided concerning some of the springs, but it is not analyzed. Maps show the geologic formations from which the springs discharge. M&A should consider the formations from which the springs discharge and analyze the chemistry provided in HAR Tables 6 through 9 and the isotope data in HAR Tables 12 and 13 in conjunction with the flow data in Table 11 to provide an improved estimate of the source of water discharging from the spring and to assess the threat caused to the spring by discharge.

### 3.6 Conceptual Model Section

M&A presents their conceptual flow model as a short listing of bullet points regarding the flow in the project area (GMR, p. 41-42) and the region (GMR, p. 42-43). These bullets are listed and discussed as to whether the data presented in the GMR or HAR supports them.
3.6.1 Local Rosemont Project Area (GMR, p. 41-42)

"Groundwater flow in the bedrock is chiefly through fractures and faults. For the bedrock complex around the proposed pit, the groundwater flow system is assumed to behave as an equivalent porous medium, which can be simulated with finite difference codes such as MODFLOW-SURFACT. Results of hydraulic testing and observations of groundwater level conditions in the Rosemont project area generally support this conclusion."

This statement is mostly correct. As long as there is interconnectivity among the fractures, as suggested by the long-term pump test and single well pump tests with observation wells, an equivalent porous medium approach to modeling is sufficient for large-scale impact prediction. There may be exceptions, but this does not obviate the idea of the porous media assumption. The pump tests however usually showed responses from different directions. M&A could have considered more anisotropy due to the prominent fracture directions.

"Hydraulic conductivity of the bedrock complex in the proposed pit area is larger relative to other areas of the bedrock as a result of higher fracture density and/or enhanced fracture connectivity."

This statement should be supported by an analysis of the fractures in drill-holes in the pit and outside of the pit. Pump test data (HAR, Table 4) does not fully support this statement. Well PC-1 has very high conductivity, values for PC-2 through PC-8 are variable with PC-3, PC-4, and PC-6 (low level) being low. Wells substantially away from the pit also have K values as high as in the pit; these include HC-5a, RP-5, and RP-6. HC-5a is north of the pit and RP-5 is south of the pit.

"Hydraulic conductivity of the basin-fill sediments in and adjacent to the bedrock complex is low, due to strong cementation and lack of faulting or fracturing, resulting in poor hydraulic connection of these deposits to surrounding areas, reduced groundwater flow toward the pit, and mitigation of the propagation of drawdown impacts in areas south and east of the proposed pit."

This is an acceptable statement because the pump tests in RP-4a and HC-2a yield low transmissivity values.

"Groundwater recharge in the higher elevations of the Santa Rita Mountains, combined with the low-permeability bedrock, sustains the higher groundwater levels observed in the proposed pit area; groundwater moves from the higher altitudes in the area of the proposed pit to the east and northeast."

This is correct but it is possible that M&A overestimated the distributed recharge in lieu of considering the geology, specifically the fractures, in their distribution around the basin.

"The steep eastward groundwater level gradient in the proposed pit area indicates a relatively low-permeability flow system that is typical of bedrock groundwater systems and strongly cemented basin-fill sediments."

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This is correct as far as it goes. The low permeability reflects the small fractures and poor interconnectedness. Fractures are only as permeable as their connection to other fractures downgradient; once drained, they refill slowly.

"Low permeability of the bedrock flow system will restrict groundwater inflow to the pit and mitigate extent of groundwater level drawdown at distance from the pit. The granodiorite core of the Santa Rita Mountains, immediately west from the proposed pit, is assumed to be competent, with very low or no permeability at depth."

The statement about the core of the mountains is correct, but the pump test data does not necessarily support the low permeability downgradient of the pit. As noted above in bullet #2, several pump tests suggest there are areas away from the pit with higher conductivity. Both short and long-term pump tests suggest higher conductivity at some wells. However, drawdown at a well west of the ridgeline during the long-term pump test is likely due to natural variability rather than a connection through the granodiorite core and should not be interpreted as resulting from a high conductivity connection along the ridgeline; see discussion below concerning pump tests.

"Pumping tests and lithologic data indicate basin-fill deposits (QTg2) in and adjacent to the south and east part of the proposed pit area are strongly cemented, unfractured and have a low permeability, unlike the basin-fill deposits (QTg and QTg1) in the deeper parts of upper Cienega Creek basin; location of the QTg2 will restrict groundwater movement to the pit and mitigate the propagation of drawdown impacts in areas south and east of the proposed mine."

This point relates to the one above about cementation of the fill deposits near the bedrock.

"A fault structure and resulting fractured rocks along Davidson Canyon is believed to have caused a higher permeability zone relative to the adjacent rock."

High conductivity west of the Empire Mountains in Davidson Canyon and further upstream probably relates to faulting but most fault/fracture zones are not this wide, based on my experience in other portions of the Basin & Range. From a modeling perspective, the cause is not important.

3.6.2 Regional Groundwater Flow System

The Cienega Creek basin fill aquifer is poorly connected to the bedrock groundwater system in the vicinity of the Rosemont mine due to the low permeability of the bedrock and strongly cemented, unfractured basin-fill sediments that separates it from the proposed pit area.

This statement repeats the comment above under Local Rosemont Project Area. It may not be correct to state that there is no connection at depth, unless there is a well through the basin fill into the bedrock.

The remaining bullet points are correct and similar to those found by Myers (2008).

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4. GROUNDWATER MODEL DEVELOPMENT

4.1 Model Code

M&A used MODFLOW-SURFACT, rather than the basic MODFLOW, implemented through the Groundwater Vistas (GWVistas) graphical unit interface, which was helpful to me as a reviewer because it is the GUI that I also use. For analysis, I converted the steady state and transient mine dewatering files to MODFLOW and reran the simulations. With few changes, the model ran just as presented by M&A.

MODFLOW-SURFACT has advantages for simulating situations where model cells become "resaturated", as in recovery from massive drawdown that dries model layers. It is commonly used in mine dewatering situations, although I have never had difficulties using MODFLOW-2000 for these situations. In fact, when a model has convergence issue, it suggests there may be problems with conceptualization.

M&A also used the solver, PEST, to estimate the parameters for the model. It is impossible to assess exactly how they did this because there is little description in the report and the model files are just a final product without intermediate steps.

4.2 Model Boundaries

It is typical to define the boundaries of a model based on topography, geology, and hydraulic considerations (Anderson and Woessner, 1992). Except where there is defined flow into or from the domain, it is common to establish boundaries to be no-flow; this gives the modeler control over where the flow enters and leaves the domain, based on the conceptual flow model. Wherever a low-conductivity formation bounds a high-conductivity formation, a two orders of magnitude change in conductivity often adequately defines a no-flow boundary. A groundwater divide or flow line may also define a no-flow boundary because flow does not cross it unless stresses substantially change its location.

Based on these considerations, all discussed in Anderson and Woessner (1992), chapter 4, the boundaries in this model are inappropriate. The boundaries in this model, with one exception, do not coincide with physical or hydraulic boundaries but rather occur on the edge of the square grid. Because these boundaries are not physical or hydraulic, there is potential for flow across all of them. The model simulated substantial area that it did not need to simulate west and northwest of the Santa Rita ridge crest. By simulating so much extra area, the model is not parsimonious (Hill and Tiedamom, 2007). This means the model is more complex than it needs to be. The first rule of model development, as outlined by Hill and Tiedeman (2007), is to start simply and add complexity only as necessary and as supported by data. In this case, there is nothing gained by modeling beyond the ridge crest or below the Narrows.
The groundwater contours, both observed and modeled, show a divide coincident with the topographic divide west of the pit. The geologic cross-sections show formations that are almost vertical — certainly not conducive to cross-divide flow. After the 32nd model period in the transient dewatering simulation, the groundwater divide moved west about 2000 feet in layer and 2400 feet in layer 7, and the point of zero drawdown is a little farther west. The GHB flows near the pit decreases much less than five percent and would be due to a decrease in gradient. There was no flow “captured” from the west side of the divide.

"The lateral boundary should have coincided with the mountain front north of the Narrows and where Davidson Canyon enters onto the basin. The model boundary should also have coincided with the Cienega Creek basin boundary in the south and southeast. Except for defined areas of flow, such as from the canyons, these boundaries should have been “no flow”.

M&A bounded most of the domain with GHB boundaries. Because these boundaries do not coincide with areas of measured or estimated flows, there is no data with which to calibrate the GHB flows. Effectively, the GHBs are unconstrained flow boundaries all around the model. This adds to the non-uniqueness of the model (see p. 23-24).

"M&A should bound the model with no-flow boundaries where they can be defined and with head-controlled flux boundaries, or GHBs in MODFLOW, at points where a flux can be identified and estimated, such as the Narrows or Davidson Canyon.

4.3 Model Layers

The bottom of the model domain is a no-flow boundary. This model has three layers beneath the bottom of the pit and the layers all have the same conductivity. They are effectively one large parameter zone. Very little flow occurred among these layers, as determined by considering the water balance of each of the layers. Conductivity zones less that 1% of an adjoining zone usually have almost no flow and can usually be considered no flow boundaries (Anderson and Woessner, 1992). The use of three bottom layers of the same conductivity is another means this model is not parsimonious. The three bottom layers should be combined into one layer.

4.4 Parameter values

M&A parameterized conductivity using the PEST calibration routine. The model worked within ranges provided for the various parameter zones which, as discussed above under the Conceptual Model, were appropriate. The GMR does not provide the specified ranges but figures of HGUs by altitude (GMR Figures 3-20) and of calibrated K by layer (GMR Figure 27-36) allow an assessment. The K figures separate units by bedrock or zones of QTg, so by comparing the figures one can estimate calibrated K by HGU.

Conductivity tends to decrease with depth within a HGU. Mountain bedrock K tends to be a couple orders of magnitude less conductive than the surrounding QTg. In general,
the conductivity values are appropriate and consistent with the pump test values. Where
the parameter zones are consistent, they correspond within an order of magnitude with
values from Myers (2008). However, a recommendation made below in the Calibration
section is that the model be recalibrated to consider the water balance and the general
sensitivity of each parameter zone.

Three important differences between the GMR and Myers (2008) concern concepts on
which M&A may have erred in their conceptual model. A third area of disagreement
may be an area for which Myers (2008) should have varied his parameter zone
somewhat. The following subsections discuss these three concepts.

4.4.1 Pit area conductivity values

M&A models the parameter zones in the pit with higher conductivity than in the
surrounding areas, especially at depth.

Hydraulically, the bedrock complex and cemented basin-fill deposits are
characterized as having low hydraulic conductivity, where groundwater
movement is controlled by discontinuous fractures and discrete faults. Results of
hydraulic testing in the area of the proposed pit indicate there are weak to
moderate degrees of hydraulic connection in the bedrock complex inside and
surrounding the proposed pit location, which likely will result in sustained
groundwater inflows to the pit. However, at distances from the proposed pit area,
long-term hydraulic testing indicates limited hydraulic connectivity. Hydraulic
connectivity in the larger bedrock complex and cemented basin-fill deposits
system tends to be low and as such will limit pit inflows over time and mitigate
lateral extent of drawdown impacts. (GMR, p. 10, emphasis added)

This description suggests the pit area has higher conductivity than surrounding bedrock
areas. This corresponds to the higher aquifer test conductivity values determined in the
HAR. Although some pump tests do not support this conclusion, a larger problem arises
with the higher conductivity values implemented into the model at depth. The bedrock in
model layers 5 through 10 is very low, except in the pit region in layers 5 through 7
(Figure 1). As shown, the conductivity values in the top four layers are similar to those
in the surrounding area with the green being 0.01 – 0.1 ft/d and the yellow being 0.001 –
0.01 ft/d. Layers 5 through 7 continue with the values near the pit, but almost within the
extent of the pit the zones change to red which is less than 0.0001 ft/d. Low conductivity
with depth begins in layer 5 (GMR Figure 31) even though geologic cross-sections show
Willow Canyon and other formations extending that deep. This low conductivity may
substantially bias the amount of flow into the pit area from surrounding zones and bias
the drawdown to a lower extent from the pit.
I completed a water balance for a cube defined in the model layers and cells near the pit; this test showed that most of the groundwater removed during dewatering emanates from the upper layers but that it flows vertically downward within the pit walls to be removed at lower layers (Figure 2); specifically the maximum amount of water entering the pit is from layer 3 and the peak amount removed is from layer 6. The dewatering rate in layer 6 is almost twice that entering in layer 3. Almost all of the dewatering occurs at the lower layers. Because the cube for which the water balance is calculated is very small (Figure 2), there is very little aquifer volume to release storage, being limited to the volume between the pit and the vertical boundary of the cube. Water released from storage is mostly water transiting from layer 3 to layer 6. Also of note, the flux through the cube prior to dewatering is a small fraction of the flux during dewatering (Figure 2).

This water balance evinces an image of a whirlpool without the swirl — flow enters the water balance cube near the surface and then plunges to near the pit bottom. An increase in K at lower layers surrounding the pit would obviously allow more flow to enter the pit at lower levels. This flow would originate both from the lower layers and through vertical flow from upper layer layers, which may be more realistic for how the flow near the pit would actually occur. Dewatering from the lower layers was of water entering from the upper layers and is due to the modeled parameters being so low. If the conductivity in lower layers was higher, for example, the drawdown which occurs near the pit in those layers would have drawn water from further distances in the lower layers which would extend the drawdown impacts further than modeled.
4.4.2 High Conductivity along Santa Rita Ridge

Figure 1 also shows the conductivity in the bedrock west of the pit, directly under the ridge, is higher than would be expected for a granodiorite core. The green, higher conductivity zones extend from the pit to under the ridge and span the upper four layers. Neither the hydraulic data nor geology justifies this higher conductivity. The fact that a well west of the ridge experienced water level changes during the long-term pump test can be explained by local recharge variations; even if there is a connection, it likely extends only a few hundred feet deep, not through four model layers.

4.4.3 Connections between the Pit Area and Davidson Canyon

M&A may also miss connections between Davidson Canyon and the proposed pit. At least three drainages, Wasp, Barrel, and McCleary Canyon, have saturated alluvium (Myers, 2007) that may coincide with faulting which could have its own fracturing.
Myers (2008) simulated a single higher conductivity zone between the pit and Davidson Canyon but did not directly identify differential conductivity zones which could correspond to specific faults. GMR Figure 3 shows substantial faulting, mostly labeled as “Fault Trace with unknown displacement” or “Inferred fault trace”, between the pit area and downstream canyons. Well PC-2 lies along a fault trace along the base of the mountain north of the pit that would connect the pit area with McCleary Canyon.

At wells PC-2 and PC-5 in the northeast part of the proposed pit, and at Tetra Tech piezometer TTBH-08-08C and Anamax drillhole P-899, located about 1/2 to 1 mile northeast of the pit, groundwater levels (hydrostatic head) in the Paleozoic rocks are sufficiently elevated to cause the drillholes or wells to flow or seep at land surface. The elevated hydraulic head in the deeper Paleozoic rocks is believed to result from their fault/fracture zones being locally in hydraulic communication with the Paleozoic rocks at higher elevation on the mountain slope. (HAR, p. 15)

The trace and connections referred to in this quote could connect the pit to the Davidson Canyon area. M&A does not model this connection.

The model should be reconceptualized in the area of the pit. The conductivity of the bedrock in all directions should be reconsidered. There should be low conductivity (or no flow boundary) west of the pit. Conductivity is not as low a modeled east and south of the pit. Additionally, it should better include potential flow pathways (and barriers) due to faulting. This would include higher conductivity cells coincident with preferential flow paths and fault boundaries to impede the flow. Conductivity values of the pathways are probably just an order of magnitude higher than surrounding bedrock and fault impedances have a conductance based on a conductivity of around $10^4$ ft/d, similar to the lower conductivity HGUs.

4.4.4 High Conductivity Zone along Davidson Canyon

The GMR discusses faulting along Davidson Canyon.

A fault zone extending through the Davidson Canyon area is of particular significance to the movement of groundwater in the area. The fault zone is inferred to occur northeast from the proposed pit, trending north along the Canyon (Figure 3). The Davidson Canyon fault zone separates the Santa Rita and Empire Mountains (Ferguson and others, 2001). It consists of at least two major faults in which the west side is down relative to the east side. The eastern fault can be traced south across the northern and western pediment of the Empire Mountains, approximately 1 mile east of Davidson Canyon. The western faults trace is concealed by alluvium (Ferguson and others, 2001). Potential hydraulic influence of this fault zone is evaluated as part of this investigation. (GMR, p. 18)

The report also indicates that it causes the conductivity values to be higher. “A fault structure and resulting fractured rocks along Davidson Canyon is believed to have caused...
a higher permeability zone relative to the adjacent rock” (GMR, p. 42). The report also suggests that faulting causes the groundwater trough in the area.

Approximately 3 to 4 miles northeast from the proposed pit and continuing down channel in Davidson Canyon, groundwater levels indicate a trough coincident with intersection of the Canyon with groundwater level and with the Davidson Canyon fault zone, which is assumed to have a higher permeability than the surrounding bedrock (Figure 22). (GMR, p. 23)

Mountains on both the northwest and southeast likely focus recharge which drains toward the lower topographic area along the canyon. The converging flow paths from the recharge probably cause the trough, not the faulting. M&A may have arbitrarily increased the conductivity within Davidson Canyon.

Hydraulic conductivity was initially assigned to Davidson Canyon by extrapolating pumping test results from the 30-day test area to the southwest. Hydraulic conductivity was then increased in a narrow zone extending in depth from layer 1 through layer 4, a thickness of approximately 1,200 feet, to a range from 0.5 ft/d to 2 ft/d (Figure 27). This zone coincides roughly with the north-south trending Davidson Canyon fault zone along the west flanks of the Empire Mountains, as described in Section 4.4. Hydraulic conductivities on either side of this simulated fault zone range from about 0.002 to 0.02 ft/d. (GMR, at 50, emphasis added)

Setting a higher conductivity appears arbitrary because doing so set the value higher than aquifer tests would suggest. Pump tests at well RP-8, which is completed in the Schellenberger Canyon formation, which is not described as fractured (HAR, vol 2), yielded Kh equal to about 0.09 ft/d (HAR, Table 4).

The presence of faulting is not in question, but the effect it has on conductivity through the canyon is. Myers (2008) simulated a higher conductivity zone through this canyon, but the conductivity was around 0.3 ft/d, not as high as 2 ft/d as found in this model. M&A’s model has many positive residuals in the canyon area, especially in the southern end. It is possible that lower conductivity values in the canyon would raise the simulated water levels to closer to the surface which would match the observed values better.

**Conductivity along Davidson Canyon may be too high. This could bias the model results by providing a conduit for flow to the northeast away from the dewatering.**

### 4.5 Vertical Anisotropy

Vertical anisotropy is the ratio of horizontal to vertical conductivity, or Kh/Kv. It is caused by bedding planes and laminae within a sequence of sediment layers and by fractures (Anderson and Woessner, 1992). Sandstone usually has higher conductivity in one direction because small particles deposit with their longer dimension in the horizontal direction. Once lithified, the sandstone would have a significant vertical anisotropy.

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Most of the bedrock layers, especially the Willow Canyon formation, are well lithified (HAR, appendix 3) with significant percentages of clay and silt. These often settle horizontally causing high K in one direction than the other. The rock in this area very likely has high K in one direction than in the other.

This model simulated bedrock and basin fill Kh/Kv equal to 1.0 and 10.0, respectively. “Simulated vertical hydraulic conductivity in the model is specified as equal to horizontal in bedrock and 1/10th of horizontal in basin-fill sediments” (GMR, p. 51). In contrast, Myers (2008) started the calibration with Kh/Kv ranging from 2 to 10 for bedrock and 10 for basin fill. Myers allowed Kh and Kv to vary independently during the calibration using the routine within MODFLOW-2000; Kh/Kv ranged from as much as 100 for some bedrock formations to slightly less than 1.0 near the pit reflecting the almost vertical dip in the formations.

Failing to accurately model Kh/Kv could cause the model to underestimate drawdown because higher vertical conductivity allows groundwater to flow among layers faster than might be realistic.

*Recalibration of the model should allow Kh/Kv to vary to higher than 1.0.*

### 4.6 Groundwater Recharge

This review discussed above that the Anderson method is not appropriate to the Cienega Creek basin, but its estimate was that 10,100 af/y was the recharge to the model domain. M&A then divided the total among three basins; Upper Cienega, Lower Cienega, and Tucson basins received 5132, 2179, and 1928 af/y, respectively (GMR, p. 52) for a total 9779 af/y. Recharge by basin does not add exactly to the total presumably because not all of it was applied as specified flux but some, 2763 af/y, was allowed to enter the Cienega basins through the GHBs.

M&A distributed half of the 10,100 af/y estimate over the entire domain based on PRISM-estimated precipitation distributions. This is not correct because it does not consider geology; the same amount of water would enter an impermeable intrusive rock as would enter highly fractured carbonate rock.

M&A applied to the rock near the top of the Santa Rita Mountains a rate of 0.43 in/y and near the pit 0.33 in/y. These rates are low compared to Myers (2008) who found that about 1.65 in/y would recharge a zone near the top of the mountain including the pit but equal to zero on the flanks of the range. Myers (2007) concluded that recharge in the mountains would occur through fractures and that washes filled with alluvium may serve as pathways for infiltration to reach the bedrock aquifer. Myers’ assumption was that, rather than distributed over the soils on the steep ridges east of the pit, most recharge would be of water that runs off to the drainages. Total recharge equaled about 650 af/y for the near-project watershed; using the digitizing tool within GWVistas, the recharge in a proximate watershed in the M&A model is about 510 af/y. It is difficult to be certain the recharge estimates are for the same area, but Myers’ (2008) estimate appears higher.

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than that in the GMR. Myers (2007) based his estimate on discharge at the site, by
determining rates based on the discharge from the upper Cienega basin, and M&A based
their method on an arbitrary division (50% of the total) of an estimate using an incorrect
method. M&A may have underestimated recharge at least for the near-project watershed
by about 20%. This would have two impacts.

- The model calibration could have resulted in lower conductivity values because
  less water was simulated as flowing through the system.
- Dewatering rates would be too low in the M&A model because of their being less
  flow through the system. Drawdown effectively captures all of the groundwater
  flow through the near-project watershed (Myers 2007, 2008), so it would equal
  the total recharge.

Some of the recharge was applied to the model domain as GHB flow because the model
domain did not coincide with the basin boundary. Recharge upgradient of the model
boundary would flow into the model through these boundaries. In the upper Cienega
basin the inflow through the GHB is considered basin recharge; in the lower Cienega
basin, the GHB inflow is considered mountain front recharge. In the upper Cienega
basin, there is a substantial additional amount that recharges at the mountain front; the
maximum amount is near the location that Gardner Canyon emerges from the mountains.
The mountain front recharge assumptions are reasonable, but they affect the flow around
the proposed pit almost not at all because there is no mountain front recharge simulated
in the Lower Cienega basin, which includes Barrel Canyon.

The recharge would change due to the mining plans, but the model does not account for
this. The leach pads would intercept recharge, the tailings impoundments would impede
recharge for a period of time, and recharge would continue through the pit area. During
pit development and dewatering, the model continues to have recharge occur within the
area of the pit, which is appropriate. During pit refill, M&A does not simulate any
recharge but rather assumes a proportion of rainfall runs into the filling pit, which is also
appropriate. One problem with the recharge simulation is the leach pads should intercept
recharge because they would have liners to capture the copper leaching from the pad.
The liners will be there in perpetuity and the facilities would be closed to minimize
infiltration. The tailings impoundments will use a dry paste technique, therefore there
would be little process water to seep into the groundwater from the area of the tailings.
Recharge may occur through the tails in the long term, but may be interrupted during the
period the tailings are being developed and afterward until seepage reaches the ground
surface.

The groundwater model only considered recharge within the pit during pit development
correctly; it was incorrect to allow recharge to continue at its steady state rate in the
area of the leach pads and tailings impoundments. During pit development, M&A
should simulate decreasing recharge in the leach pad and tailings areas. During pit
lake development, M&A should simulate zero recharge in the heaps and transient
recharge equal to that expected from a growing tailings impoundment. A simulation of
seepage through the tailings impoundment should be used to predict the long-term diminution and reestablishment of the recharge under the tails.

4.7 Simulation of Groundwater – Surface Water Interactions

Rather than simulating groundwater/surface water interactions, M&A imposed infiltration and ET discharge along two perennial reaches of Cienega Creek using injection and pumping wells (GMR, p. 54-55).

For each simulated reach, extraction wells are used to simulate groundwater discharge to the stream reach (gaining streamflow) and injection wells are used to simulate groundwater recharge from the stream reach to the underlying aquifer (losing streamflow); actual streamflow is not simulated. The gaining portions of a reach are assumed to be at the upstream end of the selected reach and losing portions are assumed to be at the downstream end of the selected reach. Groundwater discharge is equal to groundwater recharge for each simulated reach. Discharge and recharge rates are uniformly applied to the model grid cells representing the gaining and losing portions of each simulated reach. Zero groundwater interaction is assumed to occur between the gaining and losing reaches; evaporative loss from the open water surface is small and not simulated. (GMR, p. 54-55)

The appropriate way to simulate this would have been to use head-dependent flux boundaries, the ET and RIVER packages. This would be preferable because it requires the calibration to simulate the water levels near the ground surface so that water can discharge to or from the RIVER or discharge from the ET cells. The method utilized by M&A would have simulated the interactions even if the groundwater level was far below the ground surface rather than approximately equal to the river water levels.

Wells were used primarily along Cienega Creek. Above the Narrows in the upper Cienega basin are extraction wells to simulate discharge to the stream. These wells cause inappropriate and misleading flow paths near the creek. For example, a combination of a series of pumping wells (Figure 3) and narrowing of the basin caused by bedrock outcroppings caused this major disruption in the flow field (Figure 4). A small cluster of injection wells near the point that Cienega Creek emerges from the Narrows simulates secondary recharge of water (Figure 3). Together, discharge to the creek and secondary recharge could have been simulated with DRAIN cells upstream of the Narrows using the return function to return that flow for recharge below the Narrows. Further north most of the wells were extraction wells and would simulate ET.
Figure 3: Screen capture from GWVistas of the boundaries and groundwater levels in layer 1 of the groundwater model. The blue markers are locations of the wells simulating groundwater/surface water interactions. The wells clustered along a line in the southernmost 2/3rds of the domain are extraction wells, the few wells scatter just north are injection wells, and the remainder are a mixture of wells but mostly extraction wells. The primary recharge wells are along Cienega Creek near where it discharges from the Narrows. The profile on the tope shows a column 115 which tracks the profile of the creek where there are wells.

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Figure 4: Graph of flow in the east-west direction through row 104, which goes through the middle of the pit. The peak is due to the injection well simulating recharge from Cienega Creek.

4.8 Springs

The groundwater model did not directly simulate springs near the proposed pit. Because of their small size and proximity to the pit, this is probably appropriate. It is possible to simulate springs emanating from deep bedrock by using a DRAIN boundary in a deep layer corresponding with the depth of the spring, but because flux would be a very small proportion of the water balance near the pit, calibrating the spring would be difficult. Once drawdown begins with the layer, the spring would simply dry, therefore it would be sufficient for to just identify the bedrock springs within the drawdown cone and indicate they would be likely to dry as a result of the dewatering.

4.9 Calibration

The GMR provides little discussion on how the calibration was actually completed. M&A stated head values on GMR Figure 24 “represent equilibrium conditions” for the project area and were used for calibration targets (GMR, p. 46). It also states that “historical groundwater level data, combined with the absence of substantial, long-term groundwater withdrawals in the study area, strongly indicate that the groundwater flow system is in an equilibrium state” (GMR, p.46). However, GMR Figure 24 shows that water levels vary, but steady state calibration requires that each observation well have one level, not a hydrograph, and the GMR should discuss how the observed levels were chosen – whether they equaled an average at the given wells or a given time period.

Calibration involved adjusting conductivity parameters within eight hydrogeologic units, which as noted above were chosen appropriately. They utilized the PEST parameter estimation routine described as follows:

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The hydraulic conductivity values within these zones were adjusted using PEST (Doherty, 2005), a parameter estimation program, by inversion to measured groundwater levels. As part of the inverse calibration process, hydraulic conductivity values are permitted to vary within a range defined by hydraulic test interpretations for the fractured rock and basin-fill systems being simulated. In the calibration process hydraulic parameters are permitted to vary both between the zones and within the zones, resulting in representation of the final horizontal and vertical distribution of hydraulic conductivity as a continuous field. (GMR, p. 47)

PEST is a commonly used and acceptable parameter estimation routine, but the GMR does not describe details of the input to PEST nor does the groundwater model input files. **M&A should provide details of the range the parameters were allowed to “vary within” and the controls provided over the variations between and within zones. The GMR does not describe the process and the model input files do not include this information.**

The modeler allowed the conductivity to vary at each individual model cell, subject to the constraints not specified above. This resulted in more than 65,000 different parameter zones in the final model. "This continuous field distribution **recognizes there is substantial natural variation within hydrogeologic zones,** including variation of fracture occurrence, density, and permeability in the bedrock areas, and that boundaries between hydrogeologic zones are poorly defined in three dimensions" (GMR, p. 47, emphasis added). These factors do vary among and within the formations, but there is almost no information about how the parameters actually vary. The final values resulting from PEST are merely a solution that allowed the nonlinear regression, within PEST, to solve, meaning the errors from the regression were minimized within the constraints applied to the solution (not specified in the GMR). If those constraints were changed, perhaps only slightly, the solution could be substantially different. Because the residuals average far from zero (GMR, p. 56), there is vast potential for improvement.

The calibration goal was to choose parameters so that the head levels equaled observed values. The fit of the calibration is judged based on various statistics of the residuals resulting from the modeler’s choice of the best parameter choice. **M&A argues the final fit is acceptable as follows:**

> Across the larger model domain the simulated match to observed groundwater levels is reasonable. The residual mean, the average difference between observed and simulated groundwater altitudes, is 11.3 feet. As the residual mean approaches zero, the simulated groundwater altitudes more closely match the observed conditions. The absolute residual mean, the average of the absolute value of difference between observed and simulated groundwater altitudes, is 61.0 feet and represents the magnitude of the difference between observed and simulated groundwater altitudes. The residual standard deviation is 90.3 feet, and the residual standard deviation divided by the range of observed data is 2.8 percent. Values for the residual standard deviation divided by the observed data...
range should be below 10 percent for an acceptably calibrated model. (GMR, p. 56 and 57)

There is no reference to justify claiming the agreement between observed and simulated water levels is "reasonable" or that an "acceptable calibrated model" should have "residual standard deviation" less than 10% of the observed water level range. Anderson and Woessner (1992, p. 241) indicate the ratio of the root mean squared error to the total head loss in the system must be small, but do not provide a standard for comparison.

Residuals must be normally distributed and not biased toward positive or negative values around the model domain. Residuals near Davidson Canyon and the proposed pit were biased with the model predicting values that were much too low as compared to observed values; these geographic areas are discussed in detail in a section below. Two graphical comparisons, prepared using plotting software within GWVistas, also demonstrate the bias and lack of fit inherent in the model fit.

Using M&A's input files, I used GWVistas to recalculate the residuals so that I could examine them independent of the output provided in the GMR; the statistics were reproduced exactly, therefore I used other residual examination techniques within GWVistas to consider the model fit resulting from the calibration. The simulated water levels overestimate the observed values at low water levels and underestimate them at high values (Figure 5). Considering the thickness of the cluster of points (Figure 5) is about 200 even in the middle, even near the center of the observed water levels the fit is not very tight, or close to agreement, with observed values. At high water levels, the right side of Figure 5, the model underpredicts water levels by more than 300 feet. These residuals are mostly in layer 1 and reflect the inability to simulate water levels near the pit and along the Santa Rita ridge. At low water levels, the left side of Figure 5, the model overestimates observed water levels by as much as 400 feet. These are mostly in layers below layer 1; there are few observation targets in layers 5 and 6 and none in layers 7 through 10.
Figure 5: Plot of simulated model heads vs. observed heads at the calibration targets.

Figure 6 further illustrates and emphasizes the same observations. There are positive residuals at high observed levels and negative residuals at low observed levels. This demonstrates bias and inaccuracy in the final model solution.

I converted the MODFLOW-SURFACT input to MODFLOW files and ran the model in steady state. One difference is that MODFLOW uses the PCG2 solver package, not the PCG4 package used in MODFLOW-SURFACT. Initially it did not converge but stopped after 100 iteration attempts, as specified by M&A in the GWVistas file. The resulting test statistics almost exactly matched those reported by M&A. The differences were so
small they could be due to differences between packages and solvers. M&A should discuss convergence, including whether their model actually converged (Anderson and Woessner, 1992, chapter 9).

After adjusting the relaxation parameter in the PCG2 solver package from 1.0 to 0.99, the model converged to a residual mean of 0.14, standard deviation 95, absolute residual mean 61.7, and residual std dev divided by the observed data range 2.9 percent. These statistics are very close to those reported by M&A, except the mean residual was vastly improved by the switch from MODFLOW-SURFACT to MODFLOW.

It is difficult to assess where that improvement could result because there were no sensitivity analyses provided in the GMR. The composite scale sensitivity (CSS) values, as done by Myers (2008), show which parameters are sensitive which are the parameters for which the observed data can be used to aid in calibration. **At a minimum, M&A should provide the composite scaled sensitivity values for the HGUs.** The CSS shows which zones are most sensitive to the available target data.

The model solution as presented is not “unique”. Nonuniqueness is simply the situation wherein a different parameter set could describe the observed target values equally as well as the proffered values. This model is likely not unique because it did not control for flux values across certain boundaries; recharge is applied to the model as specified by the user, which controls the total flux from the model domain, but allowed to exit the domain essentially without restraint. One way to test this is to run the calibration in PEST with different starting values for the parameters (not necessarily different constraints); if the final solution yields an objective function similar to the original but with significantly different parameter estimates, the model is not unique. Essentially, it is likely that a similar distribution of simulated water levels could result from a significantly different set of parameter values because the calibration did not control the fluxes leaving the domain.

The calibration also apparently treated each head observation as equal to every other observation, even though some may impart much less information value to the calibration because they are less accurate or precise than others. Factors leading to imprecision include seasonal water level variation or a long-term trend, screen lengths spanning more than one model layer or geologic formation, uncertainty in the knowledge of the screen or intercepted formation, uncertainty about whether the measurement is perched, inaccurate measurement techniques, or many other problems. There are many ways to weight the observations, which M&A should consider. The most important difference may be that the calibration uses water levels from new and old wells.

The role that prior information was used in the model calibration is not clear. Prior information includes pump test results and other parameter observations. The GMR noted that parameter values were allowed to vary within and among HGUs, which is a means of applying prior information. However, the estimation techniques also treat such test results has target values which are met just as the head observations are met. Hill and Tiedemon have a warning about using prior information from pump tests: “prior

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information on sensitive parameters can obscure important information available from the regression" (Hill and Tiedemon, 2007, p. 33). This argues for using the values as a target. Using the values to set a limit or range on the parameter estimate may also be improper. “This occurs when prior information is used to restrict the parameter estimate from becoming unreasonable during regression. However, unreasonable parameter estimates can lead to important insight about problems with the model or with the observations” (Hill and Tiedemon, 2007, p. 33). Simply bounding the parameter estimates may not allow the calibration to reveal problems with the model – primarily the conceptual model.

The modeler should recalibrate the model considering the following factors which were not considered in the original calibration:

- CSS values so that only the sensitive parameters are calibrated within PEST
- Model uniqueness
- Water balance controls
- Weight on the head observations
- Better description of and use of prior information from pump tests

4.10 Specific Model Areas with Biased Residuals

The calibration had difficulty matching the observed heads near the pit and in Davidson Canyon, and the residuals appeared to be biased. At the pit:

Observed groundwater levels in the vicinity of the proposed pit exhibit a steep gradient from the highest altitudes of the Santa Rita Mountains east to the pit. It is expected that the model would have difficulty reproducing observed levels in this granodiorite formation, as these rocks are believed the least permeable with very limited hydraulic conductivity resulting in groundwater being poorly connected, or disconnected, from the system simulated in the model. Simulated values are hundreds of feet lower than observed in the highest altitudes of the Santa Rita Mountains west from the pit, generally less than 100 feet lower in the pit area, and matching reasonably well immediately east from the pit. We believe the match of simulated to observed groundwater levels in the vicinity of the pit is acceptable for the objectives of the model, and fairly typical for a model which is simulating groundwater movement in a fracture rock system on the edge of a mountain divide. (GMR, p. 56)

There is no inherent reason the model could not simulate observed water levels in the pit area. Matching the observed water levels in a steep area is difficult, but the difficulties should not lead to a bias, as would result from the residuals in an area being positive or negative. It suggests the modeler has missed something in the conceptual model of the flow near the pit. Conductivity parameter zones could be wrong or improperly constrained or a fault could have been missed; Myers (2008) had two cross-flow faults below the pit based on the mapped geology (WLR, 2007). If groundwater in the pit area...
were truly disconnected from the regional groundwater system, there would be a point of discharge near the pit for the postulated perched system.

M&A presents no references, standards, other studies, or other supporting documentation for its claim that the “match of simulated to observed groundwater levels in the vicinity of the pit is acceptable for the objectives of the model” or “fairly typical” for a model of fracture rock systems to be off by 100s of feet. The “objectives” are to simulate drawdown and the predictions start with the results of the steady state simulation, so the model will underreport drawdown if initial heads are the underestimated steady state values. Accuracy is most important in the area of the pit. More likely, the combination of recharge distribution and conductivity is incorrect.

The model also substantially underestimates the water levels in the Davidson Canyon area, a much larger area than the pit. A residual is the observed minus the simulated water level, and most are positive along Davidson Canyon (Figure 7). Starting in the north, the residuals are 79.3, 37.1, 72.6, 38.1, 80.2, 51.4, 20.7, 66.3, -30.8, 50.9, 91.8, -13., 12.1, 41.3, and 27.4 feet, and a similar trend continues to the south and west (Figure 7). Several springs also have positive residuals, one up to about 90, which means the water level is far below the ground surface.

The model should not systematically over and under-estimate the water levels in various parts of the domain (Anderson and Woessner, 1992). The tendency of this model to underestimate levels in at least two areas suggests there is a systematic error in some aspect of the model – either in the conceptualization, use of prior information to constrain parameters, or failure to target specific fluxes around the domain. At Davidson Canyon, this could be due to a failure to include flow through the canyon or from the springs as a target, or could be due to improper constraints on the parameter values.
4.11 Predictive Simulations

M&A conducted two transient simulations to predict future conditions. The first was for the 20 years mining period and the second for a 100-year pit lake formation period.
4.11.1 Pit Dewatering Simulation

The transient simulation has 13 quarter-year periods (90, 91, or 92 days) followed by 19 year-long periods (365 or 366 days). All stress periods have 8 time steps and time-step multiplier of 1.4.

Simulation of pit dewatering with DRAIN boundaries is appropriate (GMR, p. 58). Also appropriate is setting the DRAIN conductance high to allow groundwater to drain easily into the pit. Because the DRAIN head represents the level to which the water level must drop for pit excavation, flow to the DRAIN should occur with as little head over the DRAIN as possible. M&A set the stage or head for some of the DRAIN cells below the layer bottom, which is not appropriate but does not affect the model because these DRAINS will not simulate flow once the head is below the layer bottom. It is appropriate that the modeler did not set the head for a DRAIN in one cell above the bottom of the layer above it. The DRAIN would remove water, but this would be physically unrealistic unless the mining company put dewatering wells below the pit bottom.

The DRAIN heads appear to the set very close to the pit walls. Because of the high DRAIN conductance, the water levels are very close to the DRAIN head and therefore the pit walls. The groundwater contours at the end of mining near the pit resemble a very sharp cone that appears to correspond closely to the proposed pit (Figures 8 and 9). However, the pit will bottom at about 3050 ft msl, but the bottom groundwater contour is 3300 ft msl (Figure 8). The head in the bottom DRAIN cells is 3040, and the cell is dry at the end of mining, therefore the model does simulate water levels to drop below the pit bottom. Surrounding cells have water levels 100 or more feet higher than those in the middle.

It appears the simulation has groundwater in the pit or to close to the pit wall (Figures 8 and 9). Combined with the vertical flow occurring within a few hundred feet of the pit walls, as discussed above in the section on conductivity near the pit, the model clearly sets the DRAIN head and nearby conductivity in a fashion that minimizes the drawdown near the pit and simulates groundwater very near the pit walls (Figure 10). If dewatering wells are used, the drawdown around the wells would pull the water table away from the pit walls. If dewatering occurs by pumping it from sumps in the pit bottom, then it is appropriate to allow the water table be very near the pit wall. The GMR should discuss how dewatering will actually occur and how the model simulates that process.

Although it is beyond the scope of the GMR, pit wall stability must be considered with respect to the groundwater being so close to the pit wall. Additionally, if the groundwater is so close to the pit wall that seeps and springs form in the pit wall, there will be an ET loss from the pit wall which is effectively a loss from groundwater. GWET from the pit wall could be substantial and should be included in the model or, if not modeled, discussed in the GMR as to why it is not modeled.
Figure 8: Snapshot of pit outline and groundwater contours from GMR Figure 45.

Figure 9: Snapshot of the pit configuration from Rosemont Feasibility Study.

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4.11.2 Pit Lake Formation Simulation

The biggest impacts caused by the mine on groundwater levels would occur in the pit lake formation phase because drawdown will expand for a period as the pit lake forms. The full extent of drawdown depends significantly on the ultimate depth of the pit lake. A larger lake will cause less downstream drawdown. Pit lake modeling is a major difference between the M&A model and Myers' (2008) model. Myers (2008) assumed that evaporation was too high for a pit lake to form and M&A has simulated a pit lake filling to more than 750 feet deep and volume of 25,000 af. Myers (2008) assumed an effective pit bottom area would be about 300 acres and that inflow to the pit would not exceed the evaporation spread over that area. Based on the recent pit contours (Figure 8), the 300 acre estimate for the pit bottom was too large. However, the stage-area relationship (GMR, Figure 43) used for this modeling appears to have too little area at the
bottom of the pit. It indicates that at stage 3200 and 3400, the area will be just 4 and 16 acres, respectively, which seems incorrect compared to Figure 8.

The ultimate pit lake size would probably between that predicted by M&A and the no pit lake scenario assumed by Myers (2008). The bottom pit area will be larger than assumed by M&A and there are several sources of evaporation which will decrease the inflow to the pit lake, as will be discussed in the next paragraphs.

Simulated water levels at the end of mining were the initial conditions for the pit lake formation scenario, which was considered in a separate model simulation. This was necessary because the model structure changed as the LAK2 package was implemented. The model simulated 100 years into the future using one 36,350 day-long stress period with 1000 time steps and a time-step multiplier of 1.7. For use with the LAK2 package, the model fills the pit area with no flow boundaries (as may be seen from looking at the Trans_LAK.gwv file in GWVistas. With no flow boundaries in layer 1, recharge in the pit area is zero.

The LAK2 package simulates a head-controlled flux boundary for which the water level in the pit controls the gradient on the boundary. The flow control is similar to the GHB boundary. The package accounts for groundwater inflow, precipitation, runoff from the pit walls, and evaporation from the pit lake.

A water balance table (Table 1) created from GMR Figures 43 and 46 shows that the evaporation and precipitation rates applied to the pit lake model are incorrect. Average evaporation and precipitation rates were calculated by averaging the total reported evaporation and precipitation values for a time period (for example, years 5 and 10) and dividing by the average pit lake area for the same time period (the average of 26 and 40 acres). Table 1 shows the average evaporation and precipitation rates, derived from GMR Figures 43 and 46, to be 34 and 6.8 in/y. These rates differ substantially from the stated values of 50 and 22 in/y (GMR, p. 60).

M&A describes the evaporation rate from the lake as follows: “Evaporation is only simulated from the lake surface and is assigned a value of 50.06 inches per year (1.14 x 10^2 ft/d). This rate is approximately 70 percent of the average pan evaporation projected for the Rosemont project area. A pan coefficient of 0.70 is commonly used to reduce the pan evaporation rate to a lake evaporation rate” (GMR, p. 60). This description appears to be stating that 50.06 in/y is 70% of a higher pan evaporation value, which would be 71.5 in/y. Open water evaporation in Tucson and Arivaca is 6 and 5 ft/y (PAGWP, 2006), respectively, therefore 50 in/y would have been the correct open water evaporation for the elevation and exposure of the Rosemont pit lake. The 34 in/y calculated in Table 1 appears to be an enigma. It is also almost exactly 70% of 50 in/y which suggests that M&A applied the pan coefficient twice.

The low rainfall rate, 6.8 in/y, is 30% of 22 in/y. The runoff factor was 0.3, so this suggests that M&A somehow applied the 0.3 factor for runoff to the free-surface pit lake precipitation.

Myers: Review of Hydrogeologic Analysis and Groundwater Model of the Proposed Rosemont Ranch Mine
Table 1: Pit lake infill water balance using data from GMR Figure 43 and 46.

<table>
<thead>
<tr>
<th>Years</th>
<th>Stage (ft msl)</th>
<th>Volume (af)</th>
<th>Area (acres)</th>
<th>GW In (gpm)</th>
<th>Prec (gpm)</th>
<th>Runoff (gpm)</th>
<th>ET (gpm)</th>
<th>Net In (af/y)</th>
<th>Cum In (af)</th>
<th>ET (in/y)</th>
<th>Prec (in/y)</th>
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</tbody>
</table>

There are no values for years 70 and beyond because the stage shown in GMR Figure 46 is higher than the values shown in GMR Figure 43.
File Trans_LAK.lak is the input file for the LAK2 package. The last line in the file provides six parameters, including PRECIP, EVAP, RUNOFF, DRYRCH, IOUTOP, STAGE and the file specifies these variables as 0.52e-3, -7.88e-3, 0.0, 0.0, 8. and 0.0. Council (1999, p. 126) describes the relevant parameters as follows:

EVAP: Wetted-area-dependent flow rate (L/T): The Lake Package budget routine multiplies EVAP by the wetted area of the lake (excluding short cells) and adds the resulting flux to the lake’s volumetric budget. Specify a positive number for lake inflow or a negative number for lake outflow.

RUNOFF: Fixed lake inflow (L^3/T, positive = inflow to lake, e.g. runoff)

The other variables were not used. The input values are in ft/day and convert to the rates calculated in the previous section. A more complete description follows:

In the Lake Package, the user specifies a precipitation rate and an evaporation rate (in length/time units) through the PRECIP and EVAP input variables for each stress period. The Lake Package calculates the precipitation flux as the PRECIP rate times the total area of the lake, regardless of lake stage. The Lake Package calculates the evaporation flux as the EVAP rate times the current “wetted” lake area (the sum of the areas of all cells having a lakebed top elevation below the current stage). The EVAP value should be specified as a negative number to indicate a lake outflow. In this formulation, evaporation occurs only on the lake surface, whereas precipitation falling either on the lake surface or on the lake shore is added to the lake (i.e. precipitation on the lake shore runs off into the lake). As described in section 3.3, the Lake Package input can be modified slightly for a conceptualization where only direct precipitation on the lake surface is included in the lake budget.

The user can also specify a runoff inflow rate for each stress period (in cubic length/time units) via the RUNOFF variable. The RUNOFF variable can also be used to add a known stream inflow to a lake’s budget (instead of using a stream inflow calculated by the Streamflow Routing Package). This variable can also be used to represent a direct withdrawal from the lake (a negative value should be specified in that case). The value of RUNOFF is added directly to the lake’s budget. (Council, 1999, p. 10)

These passages from the user’s manual make clear that incorrect precipitation and evaporation values were input to the LAK2 package. It also appears that M&A did not input a runoff rate on the input file line quoted above but the quoted paragraph indicates the model calculated runoff as the precipitation rate multiplied by the pit wall area specified to drain to the lake.

Simulation with the LAK2 package must be redone with appropriate coding for evaporation, precipitation, and runoff. Specifically, the package should be run with...
the 22 in/y rainfall rate on the pit lake surface, 50 in/y evaporation from the pit lake and surrounding surface (see next paragraph), and proper runoff factor for rainfall reaching the pit walls.

Even if done properly, the LAK2 package would probably simulate too little evaporation from the pit because it simulates evaporation from the pit lake but ignores evaporation from the pit walls. It does consider evaporation of rainfall from the pit wall as the process that prevents rainfall from reaching the pit lake; it is part of the runoff factor. There are two reasons that more water will evaporate from the pit lake than would be simulated by just considering the evaporation from the open water surface.

1) Groundwater will evaporate through the pit wall surface because the groundwater is very close to the pit wall surfaces. Bare ground evaporation could occur if groundwater is within 20 feet of the surface.

2) Groundwater will enter the pit to form a pit lake from seeps on the pit walls; some will have low flow rates. These seeps will occur year round and much of the flow will evaporate.

Both of these additional losses could be accommodated by either increasing the evaporation rate from the pit lake or by adding an ET boundary on the pit wall near the pit lake.

The modeler should also reconsider the runoff factor from and potential recharge into the pit walls. The west head wall will be steep but have a small area. Distributed runoff would be a high proportion, but the access ramps would intercept, detain, or retain much of this runoff. The eastern headwall is less steep and might eventually have runoff characteristics similar to the steep natural ridge west of the pit. Similar infiltration, evaporation, runoff relations may apply. The modeler should consider whether recharge would occur through the pit walls and whether less runoff would be appropriate.

4.11.3 Simulation to Equilibrium

The predictive model was run for 100 years beyond the end of mining, but it had not reached equilibrium. Running the model to equilibrium helps the managers consider the long-term impacts of constructing the mine. Myers (2008) found that equilibrium did not occur for almost 4000 years, but if a pit lake does form the time should be less. There is substantial uncertainty around the estimate, but the model could at least bracket the potential impacts. It can be argued that the uncertainty is too much to model that far into the future. However, there would be more uncertainty around the dewatering estimates because the aquifers have never been stressed similar to what the pit will cause to the aquifers. Uncertainty is not a reason to not consider the future but it is a reason to consider the sensitivity of the predictions.

M&A should run the model to equilibrium, after making changes as recommended in this review, to provide an indication of the long-term impacts. The simulations should bracket the results using a sensitivity analysis similar to that done by Myers.
with the model as parameterized and with parameter values 1/10th and 10 times the calibrated values. The dewatering analysis would be similar to that as performed in the GMR. The pit lake filling scenario should be run for a sufficient time period that the model comes to equilibrium. The results would be three sets of water level and flux hydrographs around the model domain from the beginning of dewatering to equilibrium: the middle value would be the best estimate, similar to an expected value, and two bracketed estimates. Although these would not be a defined confidence band on the estimates, it would help indicate the uncertainty.

Alternatively, M&A could complete a stochastic analysis of future estimates wherein the model is run multiple times with differing parameter sets based on measured or estimated probability distributions. If allowed to run a sufficient number of times, this simulation would provide a confidence band around the primary estimate.

4.12 Analysis of Pump-test Results

The pump-test report describes a long-term pump test in which five wells were pumped at rates around 40 to 50 gpm and numerous monitoring wells were observed for drawdown. The design, lay-out, and analysis of the data collected during this test has errors which may bias the results of the groundwater model, possibly by providing inaccurate prior information regarding parameters. It could lead to inaccurate conceptual modeling by suggesting aquifer blocks that are incorrect.

The pump test report does not justify the purpose of a long-term pump test other than "to further assist with the evaluation of the aquifer system" (pump test report, p.1). There appears to have been no advance pump test design; rather it appears the test was performed using wells that had been installed for other hydrogeologic characterization purposes. The report describes the value of the tests as follows:

The substantial amount of data obtained during multi-well aquifer testing provides a comprehensive data set of well yields and water level changes during long-term pumping periods in various areas of the Rosemont aquifer. During pumping at essentially constant rates at the five pumped wells, water level change at the pumped and nearby observation wells reflects widespread hydraulic connections in areas where the aquifer is highly faulted and fractured and limited hydraulic connections outside these areas. Because duration of testing was sufficiently long to interpret early and late time behavior of groundwater flow regimes, heterogeneities have been identified for aquifer regions or blocks delineated essentially by geologic structure and lithology. As defined, the aquifer blocks appear to have relatively uniform fracture intensity as indicated by a "pseudo-radial" hydraulic flow regime during late stages of pumping. For these reasons, on a macroscopic scale of 1,000 feet or more, aquifer block hydraulic parameters derived in this report serve as a basis for development of the "Rosemont East" numerical groundwater flow model using an equivalent porous medium approach. (pump-test report, p. 4)
Water level changes at the monitoring wells reflect "widespread hydraulic connections", but overlapping drawdown complicates the numerous sophisticated diagnostic and solution techniques utilized to estimate aquifer parameters (pump test report, sec. 4.2.1 and 4.2.2). Drawdown at a point in a confined aquifer is the linear sum of drawdown caused by all of the pumping wells in that aquifer. If there is heterogeneity in the aquifer each well's contribution to the drawdown will be unknown. Drawdowns in an unconfined aquifer cannot be linearly summed. Even at a pumping well the same principles of overlapping drawdown cones apply. That is why most pump tests use only one pumping well. As Fetter notes: "[i]ntersecting cones of depression during an aquifer test should be avoided" (Fetter 2001, p. 210): analytic techniques for estimating aquifer parameters from pump tests do not directly account for the overlap. M&A acknowledges the problem, noting pump tests assumption include "that pumping rate is constant and other wells pumping in the area do not affect drawdown" (pump test report, p. 12).

There is another important but simple error made that confounds the results and how the data is used in the modeling — they used incorrect aquifer thickness for the wells. Aquifer thickness is the thickness of a saturated aquifer layer which discharges water to the well as it pumps. Ideally for pump tests in a confined aquifer, the top and bottom of the screen coincides with the water producing part of the confined aquifer. "If at all feasible, the well should be open throughout the entire thickness of the aquifer" (Fetter, 2001, p. 210). This is not the case here, and the report estimates thickness incorrectly. For example, M&A determined that pumping well PC-5 had an aquifer thickness of 2001 feet, as described here:

The well penetrates steeply dipping and fractured Mesozoic and Paleozoic rocks (Willow Canyon Formation, Concha Limestone, Scherrer Formation, and Epitaph Limestone) to a depth of 2,001 feet. Depth to prepumping water level was 0.05 feet below land surface (bgs). Perforated interval of the well extends from a depth of 109 to 2,001 feet. Using depth to water level and bottom of perforated interval, aquifer thickness at this location is assumed to be about 2,000 feet. (pump test report, p. 18-18)

The water level rose above the top of the screen but that is not because the saturated zone extended to that level. They determined the aquifer thickness as the difference between the water level, essentially ground surface, and the bottom of the screen. The water level in the well rises to the level coinciding with the highest pressure in any of the formations or fracture zones intersecting the screen. The water level represents a potentiometric surface of the water producing zone which is under the greatest pressure. There is no reason it coincides with the top of the aquifer and in a confined aquifer it specifically rises above the top of the aquifer.

An additional problem with well PC-5 is that it screens four formations, as noted. The lithology for well PC-5 (HAR, App. C) shows Willow Canyon to 930 ft, Concha limestone to 1060 ft, Scherer to 1490 ft, and Epitaph to 2010 ft. The number of formations reflects the deeply dipping formations shown on the geology cross-sections through the pit. Each formation is lithified and without noted fracturing; the primary Myers: Review of Hydrogeologic Analysis and Groundwater Model of the Proposed Rosemont Ranch Mine
differences appear to be in particle size distributions although each has significant gravel sizes. The particle sizes vary sufficiently that the conductivity probably varies substantially. The geophysical logs show much variability with short sections probably showing significant fractures which would produce most of the water. Even if all of the formations produce water, the screen will cause the test to average properties over the formations and high conductivity of the fracture zones will not be identified.

The other four pumping wells have the same problems with the estimated aquifer thickness.

M&A monitored well 1445 on the west side of the Santa Rita Range during the pump test. It experienced about 0.5 feet drawdown during the test, although it is more than 6,800 feet from the nearest pumping well. During 2008, the water level varied up to about 4 feet (HAR, Figure B-33). It is also very shallow, around 200 feet deep. Drawdown did not commence until several days after the first well began to pump (pump test report Figure B-18). It had also rained less than an inch between late September and December (HAR Figure B-33). It is therefore not certain the pump test caused the 0.53 feet of drawdown because the drawdown is about 12% of the annual variability and it coincides with a dry period; being a shallow well, it may respond with short lag time to changes in recharge which would have been caused by the short-term dearth of rain.

In summary, there are four reasons the results of the long-term pump test should not be used as was done in the modeling effort.

- The aquifer thickness was not appropriately calculated.
- The aquifer parameters are averaged over substantially different formations.
- There is likely an overlap in drawdown caused by pumping five separate wells at once.
- Conclusions regarding drawdown at well 1445 may assume a connection between water level changes and the pump test when they are actually due to short-term meteorological differences.

The long-term pump test does contain important prior information. The stress applied to the aquifer by pumping five wells exceeds any previously applied stress and should provide usable information beyond the simple transmissivity and storativity values. The use of this information will be specifically considered as part of this analysis. Rather than simple pump tests, the exact pumping and drawdown hydrographs should be used in a groundwater model to calibrate parameters, including storage coefficients. The effect of faults may also be apparent.

This data should either be used in M&A existing model to improve the calibration or in a more detailed model of the pump test area. If the later is done, the calibrated values could be input to the predictive model as prior information to use in calibration.
5. CONCLUSION

The numerical model likely underpredicts the impacts of dewatering and pit lake development because of several inaccuracies in the conceptual flow model and an incorrect simulation of the pit lake.

The conceptual flow model errors that will cause the model to underestimate impacts are an overestimate of conductivity for Davidson Canyon and the areas beneath the pit, the low conductivity formation directly surrounding the pit, and the failure to link the pit with the flow paths along Davidson Canyon. Recharge in the project area near the pit is underestimated.

The numerical model has a poor fit due to the residuals being biased to positive or negative values in certain areas. The simulation of the pit lake will cause the model to underpredict the impacts. The lake routine may simulate the pit lake as being too small due to errors in the implementation of the lake package and failure to consider additional evaporation from the pit area. The model as presented also does not fully consider the long-term impacts because it was not run to equilibrium.

6. REFERENCES


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<th>Resource</th>
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<tr>
<td>Primary productivity</td>
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<tr>
<td>Wildland fire</td>
<td>Longer fire season and more intense fires</td>
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<tr>
<td>Soils</td>
<td>Increase in carbon loss from soils. Many unknowns remain.</td>
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<td>Water absorption/runoff</td>
<td>Variable and unknown. More intense monsoon storms can lead to erosion</td>
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<tr>
<td>Groundwater recharge</td>
<td>Less rainfall, more intense storms, and an increased demand for water will lead to lower water tables</td>
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<tr>
<td>Shallow groundwater, seeps, springs, and perennial streams</td>
<td>Less water for these areas and the species that rely on them. This will lead to further degradation of this already endangered resource</td>
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<td>Vegetation communities</td>
<td>Upland vegetation communities will move upslope. Changes will be particular pronounced at the ecotones, or area of overlap, between communities</td>
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<td>Species</td>
<td>Likely increase in non-native plant species such as buffelgrass. Winter annuals will become less abundant. Moisture stress on plants will increase. Wildlife species will move to appropriate habitats, but some species, particularly at the tops of the Sky Islands, may be lost.</td>
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<td>Phenology (timing of flowering, fruiting, migration etc.)</td>
<td>These natural events will change their timing to earlier or later, depending on the species and season. May cause problems with plant/pollinator interactions.</td>
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Though climate change impacts will not be as severe as those caused by outright habitat destruction, it will nevertheless create some serious challenges to the long-term maintenance of biodiversity in Pima County. First and foremost, it will require that Pima County seek ways to reduce our carbon emissions. Pima County is making real, concrete steps in this regard through our Sustainability Program. The Board's approval of the Sustainability Action Plan for County Operations (2008), and support for its implementation since then, has led to reductions in energy use in County facilities, renewable energy development at Roger Road Wastewater Treatment Facility, a reduction in vehicle miles traveled with County vehicles, and the purchase of sizable fleet of hybrid vehicles. It is anticipated that Pima Association of Governments will have data available in March 2010 to show whether—and by how much—County actions have reduced the green house gas emissions. In addition, it will be important for the County to continue to promote a more compact urban form and mass transit options, which will reduce the carbon footprint of the citizens of Pima County by reducing the number of vehicle miles driven.