CHAPTER FOUR

GROUND-WATER FLOW MODELING

Model Purpose

Ground-water flow through the Mint Wash and Williamson Valley System (MWWVS) was simulated using a three-dimensional finite-difference ground-water flow model (Figures 21, 22 and 23). The purposes of the ground-water flow model were to quantify sustainable yield for the ground-water flow system, create sensitivity analyses of the MWWVS aquifers' properties, produce predictive modeling results based on safe yield and sustainable yield water use scenarios, and predictive results to the current pumping condition and the proposed American Ranch Build Out condition. The sustainable yield was determined to be ground-water yield through pumping without significantly affecting the perennial springs nor the riparian habitat of the area. The sensitivity analyses quantified the uncertainty of the calibrated model by quantifying the effects that uncertainty in the aquifer parameters had on the model (Anderson and Woessner 1992), and provided insight to how the aquifers might react to changes in recharge, e.g. due to climatic changes. The predictive modeling results were compared to the concept of sustainable yield.

Model Objectives

The objectives for this ground-water flow model included calibrating the model to a steady-state condition using the geological and hydrogeological characterization to establish an interpretive model. Additionally, the model was calibrated to the transient condition using the established steady-state calibration and hydrographs. The model results document a method to quantify the sustainable yield of a ground-water flow system using a numerical ground-water flow model. The transient calibration was used to simulate potential future water use scenarios. A final objective was to document the effects that current water usage is having on the hydrological system of the Mint Wash and Williamson Valley Area.

Methods

Conceptual Model

The Paulden Conglomerate and the Prescott Granite are volumetrically the most extensive hydrostratigraphic units in the MWWVS, and therefore have the greatest storage of the active model area. Cross sections show that the Paulden Conglomerate is approximately 900 feet (252 meters) thick (Woodhouse 2000) in the Williamson Valley Basin (Figures 6, 8, 9). The conglomerate is the main unit in the northern half of the study area at land surface (Plate 1). The southern half of the study area is predominantly Prescott Granite and Yavapai Series Metamorphic rocks, or a combination of the two.

The layers of the model were established based on the conglomerate and the granite. The granite is assumed to be 400-500 feet (120-150 meters) thick as a water bearing unit due to the overburden of the rock sealing most fractures below that depth (Driscoll 1986, Freeze and Cherry 1979, Meinzer 1923). Depth of granite fractures for use as a ground-water flow conduit has been determined for several plutons through case studies. Many of the studies were conducted in granite located in areas that do not have a history of extensional tectonics. Extensional tectonics would likely increase the depth of granite fractures that contribute to ground water flow. The assumed 400-500 feet thickness of the Prescott Granite hydrostratigraphic unit may be conservative due to the extensional tectonics that have been documented in the area.

The conglomerate was assumed to be approximately 900 feet (274 meters) thick based on preliminary analyses of geophysical data for the area (Woodhouse 2000). The layers for the model were descritized by the assumed thicknesses of these two units.

Two layers of equal thickness were created to simulate the vertical distribution of hydrostratigraphic units. Each layer was set at 450 feet (137 meters) thick. Areas that were composed of fractured Proterozoic media were represented by the top layer, while layer two was set as a no flow or inactive area (Figures 22 and 23). The areas that had conglomerate at the surface were modeled using a combination of both layers to represent the assumed 900 feet (274 meters) thickness.

The other hydrostratigraphic units that were modeled include the Mint Valley Basalt, Yavapai Series schist and gneiss, and the Mixed granite/gneiss/schist hydrostratigraphic unit. The Mixed granite/gneiss/schist hydrostratigraphic unit (Mixed unit) is located towards the center of the field area north-northwest of the Yavapai Series metamorphic complex and west of Table Mountain (Plate 1).The Mixed unit was treated as a fractured medium, and was simulated in the first layer only, based on the same assumptions used for the Prescott granite.

The areas that were simulated in both layers include the northwestern portion of the model area representing Williamson Valley, and the lower half of the Mint Wash and Granite Basin aquifers. These regions represent mapped conglomerate and associated alluvium (Plate 1). The area where conglomerate is exposed was modeled using both layers.

Recharge zones were distributed throughout the model based on the permeability of the lithologies, and the elevation of the region. The assumption that precipitation increases 1.5 inches (3.8 cm) per 1,000 feet (305 meters) elevation increase was used when assigning recharge zones to the model grid (Springer 1998). Recharge zones were delineated along lithological contacts due to the different permeabilities between fractured media (Larsson 1976) versus sedimentary media, and was concentrated along washes due to the saturated conditions caused by runoff from precipitation events.

Water Budget

Inputs of water to the MWWVS include direct recharge, flow from the hydraulic headwaters at Granite Mountain, and flow from the Santa Maria Mountains. The outputs include pumping for irrigation and residential use, discharge through baseflow, and evapotranspiration.

The inflows and outflows of the ground-water system influenced the model design. Model boundaries were set at areas of baseflow, inflow and outflow. Specified flows were defined at cells located with wells. The total value for discharge due to pumping was evenly distributed through the specified flow cells by taking the calculated pumping value defined in

Chapter Three and distributing it evenly to each cell assigned to represent pumping wells. Recharge was distributed throughout the study area to account for the recharge value reported in the water budget.

Software Selection

The processor software chosen for this model is MODFLOW, a three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh 1996). Though the geology and topography of the study area are complex, a finely spaced finite-difference grid was used to simulate the system.

MODFLOW is the standard finite-difference model code used today. It is free and widely used, making the MWWVS model easy to replicate. Updated versions of MODFLOW have improved many limitations of the original code, and have made the software more versatile. The most up to date version available with the selected pre and post-processor is MODLFOW^{win32} (ESI 1998), and was used for this modeling effort.

MODFLOW is solved using a finite-difference governing equation. Hydraulic head is calculated at the node in the center of each cell, and is the average value calculated from the adjacent cells (McDonald and Harbaugh 1988). All of the hydraulic properties are constant throughout the cell.

The pre and post processor used for the model was ESI's Groundwater Vistas version 2.x (ESI 1998). Groundwater Vistas version 2.0 is constantly being updated with patches available on the internet as errors are encountered by users, making the software versatile and up to date.

ESI's Groundwater Vistas has a highly developed graphical user interface making it user friendly. Errors found in the MODFLOW output file are easy to fix due to Groundwater Vistas' file structure and graphical user interface. Groundwater Vistas has an effective import/export utility compatible with widely available GIS software allowing for the creation of figures displaying the modeling output as well as georeferenced surfaces of the study area created in the GIS software.

ESI's Groundwater Vistas provides it's own version of MODFLOW as well as the USGS version of the modeling code (ESI 1998). ESI has created a Windows version of MODFLOW called MODFLOW^{win32} (ESI 1998) which is a Windows platform (Microsoft 2000) based version of MODFLOW. The Windows version of MODFLOW allows Microsoft Windows to communicate to Groundwater Vistas when a simulation is terminated, so Groundwater Vistas can automate the modeling process.

Automated sensitivity analyses and automated calibration are options available on Groundwater Vistas due to MODFLOW^{win32}. The modeler can write a text file listing changes in parameter values for automated modeling runs in Groundwater Vistas. The results are presented by Groundwater Vistas as text files, graphs, and contoured hydraulic head files produced for each run. Both the automated calibration and the automated sensitivity analyses functions were used in the creation of the MWWVS model. The results of the automated sensitivity analyses were used to determine the most sensitive parameters to help attain calibration. The automated calibration was not very useful for this study because it was used while the model was still numerically unstable, which did not allow the automated calibration attempts to converge.

Spatial Descritization

The region was divided into a grid with two layers of cells. Each layer has 156 columns and 272 rows of cells (Figures 22 and 23). Each cell represents 125 meters in the x-direction, 125 meters in the y-direction, and 137 meters in the z-direction. The model contains 84,864 total cells with 43,410 active cells. The total model surface area is 663 km^2, the total model volume is 182 km^3 with an active model volume of 94 km^3.

Inactive areas were established where no water level data could be collected due to lack of wells. Layer 2 also has inactive cells that underlie the fractured media due to the assumed thickness of the hydrostratigraphic units in the fractured crystalline rock.

Elevation of the model grid was imported from Digital Elevation Models (DEM) made available by ALRIS (2000). The elevation data in the DEMs were imported as top elevation zones to layer 1 in Vistas. The elevation databases were set to 1 meter accuracy for the elevation value assigned to each cell from the imported DEM.

The top elevation of layer 2 and the bottom elevation of layer 1 were both 137 meters below the top of layer 1. The top elevation zones from layer 1 were copied into the bottom of layer 1 and the top of layer 2 with a zone decrement of 137 meters. This set layer 1 to be exactly 137 meters thick at each cell.

The bottom elevation of layer 2 was set the same way as the bottom elevation of layer 1. The zones from the top elevations of layer 2 were copied into the bottom of layer 2 with a zone decrement of 137 meters. This made layer 2 exactly 137 meters thick at each cell.

Boundaries

The boundaries for the numerical model are similar to the boundaries of the MWWVS conceptual model and are shown in Figures 22 and 23. The boundaries are physical, hydrological, or based on the availability of data. The boundaries were altered throughout the modeling process as areas of numerical instability were identified.

The northern boundary is the confluence of the Williamson Valley surface water flow system with the Big Chino Valley flow system (Figure 21). The confluence is located just north of the Sullivan Buttes, and is parallel to the UTM northing base line. The boundary is a hydrologic boundary.

The eastern boundary is the western base of the Sullivan Buttes, and extends farther east, south of the Sullivan Buttes to include Table Mountain and the residential developments east of Mint Wash. The boundary was determined by the availability of data as well as a surface-water divide. The boundary at the Sullivan Buttes was established due to a lack of wells within the buttes and is not the physical divide represented by the crest of the Sullivan Buttes. The southern portion of the eastern boundary is a very subtle physical divide as represented by the surface hydrology. The area adjacent to this boundary within the model drains into Mint Wash, the adjacent area outside of this model boundary drains into Little Chino Valley.

The southern boundary was determined by the availability of water level data. Granite Mountain was excluded from the model area due to the lack of wells and water-level data. The southern boundary is set at the base of Granite Mountain. Mixed hydraulic head boundary cells were placed around Granite Mountain and represent mountain front recharge (Figure 22).

The southern boundary west of Granite Mountain was also established by the availability of data. The area excluded from the model is either National Forest or minimally developed, and wells were not available to collect water level data.

The western boundary is set at the foothills of the Santa Maria Mountains. The western boundary represents the physical boundary present at the crest of the Santa Maria Mountains. The western boundary is linear, parallel to the UTM Easting base line, similar to the linear crest of the Santa Maria Mountains.

An internal boundary is present extending north from the southern boundary covering Granite Mountain connecting to the eastern boundary of the model area representing the Sullivan Buttes (Figure 21). This boundary represents the ground-water divide indicated on the potentiometric surface map of the MWWVS (Figure 19), and was inserted during the calibration process to optimize the calibration of the model.

Parameter Values - Hydraulic Conductivity

Initial estimates of hydraulic conductivity values for the hydrostratigraphic units were developed from aquifer tests and specific capacity estimates (Table 5). The values attained in the hydrogeological characterization of the MWWVS were used as initial parameter values for the model (Table 3). The values were altered through trial and error during calibration.

The limited aquifer test and specific capacity data for each hydrostratigraphic unit made it difficult to create an error limit for the values of the parameters. Variograms are commonly used in modeling to create error limits for parameter values based on the variability of the values in space. Heterogeneous materials will produce different parameter values based on the location of the measurement. Several measurements of the same parameter at different points within a heterogeneous material will provide a range of values for that parameter. Variograms quantify the uncertainty of parameter values based on heterogeneity. The uncertainty can provide an allowable error range, which can be used to validate the final calibrated property values. The only measure of the validity of the final calibrated hydraulic conductivity values is a range of measured values for different lithologies as reported in hydrogeology text books (Table 5) (Domenico and Schwartz 1998).

Initial values for the vertical anisotropy of the hydraulic conductivity (K) were assumed to vary between 3:1 (horizontal K:vertical K) and 100:1. The initial values were not considered to be representative of the actual values, and calibration was the process responsible for attaining representative values of vertical anisotropy.

Anisotropy was not available through any of the aquifer tests. Neuman's (1975) unconfined analytical method provides anisotropy estimates for aquifer tests where water level is monitored at an observation well. The only aquifer test with water level data from an observation well was the test performed on ARwell 52 with observation well ARwell 54, but the test was deemed invalid due to significant dewatering of the aquifer during the aquifer test, and k_x:k_z could not be determined.

Parameter values - Recharge

Initial estimates of recharge were calculated using the precipitation data from three rain gages located throughout the study area (Figure 25). Two methods for estimating recharge from precipitation data were used.

A previous study in the vicinity of the MWWVS assumed that 4% to 5% of total precipitation forms direct recharge (Corkhill and Mason 1995). This assumption was used as an initial estimate of the recharge values for the different zones in the MWWVS model.

The other method for calculating recharge was by using an equation developed by Rabinowitz et al. (1977) for a precipitation-recharge relationship. Rabinowitz estimated the total amount of recharge to an aquifer in New Mexico from precipitation by measuring tritium concentrations of the water discharging from the aquifer. The equation is:

$$\mathbf{R} = f\mathbf{P}_i \quad \text{where:} \quad f = k(\mathbf{P}_i/\mathbf{p})$$

and R = annual recharge, P_i = annual precipitation of the ith year, f = proportionality factor, p = mean annual precipitation (all in the same units), and k = normalizing factor. These values are reported along with the values attained using the 4% to 5% precipitation assumption and the final calibrated values (Table 6).

As can be noted from Table 6, the two methods of recharge estimation from precipitation data overestimated the representative recharge values attained through calibration. Methods of recharge estimation based on percentages of precipitation data can be misleading and should not be used by practitioners (Watson et al. 1976, Gee and Hillel 1988). Empirical precipitation-recharge expressions can be useful estimates of recharge if the constants have been derived from careful observation and measurement, and should not be used on any other ground-water basin for recharge determination (Simmers 1997). The values calculated using these different methods of recharge estimation were used to provide initial values to the recharge zones, but calibration was used to provide representative values of recharge for the zones and conceptual water budget.

The recharge values used in the model account for natural recharge, recharge induced anthropogenically through septic systems, and evapotranspiration caused by features other than riparian vegetation or perennial springs. Septic systems are a variable that could not be accounted for in this recharge model due to the limited septic return data available for the MWWVS. This may have been another factor contributing to the discrepancy between the calculated recharge values and the calibrated recharge values. Evapotranspiration that was not caused by perennial springs or riparian vegetation was included in the recharge parameter to minimize the number of variables presenting uncertainty to the calibration process. No measurements of field evapotranspiration were collected, and no values for average field evapotranspiration representative of the climate at the study area were found in the existing literature.

Parameter Values - Storage/Specific Yield/Porostiy

Storage, specific yield and porosity were modeled in the transient condition (Figure 24). No valid absolute storage data was available for the MWWVS, so the constraint on the values used were based on literature values. A qualitative relation of the storage values between the lithologies was established through analysis of the hydrographs included as Figures 14 through 18. Average absolute storage values for lithologies found in the MWWVS were estimated (Domenico and Schwartz 1998), and are in Table 7.

Initial storage, specific yield, and porosity values were adjusted through the transient model calibration process. The storage parameters affected the magnitude of water level change with time. These values were adjusted until the simulated hydraulic heads hydrograph had a similar degree of water-level change over the study period to the observed hydraulic head hydrographs. The storage/specific yield/porosity values used in the calibrated model fall within the range indicated in Domenico and Schwartz (1998).

Parameter Values - Evapotranspiration

Zones of active evapotranspiration were modeled in areas of observed perennial or ephemeral springs and riparian vegetation (Figure 26). Values of evapotranspiration and extinction depths were established from a previous water use study by Wright (1997). Wright's study established water use by riparian plants in central Arizona. The study established average water use for mature cottonwood, young cottonwood, and mesquite. Wright also established values for pan evaporation in semi-arid central Arizona. The pan evapotranspiration value was modeled in areas of observed perennial springs. Wright also established the extinction depths for evapotranspiration along springs and for different species of riparian vegetation. The extinction depths were incorporated into the model simulations.

Evapotranspiration was not altered during model calibration process from the values that Wright established. Evapotranspiration was a negligible percent of the total water budget, and it was assumed that any alteration of these values would not create a significant change in the modeling results (Table 8).

Parameter Values - Drains

Drain cells were input to the calibrated steady-state and transient models to dewater the area where the simulated water levels exceeded the top elevation of layer one. This occurred in the model grid that represented perennial springs in the MWWVS. The cells where the simulated water levels exceeded the top of layer one had to be dewatered until the water table was at or below the top of layer one so MODFLOW would account for all of the water in the mass balance.

The conductance of the drain cells were altered until the values were optimized by assigning the lowest value of conductance to the cells to dewater the cells to the level of the top of layer one. The drain cells were only activated to attain the mass balance / water budget output of the model simulations. No drains were active when the water table was modeled so as to not affect the modeled water table with drains that were input as a tool to correct the water budgets. The drains are virtual dewatering features that affect the modeled water table.

The water budgets were altered as a result of the introduction of drain cells. The conductance was minimized so the drains would have a minimal affect on the simulated water budgets. The drains affected the evapotranspiration (ET) and flux out values in the MODFLOW mass balance. The volumes of water discharged through the drain cells are likely a combination of water removed from ET and flux out. For the purposes of this study the volumes of water discharged through drains was assumed to be removed entirely from ET. The ET rates listed in Table 11 - Table 14 include the value of water discharged through the drain features. This assumption altered the water budgets because the water accounted for through the drains is a combination of ET and flux out.

Sustainable Yield Estimation

Sustainable yield has been defined as water use to support human communities without degrading the hydrological cycle and the ecosystems that depend on water (Gleick 1998). Sustainable water yield for the MWWVS was determined to be a yield above which perennial springs would dry out or the root zone of the riparian habitat would significantly dewater through ground-water drawdown due to pumping. Most of the perennial springs within the

MWWVS have water levels within 1 foot (0.30 meters) of land surface. Lowering the water table one foot (0.30 meters) would dry out the springs located in the MWWVS, and may significantly dewater the root zone of the riparian habitat.

Virtual Observation wells were placed in model cells representing springs and riparian communities within the MWWVS (Figure 28). Discharge rates were varied to create different drawdown scenarios at the observation cells. Sustainable yield was defined as a well discharge that created 1 foot (0.30 meters) of drawdown from the non-pumping condition to the respective pumping condition at any of the observation cells.

The model area was divided to represent the three aquifers identified in the hydrogeological characterization (Figure 29). Zone water budgets were produced for the Granite Basin Aquifer, Mint Wash Aquifer, and Las Vegas Aquifer (Table 12 - Table 14). The zone budget for the whole model area is included as Table 11 for a comparison of the individual aquifers versus the MWWVS..

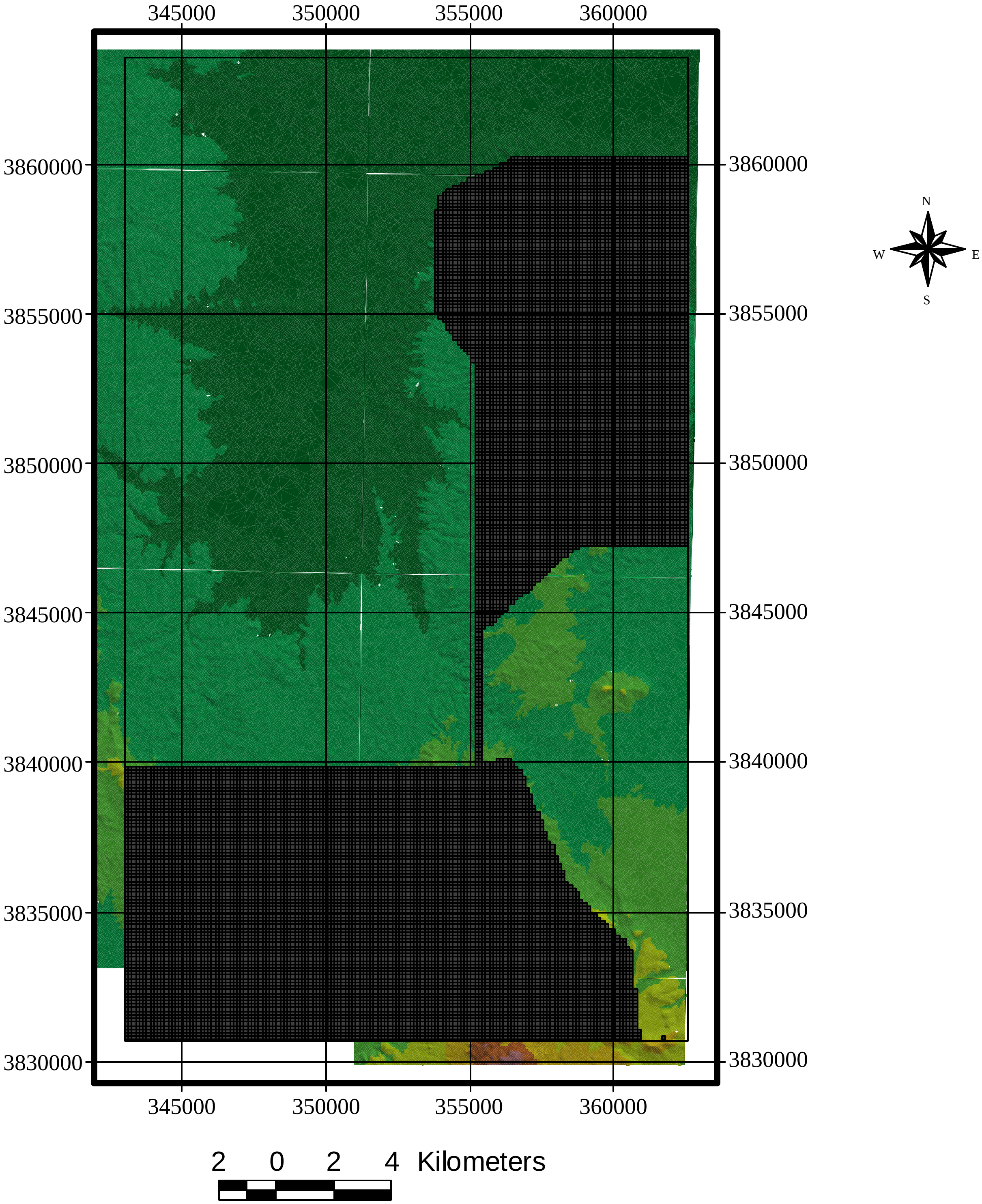
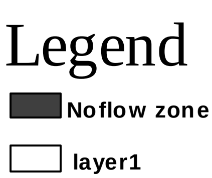


Figure 21 - Triangular Irregular Network (TIN) of the MWWVS overlain by the active and inactive model area.
Coordinate grid is UTM Northing and Easting.



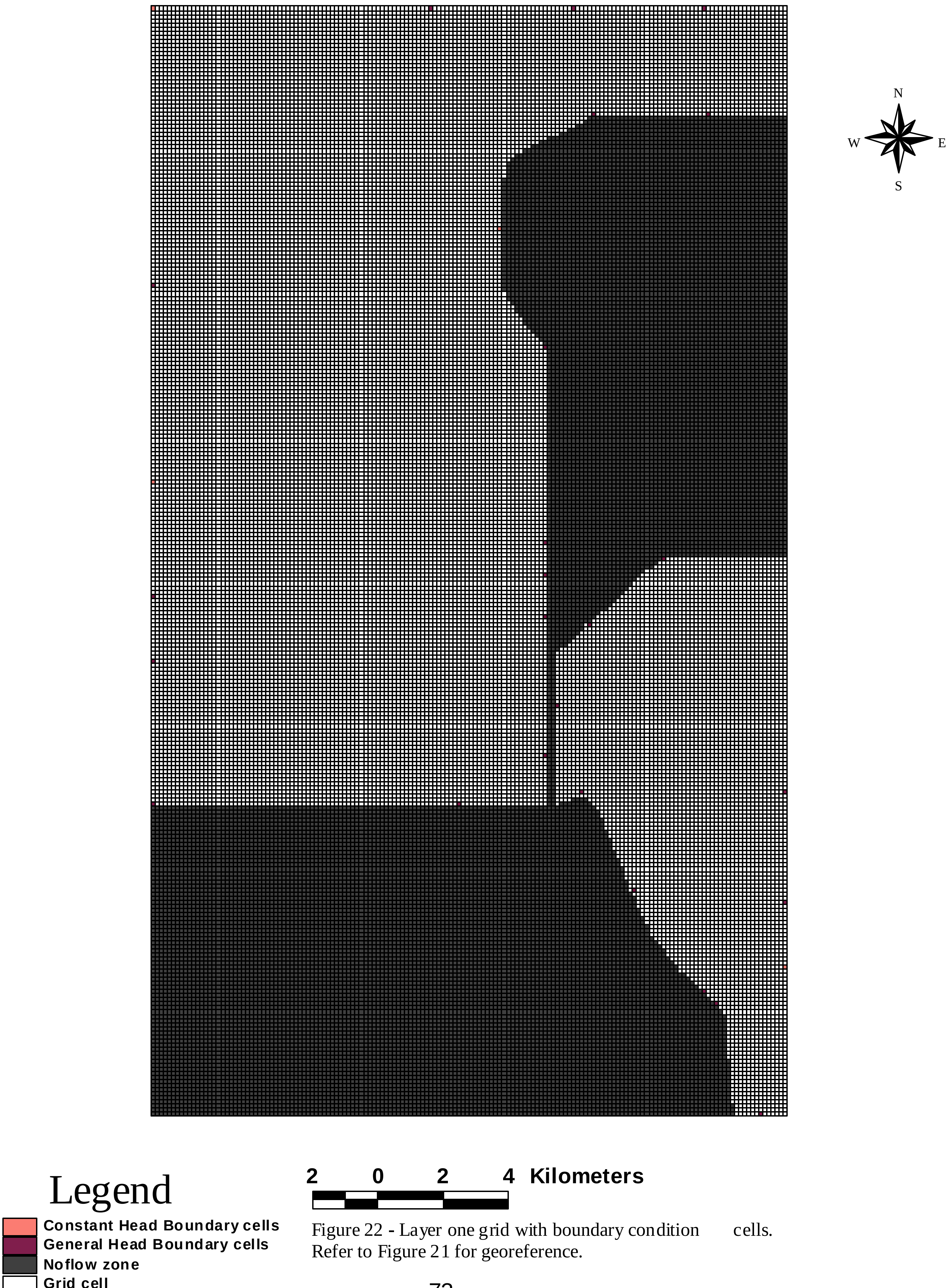


Figure 22 - Layer one grid with boundary condition cells. Refer to Figure 21 for georeference.

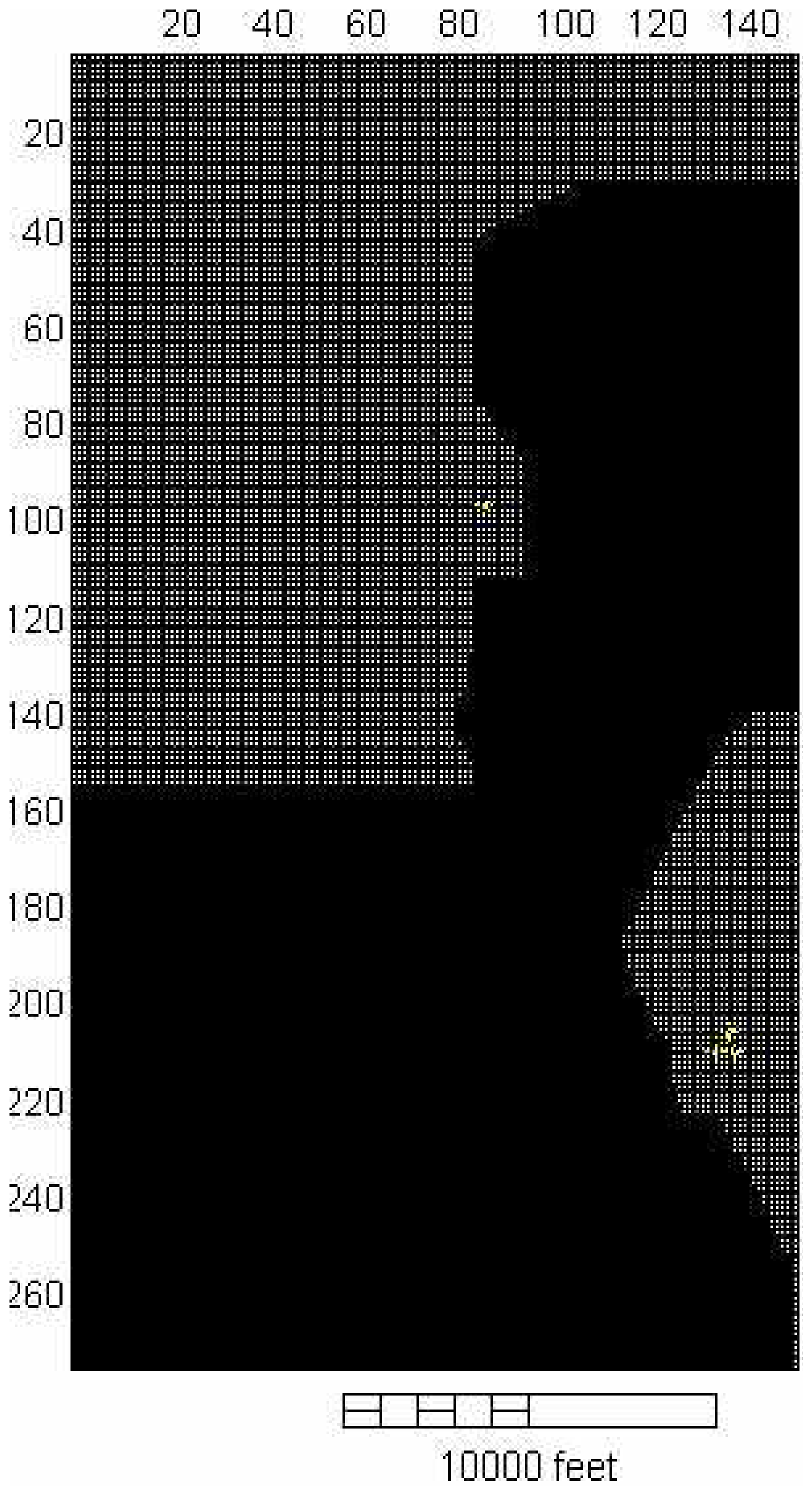


Figure 23 - Layer two model grid. Row and column numbers are listed on the left and top boundaries of the grid.

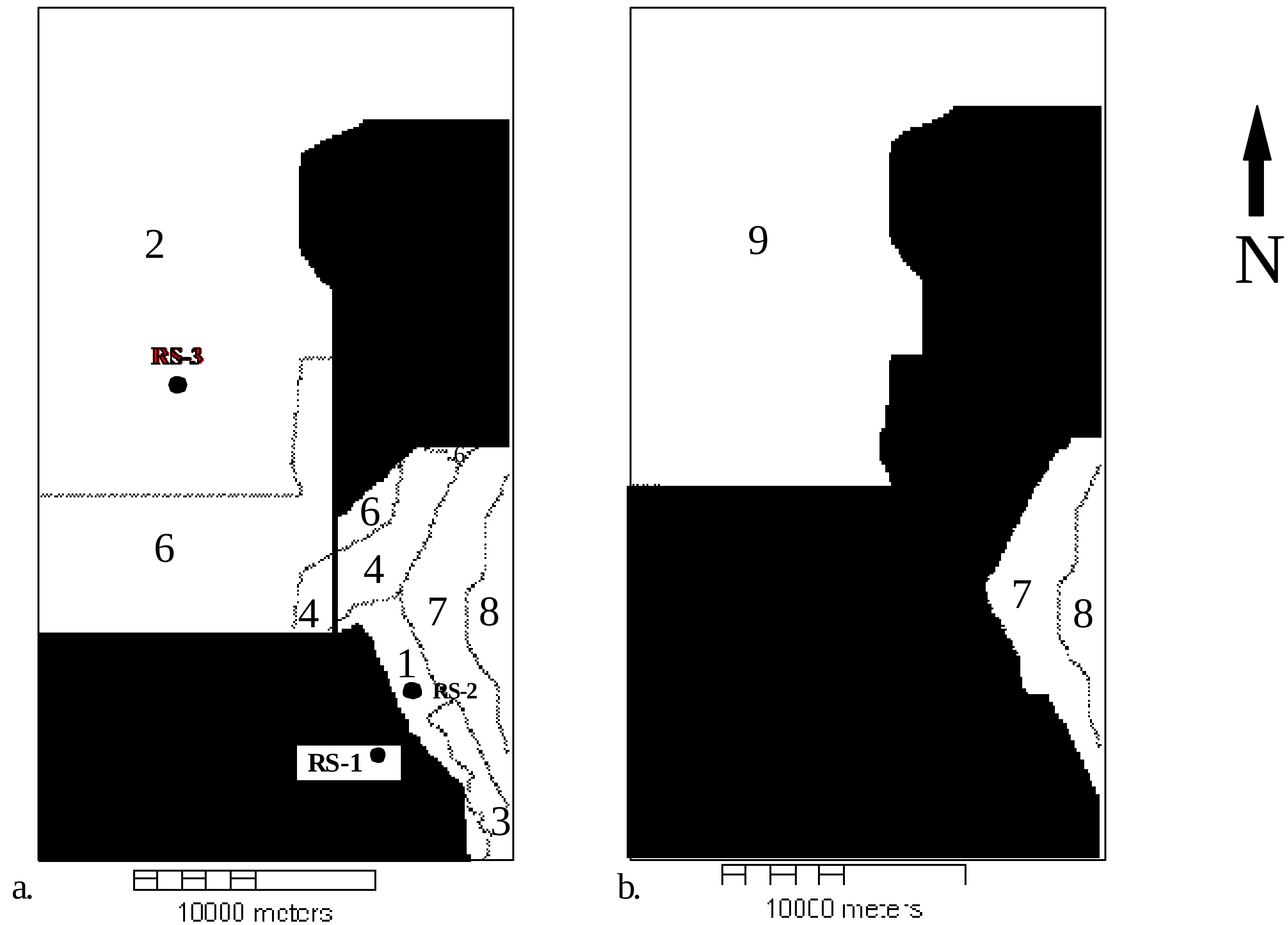


Figure 24 (a) - Zone distributions of horizontal and vertical hydraulic conductivity, storage, specific yield, and porosity in layer 1. The three RS locations indicate the approximate location of the rain stations. Data collected from the rainstations are included in appendix 3.

Figure 24 (b) - Zone distributions of horizontal and vertical hydraulic conductivity, storage, specific yield, and porosity in layer 2 . Refer to Table 5 for Zone values. Refer to Figure 21 for georeference.

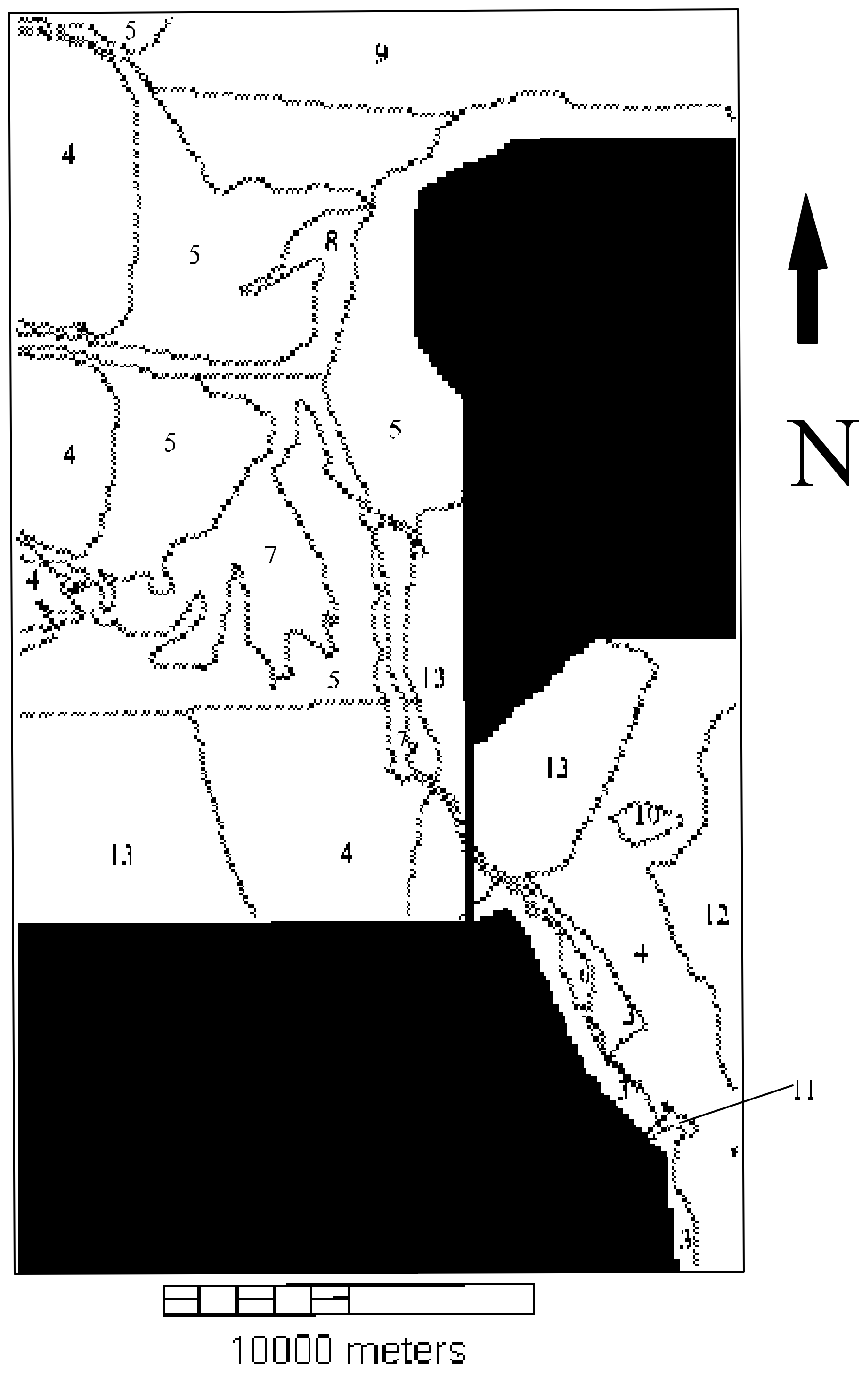


Figure 25 -Zone distribution for recharge in layer 1. Refer to Figure 21 for georeference.

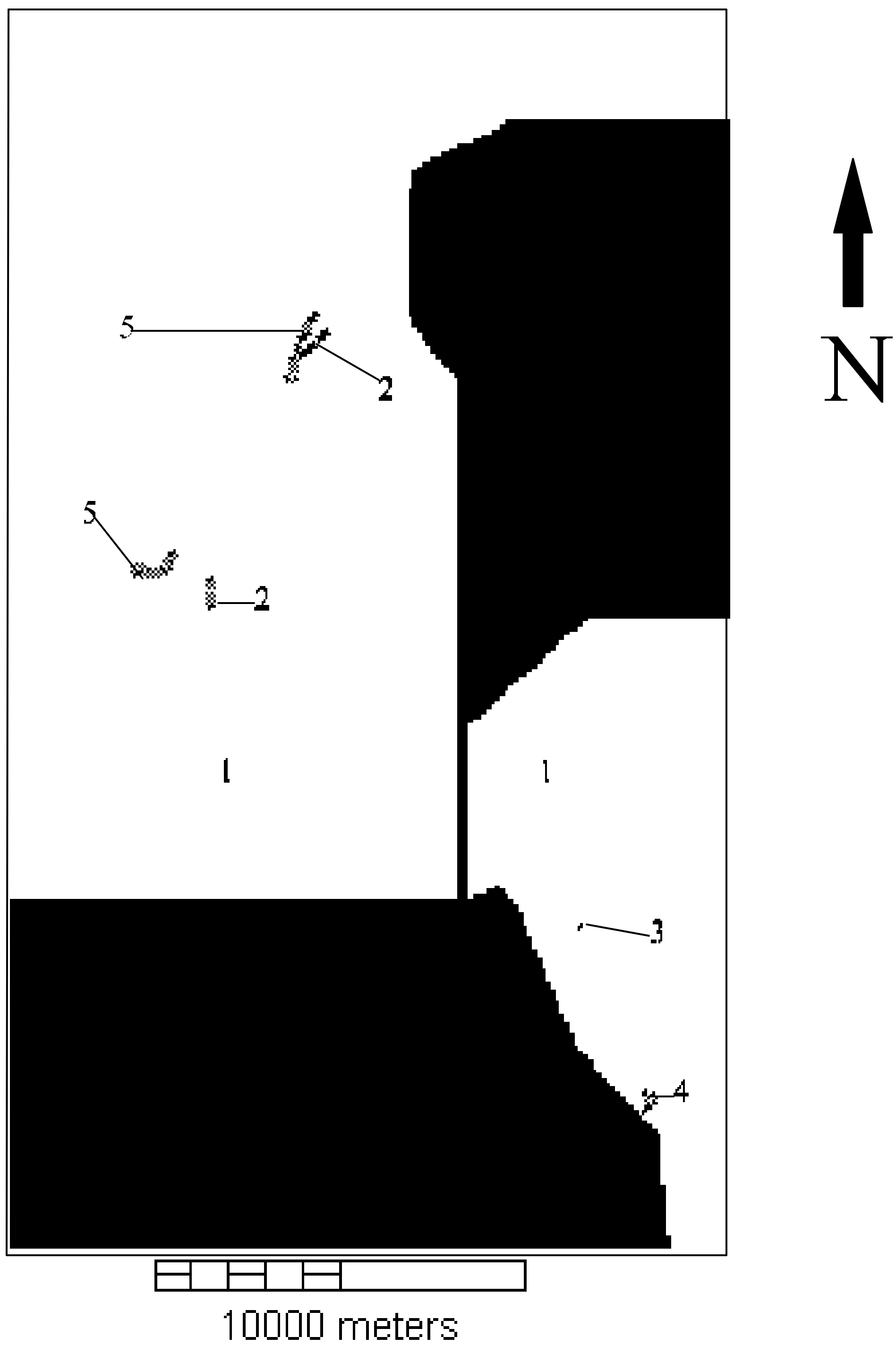


Figure 26 -Zone distribution for evapotranspiration in layer 1.
Refer to Figure 21 for georeference.

Results

Steady-State Calibration

Steady-state model calibration was initiated using the initial parameter values estimated from the aquifer tests and specific capacity values discussed in Chapter Three. The model was calibrated using 24 targets representing wells where monthly water-level measurements were collected and additional wells to provide more targets for the calibration. The water-level data were collected at the end of the study period in August, 2000.

The model was calibrated through trial and error parameter adjustment. The most sensitive parameters were identified through an initial sensitivity analysis, and these parameters were adjusted until the model approached calibration. Changes were made in the grid cell spacing as well as the active versus inactive regions.

When the model approached the calibration criteria, parameter values in problem zones were altered through trial and error to improve calibration. The ground water divide between the Las Vegas aquifer and the Mint Wash aquifer was modeled as an inactive boundary. The model could not be calibrated without the simulation of the ground-water divide as an inactive area unless the k_x=k_y (horizontal hydraulic conductivity) and k_z (vertical hydraulic conductivity) zone values were changed to unrealistic values.

Two statistical measures of the calibration of a model are the root mean square error (RMSE) and the mean absolute error (MAE). The mean absolute error is the mean of the absolute value of the difference between measured and simulated hydraulic heads. The root mean square error is the average of the squared difference in measured and simulated hydraulic heads (Anderson and Woessner 1998):

$$\mathbf{MAE} = \frac{1}{n}\sum_{i=1}^{n} \left|(h_m - h_s)_i\right|$$

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5}$$

where n is the number of observations, h_m is the measured hydraulic hydraulic head, and h_s is the simulated hydraulic hydraulic head.

The calibration criteria for the steady-state model was established using the criteria outlined in Anderson and Woessner (1992). The criteria outlined for a steady-state model include a Root Mean Squared Error (RMSE) of observed versus simulated hydraulic heads no greater than 5% of the total hydraulic head change across the model. A model that reaches this criterion is considered a “good model” (Anderson and Woessner 1992) (Figures 30 and 31). Another criterion for steady-state as well as transient calibration is how well it’s simulated water budget compares to the conceptual water budget. A condition of a ground-water model is that all water in and out of the system is accounted for, as well as any change in the storage. Therefore the mass balance for any time step in a model should have less than a 1% discrepancy (Table 9).

After the steady-state model was calibrated, the transient model was calibrated. The transient calibration involved altering several model parameters, including parameters that had been established through the steady-state calibration. Upon the calibration of the transient condition, the steady-state condition was re-calibrated with the transient parameter values to assure that the model satisfied the calibration criteria for both the steady-state and transient conditions.

Transient Calibration

The transient model was calibrated using a semi-quantitative calibration. The calibration criteria included maintaining the mass balance requirements for each time step (less than 1% discrepancy), but the hydraulic heads were not validated quantitatively. The qualitative criteria for the transient calibration was to create simulated hydraulic heads which had the same trends and the same magnitude of change as the observed hydraulic heads.

The transient calibration had two objectives. The first was that the transient calibration would serve as a validation of the steady-state calibration. The transient calibration would also establish the framework for the creation of predictive scenarios, which is an objective of this study of the MWWVS. The predictive scenarios had different pumping scenarios to simulate potential water use in the area. All of the other model parameters remained constant for the predictive scenarios.

The stresses included in the steady-state model were broken down into 12 time steps that were used in the transient design. The boundary conditions included recharge, evapotranspiration, and discharge wells.

Recharge was distributed throughout the stress periods to reflect the precipitation throughout the study area. The calibrated steady-state recharge values (Table 6) were distributed throughout the stress periods to represent the percentage of total precipitation during the respective month (Appendix 3), based on the data gathered at the nearest rain gauge.

Periods of increased recharge were modeled to reflect the late summer during the monsoon season, and winter. The distribution of recharge was based on precipitation data collected at three rain gages distributed throughout the study area.

Discharge of the domestic pumping wells was temporally divided to represent the assumptions of water use that were described in Chapter Three. Twenty percent of the wells reflected field observed pumping schedules for irrigation wells, with discharge occurring in the spring and early summer. The remaining 80% were modeled as domestic wells, with continuous water use year round. The distribution of water well use was established from the ADWR well registry for the area (ADWR 2000).

Evapotranspiration was modeled in cells representing areas of surface water or riparian habitat (Figure 26). Evapotranspiration was distributed throughout the stress periods to represent the summer months where evapotranspiration would be greatest. No evapotranspiration was modeled for the winter months from October '99 through March '00. Though there may be evapotranspiration during the winter, this amount was assumed to be negligible in the scope of the water budget.

Sensitivity Analyses

Sensitivity was defined as an absolute value of the calibrated versus observed hydraulic head residuals for this model as a change in a parameter value to the extent that the model departs from the calibration criteria. Sensitivity was also defined qualitatively along a relative scale. The parameters that were analyzed for sensitivity were compared to each other and identified as the most or least sensitive parameter.

Sensitivity analyses were created for one parameter and one boundary condition at a time. Hydraulic conductivity for all active zones was analyzed for sensitivity in the steady-state condition (Figure 32). The analysis was quantified by using the calibration criteria. The variable was changed increasingly away from the calibrated value until the model no longer met the steady-state calibration criterion based on the RMSE value.

Recharge was analyzed for sensitivity in the steady-state condition (Figure 33). This variable was changed by orders of magnitude greater than, and less than, the calibrated value to quantify the sensitivity. As with hydraulic conductivity, recharge was varied until the model no longer met the steady-state calibration criterion based on the RMSE value.

Recharge and hydraulic conductivity have similar sensitivities. Sensitivity in this model is more a function of the zone than the parameter. Some of the zones for both recharge and hydraulic conductivity were highly sensitive relative to other zones that are not very sensitive over a parameter change of several orders of magnitude. Comparatively, recharge zones appear to be slightly more sensitive than the hydraulic conductivity zones, due to several recharge zones that make the model exceed the calibration criteria represented by the top of the graphs (Figures 32 and 33) with a relatively low variance from the calibrated value.

The recharge and hydraulic conductivity zones that were closer to the headwaters (Granite Mountain) appear to be more sensitive to changes in recharge and hydraulic conductivity values. The area closer to the headwaters have a higher ground water gradient (Figure 19), as well as more recharge (Figure 32 and Table 6). These factors may be responsible for the relatively high sensitivity of these zones to changes in parameter values.

Table 5 - Initial values, literature values, and calibrated values for hydraulic conductivity.

Lithology	Initial Value (m/yr)	Literature Value (m/yr)	Calibrated Value (m/yr)	Calibrated Vertical Anisotropy
Granite (zone 1)	460	0.2-9000	330	1.7:1
Conglomerate (zone 2)	990	30-20,000	990	1.4:1
Basalt (zone 3)	88	10-600,000	220	11:1
Gneiss/schist (zone 4)	N/A	0.2-9000	50	10:1
Granite/Gneiss/ Schist (zone 6)	N/A	0.2-9000	300	100:1
Weathered Granite (zone 7)	N/A	100-2000	300	150:1
Conglomerate (zone 8)	N/A	30-20,000	6,000	1:1
Buried Conglomerate (zone 9)	N/A	30-20,000	700	1:1

Table 6 - Initial values and calibrated values for recharge.

Recharge Zone	Initial Values (m^3/yr/cell)	Calibrated Values (m^3/yr/cell)
1	0.024	0
2	0.022	0
3	0.017	0.03
4	0.016	0.01
5	0.014	0.0005
6	4.82	2.5
7	0.3	0.001
8	0.3	0.0003
9	0.3	0.0001
10	3.2	0.2
11	6.8	3.6
12	N/A	0.001
13	N/A	0.04

Table 7 - Literature and calibrated values for specific yield and porosity.

Lithology	Literature Specific Yield Range	Calibrated Specific Yield	Literature Porosity Range	Calibrated Porosity
Granite (zone 1)	N/A	0.15	0.01-0.6	0.2
Conglomerate (zone 2)	0.35-0.03	0.2	0.01-0.4	0.2
Basalt (zone 3)	N/A	0.15	0.01-0.6	0.2
Gneiss/schist (zone 4)	N/A	0.1	0.01-0.6	0.15
Granite/Gneiss/Schist (zone 6)	N/A	0.1	0.01-0.6	0.1
Weathered Granite (zone 7)	N/A	0.2	0.01-0.6	0.3
Conglomerate (zone 8)	0.35-0.03	0.2	0.01-0.4	0.2
Buried Conglomerate (zone 9)	0.35-0.03	0.1	0.01-0.4	0.1

Table 8 - Evapotranspiration rates and extinction depths used in calibrated model.

Evapotranspiration Zone	Evapotranspiration Value (m^3/yr/cell)	Extinction Depth (meters)
1	0	0
2	3.68	3.0
3	2.06	1.8
4	2.8	1.0
5	3.74	3.0

Table 9 - Calibration statistics for the steady-state and transient models.

Time (Stress) Period	Total Head Change Across Model (meters)	RMSE (meters)	RMSE % of Total Head Change (%)	Water Budget Error (%)
steady-state	239.73	5.42	2.3	0.04
Aug, 99 (1)	240.04	7.87	3.3	-0.11
Sep, 99 (2)	237.37	8.06	3.4	-0.07
Oct, 99 (3)	234.03	8.14	3.5	-0.10
Nov, 99(4)	234.85	8.10	3.5	-0.12
Dec, 99 (5)	234.44	7.94	3.4	-0.12
Jan, 00 (6)	239.68	8.10	3.4	-0.13
Feb, 00 (7)	239.80	8.33	3.5	-0.14
Mar, 00 (8)	238.67	8.46	3.5	-0.14
Apr, 00 (9)	236.26	8.30	3.5	-0.15
May, 00 (10)	234.83	7.30	3.1	-0.17
Jun, 00 (11)	237.88	4.18	1.8	-0.18
Jul, 00 (12)	239.93	4.40	1.8	-0.18

Table 10 - Drawdown observations made at areas of interest (AOIs) representing springs and riparian habitat for comparison with the sustainable yield criteria.

Observation Point	Current Condition Drawdown (meters)	Safe Yield Drawdown (meters)	Sustainable Yield Drawdown (meters)
1	0.23	8.0	0.3
2	0.15	7.0	0.2
3	0.18	6.5	0.27
4	0.24	9.5	0.3
5	0.2	7.5	0.25
6	-0.1	0.7	-0.1
7	-0.08	0.8	-0.07
8	-0.005	0.62	0.0

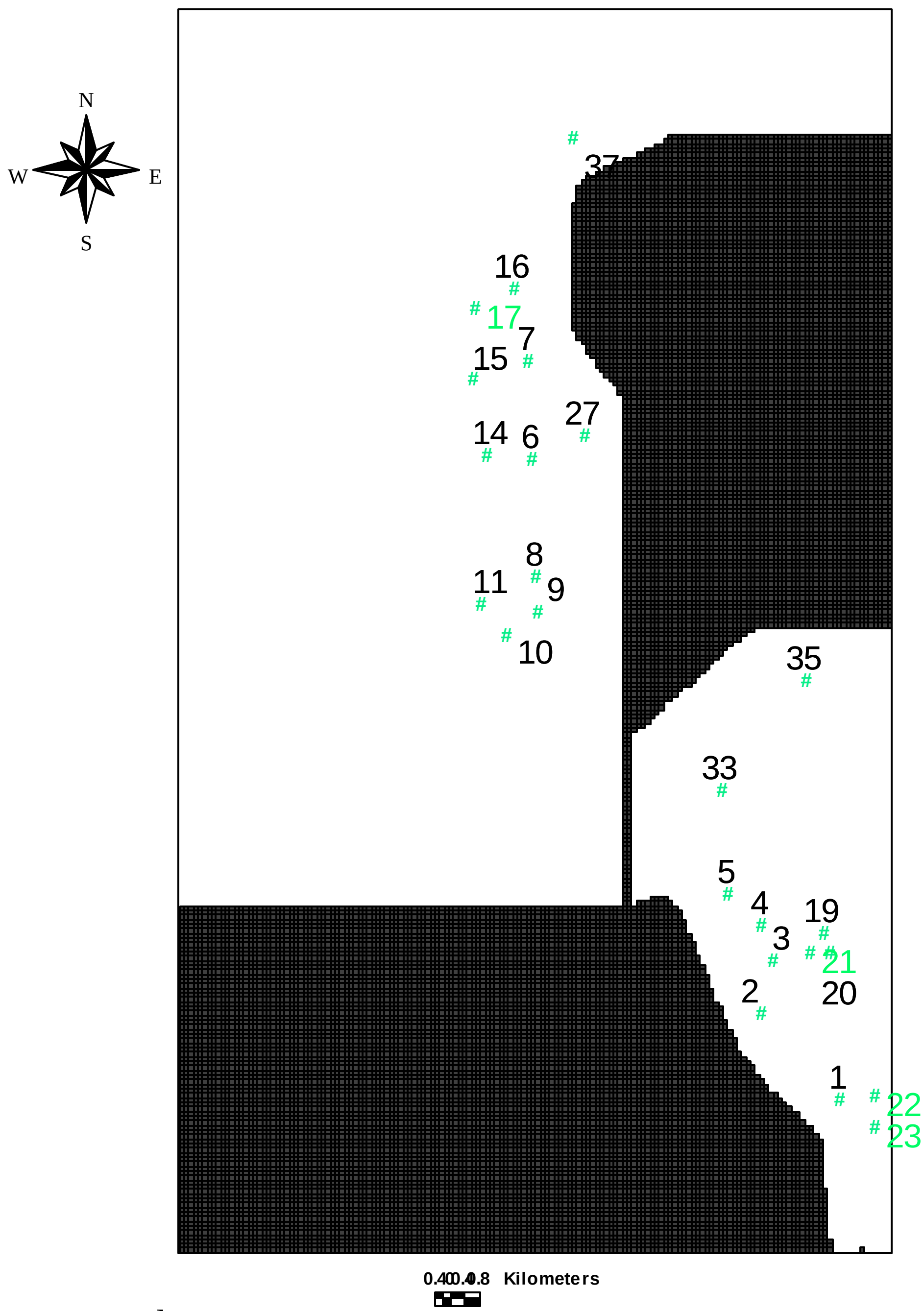


Figure 27 - Map showing the location of the steady-state and transient targets. Targets used in the transient condition include targets 1-17. Refer to Figure 21 for georeference.

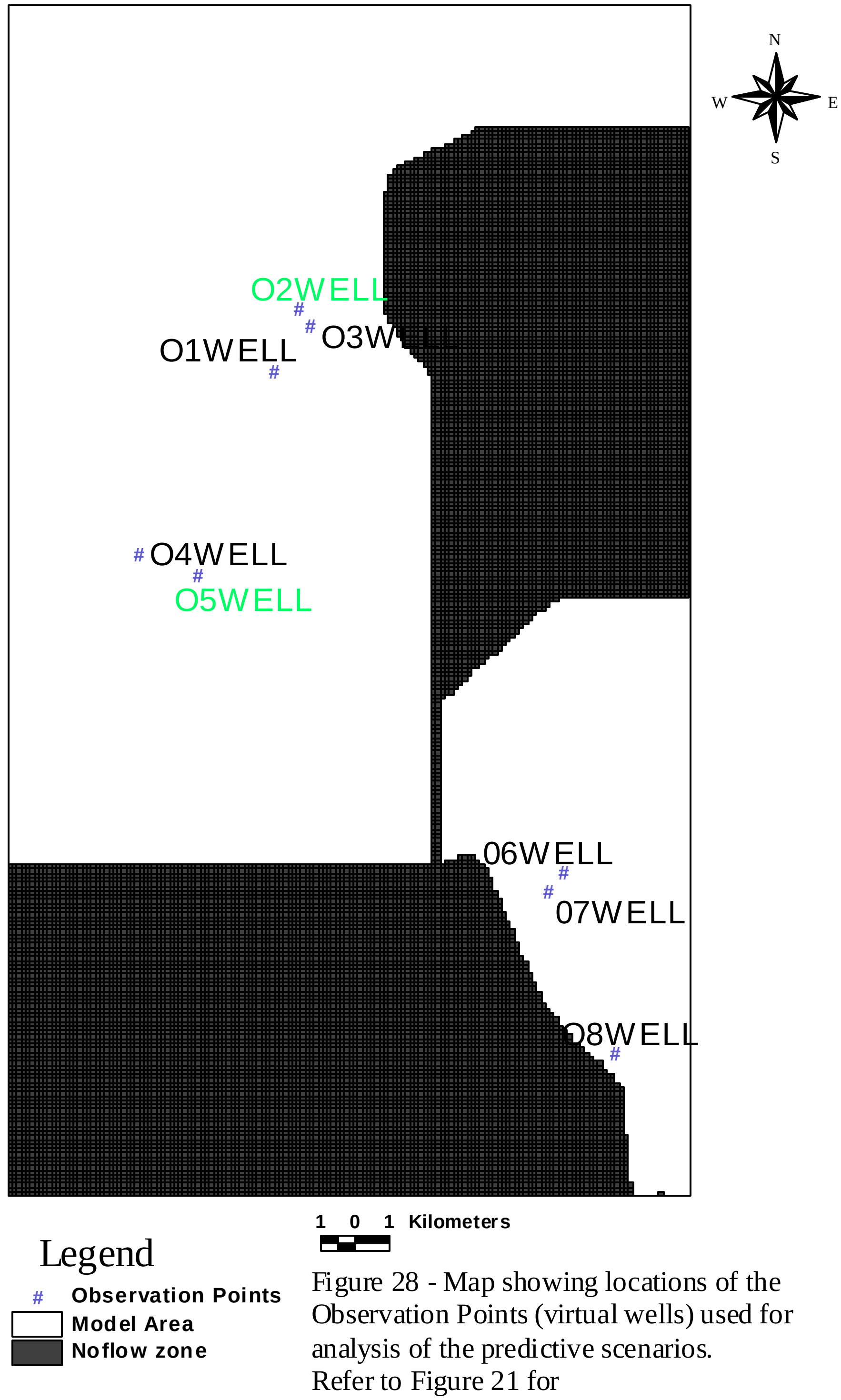


Figure 28 - Map showing locations of the Observation Points (virtual wells) used for analysis of the predictive scenarios. Refer to Figure 21 for georeference.

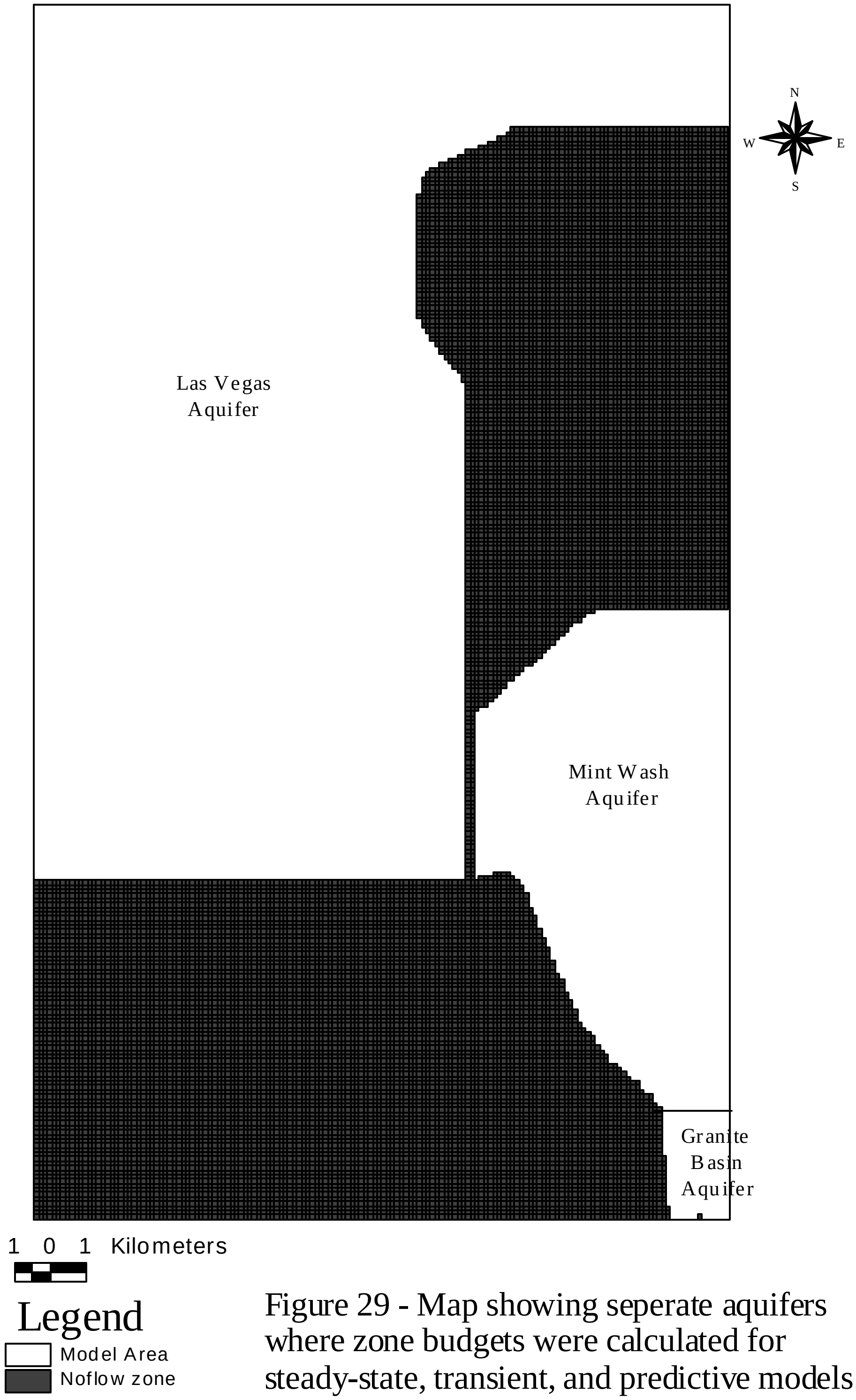


Figure 29 - Map showing seperate aquifers where zone budgets were calculated for steady-state, transient, and predictive models. Refer to Figure 21 for georeference.

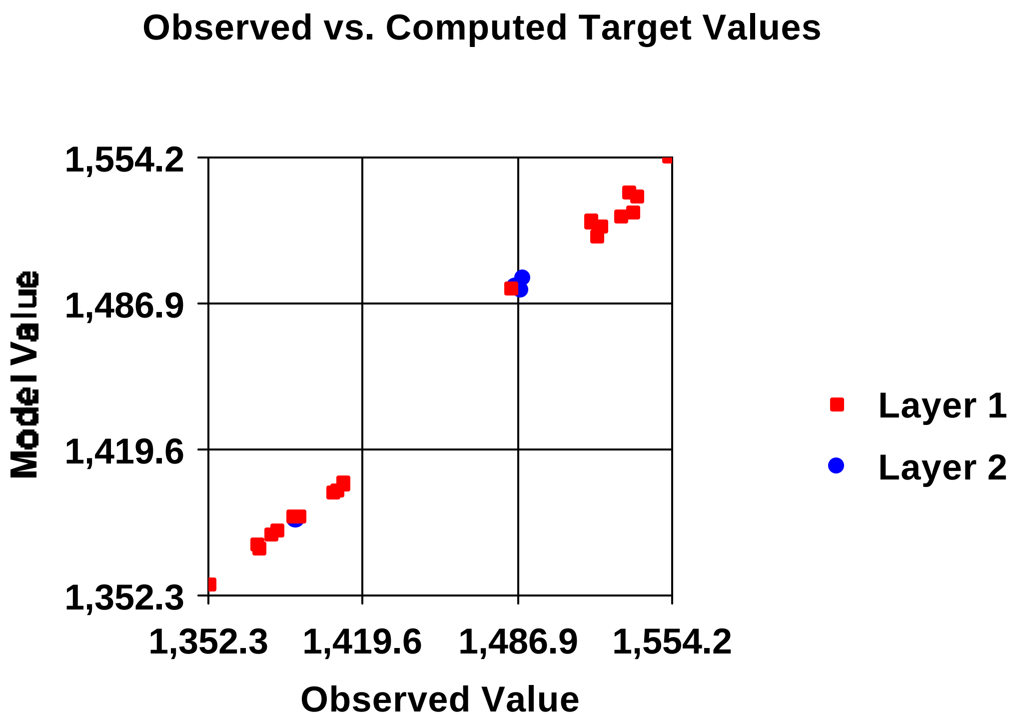


Figure 30 - Observed vs. Computed target values for the steady-state calibration.

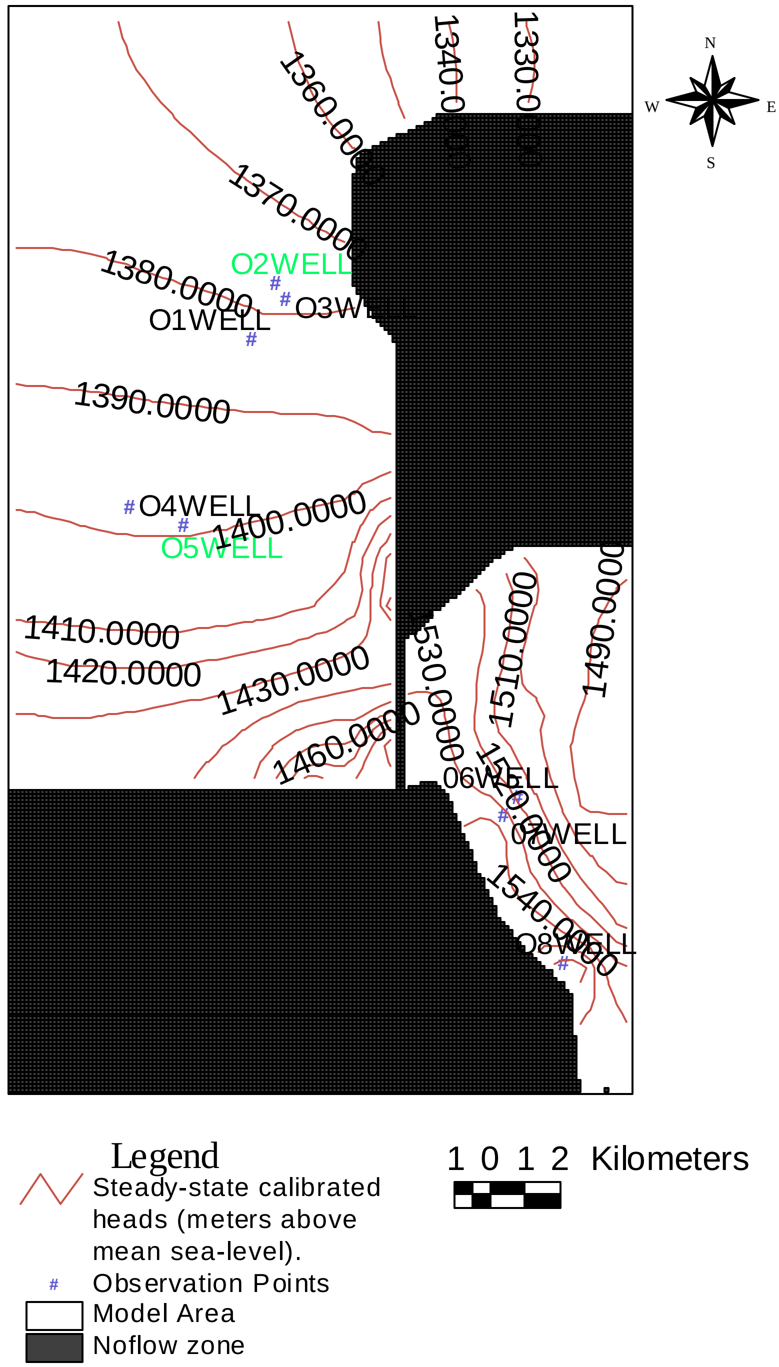


Figure 31 - Contoured surface of the calibrated steady-state model.

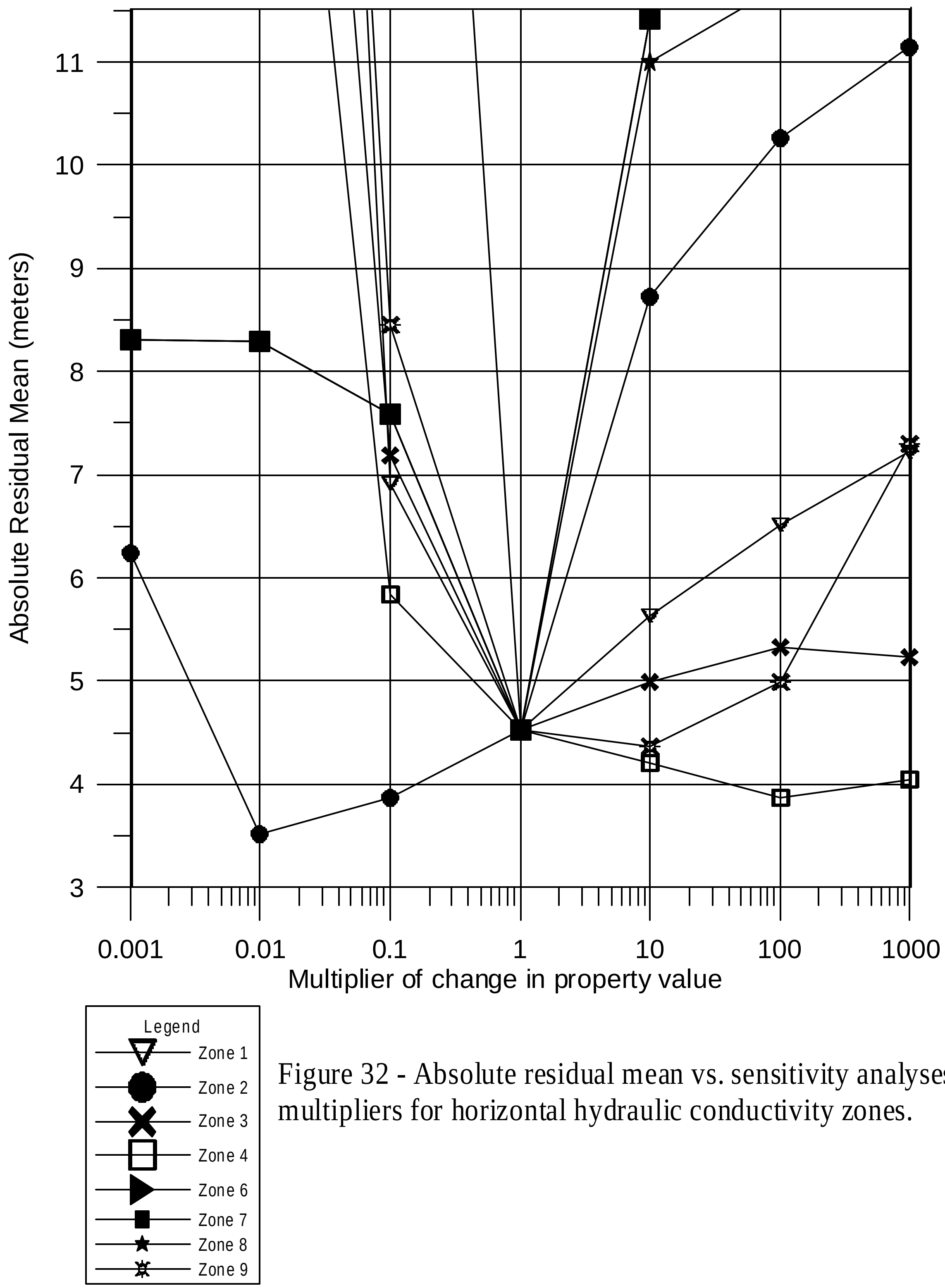


Figure 32 - Absolute residual mean vs. sensitivity analyses multipliers for horizontal hydraulic conductivity zones.

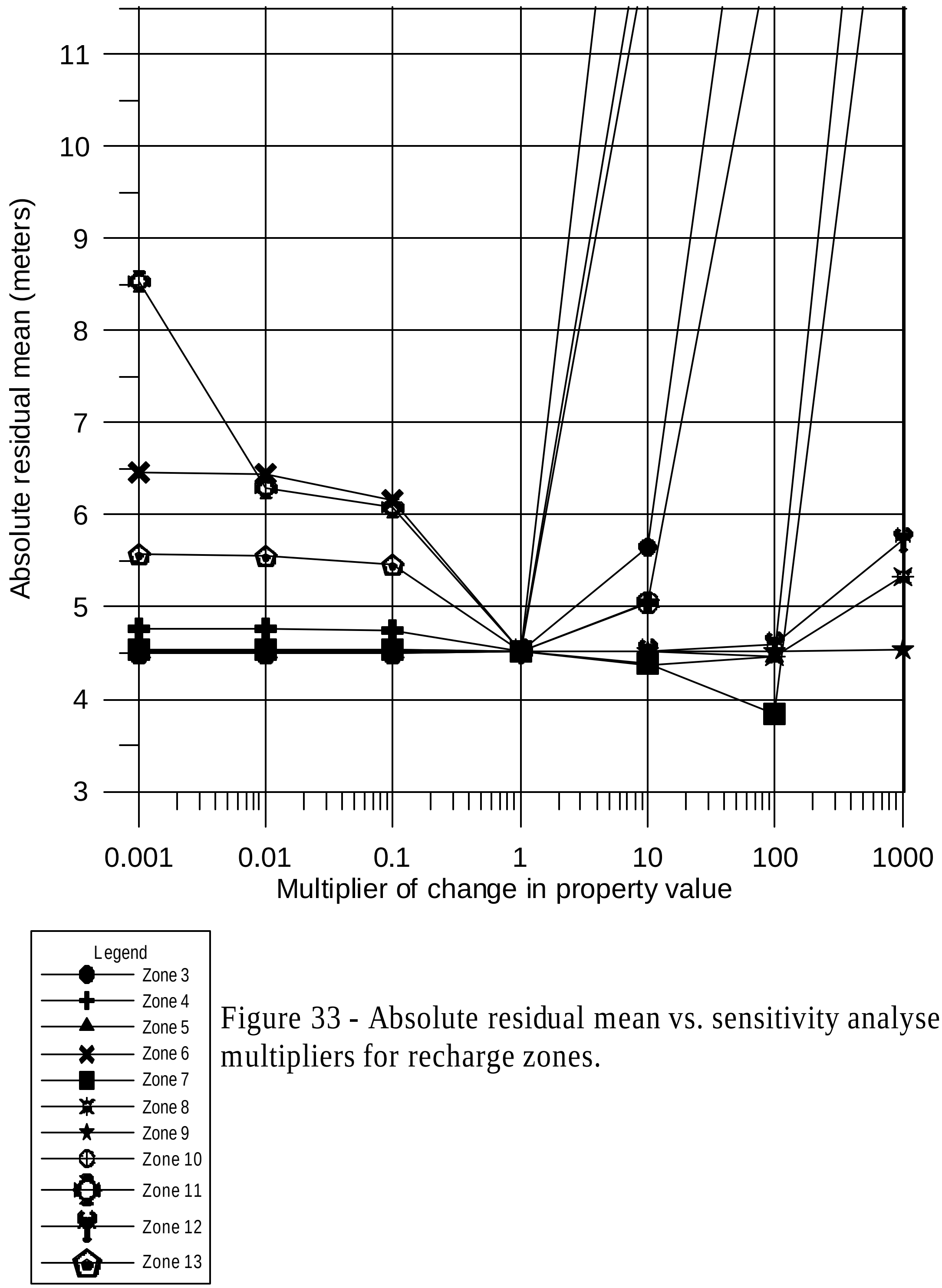


Figure 33 - Absolute residual mean vs. sensitivity analyses multipliers for recharge zones.

Predictive Simulation Scenarios

Safe Yield

Safe yield is a concept used by Arizona Department of Water Resources (ADWR) to manage ground water in the Active Management Areas (AMA) within Arizona. Safe yield is defined as a quantity of water use per year that does not exceed the amount of water that is naturally recharged to the ground-water system. The threshold for safe yield was modeled for this scenario. The total discharge out of the private and irrigation wells was set to equal the amount of recharge that was determined through calibration of the steady-state model. This recharge rate was applied for 10-year long stress periods in the transient, predictive scenario. The length of the stress periods was changed to ten years to examine the long term affects of these water use scenarios. The water budgets calculated by the model simulation for the predictive scenarios are included in Tables 10-13.

The results of the model simulation indicate that drawdowns for the safe yield scenario exceed the sustainable yield criteria (Figure 34, Table 10, Appendix 6). Drawdown at the modeled springs and riparian habitats (areas of interest, AOI) exceeds 0.3 meters (1 foot), and therefore exceeds sustainable yield. Drawdown averages 5.1 meters at the AOIs, which is an order of magnitude greater than the drawdown allowed by the sustainable yield criteria.

Sustainable Yield

The threshold of sustainable yield was modeled to be able to quantify the maximum yield that could still be considered sustainable. This was simulated using a trial and error method varying the pumping values at the wells until a stable hydrograph was produced. This was determined to be the sustainable yield threshold. All of the other parameters were maintained at their respective calibrated values.

The sustainable-yield threshold was found to be greater than the current water use scenario, but less than the safe yield scenario (Figure 35, Appendix 7). The sustainable yield simulation had a maximum drawdown of 0.3 meters at an AOI, which is near the definition of sustainable yield for this system. The yield for this scenario is 15% greater than the yield used for the calibrated current water use scenario.

Calibrated Water Use

A model scenario was created to examine the long-term impacts to the MWWVS of current amounts of water use. All parameter values derived during the steady-state calibration were used fir this scenario, except longer stress periods were applied. The stress periods were extended to ten years for each stress period. Ten stress periods were modeled to examine the potential effects of water consumption at the current rate over the next one hundred years.

The current water use scenario remained within the sustainable-yield criteria and therefore is considered sustainable (Figure 36, Appendix 5). Drawdown did not exceed 0.30 meters at any of the AOIs at any time throughout the 100 year, current-use scenario.

American Ranch Build Out

The American Ranch Build Out scenario was developed using the current-use scenario, with four additional pumping wells to simulate the proposed development at the American Ranch. The pumping values for the wells were established using water demand values that were reported in the ground-water study conducted by Clear Creek Associates (Glotfelty 2001).

The Clear Creek report provided water use values of 149.8 acre-feet / 1.84×10^5 meters^3 for the first year, 126.4 acre-feet / 1.55×10^5 meters^3 for the following nine years, and 109.9 acre-feet / 1.35×10^5 meters^3 for the remaining ninety years of a one hundred year period for the proposed development. This water use was divided between the four wells (Figure 37) added to the model for this scenario. Tables 11 through 14 display the output water budget calculated in the model simulation.

The hydrographs of observation points four and five in the Las Vegas Aquifer indicate that the water demand required for the American Ranch development exceeds the sustainable yield criteria established for the MWWVS (Appendix 8). Drawdown at two of the observation points within the Las Vegas Aquifer exceed 0.30 meters / 1 foot. Drawdown at these observation points exceeds the sustainable yield calibration by tenths of a meter.

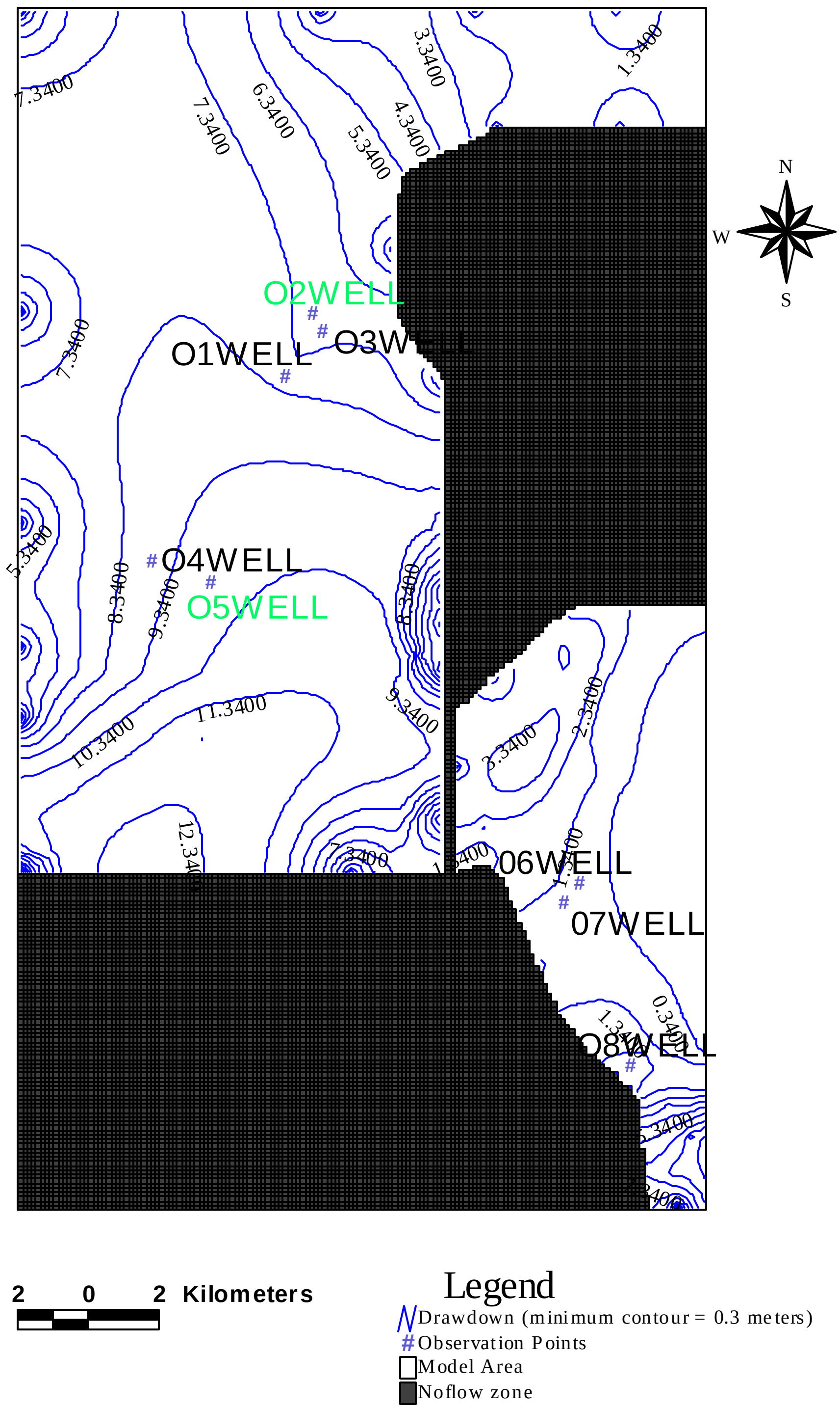


Figure 34 - Contoured model surface displaying drawdown after 100 years in the safe yield condition. Refer to Figure 21 for georeference.

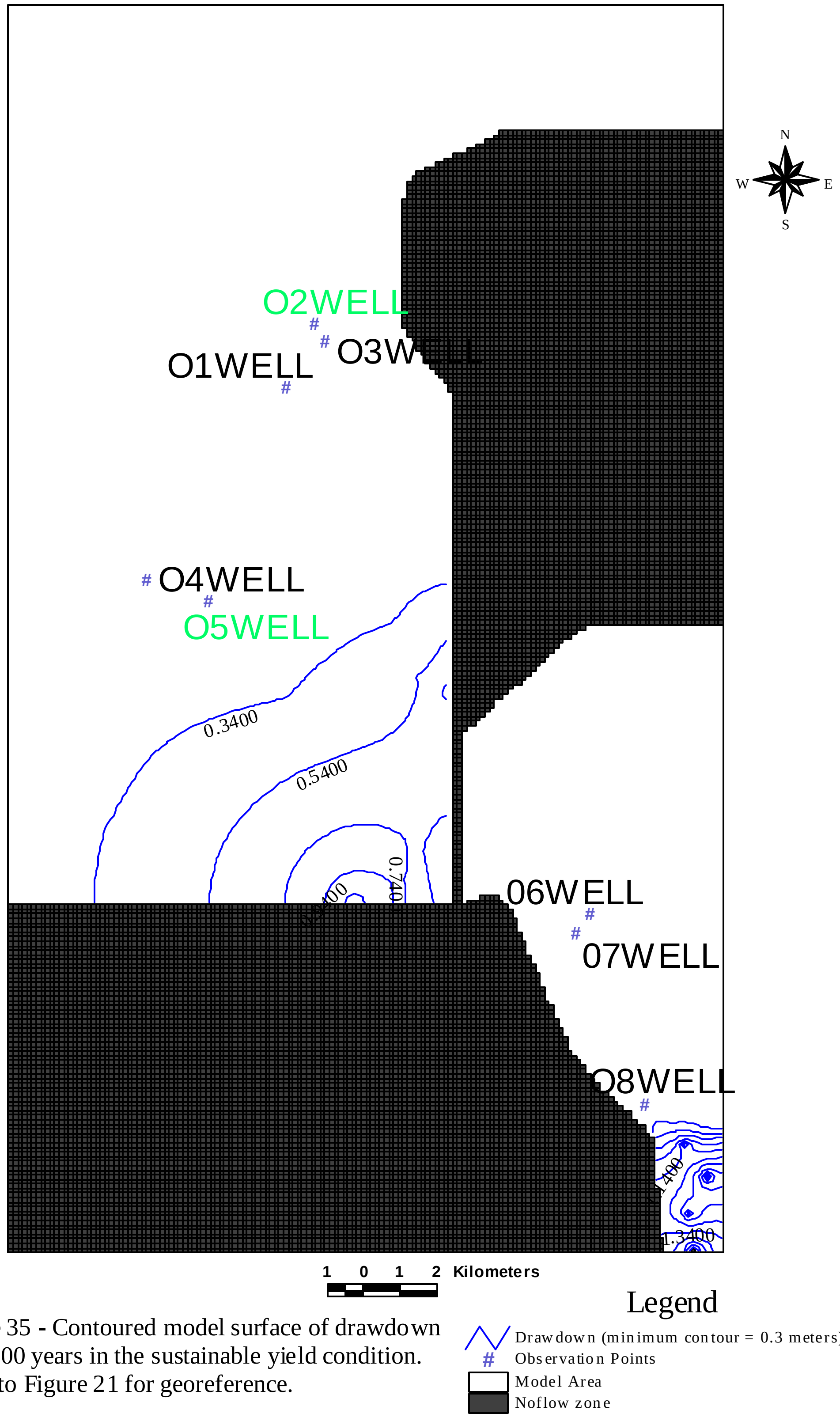


Figure 35 - Contoured model surface of drawdown after 100 years in the sustainable yield condition. Refer to Figure 21 for georeference.

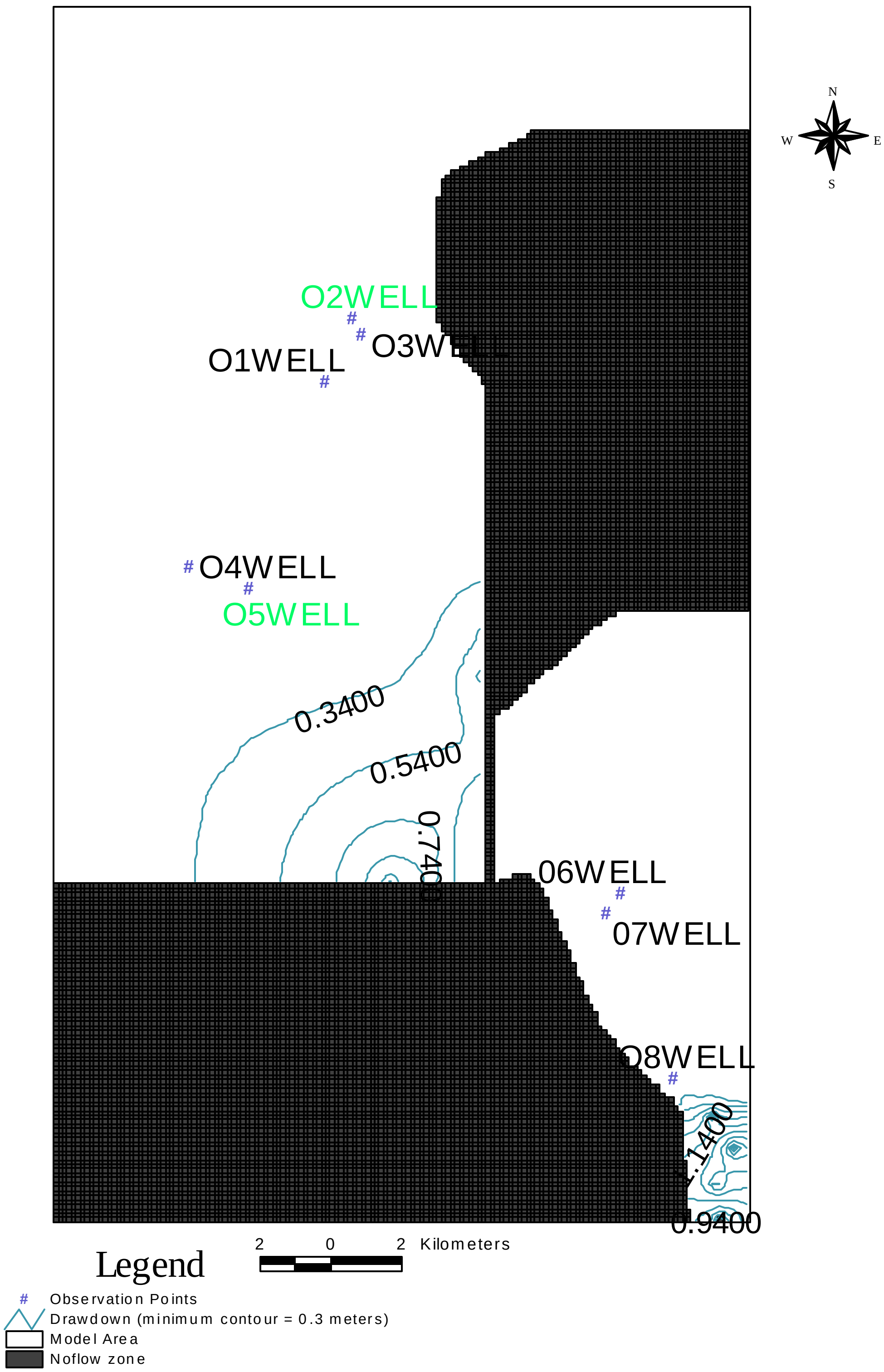


Figure 36 - Contoured model surface of drawdown after 100 years in the Current Water Use condition. Refer to Figure 21 for georeference.

Figure 37 - Contoured model surface of drawdown after 100 years in the American Ranch Build Out condition. Refer to Figure 21 for georeference.

Table 11 - Water budgets of the calibrated current-use condition and three predictive scenarios for the MWWVS model area.

Water Budgets	Current Water Use (m^3/ac-ft)	Safe Yield (m^3/ac-ft)	Sustainable Yield (m^3/ac-ft)	American Ranch Buildout (m^3/ac-ft)
In				
Change in Storage	N/A	N/A	N/A	N/A
Flux In - Underflow	$9.1x10^7$ / $7.4x10^4$	$1.2x10^8$ / $9.8x10^4$	$7.9x10^7$ / $6.4x10^4$	$9.2x10^7$ / $7.5x10^4$
Recharge	$9.4x10^7$ / $7.6x10^4$	$9.4x10^7$ / $7.6x10^4$	$9.4x10^7$ / $7.6x10^4$	$9.4x10^7$ / $7.6x10^4$
Out				
Change in Storage	980 / 0.80	240 / 0.20	$1.4x10^3$ / 1.1	870 / 0.71
Flux Out - Underflow / Drains	$1.3x10^8$ / $1.1x10^5$	$1.1x10^8$ / $8.9x10^4$	$1.3x10^8$ / $1.1x10^5$	$1.3x10^8$ / $1.1x10^5$
Pumping Wells	$4.2x10^6$ / $3.4x10^3$	$9.8x10^7$ / $8.0x10^4$	$4.9x10^6$ / $4.0x10^3$	$5.6x10^6$ / $4.6x10^3$
ET	$5.4x10^7$ / $4.4x10^4$	$2.4x10^6$ / $2.0x10^3$	$3.5x10^7$ / $2.8x10^4$	$5.4x10^7$ / $4.4x10^4$
Percent Discrepancy	-0.002%	-0.003%	-0.003%	-0.003%

Table 12 - Water budgets of the calibrated current-use condition and three predictive scenarios for the Las Vegas Aquifer.

Water Budgets	Current Water Use (m^3/ac-ft)	Safe Yield (m^3/ac-ft)	Sustainable Yield (m^3/ac-ft)	American Ranch Buildout (m^3/ac-ft)
In				
Change in Storage	N/A	N/A	N/A	N/A
Flux In - Underflow	$6.4x10^7$ / $5.2x10^4$	$8.4x10^7$ / $6.8x10^4$	$5.2x10^7$ / $4.2x10^4$	$6.5x10^7$ / $5.3x10^4$
Recharge	$2.6x10^7$ / $2.1x10^4$	$2.6x10^7$ / $2.1x10^4$	$2.6x10^7$ / $2.1x10^4$	$2.6x10^7$ / $2.1x10^4$
Out				
Change in Storage	450 / 0.37	67 / 0.054	1000 / 0.81	380
Flux Out - Underflow / Drains	$3.3x10^7$ / $2.7x10^4$	$2.9x10^7$ / $2.4x10^4$	$4.0x10^7$ / $3.2x10^4$	$3.3x10^7$ / $2.7x10^4$
Pumping Wells	$2.2x10^6$ / $1.8x10^3$	$7.8x10^7$ / $6.3x10^4$	$2.8x10^6$ / $2.3x10^3$	$3.6x10^6$ / $2.9x10^3$
ET	$5.4x10^7$ / $4.4x10^4$	$2.4x10^6$ / $2.0x10^3$	$3.5x10^7$ / $2.8x10^4$	$5.4x10^7$ / $4.4x10^4$
Percent Discrepancy	-0.001%	-0.003%	-0.004%	-0.002%

Table 13 - Water budgets for the calibrated current-use condition and three predictive scenarios for the Mint Wash Aquifer.

Water Budgets	**Current Water Use (m^3/ac-ft)**	**Safe Yield (m^3/ac-ft)**	**Sustainable Yield (m^3/ac-ft)**	**American Ranch Buildout (m^3/ac-ft)**
In				
Change in Storage	N/A	N/A	N/A	N/A
Flux In - Underflow	$2.8x10^7$ / $2.3x10^4$	$2.6x10^7$ / $2.1x10^4$	$2.8x10^7$ / $2.3x10^4$	$2.8x10^7$ / $2.3x10^4$
Recharge	$6.8x10^7$ / $5.5x10^4$	$6.8x10^7$ / $5.5x10^4$	$6.8x10^7$ / $5.5x10^4$	$6.8x10^7$ / $5.5x10^4$
Out				
Change in Storage	500 / 0.41	160 / 0.13	460 / 0.37	470 / 0.38
Flux Out - Underflow / Drains	$9.4x10^7$ / $7.6x10^4$	$7.7x10^7$ / $6.3x10^4$	$9.4x10^7$ / $7.6x10^4$	$9.4x10^4$ / 76
Pumping Wells	$1.8x10^6$ / $1.5x10^3$	$1.8x10^7$ / $1.5x10^4$	$1.9x10^6$ / $1.5x10^3$	$1.7x10^6$ / $1.4x10^3$
ET	--	--	--	--
Percent Discrepancy	-0.003%	-0.002%	-0.002%	0.0006%

Table 14 - Water budgets for the calibrated current-use condition and three predictive scenarios for the Granite Basin Aquifer.

Water Budgets	**Current Water Use (m^3/ac-ft)**	**Safe Yield (m^3/ac-ft)**	**Sustainable Yield (m^3/ac-ft)**	**American Ranch Buildout (m^3/ac-ft)**
In				
Change in Storage	N/A	N/A	2.8 / 0.0023	N/A
Flux In - Underflow	1.2×10^5 / 98	1.0×10^6 / 810	6.0×10^5 / 490	6.0×10^5 / 490
Recharge	5.3×10^5 / 430	7.7×10^5 / 630	8.2×10^5 / 670	8.2×10^5 / 670
Out				
Change in Storage	14 / 0.012	22 / 0.018	N/A	16 / 0.013
Flux Out - Underflow / Drains	4.03×10^5 / 330	7.8×10^5 / 630	1.2×10^6 / 980	1.2×10^6 / 980
Pumping Wells	8.30×10^4 / 67	1.0×10^6 / 810	2.6×10^5 / 210	2.5×10^5 / 200
ET	--	--	--	--
Percent Discrepancy	0.0008%	-0.0007%	-0.003%	0.0006%