CHAPTER THREE

HYDROGEOLOGICAL CHARACTERIZATION

Purpose and Objectives

A detailed study of the hydrogeology of the Mint Wash / Williamson Valley area has not been published. The few reconnaissance-level studies that have been conducted for the area and are available to the public are outdated, and have no written documentation of the study methods. The hydrogeology of the Mint Wash / Williamson Valley area has been characterized in this study in greater detail than previous studies and using updated methods.

The characterization of the area includes a conceptual model, hydrographs of water-levels in wells and a dynamic steady-state potentiometric surface map, permeability measurements, aquifer tests, and a conceptual water budget. These tools were used to build a numerical model of the ground water of the MWWVS.

Introduction

The MWWVS is an area with complex geology, making the accurate creation of a conceptual model integral in understanding the hydrogeology. The conceptual model was created using the known geology of the area, assumed qualitative values for the major hydrostratigraphic units for recharge and hydraulic conductivity, the topography of the area, and basic hydrogeologic concepts.

The conceptual model displays the main areas of recharge, major areas of discharge, the hydraulic headwaters and discharge boundaries, and the general direction of flow for the regional ground-water system (Figure 12). Granite Mountain, located in the southern region of the study area, forms the hydraulic headwaters for the entire system. Granite Mountain produces the largest amounts of recharge due to the high elevation of the mountain and the highly fractured granite, which is highly permeable (Larsson 1972). High levels of recharge also occur along the washes which receive additional precipitation from runoff (Simmers 1997). The Santa Maria Mountains are not included in the study area, but are responsible for a large inflow of ground water from the west. The main discharge areas due to pumping in housing developments occur to the east and north of Granite Mountain in Mint Valley, and on the western flanks of the Sullivan Buttes. There is pumping in central and western Williamson Valley, though most of that pumping is seasonal, for irrigation. The main natural discharge boundary for the system is the northeastern corner of the study area, north of the Sullivan Buttes through ground-water flow.

The southern boundary for the MWWVS is defined as Granite Basin in the southeastern region, and Mount Josh in the southwest. The western boundary is formed by the foothills of the Santa Maria Mountains. The eastern boundary, which forms the surface-water divide, is formed by a discontinuous range consisting of the Sullivan Buttes and

Table Mountain. The Williamson Valley Wash and Big Chino Wash surface water confluence is assumed to be the confluence for the ground-water flow systems from Williamson Valley and Big Chino Valley.

The main hydrostratigraphic units in the MWWVS include the Paulden Conglomerate (Tc), the Prescott Granite (pCg), and the Mint Valley Basalt (Tb) (Plate 1) (Figures 5 - 9). The Prescott Granite is volumetrically the largest hydrostratigraphic unit in the southern half of the study area, and forms the basement for the overall system. Tension fractures are the dominant conduit for fluid flow in the granite. The Mint Valley Basalt occurs in the southern portion of the field area, and is a relatively thin layer in which fractures are also responsible for fluid flow. The Paulden Conglomerate is volumetrically the largest water-bearing unit in Williamson Valley, and covers most of the surface of the field area. Pore space allows for fluid flow in the Paulden Conglomerate.

Background

Water use in the Mint Wash / Williamson Valley area was predominantly for irrigation prior to the sub-division and development of several ranches, and thus seasonal. The only other water use was domestic use for ranchers.

Land subdivisions of the ranches began to occur in the second half of the 1900s. Several ranches were sold and subdivided by developers in the 1980s. The recent population boom in central Yavapai County has created demand for more development in the area.

Presently there are over four ranches which have been subdivided creating several hundred single family home sites in the Mint Wash and Williamson Valley area.

The hydrography of the area is rare in central Arizona. The shallow water table has created several perennial springs and extensive riparian vegetation in the area (Figure 13). Sustainable yield must be addressed for the MWWVS to protect the ecosystem that has formed, which is dependent on the availability of shallow ground water. Sustainable yield is water use to support human communities without degrading the hydrological cycle and the ecosystems that depend on water (Gleick 1998). A sustainable yield for the MWWVS is defined and further addressed in the sensitivity analyses produced by the ground-water flow model.

Methods

Well Network Monitoring

A monitoring network of 12 wells was established in August of 1999, and for the first several months of measurement several additional existing wells were added to the network to a total of 17 wells to fill in gaps in spatial coverage. Water levels in the wells were measured using a Solinst ground-water sounder with a maximum range of 150 meters and an accuracy of +/- 0.01 meter (Solinst 2000). The probe was triple washed with bleach, non-phosphate soap, and distilled water. The 15th of every month was established as the date of measurement to avoid conflicts with any major holidays, in which the well owners would not be able to provide access.

The distance from the top of the well casing to land surface was measured for every well. The well casings were marked so every reading was consistently measured from the same point on the well casing. The elevation and location of each well was measured using a Trimble GPS receiver with an external antenna and a Trimble Pathfinder field computer. The rover station readings were differentially corrected using the Prescott National Forest Service base station available through the Trimble Pathfinder software. The average horizontal 95% confidence precision was approximately +/- 1.5 meter, while the average 95% confidence precision for the vertical dimension was approximately +/- 2.5 meters. Appendix 1 lists the wells used as monitoring wells, and the wells added for the synoptic water-level reading, their locations, as well as the 95% confidence precision of their location.

Water-level data was entered into a spreadsheet in meters above sea-level. Hydrographs were produced for each hydrostratigraphic unit in Grapher 2.0 (Golden Software 2000) (Figures 14-18). The hydrographs for each unit were used to qualitatively compare the storativity of the different hydrostratigraphic units.

Potentiometric Surface Map

A potentiometric surface map (Figure 19) was created using data collected during a synoptic water-level reading on the 14th and 15th of July, 2000. The month prior to the synoptic water level reading was free of rainfall or any other major climatic events. The 17 monitoring wells used to create the hydrographs were used along with 19 extra wells that were added to fill gaps in the water level data. All pumps were shut down 1 hour prior to measurement to allow for recovery of any drawdown. This recovery time was determined from aquifer test data:

all of the wells fully recovered within 1 hour during the aquifer tests, and the wells that were stressed only enough to simulate average discharge from a domestic well recovered within 10 minutes.

The water level data was plotted on a TIN (Triangular Irregular Network) surface of the study area. A topographic contour map was created in ArcView (ESRI 1999) using 1:24,000 quadrangle Digital Elevation Models provided by the Arizona Land Resource Information System (ALRIS 2000).The water-level contour interval is 20 meters. Most of the ground-water contours are dashed due to the uncertainty of the location of the ground-water contours. Adequate spatial distribution of wells were lacking in most of the study area and the water-level could not be determined for large areas (Figure 19). Most of the study area is either rural, National Forest land, or undeveloped. The potentiometric surface map was analyzed to determine ground-water flow paths, ground-water divides, and delineate aquifers.

Permeability

Recharge to ground water is concentrated along the washes in the MWWVS. Saturated hydraulic conductivity was measured at several points within the major washes to determine the saturated infiltration capacity of the material. The hydraulic conductivity measurements provided recharge rates for the washes during saturated conditions.

A Guelph Permeameter was used to measure the saturated vertical hydraulic conductivity of the washes. The Guelph Permeameter has a limited to a range of 10^{+1} to 10^{-3} meters/day for hydraulic conductivity (Soilmoisture Equipment Corp. 1986). The permeability of several points along the washes exceeded the capability of the Guelph Permeameter. The range provided a minimum for the value of the permeability of those points along the washes. The successful measurements were compared to the infiltration rates reported within the Soil Survey of the western part of Yavapai County (Wendt et al. 1976). The rates measured matched the range of infiltration rates reported by the soil survey. The areas that had hydraulic conductivity values too high for the permeameter to measure were reported in the survey as having possible hydraulic conductivity values exceeding the range of the Guelph Permeameter. The permeabilities reported in thesoil survey of the western part Yavapai County were assumed to be accurate, and were used to estimate the hydraulic conductivity values of the sections of the washes that had hydraulic conductivities out of the range of the Guelph Permeameter.

Permeability measurements and grain size analyses of the wash material were conducted at the same sites. Permeability of sedimentary materials is controlled by the grain size distribution. The grain-size analyses were used to map out the sites where permeability would be most likely to vary.

Aquifer Tests

Aquifer tests were conducted and analyzed on several wells within the study area to calculate values for transmissivity and storativity. Existing well pumping test data were available for three wells within the Prescott granite, and one within the Paulden conglomerate. Values for transmissivity and storativity were estimated for the Mint Valley basalt using the Theis method for transmissivity and storativity estimation using specific capacity (Wellendorf 2000).

An aquifer test for the Prescott granite was conducted as part of this study on well number 2 (location of RS-2, Figure 24). Discharge was induced through a submersed pump, approximately 44 meters below land surface. Discharge was measured every 5 minutes during the first hour of the test, then every half hour for the remainder of the test and the mean of the discharge values was used in the aquifer property calculations. The schedule for water level measurement is outlined in “A Manual of Field Hydrogeology” (Sanders 1998).

All of the wells were screened in an unconfined aquifer, and the Neuman (1975) method of aquifer test analysis was used for the pumping well. The Neuman method was the most accurate analytical method for pumping test analysis based on the unconfined nature of the aquifer and the assumptions and limitations of the method and aquifer test.

The recovery for well 2 was analyzed using the Theis (1936) straight line method;

$$\mathbf{T = 264Q/Delta(s\text{-}s')}$$

(Driscoll, 1986). Theis’ corollary to the non-equilibrium equation and Jacob’s modification to the non-equilibrium equation are analytical methods available in the current literature for well recovery analysis.

Water Budget

A water budget was calculated using precipitation data from three rain gauges distributed throughout the field area (Figure 31) for recharge estimates, well registration data for pumping estimates (ADWR 2000), and Darcy’s Law for an estimate of natural discharge (Fetter 1996) (Domenico and Schwartz 1998). The water budget provides a quantitative comparison of total discharge and recharge to the system, which was used to check the “goodness” of the mass balance created in the model output.

Darcy’s Law is mathematically represented by the following equation:

$$\mathbf{Q = -KA(dh/dl)}$$

where Q = discharge (m^3/yr), K = horizontal hydraulic conductivity (m/yr), A = cross sectional area (m^2), and dh/dl = ground-water gradient (dimensionless). Darcy’s Law was applied to estimate the natural discharge by using the potentiometric surface map to find the gradients along inflow and outflow boundaries, and the results of the aquifer tests to estimate values for hydraulic conductivity. The conceptual model and data from well logs provided information enabling an estimation of the saturated thickness to calculate the cross sectional area.

The storage within the aquifer was calculated with the numerical ground-water flow model because no multiple-well aquifer analysis data were available. The transient simulation included storage parameters to estimate volumes of water change in storage.

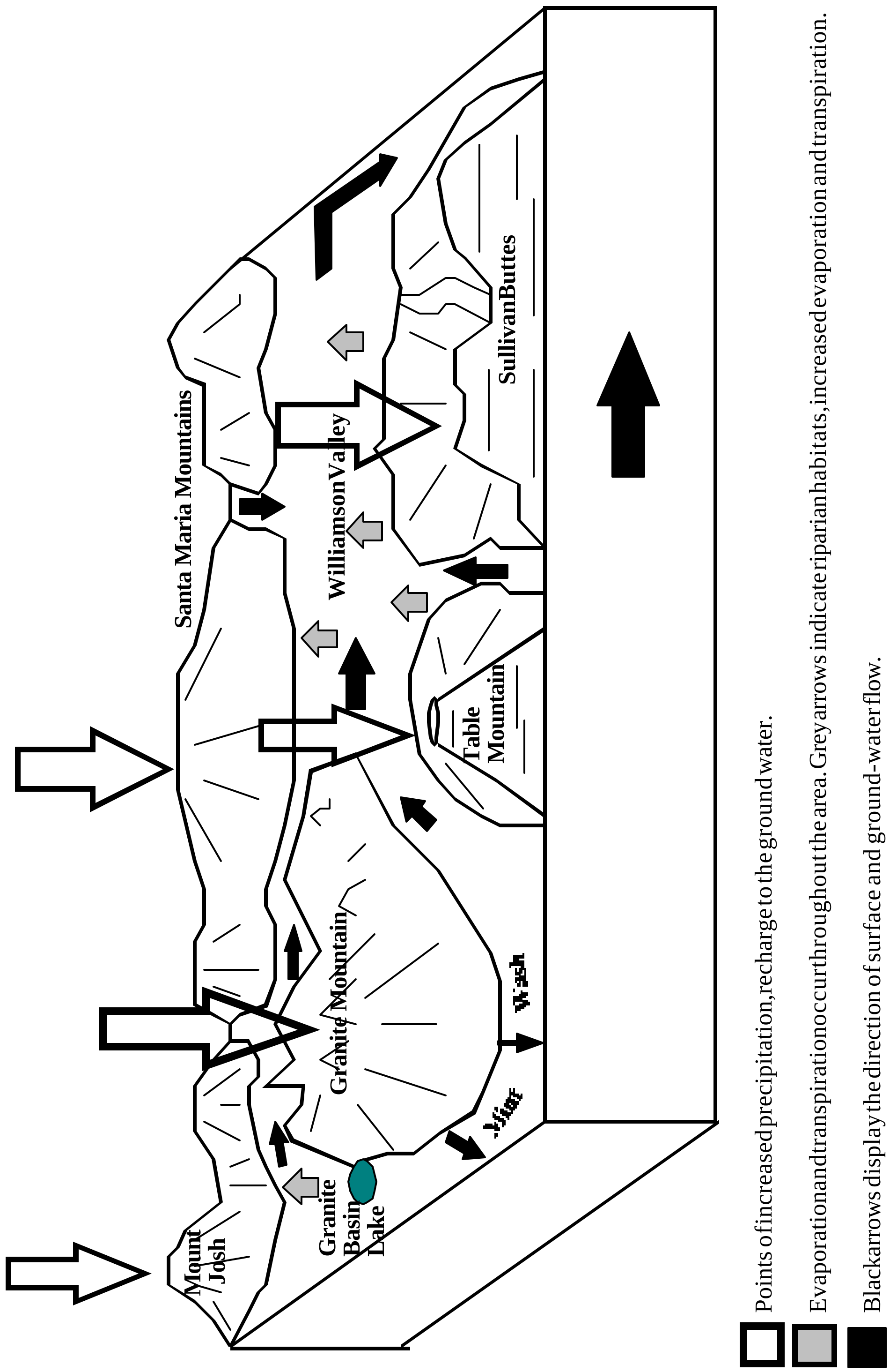

Figure 12 - Conceptual model for the MWWVS.

a. **b.**

Figure 13a. Riparian vegetation dependent on a shallow ground-water supply. The site is shown on Figure 19.

Figure 13b. Perennial springs supplied by shallow ground water. The site is shown on Figure 19.

Results

Hydrographs

Hydrographs for all of the wells within each hydrostratigraphic unit (Figures 14-18) were compiled from the water level data collected the 15th of every month, and show the responses of the water table to stresses throughout the year. The magnitude of the response for a given well provides qualitative information on the storativity of the unit.

The climate in the region of Yavapai County has seasonal precipitation; the wet monsoon seasons in the late summer / early fall, and in late winter / early spring snow melt. The 1999-2000 water year had below average precipitation as compared to precipitation data reported in the western part Yavapai County soil survey (Appendix 3) (Wendt et al. 1976). The long term average for the area as reported in the Soil Survey for Western Part of Yavapai county is 18.24 inches (Wendt et al. 1976). The ground-water levels showed minimal response to the wet seasons during the study period. The hydrograph of the well within the Mint Valley basalt showed a continual decline in water level throughout the year. The degree of water-level change at this well location was high, relative to the wells found in the other hydrostratigraphic units. This high magnitude of water-level change represents low storage values for the Mint Valley basalt.

The water levels in wells in the Prescott granite exhibited large fluctuations of the water-table relative to those in the Paulden conglomerate. The storage values of the granite are apparently lower than those of the conglomerate.

The wells in the conglomerate were graphed separately by location in the valley or along the range within the study area (Figures 17 and 18). One of the composite hydrographs for the conglomerate includes the wells that are in the Williamson Valley basin, and the other wells that are on the slopes of the Sullivan Buttes. These locations had different levels of response to the stresses, though both had fluctuations of lesser magnitude than Mint Valley basalt or Prescott granite wells. The wells in the conglomerate in Williamson Valley exhibited the least amount of water-table fluctuation. This is most likely due to the distance from major sources of recharge. The wells along the Sullivan Buttes show a higher degree of fluctuation due to their proximity to major recharge areas along the topographic highs.

Potentiometric Surface Map

The potentiometric surface map was constructed using the synoptic water-level readings from the July 14th-15th, 2000 measurements (Figure 19). The data were placed on a composite TIN surface of the DEMs available for the field area.

The hydraulic headwaters for the entire system are Granite Mountain. There is radial ground-water flow from the mountain to the surrounding topographic depressions. Ground-water divides extend in the directions of the ridge of Granite Mountain. The ground-water divide splays to the north at the aquitard created by the metamorphic rocks. The area of the aquitard has been drilled several times with little significant water productivity (Figure 20).

At least three distinct aquifers can be identified on the potentiometric surface map (Figure 19). The upper Granite Basin aquifer flows from granite mountain toward the southeast and consists of Mint Valley basalt above Paulden conglomerate. Depending on the exact location of the ground-water divide, one to three of the wells measured yield water from this aquifer.

The second distinguishable aquifer flows from the concave side of Granite Mountain toward the northeast. The upper Mint Wash aquifer is composed of highly fractured Prescott granite, while the lower aquifer has Paulden conglomerate above the granite. The upper Mint Wash discharges to the east of the study area towards the Little Chino aquifer. Most of the flow in this aquifer occurs through fractures.

The third aquifer is the most extensive in the MWWVS. The Las Vegas aquifer extends from west of Granite Mountain up north through Williamson Valley, and discharges out of the system north of the Sullivan Buttes to the adjacent, Big Chino aquifer, which is down-gradient. The main water-bearing unit in this aquifer is the Paulden conglomerate. This is volumetrically the largest aquifer. Most of the wells in this study yield water from this aquifer.

The potentiometric surface map (Figure 19) suggests that the different aquifers are hydraulically connected and all have the same hydraulic headwaters. The aquifers flow in different directions and discharge to different sub-basins, which is important to consider when managing aquifers.

Permeability

The limited range of measurement of the Guelph Permeameter resulted in two successful permeability measurements (Table 2). The successful measurements were compared to the measurements reported in the Soil Survey of the western part of Yavapai County (Wendt et al., 1976).

Saturated hydraulic conductivity measured in the field fit near or within the range of infiltration rates reported by the soil survey. The sites where the permeability values exceeded the range of the permeameter were also compared to the data in the soil survey, and the possible permeability values reported were out of the range of the Guelph permeameter (Table 2). The sites that indicate that no measurement was conducted with the Guelph Permeameter are sections along the wash where it was determined through failed permeability measurement attempts that the soil was out of the range of the Guelph Permeameter.

The limited results of the permeability study were considered during the calibration of the ground-water flow model to estimate recharge through the washes during saturated conditions. Saturated conditions in major washes is felt to be a major component of recharge in a semi-arid ground-water basin.

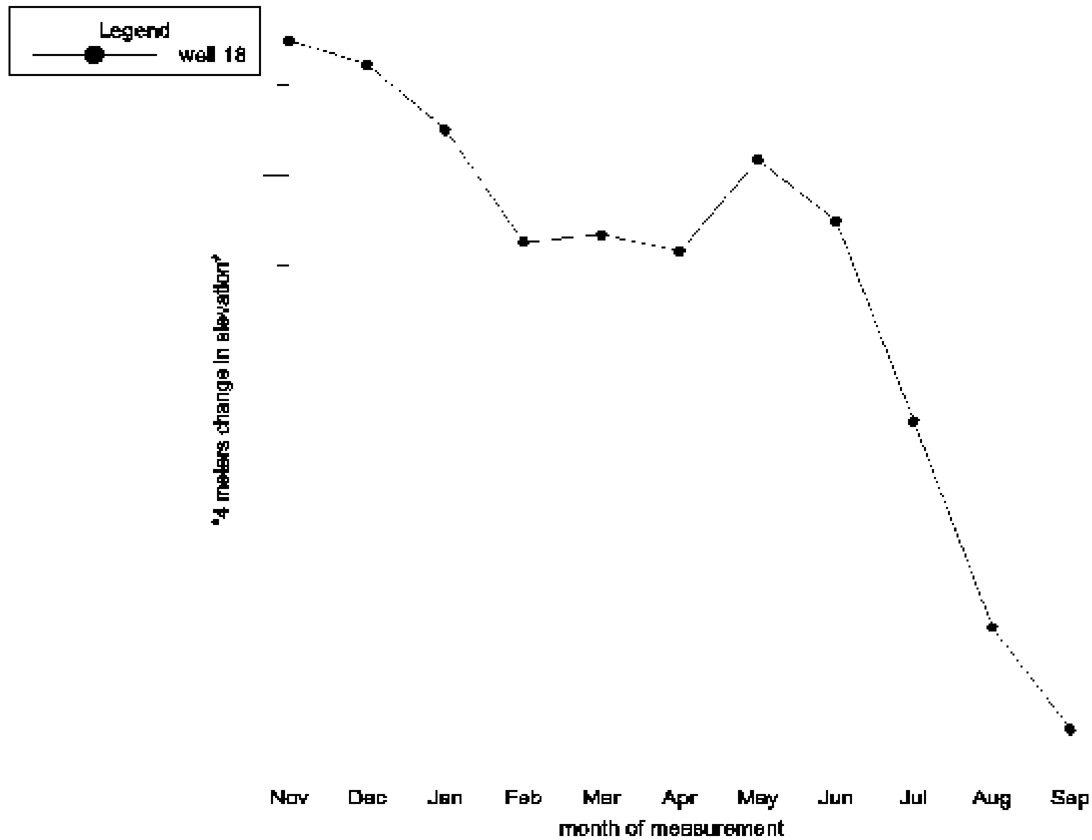

Figure 14. Hydrograph for well 18 in the Proterozoic gneiss and schist (Yavapai Series) from Aug '99 through Sep '00, MWWVS.

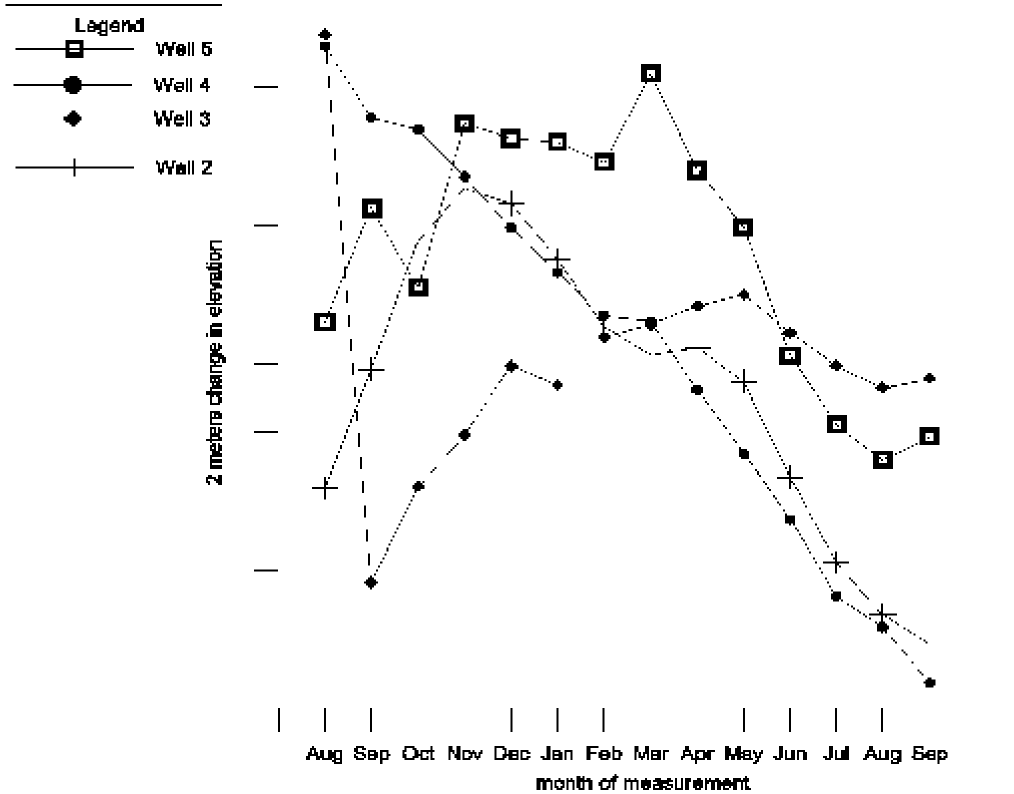

Figure 15. Hydrograph for wells 2, 3, 4, and 5 in the Prescott Granite from Aug ‘99 through Sep ‘00, MWWVS.

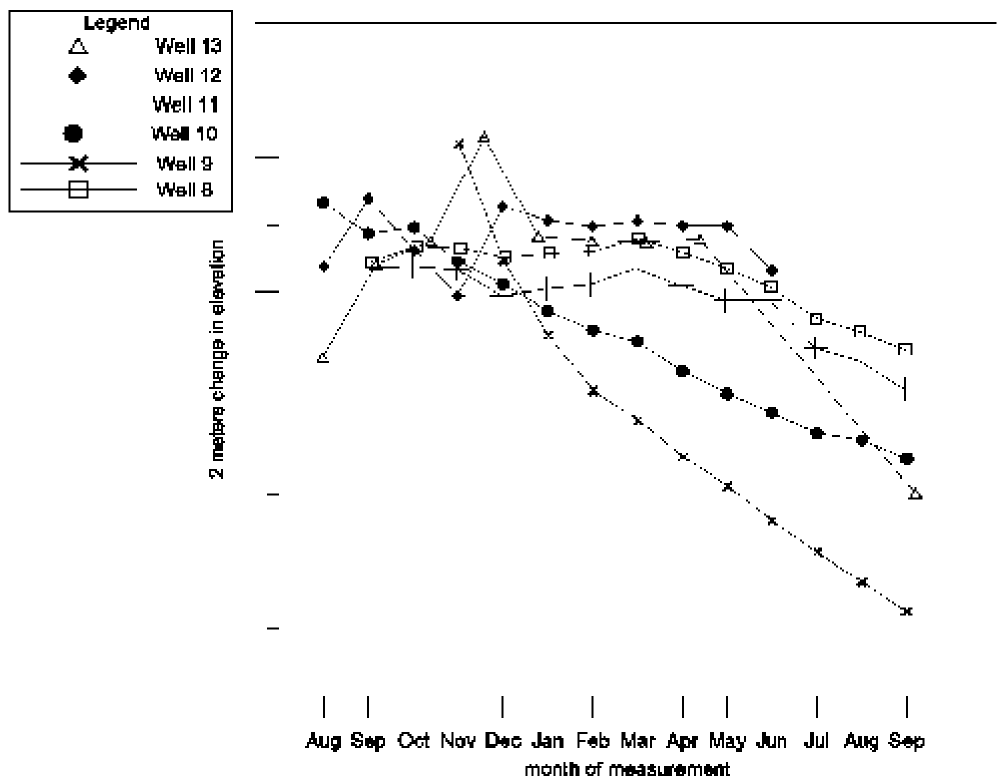

Figure 16. Hydrograph for wells 8, 9, 10, 11, 12, and 13 in the Paulden Conglomerate from Aug '99 through Sep '00, Williamson Valley, MWWVS.

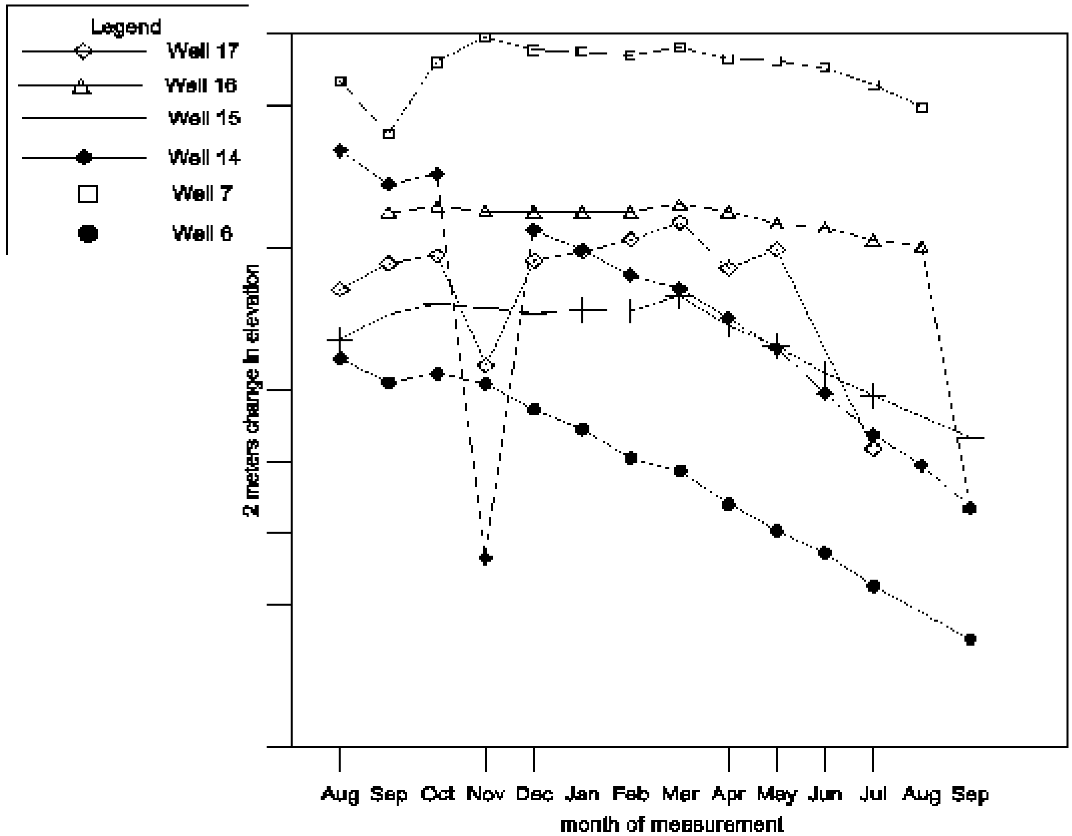

Figure 17. Hydrograph for wells 6, 7, 14, 15, 16, and 17 in the Paulden Conglomerate from Aug '99 through Sep '00, Sullivan Buttes, MWWVS.

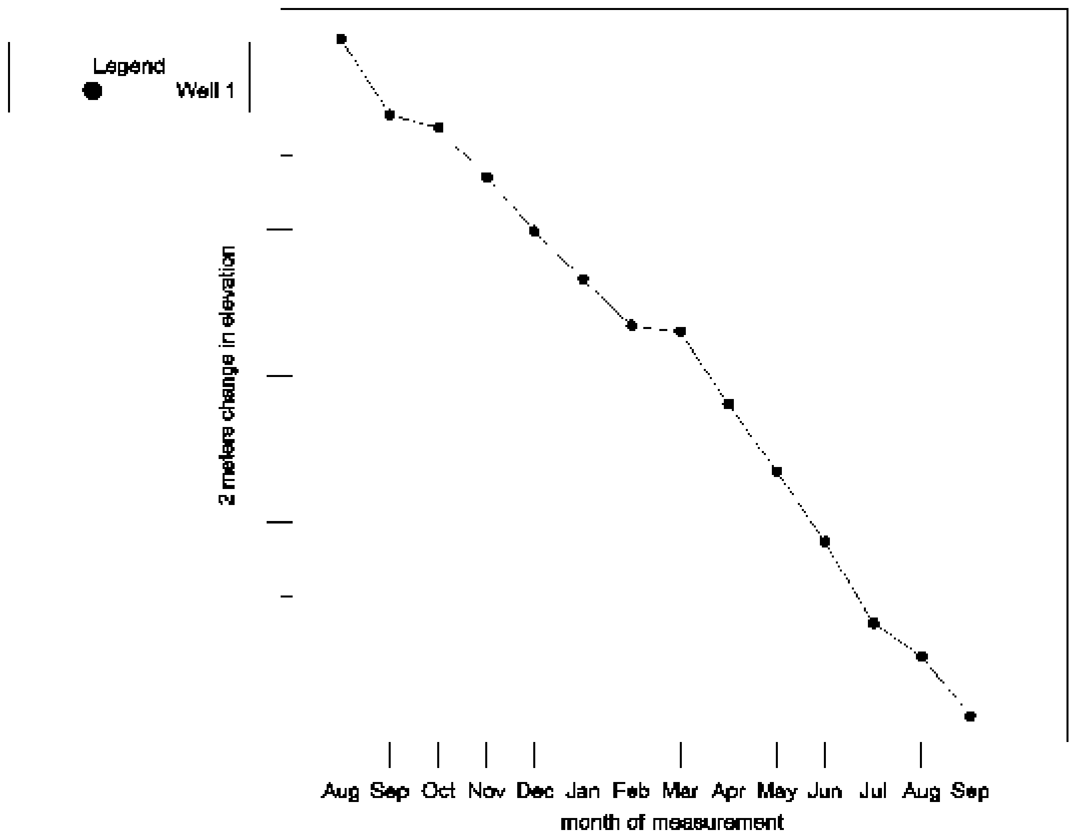

Figure 18. Hydrograph for well 1 in the Mint Valley Basalt from Aug '99 through Sep '00, MWWVS.

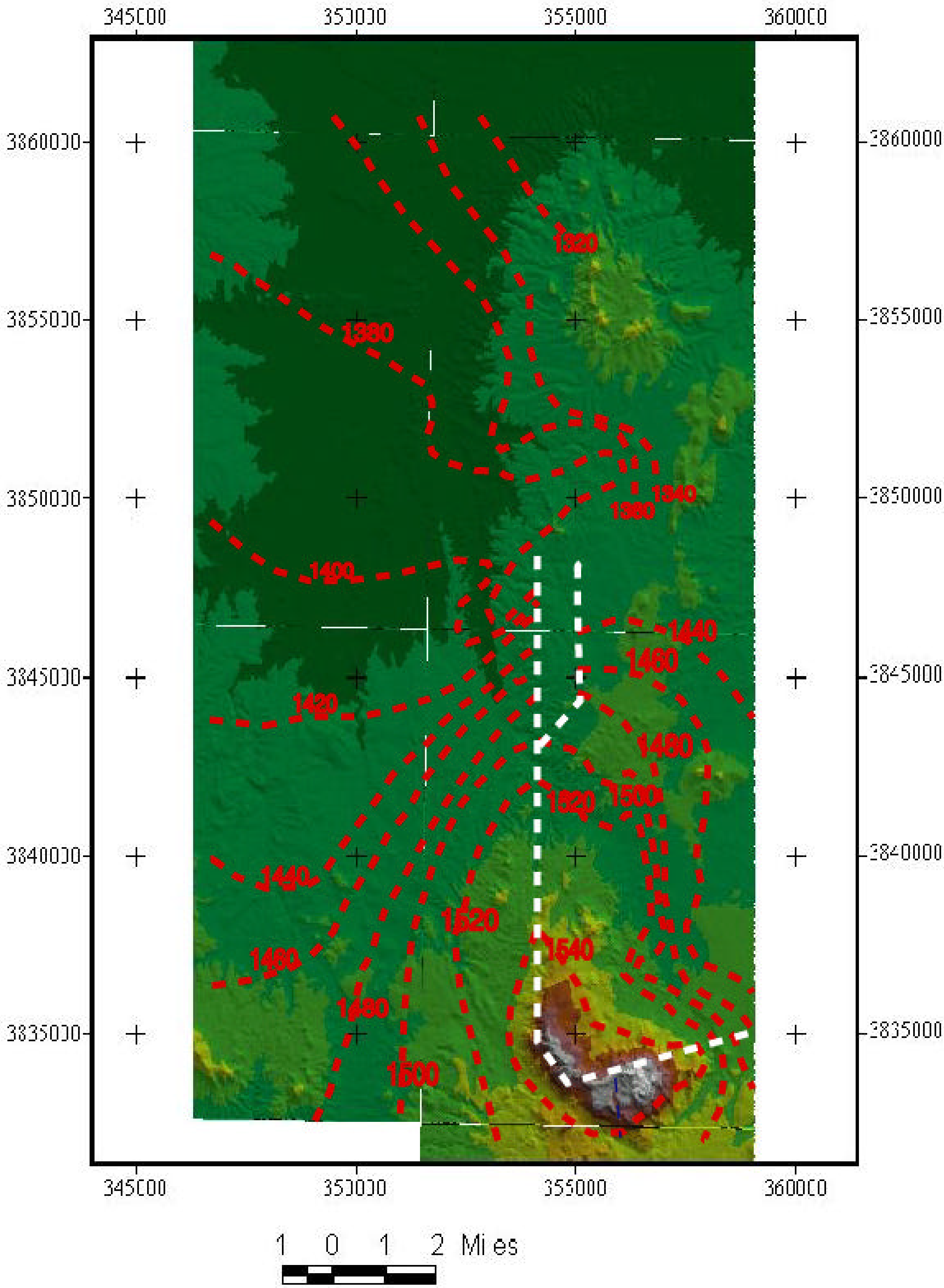

Figure 19 - Potentiometric surface map of the MWWVS. Water level data was collected July 14&15, 2000. Red lines represent ground-water contours. The white lines are ground-water divides. Grid is UITM Easting and Northing.

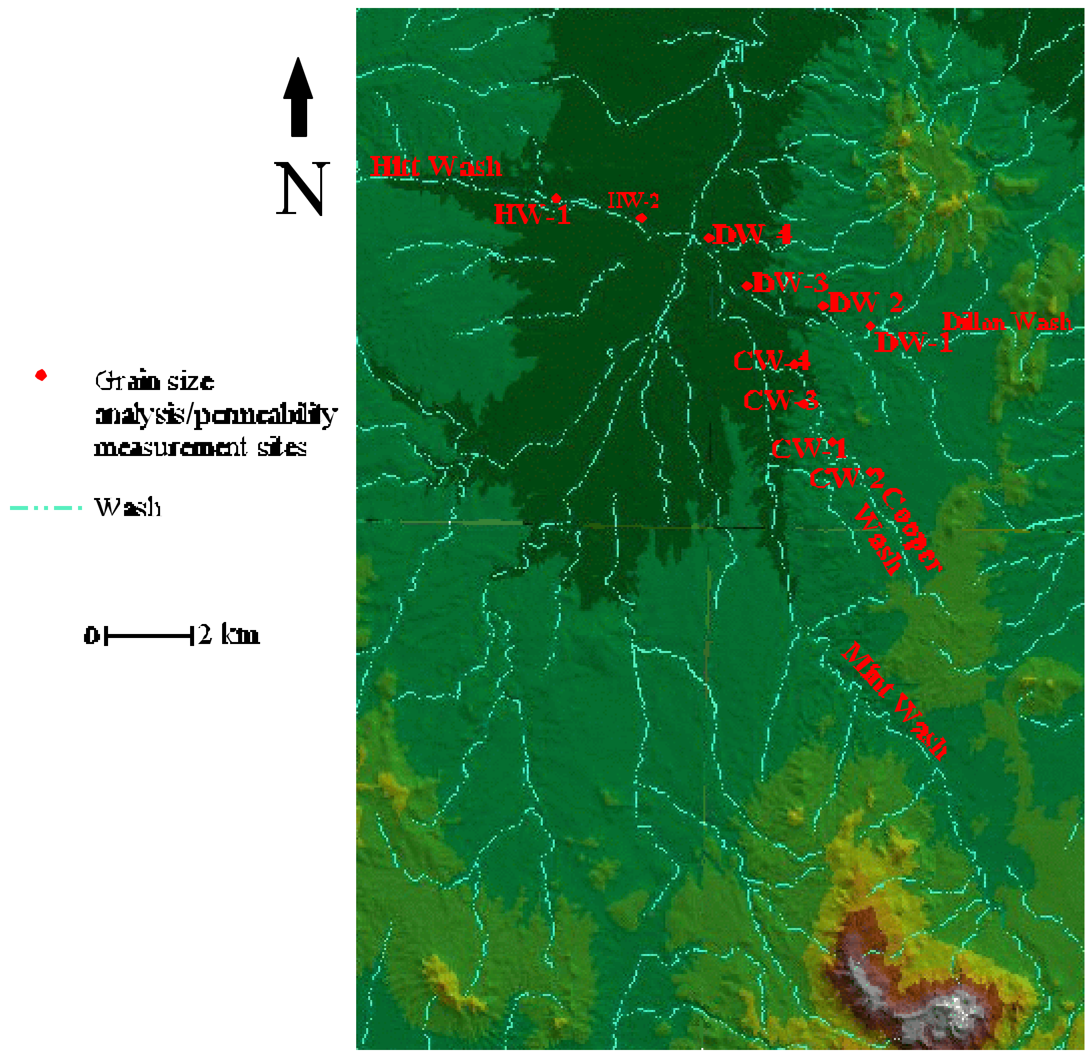

Figure 20. Sites for grain-size analyses and permeability measurements for the MWWVS.

Table 2. Results of the grain-size analyses and permeability measurements. See Figure 26 for location of measurements.

Site	Guelph Permeameter measurement (cm/sec)	Grain-Size Analyses (% of sample)			Permeability reported by Soil Survey (cm/sec)
		Gravel	Sand	Fines (silt and clay)	
CW-1	Out of Range	33	66	1	0.0014-0.0042
CW-2	Out of Range	25	74	1	0.0014-0.0042
CW-3	Out of Range	28	72	1	0.00042-0.0014
CW-4	No Measurement	19	81	0	0.00042-0.0014
DW-1	No Measurement	71	29	0	0.00042-0.001
DW-2	No Measurement	30	70	0	0.00014-0.00042
DW-3	Out of Range	64	35	1	0.00014-0.00042
DW-4	0.00013	34	64	2	0.00014-0.00042
HW-1	Out of Range	21	79	0	0.00014-0.00042
HW-2	0.00021	29	65	6	0.00014-0.00042

Aquifer Tests

The data from several aquifer tests were analyzed using graphical analysis methods. The aquifer tests available included one aquifer test in the Paulden conglomerate (Las Vegas aquifer), and three aquifer tests in the Prescott granite (Mint Wash aquifer). Transmissivity and storativity were estimated for the Mint Valley basalt using average specific capacity values (Wellendorf 2000) and the Theis equation for estimating transmissivity and storativity from specific capacity data (Fetter 1994).

The pumping data for the aquifer test on the Navarro conglomerate were plotted semi-logarithmically with drawdown on a linear y-axis and time on a logarithmic x-axis (Appendix 3). The Neuman analytical method (Neuman 1975) for an unconfined aquifer was used to analyze the data. The early time data fit well on the ' = 0.01 Neuman type curve. There was no late time data evident to match to the Neuman late time curve nor was there an observation well, so an estimation of specific yield was not attained. The results produced are reported in Table 3. The same method was used for the pumping data for all of the aquifer tests available for the Prescott granite (Table 3).

The aquifer test for well-2 is the only test conducted as part of this study. All of the assumptions for the Neuman analytical method were met to secure a valid aquifer test. The test did not last long enough to produce late time data to estimate specific yield.

The aquifer test for well 52 was deemed invalid, though the results are still reported. The total drawdown exceeded 20% of the assumed saturated thickness of the aquifer. Analytical methods are only valid for aquifer tests in which the drawdown does not exceed

10% of the saturated thickness.

Specific yield was estimated using the late time data from the aquifer test on well 51. The test on well 51 was the most complete of the tests. All of the assumptions for the Neuman method were met. The initial hydraulic conductivity value in the ground-water flow model is based on this aquifer test.

Table 3. Aquifer parameters for the major hydrostratigraphic units using aquifer tests and specific capacity estimates.

Aquifer Test	Hydrostrat. Unit	T(m2/yr)	Thickness (m)	K(m/yr)	Storativity
ARwell-51	Prescott pCg	69000	152	460	n/a
ARwell-52	Prescott pCg	10000	152	69	n/a
ARwell-54	Prescott pCg	15000	152	95	0.00035
Well-2	Prescott pCg	18000	152	120	n/a
Well-2 (recovery)	Prescott pCg	440000	152	2900	n/a
Well W-1	Paulden Tc	44000	44	990	n/a
Tb-specific capacity	Granite Basin Tb	4400	50	88	0.0004

The recovery data for well-2 were analyzed using the Theis straight line recovery method (Driscoll 1986). Residual drawdown after the cessation of pumping is measured at a logrithimic interval until full recovery. The calculated recovery is plotted on a linear y-axis, while the time since pumping stopped *t'* is the logarithmic x-axis (Table 3) (Figure 21).

The transmissivity and storativity of the Mint Valley basalt were estimated using an equation created by Theis (1963) for specific capacity measurements:

$$\mathbf{T=(Q/(\mathit{h}_o-\mathit{h}))(2.3/4\pi)\log(2.25Tt/r^2S)}$$

where $Q/(ho-h)$ is the specific capacity of the well (m^3/day/m), t is the period of pumping (day), r is the radius of the pumping well (m), T is aquifer transmissivity (m^2/day), and S is aquifer storativity (dimensionless). Storativity and transmissivity are both variables for the specific capacity equation, so an accurate approximation of either values must be determined to accurately estimate the other.

Aquifer tests provide values for aquifer parameters, but the major limitation is that it is a local value, and may not be representative of the entire hydrostratigraphic unit. Aquifer test analysis is best used in local studies, or regional studies when sufficient aquifer tests are available to use statistics to create semi-variograms. For the purpose of this study, the limited data were applied as initial values in the ground-water flow model, and the parameter values were varied through the calibration process and representative values for the hydrostratigraphic units were determined.

Water Budget

The water budget includes estimates of discharge and recharge to the MWWVS utilizing limited data and several assumptions. Recharge was estimated from precipitation data from three rain gages stationed at different locations in the study area (Figure 31) (Appendix 3). A percentage of 4 to 5% has been estimated to be the amount of total precipitation that goes to recharge the ground-water in this region (Corkhill and Mason 1995). Precipitation was assumed to vary with elevation throughout the study area. Areas that were lacking in precipitation data were assigned approximate values based on the nearest precipitation data source and the assumption that in Arizona there is an additional 1.5 inches (3.8 cm) of precipitation per year per 1,000 feet (300 meters) of additional elevation (Allen 1995). Initial recharge values were estimated throughout most of the study area using this assumption. Recharge through washes is a combination of direct precipitation recharge and the permeability of the washes during saturated conditions multiplied by the amount of time during the study period that the washes were saturated. Mint Wash adjacent to Granite Mountain was assumed to be saturated approximately 30 to 45 days during the study period (Maslansky 2000) at approximately 40% of the wash area. Washes along the Sullivan Buttes, Santa Maria Mountains, and Williamson Valley were assumed to be saturated due to precipitation events approximately 2 to 3 days (Maslansky 2000) during the study year at 10% of the wash area. The use of percentages of precipitation values for recharge can produce errors and should not be used by practitioners to calculate recharge values (Watson et al. 1976, Gee and Hillel 1988), so the calibrated values in the ground-water flow model are assumed to be the most accurate recharge values for the MWWVS.

Natural discharge through sub-surface flow in or out of the MWWVS was estimated using Darcy's Law (Domenico and Schwartz 1998). Discharge due to pumping was estimated using the Arizona Department of Water Resources Well Registry CD to find the number of wells within the study area (ADWR 2000). Using the same database, the wells were differentiated by use: domestic, irrigation, and second family home, based on the well owner's address. The rule of thumb for the region on values for water use were used to find the average water use per well per year. These assumptions include 180 gallons/day/person and 2.3 people per home (Wellendorf 2000). Second family homes were assumed to use the same quantity of water, but only for half of the year.

The results of the water budget are included in Table 4. This conceptual water budget is used to help calibrate the mass balance of the steady-state model. The inflows and outflows reported by the model should be within the same order of magnitude as the values reported in the water budget.

There are discrepancies in the water budget due to the uncertainty in the recharge value and the inflow and outflow through the boundaries of the study area. Many of the boundaries were assumed in the potentiometric surface map due to the lack of available water-level data. The gradient and saturated thickness of the aquifer at these boundaries could vary from the actual values. The uncertainty of the inflow value and the recharge value could both introduce error in the water budget. The recharge value seems the most likely cause for the error in the water budget due to it's high value relative to the other components in the water budget.

Table 4. Initial water budget for the MWWVS.

Ground-Water Movement	Inflow (m^3/yr) / (ac-ft/yr)	Outflow (m^3/yr) / (ac-ft/yr)	Difference / (ac-ft/yr) (m^3/yr)
Recharge	$2.9x10^7$ / $2.4x10^4$	-------------------	------------------
Inflow	$1.1x10^7$ / $8.9x10^3$	-------------------	------------------
Pumping	------------------	$4.5x10^5$ / $3.6x10^2$	------------------
Outflow	------------------	$1.6x10^7$ / $1.3x10^4$	------------------
Total	$4.0x10^7$ / $3.2x10^4$	$1.6x10^7$ / $1.3x10^4$	$2.4x10^7$ / $1.9x10^4$