AN ABSTRACT OF THE THESIS OF

Robert Peter Healy for the Degree of Master of Science in Geosciences presented on January 21, 2000. Title: A Hydrogeologic Study and Groundwater Model of Parrett Mountain, Oregon.

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This thesis presents a hydrogeologic study of the Parrett Mountain Region, located approximately 20 miles south of Portland, Oregon. The aim of the study was to investigate the impacts of Columbia River Basalt on the regional groundwater system, to expand our understanding of flow through fractured basalt, to improve management practices in the area, and to provide local detail for a regional groundwater model being developed by the USGS. An equivalent porous medium model with steady state heads was developed of the area using MODFLOW, a finite difference method for modeling groundwater flow. The data used to develop the model included (1) geologic stratigraphy of the area; (2) time averaged 1995-1996 water level data; and (3) local hydraulic properties measured by aquifer pump tests.

Based on the hydrogeologic study we determined that using a continuum approach was the most appropriate method for modeling the flow system. We also found that during model calibration no faults were necessary to reach calibration goals, suggesting that faults do not play a significant role in regional groundwater flow at steady state. Finally, based on available data, we were unable to determine the role of basalt flow tops on groundwater flow. By using the calibrated flow model the impact of projected population increases were investigated to aid in groundwater management practices. Based on assumptions of uniform population

increases and a uniform pumping distribution, it was found that an increase of approximately 8,000 people would result in drawdown estimates of less than 2 meters throughout the model.

A Hydrogeologic Study and Groundwater Model of Parrett Mountain, Oregon

By

Robert Peter Healy

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Robert Peter Healy, Author

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A Hydrogeologic Study and Groundwater Model of Parrett Mountain, Oregon

1. Introduction

This thesis presents a hydrogeologic study of Parrett Mountain, Oregon. The area is located near the city of Sherwood where Clackamas, Yamhill, and Washington Counties intersect. The study focuses on the impacts of Columbia River Basalt (CRB) on groundwater flow within the region and has the following goals:

1. To expand our understanding of flow through fractured basalt.
2. To improve management practices in the area.
3. To provide local detail for a regional groundwater model being developed by the United States Geological Survey (USGS).

Areas within the Parrett Mountain Region have undergone significant water level declines associated with groundwater development (Brodersen, 1994). To achieve the above mentioned goals and to investigate water declines a steady-state groundwater model using the finite difference method under MODFLOW (McDonald and Harbaugh, 1988) was constructed and calibrated to 1995-1996 time-averaged head data. To aid in aquifer management practices forward simulations were run investigating the effects of population growth on the groundwater flow system.

1.1 Importance

The focus of my efforts in this study was to gain a greater understanding of groundwater flow in the fractured Columbia River Basalt of the Parrett Mountain region. The forces driving this study were two-fold. The first was a set of scientific questions:

1. Can the Effective Porous Medium (EPM) approach to groundwater modeling be applied to Columbia River Basalt (CRB) over this large of an area, resulting in faults and matrix blocks acting as a continuum? Another possible approach to modeling CRB was through the used of a discrete fracture (DF) model. This approach assumes that water flows through a fracture network where the flux depends on the fracture aperture, the fracture width, the fracture length, and network interconnection.
2. Do major faults in the area significantly influence flow?
3. Does the majority of flow occur on basalt flow tops as some hypothesize, or does it occur vertically as well?

The second force driving this study was a groundwater management issue exhibited by the impacts of historic groundwater uses in the area, as well as the implications of future population growth. CRB aquifers within the Willamette Valley are typically high yielding, but have low storage capacities. Consequently areas that have undergone significant development have also experienced long-term water level declines. Some wells within the Parrett Mountain area have shown declines of up to 16 meters (Miller et al., 1994). Since Parrett Mountain is within easy commuting distance to Portland, and both Portland and the counties surrounding Parrett Mountain are expected to grow in the future, it is possible that Parrett Mountain's water resources will be strained with a greater demand. By studying the area I hoped to gain a better understanding of the CRB hydrologic system, which could be used to improve management techniques and thereby help prevent further water level declines.

This investigation also has implications for the Willamette Valley as well, in that there are geologic similarities between Parrett Mountain and other basaltic aquifers in the valley. What is learned from the results of this study might be applied to other CRB aquifers within the Willamette Valley.

1.2 Project Goals

Upon the initiation of this study of the Parrett Mountain aquifer, there were four research objectives that I wished to investigate.

1. Determine how well MODFLOW (McDonald and Harbaugh, 1988), a finite difference method designed for porous media, models steady state flow in a fractured basalt at the scale of 74 km^2.
2. Evaluate the hydrologic characteristics that most affect the flow system, including fault and basalt flow influence.
3. Determine whether long-term water level declines can be mediated in the aquifer system.
4. Develop predictive hydrologic scenarios to assess the impact of groundwater development to the region's aquifer.

1.3 General Approach to Accomplishing Goals

In order to complete the hydrogeologic study of the Parrett Mountain area, the following steps had to be taken.

1. Compilation of all previously collected data from the Parrett Mountain area. The data were provided by the Oregon Water Resources Department (OWRD), and the United States Geologic Survey, and included such information as the geological extent of the CRB, recharge rates, pumping rates, head data, stream data, and well logs. Fieldwork was performed to collect stream discharge data in the area. The fieldwork summary and results are available on the Data CD.
2. Construction of a conceptual model of the Parrett Mountain area, including defining the hydrostratigraphic units in the system and estimating hydrogeologic properties such as horizontal and vertical hydraulic conductivity.

3. Selection of a computer code. I used MODFLOW, a 3D finite difference spatial modeling package (McDonald and Harbaugh, 1988) coupled with GMS (Groundwater Modeling System), a pre- and post-processor for MODFLOW.
4. Building the model. The process included designing the grid, setting boundary conditions, and preliminary selection of values for aquifer parameters and hydrologic stresses.
5. Model calibration. Calibration of the model demonstrates that the model is capable of producing heads and flows similar to those measured in the field. The model was calibrated by altering model input parameters until model results reasonably matched field data.
6. Sensitivity analysis. A sensitivity analysis is used to quantify uncertainty in the calibrated model by measuring uncertainty in the estimates of the aquifer parameters, stresses, and boundary conditions. Each parameter was systematically varied within an established range. The magnitude of the change in head was calculated for each alteration, resulting in a measure of the sensitivity of the solution to that particular parameter.
7. Quantitative predictions of the system's response to future events. The model was run using the calibrated parameters, and altering only those parameters expected to change in the future. For Parrett Mountain future changes depend on management issues linked to population growth and groundwater availability, and entailed increasing well pumping rates, simulating a higher demand for water.

1.4 Literature Review

Significant research has occurred investigating the use of continuum models (porous medium models) to simulate groundwater flow through fractured media. Long et al.

(1982) stipulate that fractured rock behaves as a continuum when (1) there is an insignificant change in the value of the equivalent permeability with a small addition or subtraction to the test volume and (2) an equivalent symmetric permeability tensor exists which predicts the correct flux when the direction of a constant gradient is changed. The first point implies that a continuum model may be used when the Representative Elementary Volume (REV) is obtained. The REV, defined as the volume at which the parameter of interest ceases to vary as the system volume is increased, represents a good statistical sample of system heterogeneity. The second point implies the flow system produces a constant gradient with linear flow lines in a homogenous anisotropic system.

Varying approaches have been taken to determine under what conditions these criteria are met for fractured media. For instance, Berkowitz et al. (1988) examined the conditions under which contaminant transport in fractured media could be described by an EPM model. A two dimensional mathematical numerical model for flow and contaminant transport was developed allowing for contaminant transport through advection, diffusion, and dispersion in both fractures and porous blocks. The authors investigated concentration distributions under different flow conditions and medium properties and found that within the range of considered parameters, and except for the region close to the source, an EPM model was sufficient for modeling contaminant transport.

In another example, Cacas et al. (1990) developed a discrete fracture network of a granite uranium mine at Fanay-Augeres, France, instead of using an EPM model. One of the goals of the study was to predict global scale flux and also its variability at a more local scale. EPM models are not capable of adequately interpreting small scale measurements and could therefore not be used in this instance.

Gerhart (1984) used an EPM model to simulate the groundwater flow system in the Lower Susquehanna River Basin in Pennsylvania and Maryland. Gerhart justified using this approach through evidence provided from local multi-well aquifer tests. His condition for using an EPM model was that secondary fracture openings are sufficiently numerous and interconnected. During the multi-well aquifer tests water-levels in nearby observation wells were usually affected by the nearby pumping well. Also a three mile long and one mile wide cone of depression caused by dewatering of Carbonate rock quarries was observed. Gerhart viewed both instances as evidence of a high degree of interconnection of secondary fracture openings. To further support the used of an EPM model Gerhart used a uniform grid spacing of one mile to encapsulate a representative volume of the aquifer.

The most significant contribution for the purpose of this study was presented by Khaleel (1989), who he investigated the scale dependence of continuum models for Columbia River Basalt. In this study numerical simulations were carried out on a two dimensional interconnected network of hexagons (columns), representing a conceptual model of the Columbia River Basalt. Results indicated that for an interconnected network with unfilled fractures, continuum models are equivalent to discrete models at 6 times the column diameter. For an interconnected network with clay-filled fractures continuum models are equivalent at 22 times the column diameter. If a typical column diameter is one meter, with clay filled fractures, the model must be 22 times the column diameter for the EPM approach to work.

Various groundwater investigations have been performed using the EPM approach, which model Columbia River Basalt aquifers in Washington and Oregon. As with the Parrett Mountain study the motivating force behind the modeling efforts described below has been groundwater elevation declines due to increasing groundwater demands. MacNish and Barker (1976) simulated a basalt aquifer system in the Walla Walla River Basin located in Washington and Oregon. This was a one layer model which used empirical methods to approximate vertical fluxes to and from the aquifer. Barker (1979) simulated groundwater flow of a basalt aquifer system in the Pullman-Moscow Basin, Washington and Idaho. Here Barker (1979) modeled a two layer system, defining the deep aquifer system as the primary aquifer system and grouping all overlying Columbia River Basalt aquifers into the upper aquifer zone. Prych (1983) constructed a multi-layer steady-state groundwater flow model of the Lower Status Creek basin, where representative transmissivity and leakance values were used for each model layer. Davis-Smith et al. (1988) constructed a three-dimensional finite-difference model to simulate the groundwater flow of the Umatilla Plateau and Horse Heaven Hills area located in Oregon and Washington. In this study vertical hydraulic conductivity values were derived empirically from previous studies in the Columbia Plateau. Hansen et al. (1994) simulated groundwater flow of the Columbia Plateau Regional Aquifer System, in Washington, Oregon, and Idaho. For this modeling effort model layers were based on the geologic units of the CRB. Little information on vertical conductance between model layers was available at the site. Initial estimates were based on previous studies of other CRB sites and were adjusted during calibration. Morgan and McFarland (1994) simulated the groundwater flow system in the Portland Basin, Oregon and Washington. In their study vertical anisotropy ratios of hydraulic conductivity were first estimated for each hydrogeologic unit from published values for similar classes of sediments and were then modified during calibration of the numerical model. Packard et al. (1996) simulated flow in the basalt aquifers of Horse Heaven Hills, South-Central Washington, to determine the effects of development alternatives. In Packard's study model layers were differentiated based on geologic units of the CRB in the area. Vertical hydraulic conductivity values between layers were derived from five numerical cross section models.

There are two common themes in previous groundwater simulations of CRB aquifer systems; methods of layer distribution and estimation of vertical conductance. The more sophisticated models differentiate model layers based on the distribution of CRB geologic units. For systems where the vertical extent of geologic units is uncertain or unknown, this method of layer construction is not possible. While layer distribution should be based on geologic data, vertical conductance should be estimated based on site-specific, field-measured data. In all CRB groundwater studies mentioned above, field-measured vertical hydraulic conductivity estimates were unavailable. All the multilayer models discussed above use calibration to arrive at vertical hydraulic conductivity estimates. Packard at al. (1996) used the most robust method by using five numerical cross section to estimate vertical conductance. However, even using this approach much uncertainty remains in vertical conductivity estimates.

Literature focusing specifically on the Parrett Mountain area included work by Brodersen (1994) and Miller et al. (1994), who presented Parrett Mountain geology and an assessment of Parrett Mountain groundwater conditions. The information taken from these two studies was used to develop the conceptual model for the area. Larger scale geologic studies pertaining to the Parrett Mountain region include work by Beeson

(1989), who investigated the geologic structures that controlled flow emplacement patterns. Also included are Reidel's (1989) stratigraphic descriptions of the Grand Ronde Basalt unit of the CRB. Information gleaned from these studies is presented in Section 2.2.

1.5 Mathematical Model

This subsection gives a brief description of MODFLOW, the code developed by the USGS (McDonald and Harbaugh, 1988) that was chosen to simulate groundwater flow in the Parrett Mountain Region. Three dimensional movement of groundwater through porous media can be described by the following partial-differential equation representing transient anisotropic confined conditions.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}-R^* \qquad (1\text{-}1)$$

(Domenico and Schwartz, 1998).

where:

K_x, K_y, and K_z [LT^{-1}] are hydraulic conductivity values in the x, y, and z directions respectively;

h [L] is head;

S_s [L^{-1}] (specific storage) is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head; and

R^* [T^{-1}] defines the volume of inflow into the system per unit volume of aquifer per unit of time.

MODFLOW is a quasi-3D groundwater flow model which uses the finite difference method to solve the groundwater flow equation. MODFLOW is quasi-3D because it uses a leakance term to represent vertical flux through the model. The leakance term allows the modeler to combine multiple layers with variable thickness and vertical hydraulic conductivity values into one term, resulting in increased simulation speeds. A further description of the leakance is described in subsection 3.3. Using an iterative process and external boundary conditions based on specific site conditions, MODFLOW solves the finite difference groundwater flow equation for each grid cell, resulting in simulated heads in each cell. System boundary conditions are described in detail in subsection 3.2.

2. Conceptual Model

This section presents my conceptual model of the Parrett Mountain area, which was used as a basis for the steady-state groundwater model. The section includes a brief description of the site setting, followed by the system geology and hydrogeology. The hydrogeologic information presented below is directly applicable to the groundwater model and consists of the description of the hydrostratrigraphic units, horizontal hydraulic conductivity, and vertical hydraulic conductivity.

2.1 Site Setting

The Parrett Mountain Study Area (Figure 2-1) is located in the northern section of the Willamette Valley, in northwest Oregon. The study area occupies 74 km^2, with sections located in Washington, Clackamas, and Yamhill counties. The model region (287 km^2 in area) includes three small cities: Sherwood City to the north, Wilsonville to the east, and Newberg to the west. Only Sherwood is located within the study area. The Willamette River borders on the south, and Chehalem Mountain borders on the northeast.

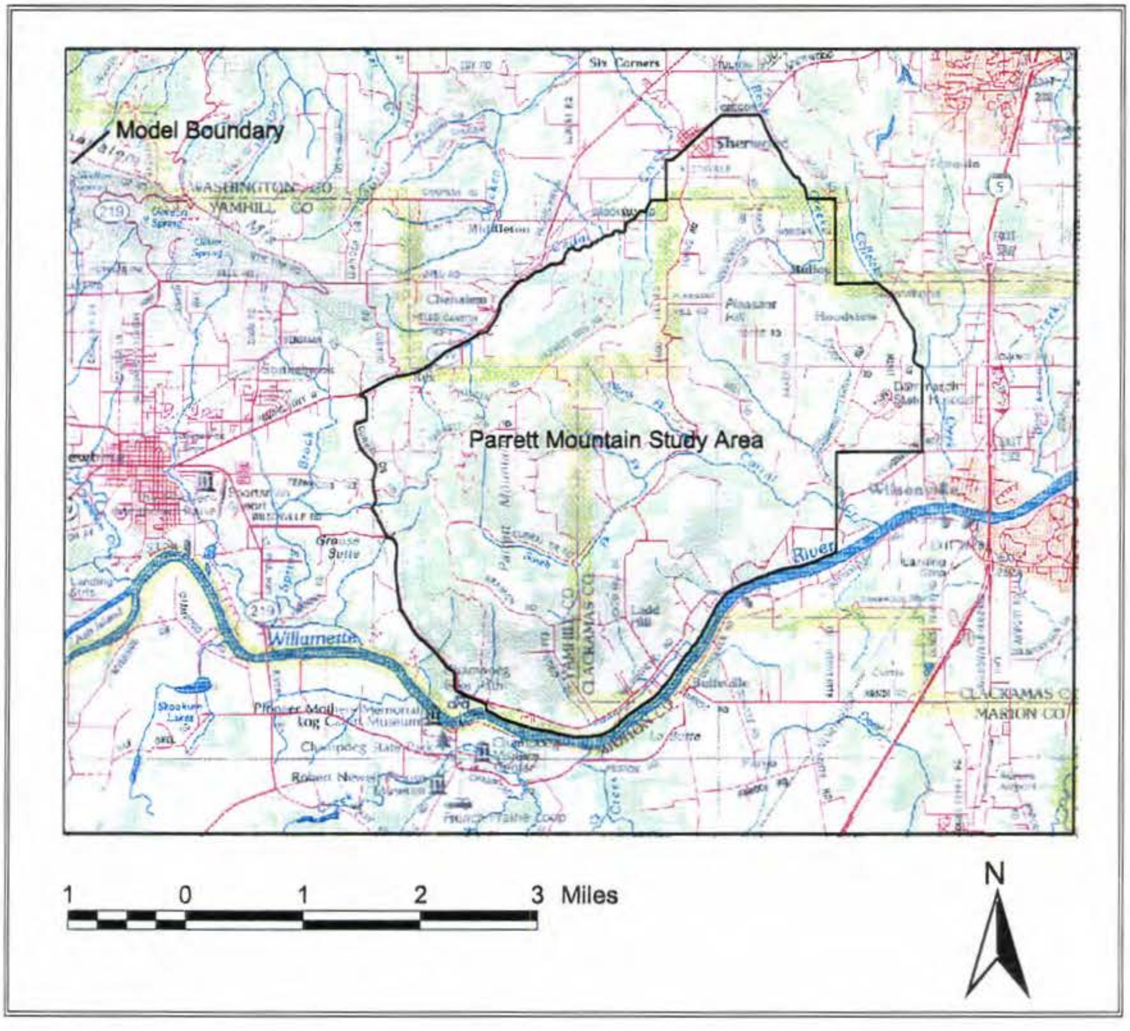


Figure 2-1: Parrett Mountain Study Area

2.1.1 Population

As of 1994, approximately 4,500 people lived in the Parrett Mountain region, with 3,500 as rural residents. The study area is within easy commuting distance to Portland and consequently its population is expected to grow significantly as Portland grows.

Figures 2-2a and 2-2b display predictive population growth trends for Clackamas, Washington, and Yamhill Counties, and Willsonville, Newberg, and Sherwood cities respectively. As seen in Figure 2-2c, Portland's historic population statistics demonstrate a distinctive growth trend from 1980 to 1995, which will likely continue into the future (Center for Population Research, 1995; County Population Forecast, 1997).

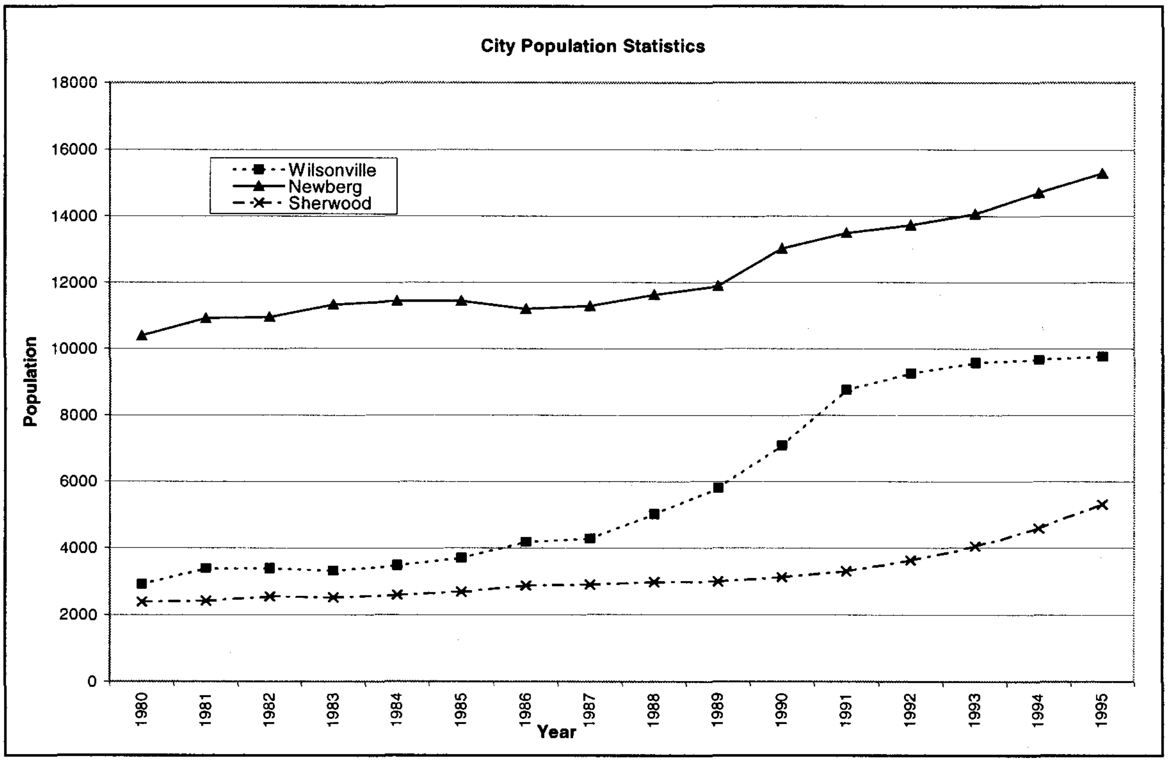


Figure 2-2a: City Population Statistics (Center for Population Research, 1995)

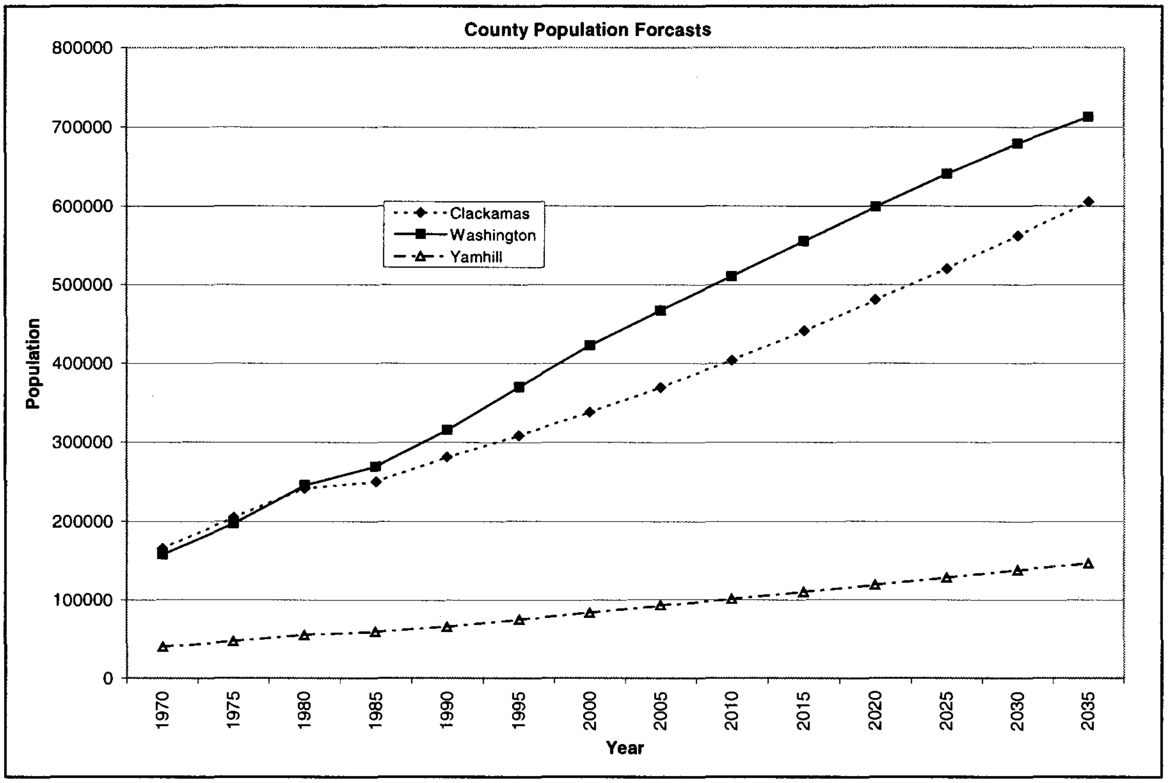


Figure 2-2b: County Population Statistics (County Population Forecast, 1997)

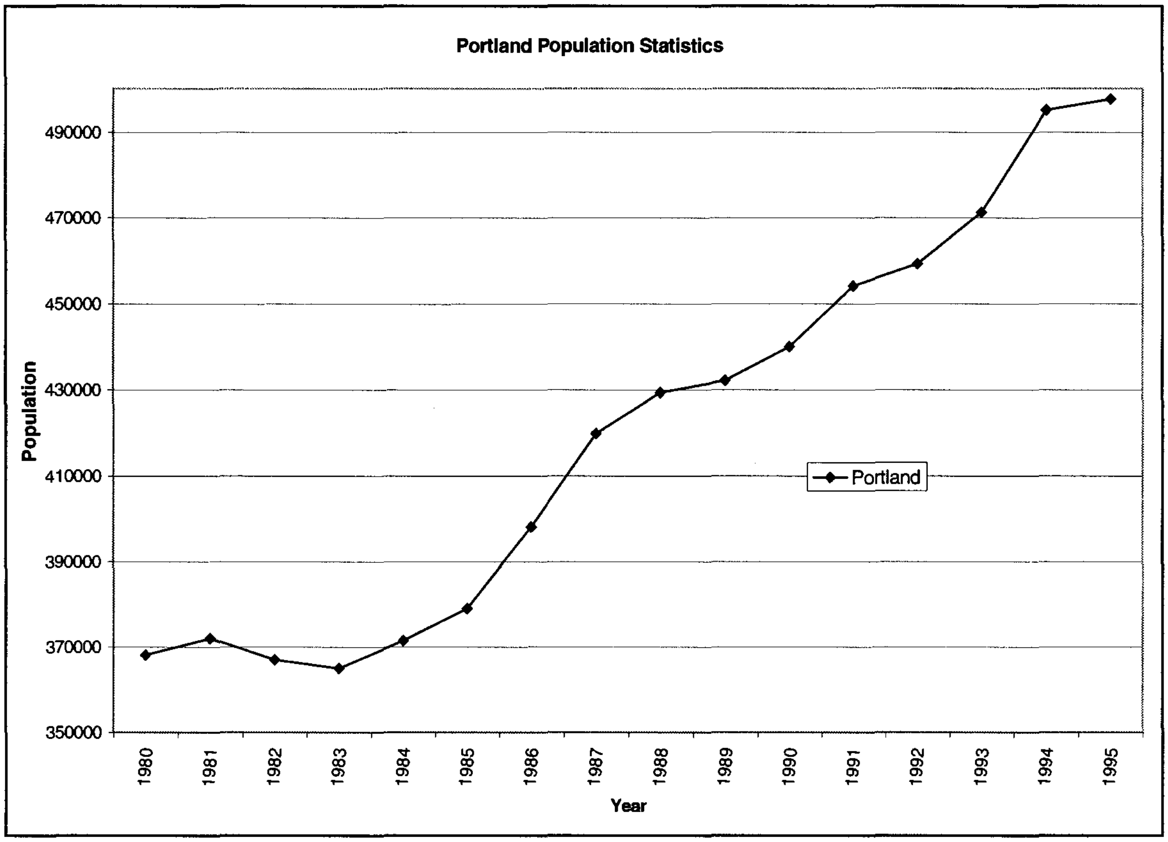


Figure 2-2c: Portland Population Statistics (Center for Population Research, 1995)

2.1.2 Geography

Parrett Mountain study area elevations range from 18 meters at Willamette River to 381 meters at the peak of mountain. Generally slopes increase gradually from the valley floor to higher ground. Based on the topographic slope and aspect approximately 25% of Parrett Mountain study area drains north into the Tualatin River, via Cedar Creek, while the remainder drains into the Willamette River (Miller et al., 1994). There are numerous small springs in the mountain that can be either intermittent or perennial.

2.1.3 Climate

Parrett Mountain has a temperate climate, with moist winters and warm dry summers. Figures 2-3a, 2-3b, 2-3c and 2-3d display precipitation data collected from the nearest climate station located on the western side of Parrett Mountain (Oregon Climate Service Web Page, 1999). There are approximately 1.07 meters (42 inches) of precipitation annually, most of which occurs as rain. Seventy five percent of the annual precipitation occurs between the months of October and March. Figure 2-3d displays the precipitation and temperature data collected from the nearest climate station. It can be seen by comparing Figures 2-3b and 2-3c that both 1995 and 1996 were wetter than average years.

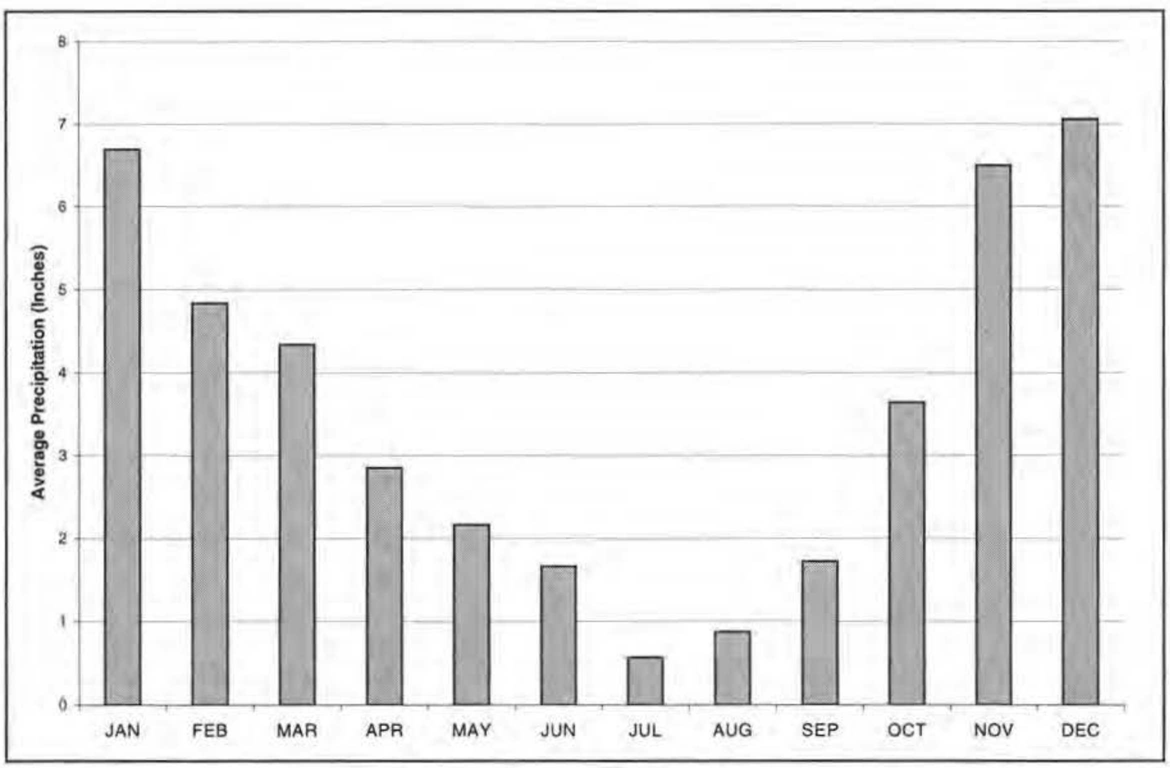


Figure 2-3a: Average Monthly Precipitation (Oregon Climate Service Web Page, 1999)

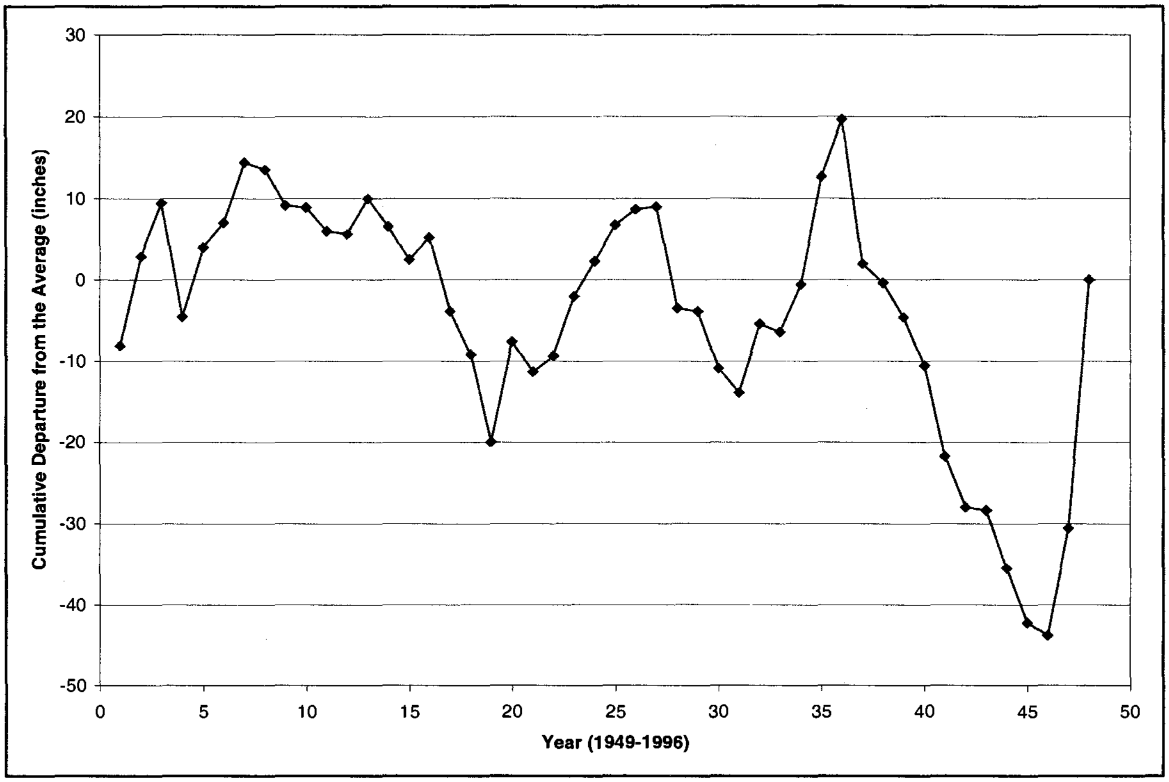


Figure 2-3b: Annual Precipitation (Oregon Climate Service Web Page, 1999)

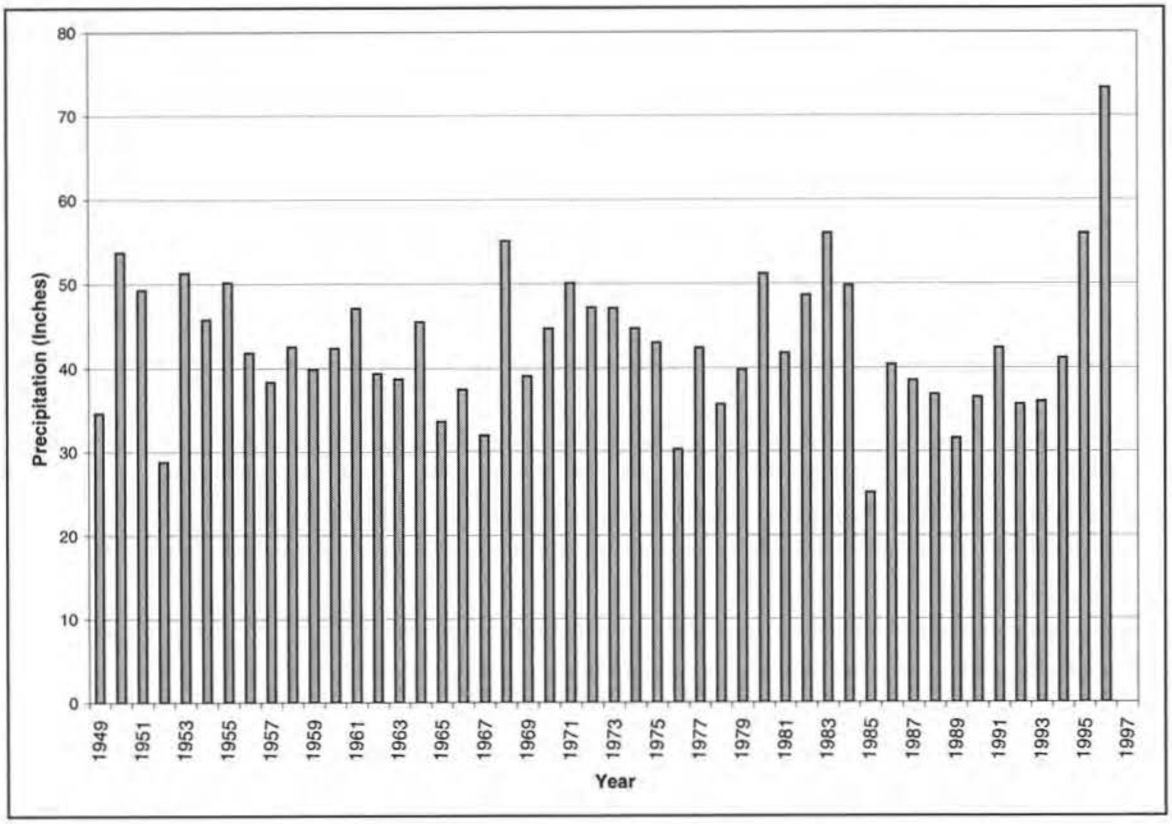


Figure 2-3c: Cumulative Departure (Oregon Climate Service Web Page, 1999)

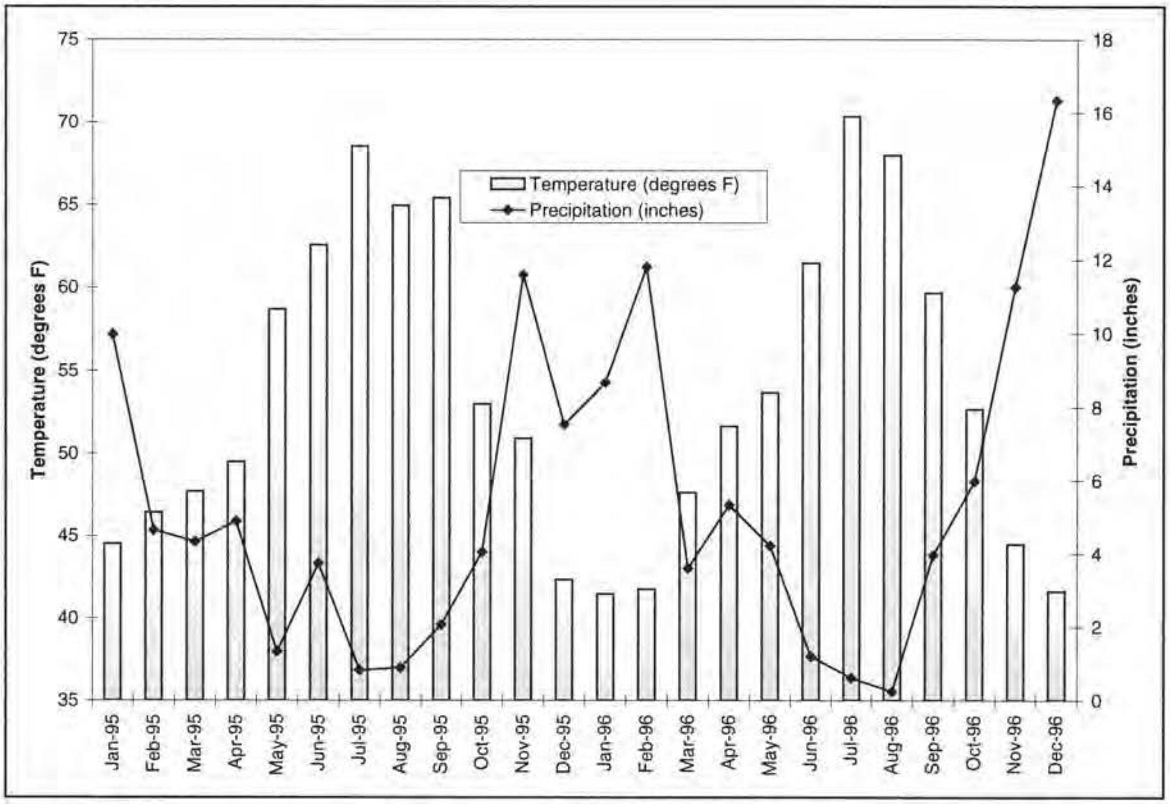


Figure 2-3d: Parrett Mountain Precipitation and Temperature Data (Oregon Climate Service Web Page, 1999)

2.2 Geologic Setting

The geology of Parrett Mountain (Figures 2-4, 2-5, 2-6, and 2-7) consists of multiple layers of Miocene-aged CRB flows which unconformably overlie a thick sequence of marine sedimentary rocks which are Oligocene-Miocene in age. Deposits of Quaternary alluvium and colluvium locally overlie the basalt, primarily within stream valleys and at lower elevations (Brodersen, 1994).

2.2.1 Marine Sedimentary Rocks

The oldest sediments in the Parrett Mountain region are undifferentiated marine sedimentary rocks ranging from Oligocene to Miocene in age. The marine sediments are composed of tuffaceous, quartzitic, and granitic silt and clay deposits with lenses of fine sands gravel, and carbonaceous siltstones and claystones (Frank and Collins, 1978;

Hart and Newcomb, 1965). Schlicker et al. (1967) stated that the Oligocene rocks are distinct in gross character, but have no persistent lithology in the map area to permit recognition of separate formations. A maximum unit thickness of 1500 m (5000 feet) was determined by Frank and Collins (1978).

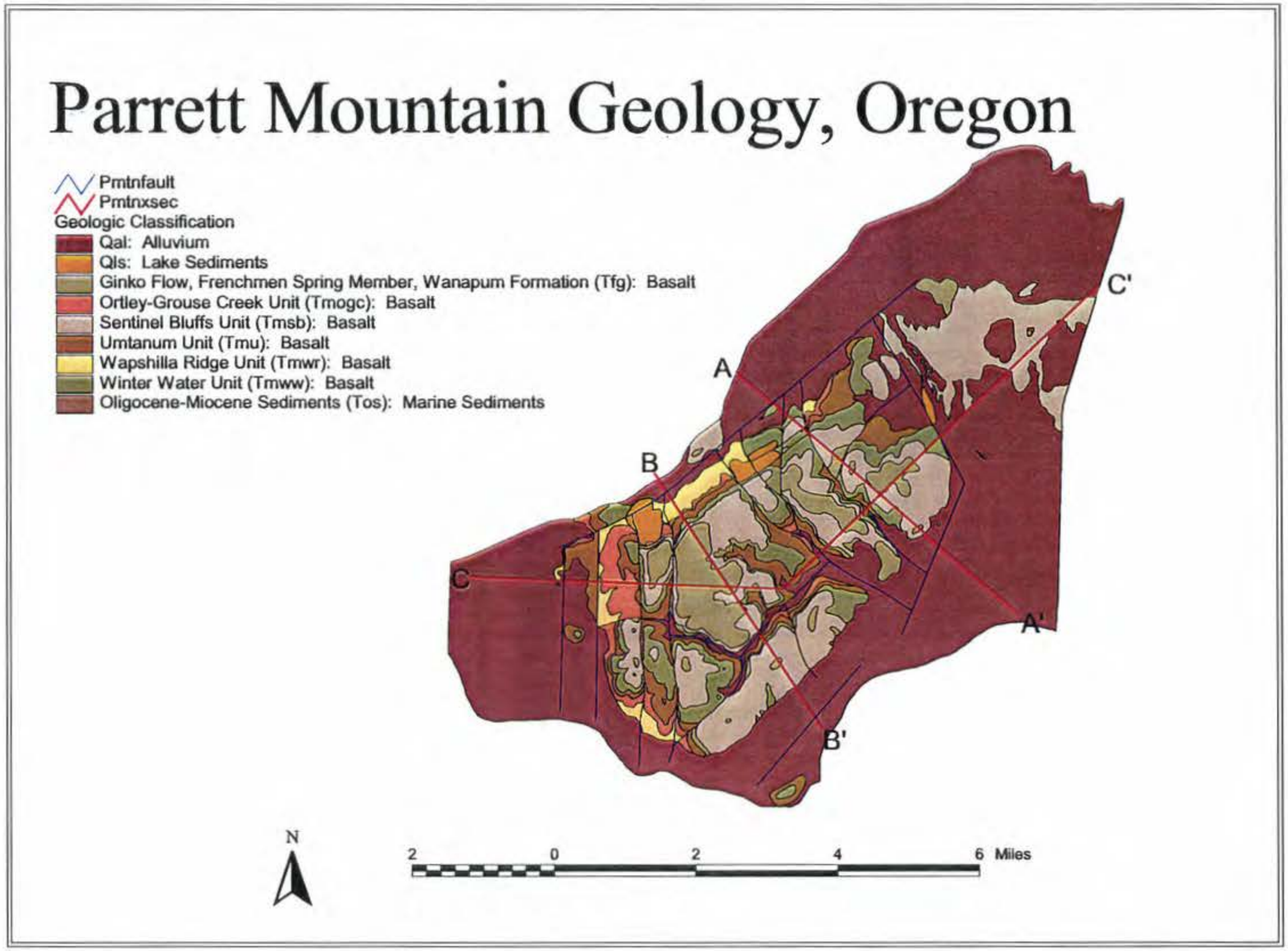


Figure 2-4: Parrett Mountain Geology (Miller, 1994)

Parrett Mountain Cross Section A

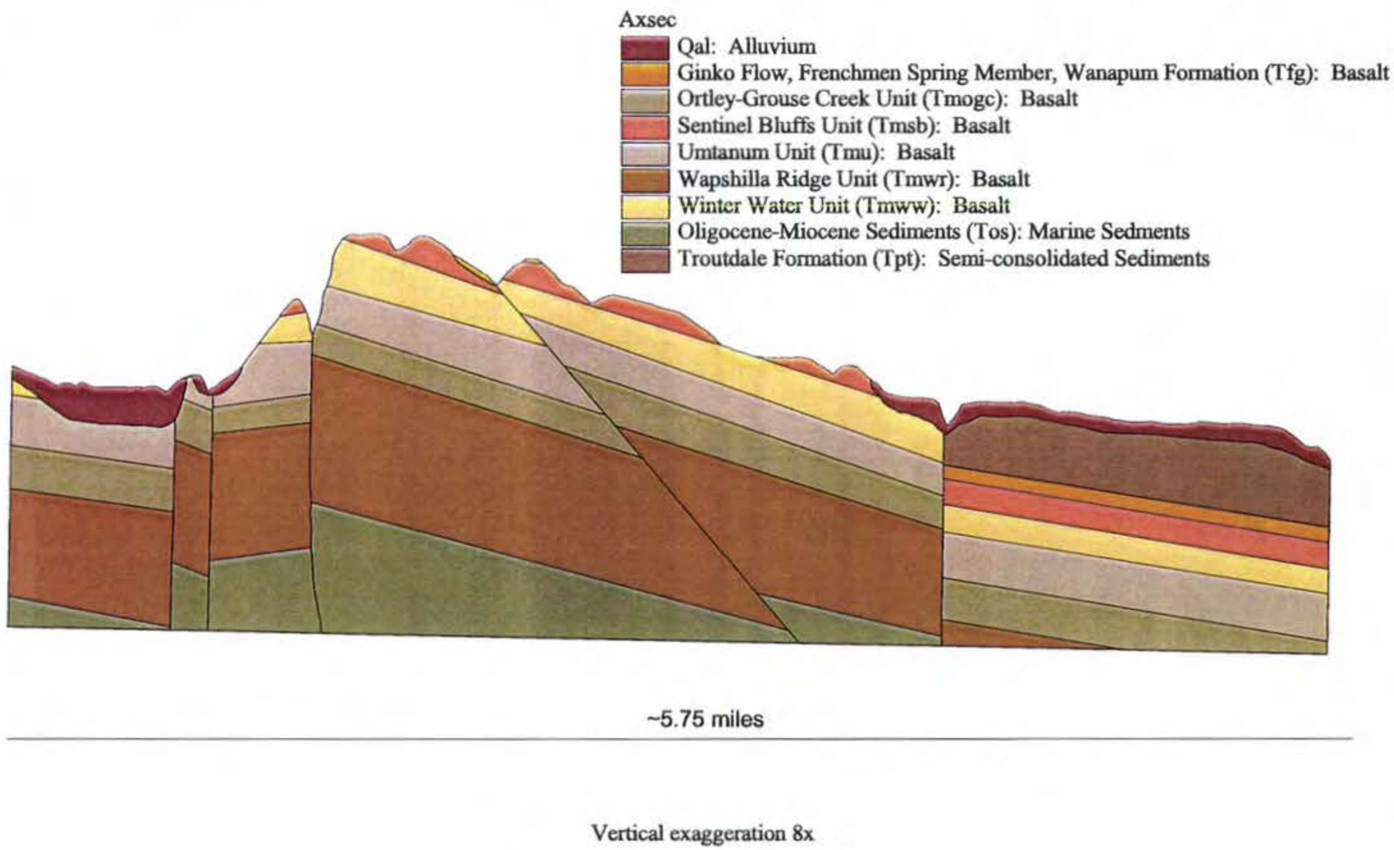


Figure 2-4: Parrett Mountain Geology (Miller, 1994)

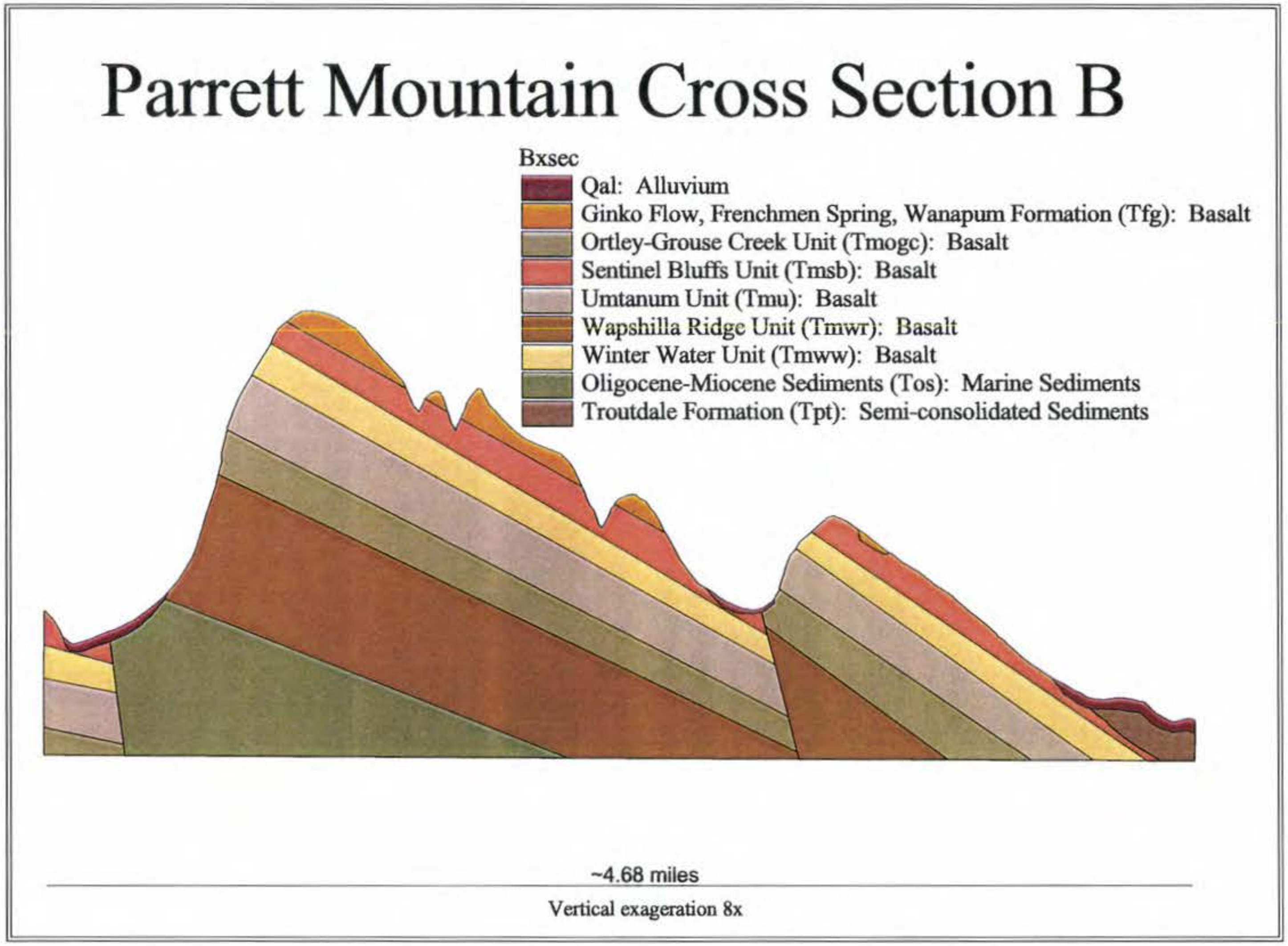


Figure 2-6: Cross Section B (Miller, 1994)

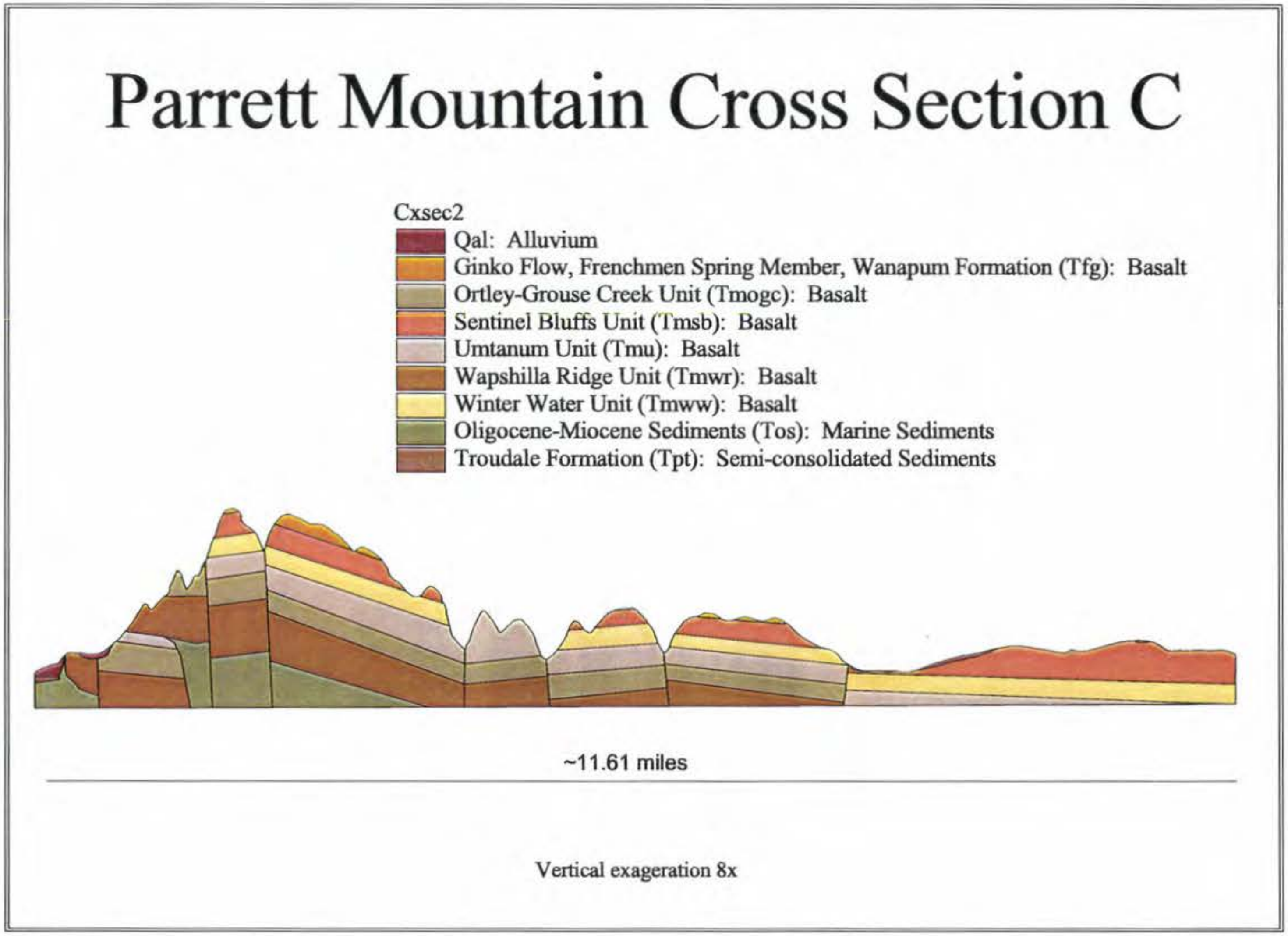


Figure 2-7: Cross Section C (Miller, 1994)

2.2.2 Columbia River Basalt

The CRB group formed as multiple flows of CRB were erupted from fissure systems in northeastern Oregon, and then moved westward toward the Pacific Coast under very low gradients (Beeson and Tolan, 1990). The basalt flows within the Parrett Mountain area range in age from 15 Ma to 16.3 Ma and include two basalt formations. In the Parrett Mountain area, the CRB have an increased thickness, corresponding to a paleotrough near Sherwood, which funneled CRB to the southwest (Beeson et al., 1989). Subsequent deformation of the CRB appears to correspond to a major period of underthrusting at the subduction zone interface in the late-middle Miocene due to increased plate convergence (Snavely et al., 1980).

The two formations of the CRB represented in the Parrett Mountain area are the Grande Ronde Basalt Formation (GRBF) and Wanapum Basalt Formation (WBF). Five of the 17 identified members of the GRBF are present. From oldest to youngest the units are the Wapshilla Ridge unit, Ortley-Grouse Creek units, Umtanum Unit, Winter Water unit, and Sentinel Bluffs unit. The Wanapum formation is represented by the Ginko flow of the French Springs Member. In general the basalt of both formations is black to dark gray, fine to medium-grained, aphyric to sparsely phyric. They commonly exhibit columnar and/or irregular hackely internal jointing (Gannett and Cadwell, 1993; Reidel, 1989). Members of the Grande Ronde Basalt formations have a narrow chemical composition range and have a relatively uniform lithology (Reidel, 1989). The chemical composition of the Ginko Unit of the WBF's French Springs member is similar to that of the GRBF. Specific descriptions of each unit are presented in Table 2-1, which is a compilation of information taken from Beeson et al. (1989), Broderson (1994), and Miller (1994).

Table 2-1 (Beeson et al., 1989; Broderson, 1994; and Miller, 1994)
Summary of Physical and Compositional Characteristics of CRBG Units in Parrett Mountain

	Grande Ronde Basalt Formation					Wanapum Formation
Formation Member	Wapshilla Ridge	Ortley-Grouse Creek	Umtanum	Winter Water	Sentinel Bluffs	French Springs
Magnetic Polarity	Reversed	Normal-Reversed	Normal	Normal	Normal	Normal
Lithology	Dark gray to black, extremely fine grained, high concentra-tion of glass, well developed microphyric texture, lenses of diktytaxitic texture, few outcrops, entablature jointing.	Medium gray to dark gray, fine grained, moderate concentra-tion of glass, poorly developed microphyric texture, diktytaxitic texture, poor exposure, entablature jointing.	Medium dark gray to black, fine to extremely fine grained, moderate to high concentrat-ions of glass, aphyric, psuedomicr-ophyric texture in weathered zones, few outcrops, entablature jointing.	Medium light-gray to gray, fine grained, small concent-ration of glass, 1-2 mm embayed plagiocla se phenocr-ysts, entablatu re jointing.	Medium to medium dark gray, coarse to fine grained, 2-4 mm plagioclase phenocrysts in lower flow, aphyric in upper flow, diktytaxitic texture, 0.9-1.8 m. thick columnar joints.	Medium to medium dark gray, coarse to fine grained, 2-8 mm plagioclase phenocrysts/ glomerocrys-ts, diktytaxitic texture, poor exposures.
Thickness	Maximum thickness is estimated at 76 to 91meters.	Average estimated thickness of 30 m with a variation from 24 to 49 meters.	Unit thickness varies from 24 to 49 meters.	Unit thickness varies from 17 to 32 meters.	Unit thickness varies from 26 to 43 meters.	The unit is confined to the tops of higher ridges and has a maximum thickness of 27 meters.
Comment	Unconform-ably overlies marine sedimenta-ry rocks. Believed to have occurred as one flow.	Locally non distinct. Three basalt flows have been identified in the unit	Maximum thickness occurs near junction of Old Parrett Mountain Road and Parrett Mountain Road. Three identifiable flows within the member.	The unit contains two flows.	Unit is thickest to the northeast and northwest, thins to the southeast near Pleasant Hill. There are two flows within the member.	The unit consists of material from the Ginko Flow

2.2.3 Quaternary Sediments

Younger deposits overlie the Columbia River Basalt units. The oldest of these deposits are Pliocene to Pleistocene in age and consist of semi-consolidated clay, silt, sand, and gravel of the Troutdale formation. Quaternary to recent rock deposits consist of undifferentiated alluvium and colluvium, consisting mostly of unconsolidated clay, silt, sand, and gravel.

Following the deposition of the CRB in the Parrett Mountain region, folding and faulting subsequently disrupted the stratigraphic units, resulting in numerous separate fault blocks, and an overall structure of basalt dipping gently to the southeast. Parrett Mountain is highly dissected by streams, many of which exhibit lineated segments. Brodersen (1994) identified 18 of these segments as faults based on preferential weathering and erosion on fault planes and fracture zones. Fifteen of the faults were interpreted as high-angle normal faults. Three were interpreted as thrust faults. Figure 2-8 displays the fault locations in the region and the resulting fault blocks. See Table 2-2 for more details.

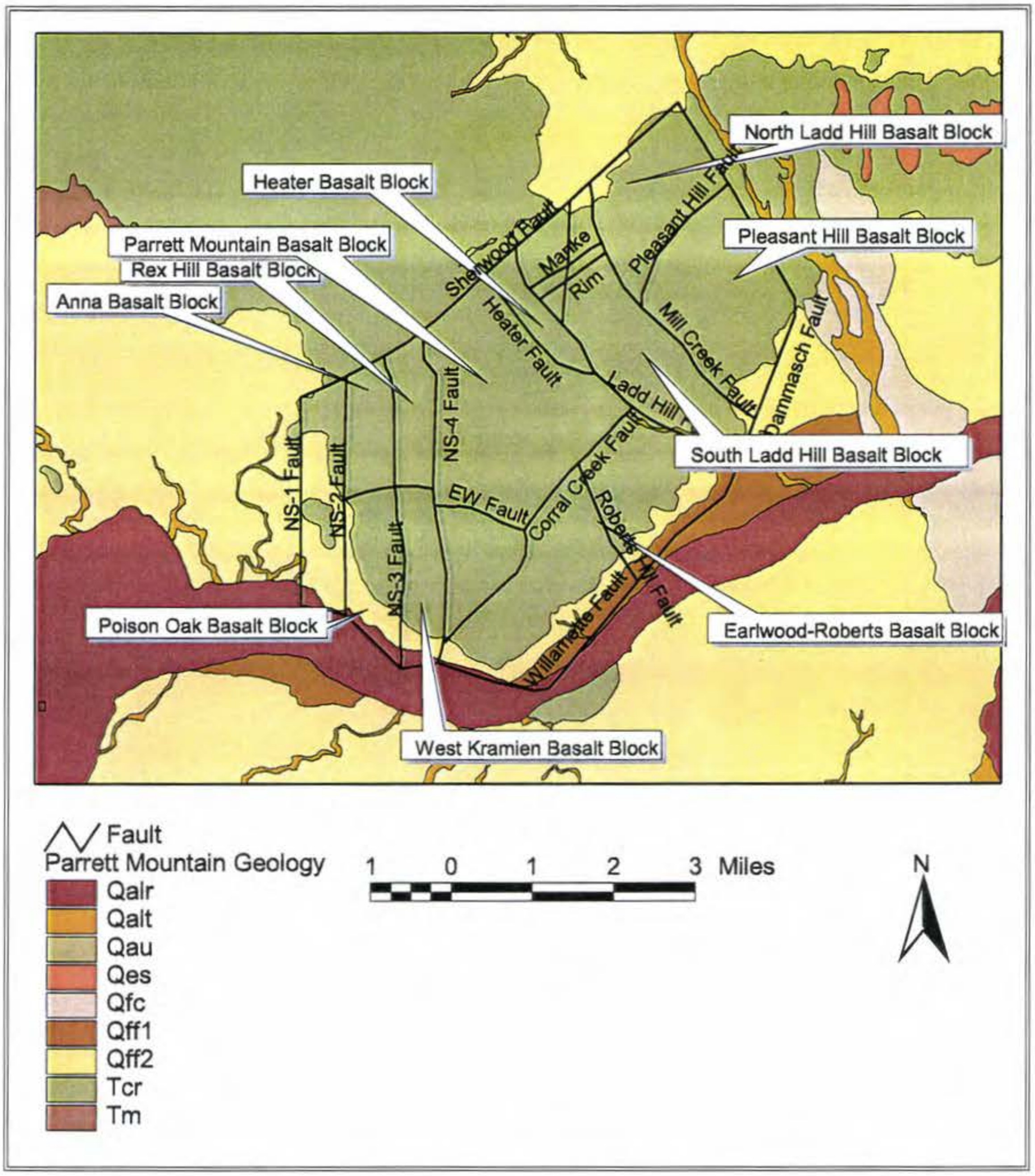


Figure 2-8: Fault Locations

Table 2-2 (Brodersen, 1994; and Miller 1994)
Summary of the Parrett Mountain Fault System

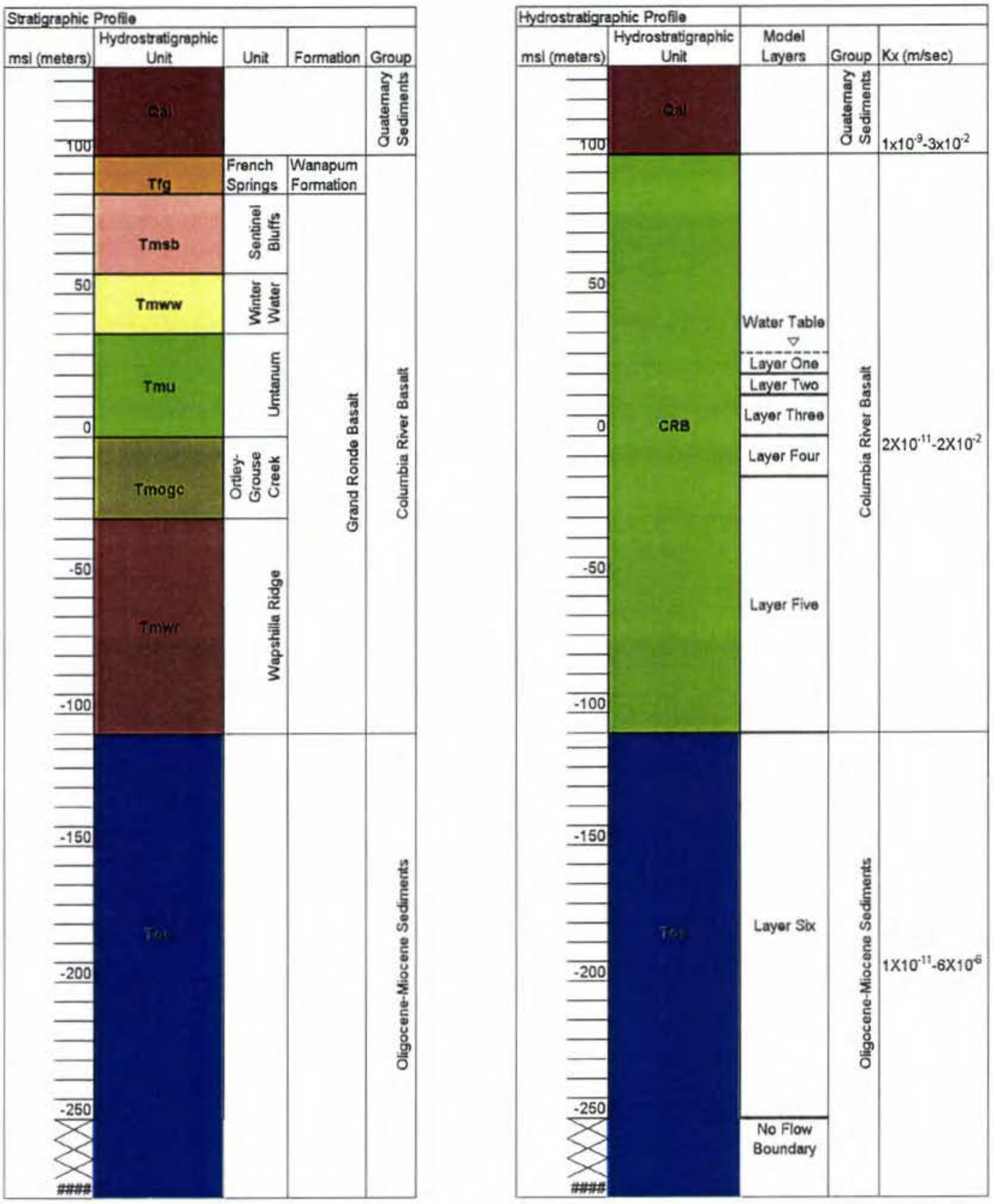
Orientation	Fault	Type	Displacement (m)	Comments
North-South Trending (5)	NS-1	High-angle normal faults	30-61	The faults terminate to the north at the northeast-southeast trending Sherwood fault. The oberst fault crosses the Manke and the Rim fault.
	NS-2		<153	
	NS-3		6-9	
	NS-4		6-9	
	Oberst		2	
East-West Trending (1)	EW	High-angle reverse fault (between NS-3 and NS-4) High-angle normal fault (between NS-2 and NS-3)	~46	This fault appears to have preceded the north-south trending faults, but followed the northwest-southeast trending faults.
Northwest-Southeast Trending (5)	Mill Creek	High-angle normal faults	30	These two faults are the most topographically distinct of all the northwest-southeast trending faults
	Ladd Hill		30	
	Heater		none	This fault is an extension of the Ladd Hill Fault
	Roberts Hill		15	This fault is observed as a semi-linear feature that separates Roberts Hill block from the Earlwood block.
	Seely Ditch		30	The fault is based on significant offset of the basalt stratigraphy, a change in the dip of the basalt unit across this line, and a highly linear topographic ridge.
Northeast-Southwest Trending (7)	Sherwood	High-angle normal fault	305 (max)	This fault was previously identified on the basis of separation of Parrett Mountain from Chehalem Mountain. Much of the fault is covered by alluvial and colluvial deposits.
	Pleasant Hill	Thrust fault (Dips <45 degrees)	61 (max)	This fault terminates at the Mill Creek fault to the southeast and at the Seely Ditch fault to the northeast.
	Dammasch	High-angle normal fault	49	This fault terminates at the Seely Ditch fault to the northeast.
	Willamette	Unknown	Unknown	This fault was mapped based on the elevation change Umtanum and Winter Water basalt boundary from Parrett Mountain to La Butte. It is difficult to discern due to the thick alluvial material covering the area.

Table 2.2 (Continued)

	Corral Creek	Reverse fault to the northeast. High-angle normal fault southwest of its intersection with the EW fault.	122 (max)	Possible explanation for the change in fault type: Two different faults. Originally a reverse fault but was altered by subsequent normal northwest trending faults. A hinge fault.
	Rim	High-angle normal fault	<9	These faults are terminated by the Mill Creek fault to the northeast and by the Ladd Hill fault to the southwest.
	Manke		<9	

2.3 Hydrogeologic Setting

The description of the Parrett Mountain hydrogeologic setting in this subsection defines the hydrostratigraphic units and presents hydrogeologic parameter values for each unit. Hydrostratigraphic units are subsurface media that have been subdivided based on similar hydrogeologic properties. Within the Parrett Mountain Region, hydrostratigraphic units include the geologic units described in Section 2.2, Quaternary Sediments, CRB, and Marine Sediments (See Figure 2-9). The CRB aquifer consists of six different Formation Members, each of which consists of one or more basalt flows. While it is likely that individual basalt flows play a role in groundwater flow patterns, the distribution and extent of individual flows is uncertain, and cannot be separated out as distinct hydrostratigraphic units. The aquifer parameters and the methods used to estimate those parameters are described below.



Notes 1) This figure is a conceptual view of system stratigraphy and hydrostratigraphy based on geologic cross sections and model construction.
2) Hydraulic Conductivity Ranges were obtained from Domenico and Schwartz

Figure 2-9: Parrett Mountain Stratigraphy and Hydrostratigraphy

2.3.1 Horizontal Hydraulic Conductivity

Values of horizontal hydraulic conductivity for wells screened in the CRB aquifer were estimated from two data sources: aquifer pump tests and specific capacity pump tests. There were 16 pump tests and 133 specific capacity tests available from Washington, Clackamas, and Yamhill counties. Methodologies for analyzing the test data are described below.

Aquifer Pump Test Data: The data from the aquifer pump tests were analyzed according to the methods expressed in Dawson and Istok (1991). Through initial examination of the test data it was determined that one test was confined with well storage, 13 were confined leaky, and two were confined. Each data set was analyzed according to the appropriate method. The two confined aquifer data sets were analyzed using the Cooper-Jacob Straight Line Method (Cooper and Jacob, 1946).

Of the 13 confined leaky aquifers only two tests had early time data. Since, in this method, late time data will not give a unique solution when matching type curves, it was assumed that the late time data fell on the same Theis curve (β = 5) as pump test 29390, one of the tests with early time data. This results in a minimum transmissivity calculated from the resulting match point. The solution of the groundwater flow equation (1-1) for a leaky confined aquifer is as follows:

$$s = \frac{Q}{4\pi T} W(u, r/\beta) \quad (2\text{-}1a)$$

$$u = \frac{r^2 S}{4Tt} \quad (2\text{-}1b)$$

$$\beta^2 = \frac{Tm'}{K_z'} \tag{2-1c}$$

where:

s [L] is drawdown during pumping;

Q [L^3T^{-1}] is the constant pumping rate;

T [$L^2 T^{-1}$] is the transmissivity;

$W(u, r/\beta)$ is the Hantush-Jacob well function;

r [L] is the radial distance from the pumping well to a point on the cone of depression;

S is aquifer storativity, dimensionless;

t is time;

m' [L] is the aquitard thickness; and

K_z' [L T^{-1}] is the aquitard vertical hydraulic conductivity.

Aquifer test data are presented in Appendix A and on the data CD. Transmissivity estimates are also presented on the data CD.

Specific Capacity (Q/s): Two methodologies were examined for estimating transmissivity from specific capacity data: (1) the Driscoll Method (Driscoll, 1989), based on the Cooper Jacob straight line method; and (2) the Regression Method (Pucci, 1987). Results from each method were compared, and the most appropriate for this application was chosen.

The Driscoll Method uses the Theis equation, where transmissivity is expressed as a function of the storage coefficient, to estimate transmissivity from specific capacity data.

$$s = \frac{2.3Q}{4\pi T}\left[\log \frac{2.25Tt}{r^2 S}\right] \tag{2-2}$$

where:

S (dimensionless) is storativity;

Q [$L^3 T^{-1}$] is the pump rate;

T [$L^2 T^{-1}$] is transmissivity;

r [L] is radius of the well;

s [L] is drawdown during pumping; and

t is time.

Transmissivity values were estimated from specific capacity data using the Solver package in Excel. This is an iterative process that uses Generalized Reduced Gradient (GRG2) nonlinear optimization. Storativity values of 0.001 were assumed for aquifers deeper than 5 meters. All aquifers less than 5 meters were assumed to have a storativity of 0.075. The time and radius change for each test change, but are generally around 120 minutes and 7.62 cm. Where either the time of the test or the radius of the well were not reported, the two previous values were used.

To convert specific capacity to transmissivity using the Regression Method, we graphed the natural log of transmissivity against the natural log of specific capacity from the same location, and fit a regression line to the data (Pucci, 1987). Figure 2-10 displays the resulting graph and the regression equation which is

$$\ln T = 1.0458 \ln(Q/s) - 2.6189 \qquad (2\text{-}3)$$

with an R^2 of 0.5765

-2.6189 is the y intercept and has the same units as ln T.

The regression equation was used to calculate transmissivity for all the data points with specific capacity data.

A comparison of the two methods was made by examining the resulting ratio of transmissivity to specific capacity. For the Driscoll Method, using the input parameters previously described, a ratio of 1.016 results. A ratio of 0.082 results from the Regression Method. Ideally these two methods should have the same ratio of T to Q/s. There are two reasons why these two methods produce different results.

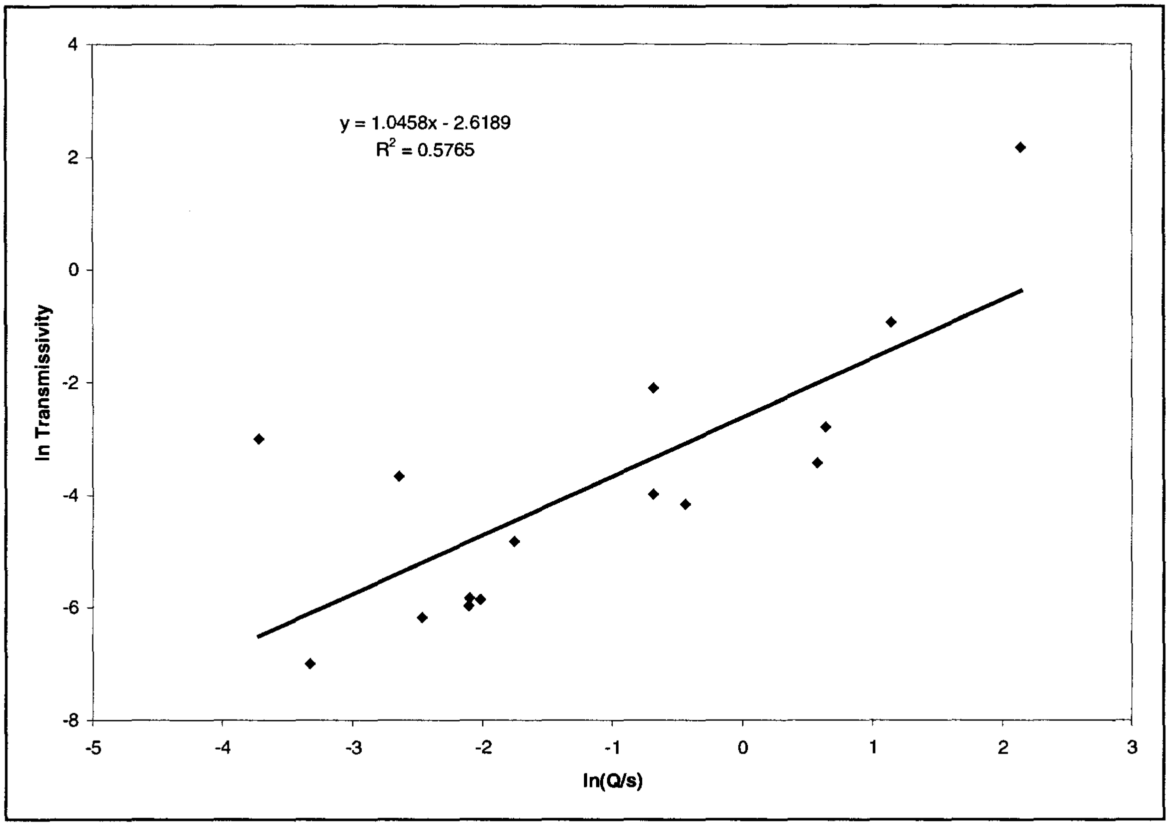


Figure 2-10: Regression Method

1) According to Darcy's law, under steady-state conditions a linear relationship should exist between transmissivity and specific capacity.

$$Q = KA\frac{\partial h}{\partial l} \qquad (2\text{-}4)$$

The conditions of the pump tests used in the Regression Method produce a regression slope of 1.0458, which is sufficiently close to one, thereby predicting that flow conditions obey Darcy's law. Applying the linear relationship, based on prolonged pumping tests, to shorter duration specific capacity tests is problematic. During extended pump tests, steady state conditions are more likely achieved. Under specific capacity tests, which last on average one to two hours, transient conditions are still applicable. Based on this the values of drawdown will increase as pumping conditions transition from transient to steady-state conditions. As drawdown increase increases transmissivity estimates decrease. Assuming that steady-state conditions are not met suggests that the current application of the Regression Method results in an overestimation of transmissivity.

2) The Driscoll Method is based on the Cooper Jacob straight line method which assumes a fully penetrating well in a confined aquifer of infinite extent. Of the 15 pump tests used, only two could be analyzed with this method. The majority of the pump tests were conducted on confined leaky aquifers. By looking at Figures 2-11a, 2-11b, and 2-11c, it can be seen that the actual drawdown is considerably less than the drawdown predicted by the Cooper Jacob straight line. If one applies the Cooper Jacob straight line method to an aquifer with confined leaky conditions, the inherently smaller drawdown associated with the confined leaky aquifer will cause an overestimation of aquifer transmissivity.

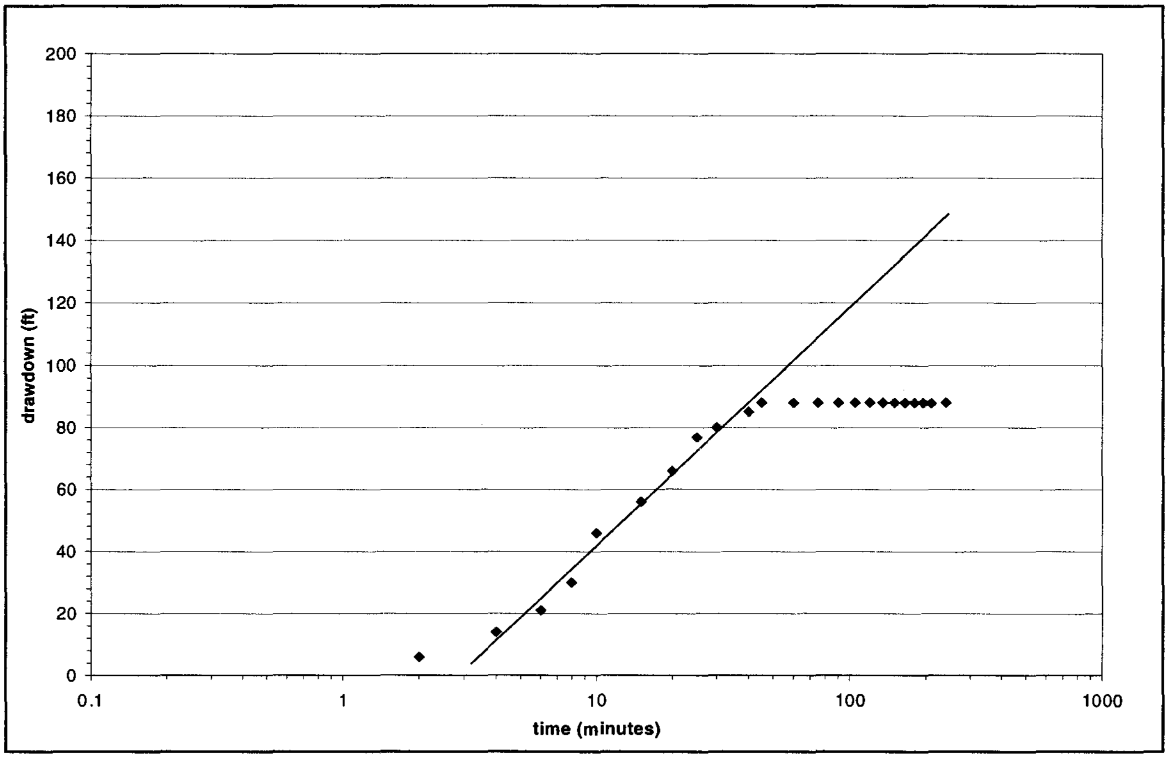


Figure 2-11a: Pump Test 29390

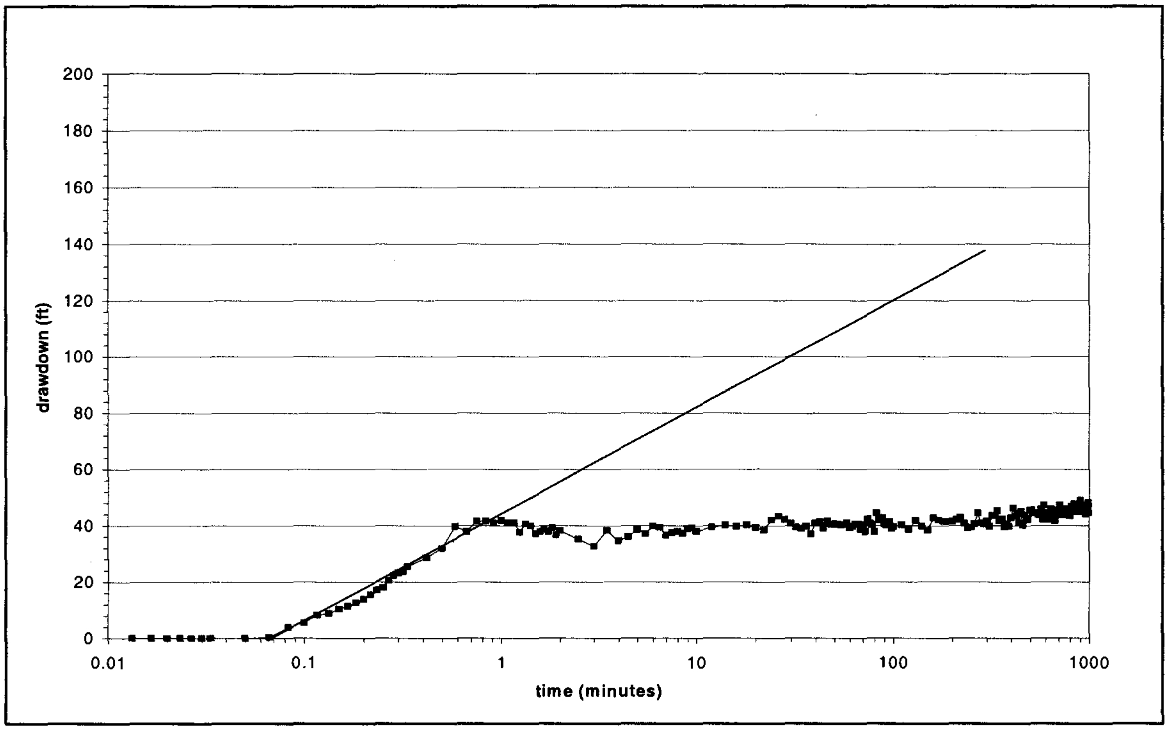


Figure 2-11b: Pump Test Well 6

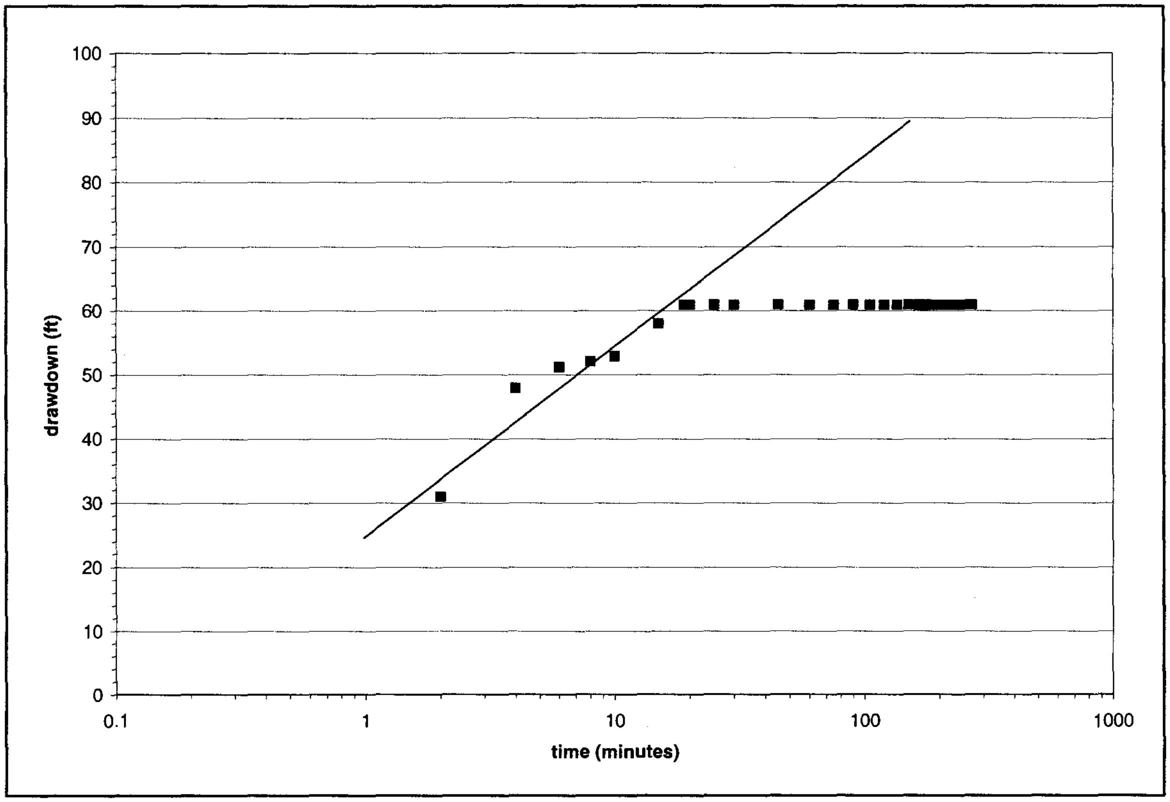


Figure 2-11c: Pump Test 18684

Based on the assessments of the two methods, the Regression Method was chosen to transform specific capacity measurements to transmissivity estimates. While neither method was perfect, it was felt that the Regression Method produced more accurate estimates, since it is likely that the difference between steady-state and transient drawdown is less than the difference in drawdown between confined and confined leaky aquifer conditions. The data CD contains the resulting transmissivity estimates from the specific capacities tests.

Average hydraulic conductivity values were estimated from transmissivity by dividing the estimated transmissivity by the length of the perforated and (or) uncased intervals of the well. In cases where the water table was deeper than the top of the well casing, the depth of the water table was substituted as the top of the screen. Table 2-3 displays the summary statistics of all hydraulic conductivity measurements estimated within the model area. For model areas that correspond with basalt, the initial horizontal hydraulic conductivity input is $1.67X10^{-6}$ m/s (mean seen in Table 2-3). In the Quaternary sediments the initial horizontal hydraulic conductivity is estimated at $1.67X10^{-3}$ m/s based on estimates of hydraulic conductivity from Domenico and Schwartz (1998). For the underlying Marine Sediments, the initial hydraulic conductivity estimate is $1.67X10^{-6}$ m/s. This is based on estimates from Domenico and Schwartz (1998) as well as model input parameters used for the Willamette Valley Groundwater Model (Dave Morgan, personal communication).

Table 2-3
Estimated Hydraulic Conductivity Measurements Summary Statistics

	ft/min	m/s
Mean	$3.88X10^{-04}$	$1.97X10^{-06}$
Median	$2.71X10^{-05}$	$1.38X10^{-07}$
Standard Deviation	$3.35X10^{-03}$	$1.70X10^{-05}$
Minimum	$2.50X10^{-07}$	$1.67X10^{-10}$
Maximum	$4.05X10^{-02}$	$2.05X10^{-4}$
Count	147	
Confidence Level(95.0%)	$5.46X10^{-04}$	$2.77X10^{-6}$

2.3.2 Vertical Hydraulic Conductivity

Little is known about the vertical hydraulic conductivity of the CRB aquifer in the Parrett Mountain region. No measurements of the vertical hydraulic conductivity have been performed at the site. What is known about the parameter comes from previous groundwater studies of the CRB at other locations in the Northwest, which are described in subsection 1.3. Each of these studies had a similar lack of data on vertical hydraulic conductivity. Hansen et al. (1994) estimated anisotropy (K_z/K_x) at 0.003

based on a range of 0.0005 to 0.1 determined from previous studies. Packard et al. (1996) used five 2-D cross sections to estimate vertical hydraulic conductivities of the Horse Heaven Hills basalt aquifers.

Based on the uncertainties associated with vertical hydraulic conductivity for my site, as well non-unique solutions to the groundwater equation encountered during calibration, an anisotropy of 0.01 was assumed for the region. This value falls within the range reported at other sites modeling groundwater flow through CRB aquifers, and represents my best estimate of site conditions based on limited data.

3. Model Design

The conceptual model of Parrett Mountain, described in Section 2, presents the geologic and hydrogeologic framework of Parrett Mountain as well as aquifer characteristics. The following subsections present the model design based on the conceptual model. This section focuses in detail on model input parameters which were not highlighted in the conceptual model.

3.1 Model Dimensions

Figure 2-1 displays the model boundary in relation to the Parrett Mountain Study Area. The model area was extended outward in order to lessen the impact of boundary condition errors on the study area. The model grid has uniformly distributed cells that are 194 meters (east to west) by 151 meters (north to south) in dimension. Figure 3-1 shows cross section C (Figure 2-6) with a conceptual schematic of the model layers. As shown, the model consists of six layers with the following thicknesses.

- Layer 1 10 meters
- Layer2 30 meters
- Layer3 50 meters
- Layer 4 50 meters
- Layer 5 Variable thickness
- Layer 6 152.4 meters

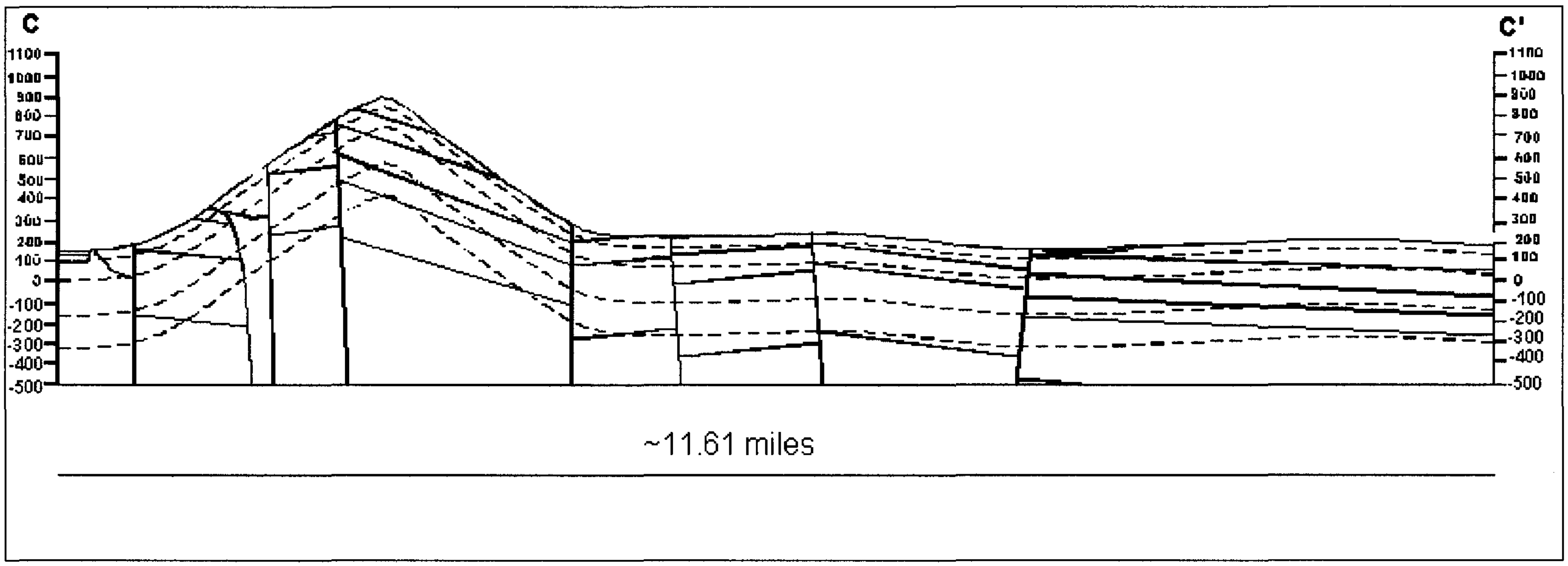


Figure 3-1: Model Layers

There are two methods used for layer distribution when setting up a MODFLOW model. In the first approach each model layer represents a hydrostratigraphic unit, where water is assumed to flow horizontally in the layer, and the layers are assumed to have uniform thickness. Under conditions where the hydrostratigraphic layers are not flat, or do not have uniform thickness, error can be introduced into the model, since these conditions create distortion of the grid. In the second approach the flow system is distributed arbitrarily into segments along the vertical axis. Since the model equations are based on assumptions that hydraulic properties are uniform within individual cells and since this condition is more likely to be met when layers correspond with hydrostratigraphic units, using the second approach to layer distribution can introduce error into the model. Determining which approach is best depends on the conditions of individual flow systems.

Due to high topographic relief in the model area, and the upthrusting of marine sediments in the western segment of the model area, the first approach to layer distribution, where model layers are based on hydrostratigraphic units, was not feasible for Parrett Mountain. Using this approach would cause significant grid distortion and therefore model error. Instead the second approach was used, where the model layers were assigned to specific elevations. Aquifer parameters were assigned to individual grid cells based on elevation and the geologic unit with which the cell corresponded. By assigning aquifer parameters in this manner, the hydraulic properties in individual cells are largely uniform, thereby satisfying model equations.

Since MODFLOW models saturated flow, the top of each grid cell in Layer 1 is set at the estimated water table. The water table was estimated through the interpolation of water levels from shallow wells and surface water bodies. The top of Layer 6 is set at –152 meters mean sea level, which is the approximate elevation of the CRB contact with underlying marine sediments. The thickness of Layer 5 was calculated by taking the difference in elevation from the top of Layer 1 from the top of Layer 6 and subtracting the combined thickness of Layers 1, 2, 3, and 4. The top of Layer 1, the water table, is variable while the top of Layer 6 is set at –152 meters below mean sea level. Subtracting the two values results in a variable model thickness. Then subtracting the combined thickness of Layers 1, 2,3, and 4 results in Layer 5 thickness. It was necessary to use a layer with variable thickness to model the higher elevations of Parrett Mountain. By having Layer 5 as variable instead of Layer 1, we were able to have greater resolution in elevations closer to the surface.

3.2 Model Boundary

Model boundary conditions are assigned to the outer boundary of the model, and are used to solve the finite difference equations within each model cell. All of the outer boundary conditions are constant head and were estimated from water table elevations.

3.3 Leakance

Leakance values between layers were calculated based on estimates of horizontal hydraulic conductivity, anisotropy, and layer thickness according to the following equation:

$$L = \frac{1}{\sum_{i=1}^{n} \frac{\Delta z_i}{K_i}} \qquad (3\text{-}1)$$

where:

L [T^{-1}] is vertical conductance or leakance;

Δz_i [L] is the layer thickness; and

K_i [L T^{-1}] is the layer vertical hydraulic conductivity.

An anisotropy value of 0.01 (K_z/K_x) was assumed to calculate vertical hydraulic conductivity from horizontal hydraulic conductivity estimates.

3.4 Rivers and Streams

Figure 3-2 depicts the areal extent of rivers and streams on the site. The Willamette River runs west to east in the southern half of the study area. All but the streams north of Parrett Mountain flow into the Willamette River. Information on stream locations were acquired partly from the regional Willamette Valley Model, while the remainder were digitized from 7.5 min quad topographic maps. River stages (elevation above streambed) were either taken from the Willamette Valley Model or estimated based on stream order. Estimated stages typically ran from 0.3 to 0.6 meters for streams, and 9 meters for the Willamette River. The Willamette River stage was taken from the Willamette Valley Model.

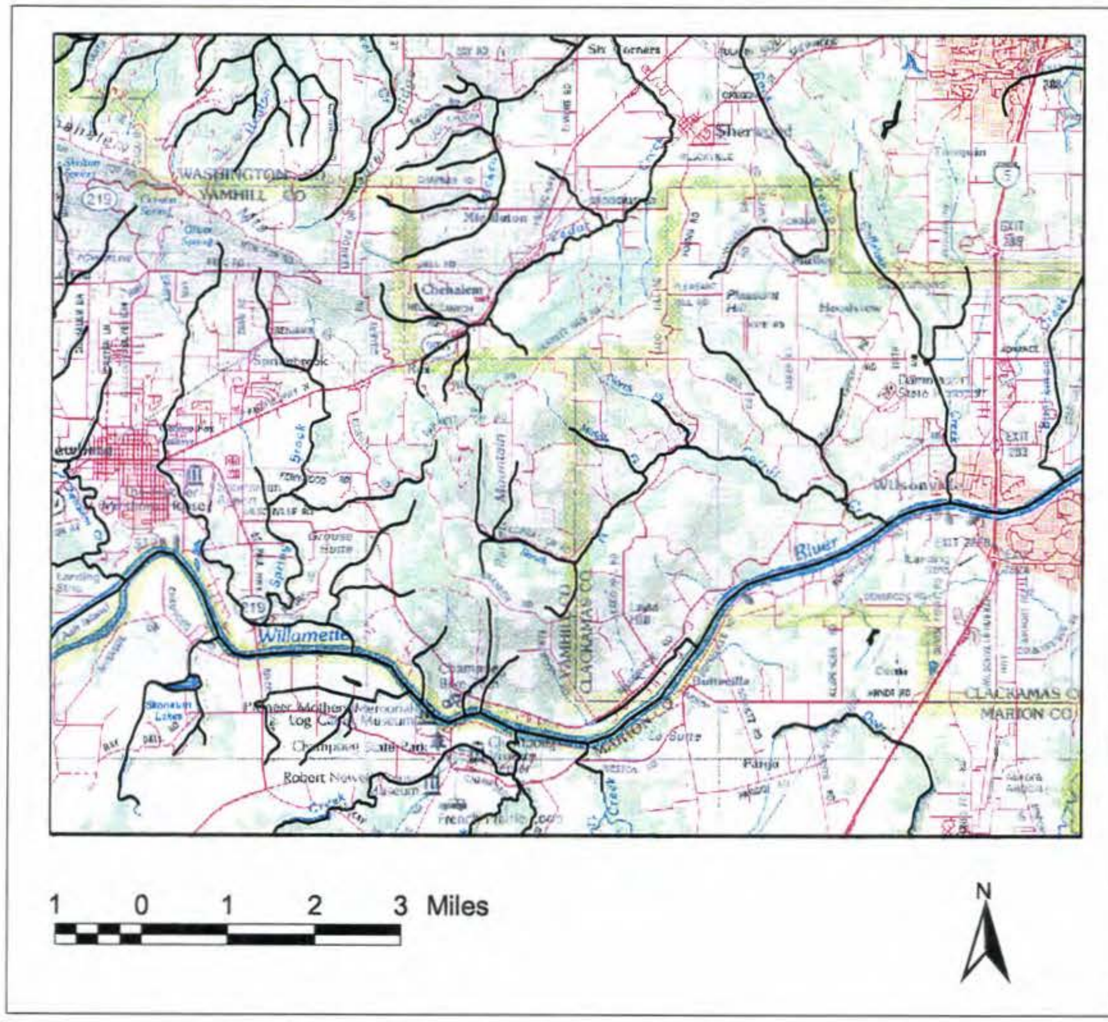


Figure 3-2: Rivers and Streams

Streambed conductance values were estimated based on the size of the stream and the unit over which the stream was flowing. Stream conductance is calculated from the equation

$$C=K_zLW/M \qquad (3\text{-}2)$$

where:

C [L^2T^{-1}] is streambed conductance;

K_z [L T^{-1}] is the vertical hydraulic conductivity;

L [L] is the length of the stream within a model cell;

W [L] is the width of the channel; and

M [L] is the vertical thickness of the stream bed.

In all cases M was assumed to be one meter, and L was assumed to be 173 meters. The stream bed length (L) was estimated as the average between the width and length of a grid cell. For both alluvium and basalt streams the width of the channel was assumed to be one meter. For the Willamette River the channel width was assumed to be 100 meters. The vertical conductivity of alluvium was assumed to be $3.0X10^{-3}$ m/s, based on an estimate of hydraulic conductivity for coarse sand and adjusted to take into account anisotropy (Domenico and Schwartz, 1998). Using the appropriate channel width and vertical hydraulic conductivity, the streambed conductance was calculated for alluvial streams, the Willamette River, and basalt streams at 3.1 m^2/s, $3.1X10^{-2}$ m^2/s, and $3.6X10^{-7}$ m^2/s respectively. The vertical hydraulic conductivity for basalt was estimated based on literature values adjusted for anisotropy (Domenico and Schwartz, 1998).

3.5 Recharge

The estimates for recharge to the model were taken from the Willamette Regional Valley Model, which were estimated through precipitation-runoff modeling (Risley, 1999). The USGS modified the Precipitation Runoff Modeling System (PRMS) to model Willamette Valley surface water/groundwater interactions. PRMS uses physically-based mathematical equations to simulate processes such as precipitation, snowmelt, evaporation, evapotranspiration, interceptions, and infiltration. During model simulation gross precipitation is reduced by vegetation interception, evaporation, and transpiration. The model also uses a daily maximum infiltration capacity, which results in a limit to daily recharge to the groundwater aquifer. The spatial distribution and magnitude of recharge in the model area are displayed in Figure 3-3.

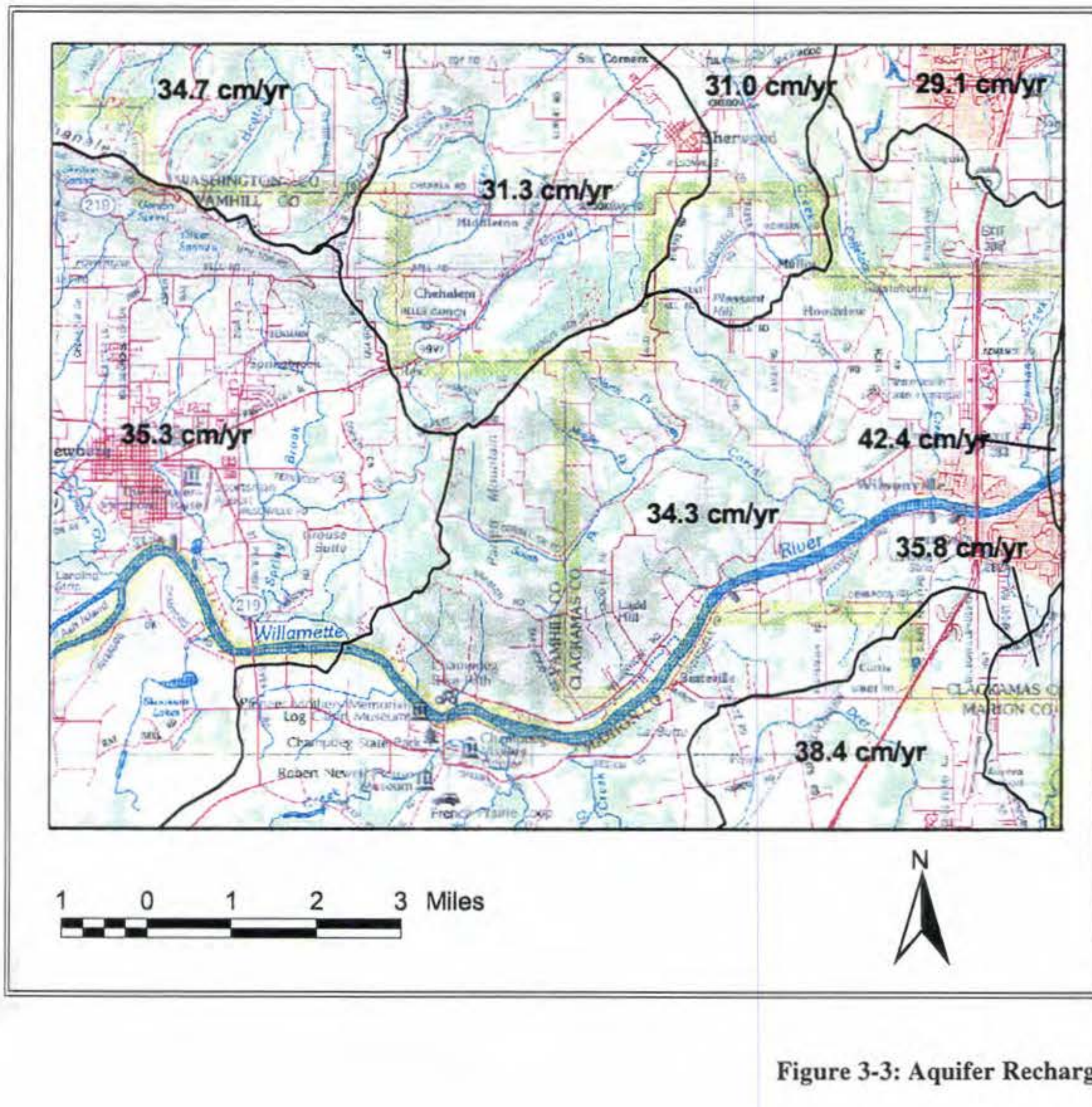


Figure 3-3: Aquifer Recharge

3.6 Pumping Wells

This subsection documents the methodology and results in selecting the pumping rates and locations within the Parrett Mountain groundwater model. Groundwater use data can be separated into three categories: municipal, irrigation, and domestic use. Specific information on each of these categories can be difficult to attain, and is often misleading.

3.6.1 Municipal Wells

Municipal usage data is the easiest to attain, and most accurate. By law cities are required to submit monthly water use records to the Oregon Water Resources Department. Records for the steady state time period 1995-1996 were obtained from this agency. Pumping rates were reported as monthly volumes in gallons. These were summed and divided over the two year time period to give an average. There was one exception to this; the city of Wilsonville reported a combined pumpage for two of its wells (CLAC 8574 and CLAC 8575). This combined calculated rate was divided in half and apportioned to each well. The process resulted in ten model wells representing ten municipal pumping wells for a combined rate of $2.81X10^{-2}$ m^3/s (446 gpm).

3.6.2 Irrigation Wells

There are 295 agriculture and irrigation permitted wells within the model area. The rates listed in these permits are the maximum allowable pumping rates. By law, to have the permit remain valid, an irrigation user must attain this maximum pumping rate at least once during a five year period (although exceptions may be granted). However, most of the permitted wells are not being used at their maximum pumping rate most of the time. To enter pumping wells into the numerical simulation, I needed to determine, on average, what percent of the permitted water-right is used. With this limited data I was unable to get an accurate pumping average, and therefore another approach was used.

Instead of using permitted rates, I extrapolated irrigation rates, provided by the USGS, to pumping estimates. Irrigation rates were estimated by determining crop type through aerial photography and basing irrigation rates on the crops water needs. It was further assumed that the wells producing irrigation water were close to the crop in question. Pumping rates were calculated from irrigation rates by multiplying by the area of the model cell falling within the irrigated zone. Wells were simulated within model cells wherever irrigation occurred.

Figure 3-4 displays irrigated areas within the model differentiated into zones overlying Columbia River Basalt and zones overlying Quaternary sediments. The majority of the irrigation occurring within the model area falls outside of the Parrett Mountain Study Area, away from the outcropping basalt. The irrigated zones that fall within the Quaternary sediments are assumed to be pumped from Quaternary sediments, and furthermore the flux is pumped from Layer 1. A total of 2173 irrigation wells are simulated in unconsolidated Quaternary Sediments. Their combined pumping rate is 26.18 m^3/minute (6916 gpm).

Water in the irrigated areas that fall within the outcropping basalt is assumed to come from a basalt aquifer. A total of 162 irrigation wells drawing water from the CRB's at a combined pumping rate of 2.11 m^3/minute (557 gpm), are simulated in the model. The flux is assumed to be drawn from the top 5 model layers. The rate from each layer has been weighted according to the layer thickness based on the following equation.

$$\frac{Q_l}{Q_T} = \frac{T_i}{\sum T_T} \qquad (3\text{-}3)$$

where:

T_l [L^2T^{-1}] is the layer transmissivity;

Q_l [L^2T^{-1}] is the layer flux;

T_t [L^2T^{-1}] is the total transmissivity; and

Q_t [L^3T^{-1}] is the total well discharge.

If we assume that the layer conductivities are equal in the CRBs, the equation reduces to

$$\frac{Q_l}{Q_T} = \frac{b_i}{\sum b_T} \tag{3-4}$$

where:

b [L] is the layer thickness.

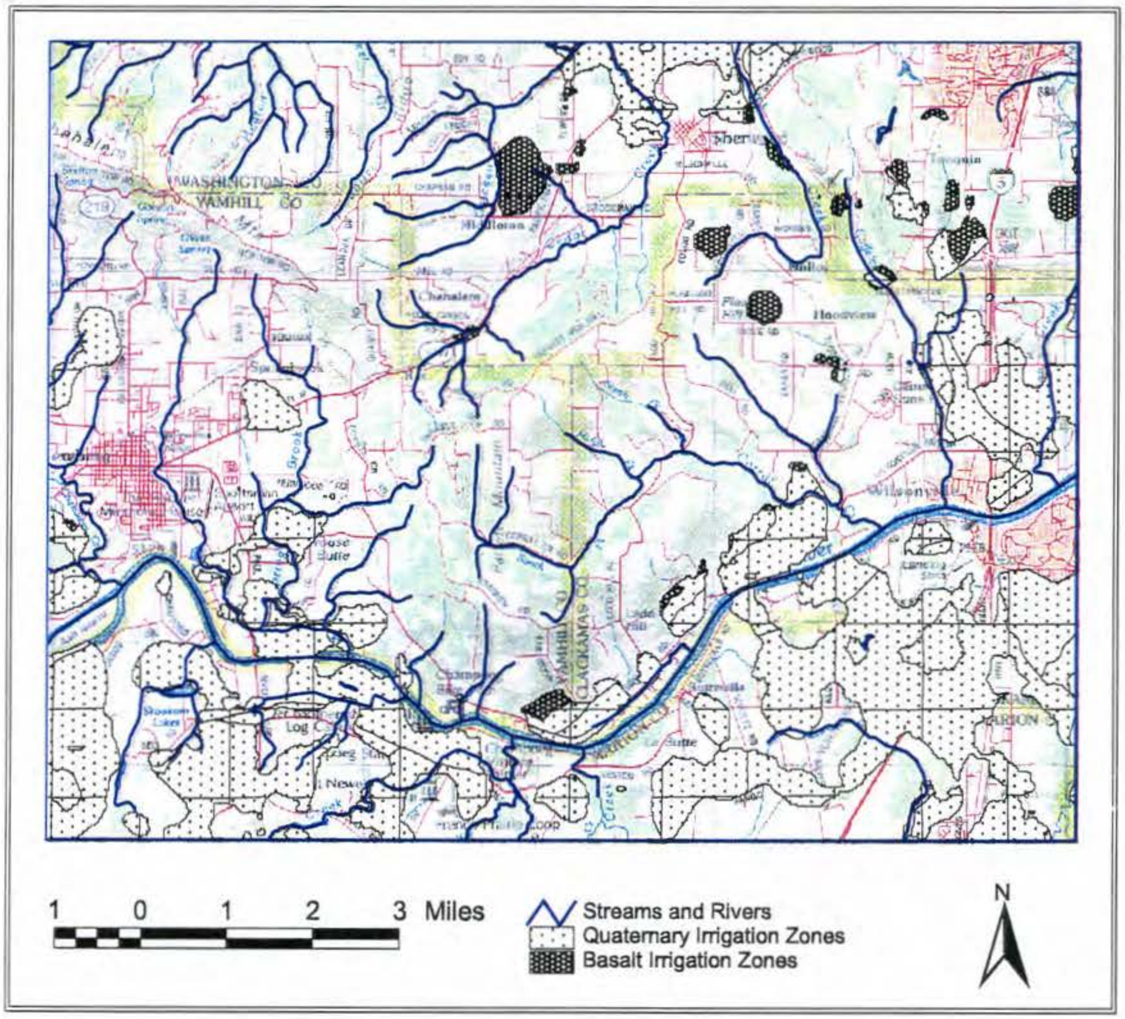


Figure 3-4: Irrigation Well Locations

3.6.3 Domestic Wells

The remaining wells in the area are domestic, 14 of which are permitted, the rest of which are not. There are more than 10,000 documented well logs corresponding to the model area. These 10,000 well logs do not all represent domestic wells, since every time a well is deepened a new well log entry is generated. Also every time a borehole is drilled a new well log entry is generated whether a well is installed or not. Wells that are no longer in use are also included as part of the documented well logs. Which of the 10,000 well logs correspond to non-permitted domestic pumping wells is unknown. Consequently information on domestic wells within the Parrett Mountain area is highly uncertain.

By looking at the state permitting laws for domestic wells, we were able to gain a greater understanding of the impact of domestic wells on groundwater. For instance the following uses do not require a groundwater permit.

1. Stock watering
2. Lawn or non-commercial garden watering of not more than one-half acre in area.
3. Single or group domestic purposed for no more than 15,000 gallons per day.
4. Single industrial or commercial purposes not exceeding 5,000 gallons per day.
5. Down-hole head exchange uses.
6. Watering the grounds, ten acres or less, of schools located within a critical ground water area.

The maximum discharge rate for non-permitted uses within the model area is 15,000 gallons per day ($6.57X10^{-4}$ m^3/s). Based on this discharge rate, the 1994 Parrett Mountain population of 4500 people, and an average household of 3.5, seven billion gallons (26.5 million m^3) of water will be extracted from the study area each year. Using the maximum allowable discharge rate for non-permitted uses to estimate yearly domestic water use is clearly not reasonable.

Miller (1994) estimated domestic groundwater use at 194 mgy (1.4 m^3/min) based on an assumption of 1000 domestic wells with an average of 3.5 persons per dwelling using 150 gpd ($4X10^{-4}$ m^3/min). Using similar logic, the average household with a non-permitted well uses 525 gpd ($1.38X10^{-3}$ m^3/min). This is less than 4% of 15000 gpd ($3.9X10^{-1}m^3$/min). Based on this average groundwater extraction rate, domestic groundwater use in 1994 for the study area was approximately 246 million gallons (931211 m^3). A rough estimate of yearly recharge was estimated by assuming that 40% of the average precipitation recharges the aquifer yearly, resulting in a recharge volume of approximately ten billion gallons (38 million m^3). Based on these approximations, domestic groundwater usage accounts for 2% of yearly recharge.

I also looked at how domestic water usage might affect groundwater elevations. Using the steady state analytical solution for a confined aquifer we estimated the maximum possible drawdown for this pumping rate.

$$T = \frac{Q \ln(R / r_w)}{2\pi(s)} \qquad (2\text{-}9)$$

where:

Q is the flux, [L^3T^{-1}]

R is the radius of influence, [L]

R_w is the well radius, [L]

s is drawdown, [L]

I assumed the well radius was six inches (0.1524 m) and R is 1000 feet (304 m). I chose a conductivity value of 0.144 m/day (1.00X10-4 m/min) as an average estimate based on pump tests from wells within the basaltic aquifers. A layer thickness of 168 ft (51.21 m) was used. This was based on the average open screened interval for the observation wells within the study area.

Using Miller's estimated numbers, an average drawdown on domestic wells is approximately 0.33 m. Assuming that the domestic wells are sparsely located, as is the case in the Parrett Mountain Region, and that they do not fall within the radius of influence of other wells, drawdown values caused by domestic wells will not significantly impact model results. Because of the low percent of domestic groundwater use to recharge, and low drawdown values caused by pumping, domestic wells are not included within the model.

There are a total of 3008 wells in the system; 10 are municipal, 162 are irrigation and are screened in basalt, and 2173 are irrigation and screened in Quaternary sediments. See Table 3-1 for model flux data from pumping wells.

Table 3-1
Model Flux Data from Pumping Wells

Extraction Well	Number of Simulated Wells	Aquifer Flux (gpm)	Aquifer Flux m^3/min	Percent of Total Flux
Municipal Wells (CRB Aquifer)	10	446	1.69	5.63
Irrigation Wells (Qal Aquifer)	2173	6916	26.18	87.33
Irrigation Wells (CRB Aquifer)	162	557	2.11	7.03
Total	3008	7919	29.98	100

4. Model Calibration and Results

4.1 Model Calibration

MODFLOW was run using the boundary conditions and input parameters described in Section 2. Error statistics were calculated from the 268 observation points distributed throughout the model. Error residuals were calculated at each observation point based on time averaged 1995-1996 groundwater elevation data and simulated groundwater elevation data. Observation point locations are depicted in Figure 4-1. The initial model run resulted in a mean absolute error of 24.57 m (See Table 4-1). Figure 4-2, displaying observed heads versus calculated heads for the initial input parameters, exhibits higher simulated head at lower elevations and lower simulated head at higher elevations.

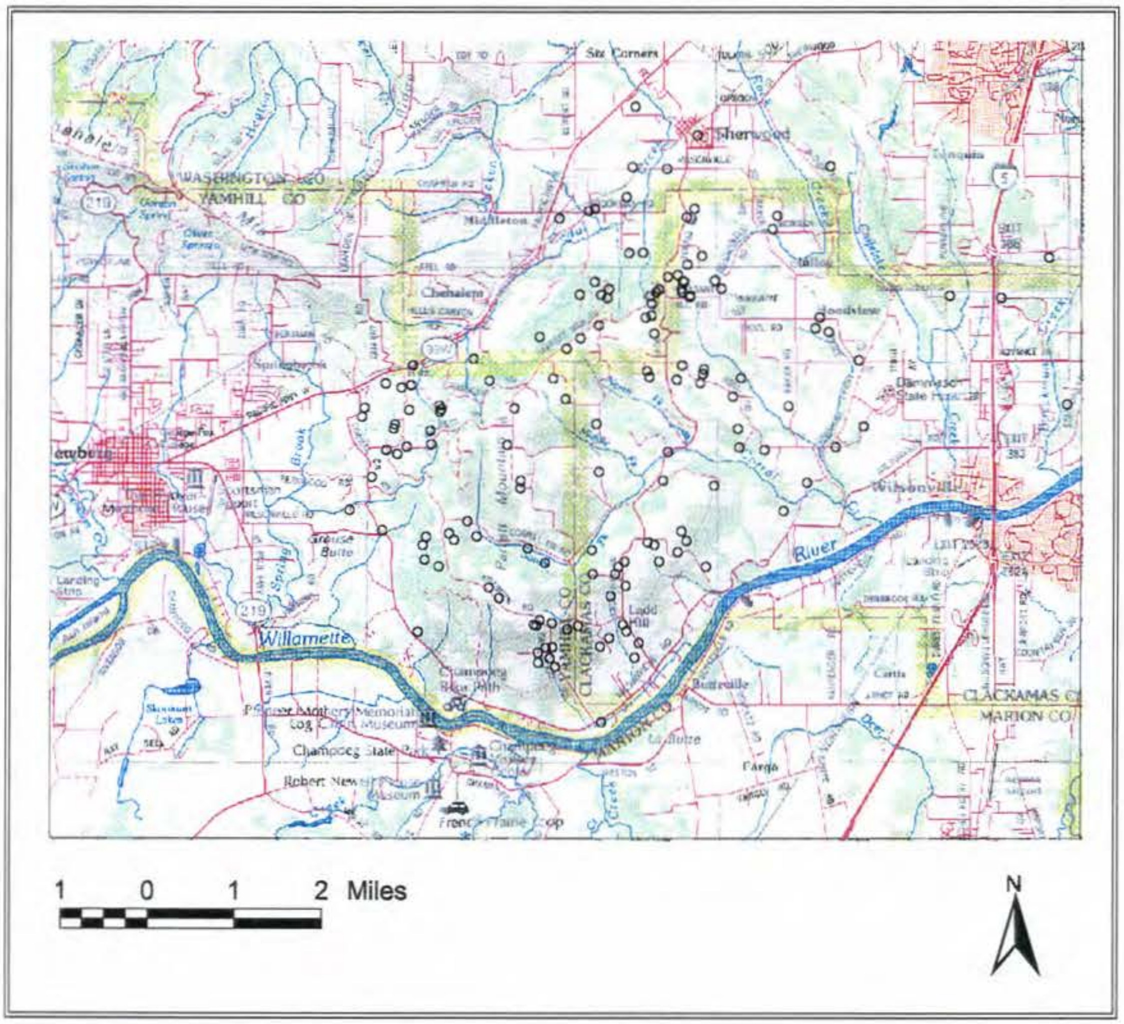


Figure 4-1: Observation Point Locations

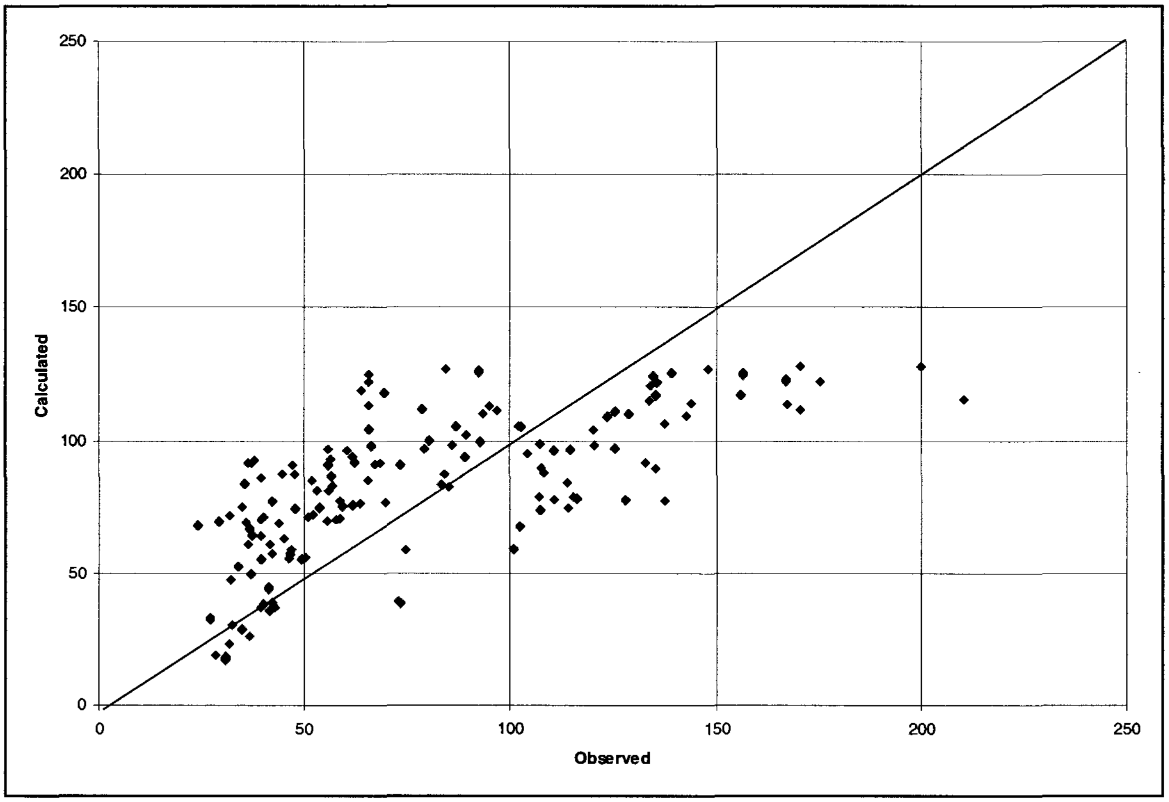


Figure 4-2: Initial Parameters, Observed vs. Calculated Heads

Table 4-1
Calibration Error Summary

Model	Description	Min (m)	Max (m)	Mean (m)	Mean Absolute Error (m)	Root Mean Squared Error (m)
Initial	Initial Input parameters used	-95.34	59.60	3.64	24.57	28.99
Model 1	All Fault Blocks were parameterized 3 at a time using UCODE. Anisotropy of 100 (K_x/K_z) was assumed.	-77.38	49.79	3.11	19.86	24.61
Model 2	Fault blocks were divided based on Model 1 runs. New zones were parameterized 3 at a time using UCODE.	-87.54	45.54	1.69	18.62	23.73
Model 3	Zones were divided again based on model 2 runs. New zones were parameterized 3 at a time using UCODE. In zones 2 and 6 both hydraulic conductivity and leakance were parameterized.	-65.14	61.12	4.31	16.41	20.29

The model was calibrated by adjusting the input parameters until the mean absolute error was minimized. Initially the model area was sectioned based on fault block locations (See Figure 4-3a), and the horizontal hydraulic conductivity and leakance were adjusted in conjunction with a 100 (K_x) to 1 (K_z) anisotropy to bring calculated heads closer to observed heads. UCODE (Hill, 1998; Poeter and Hill, 1998), a computer code for universal inverse modeling, was used to find the best estimate of horizontal hydraulic conductivity and leakance in each fault block. Parameter estimation of the sections based on the original fault blocks resulted in a mean absolute error of 19.86 m (See Table 4-1). To further improve the calibration the sectioned areas were iteratively adjusted and their parameters re-estimated with UCODE. Figures 4-3b and 4-3c display the section configuration for Model 2 and Model 3 respectively, while Table 4-1 summarizes the error statistics for each iteration. In Model 3 the horizontal hydraulic conductivity and the leakance were parameterized in two of the 18 sections (Sections 2 and 6).

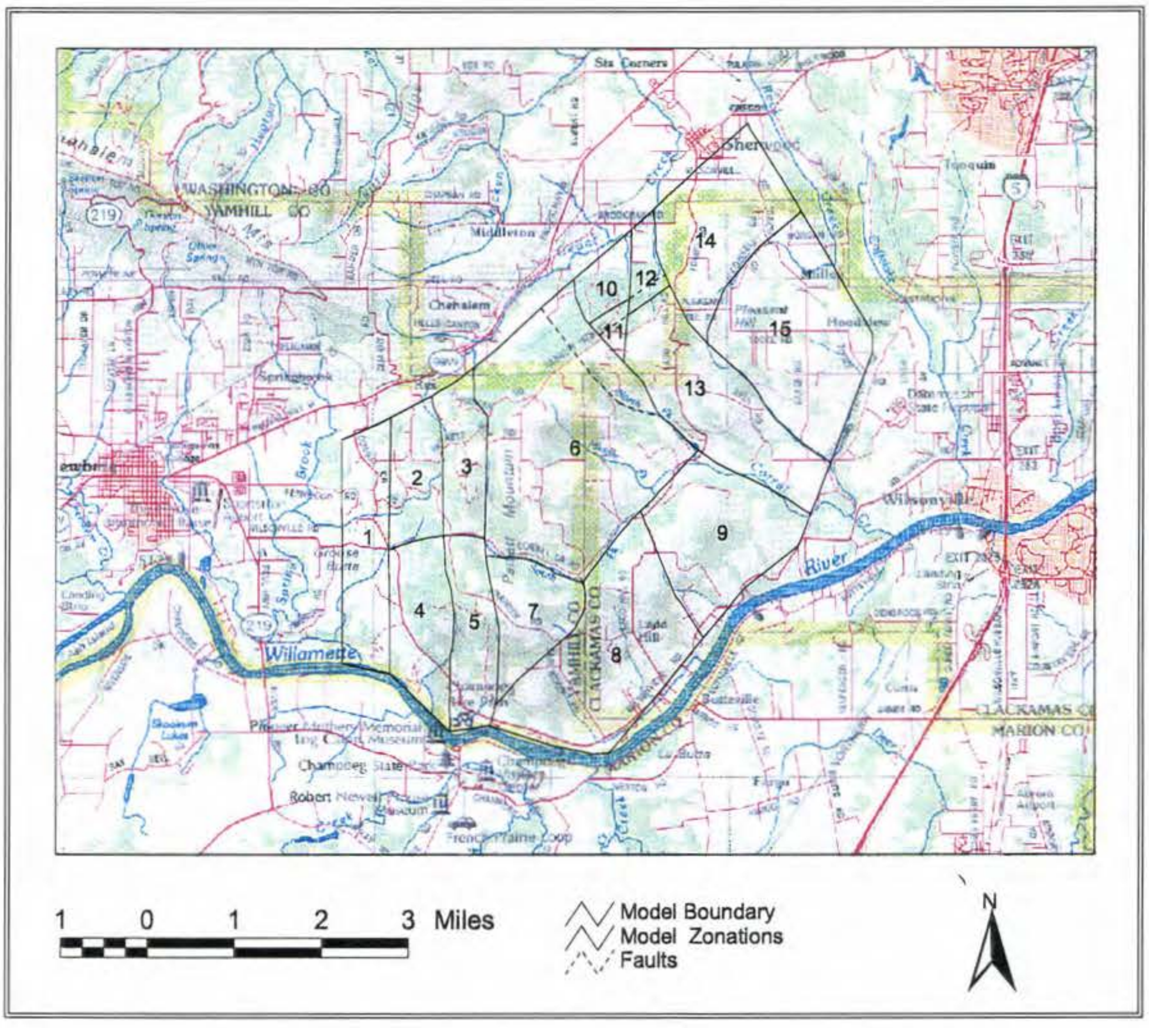


Figure 4-3a: Model 1 Zones

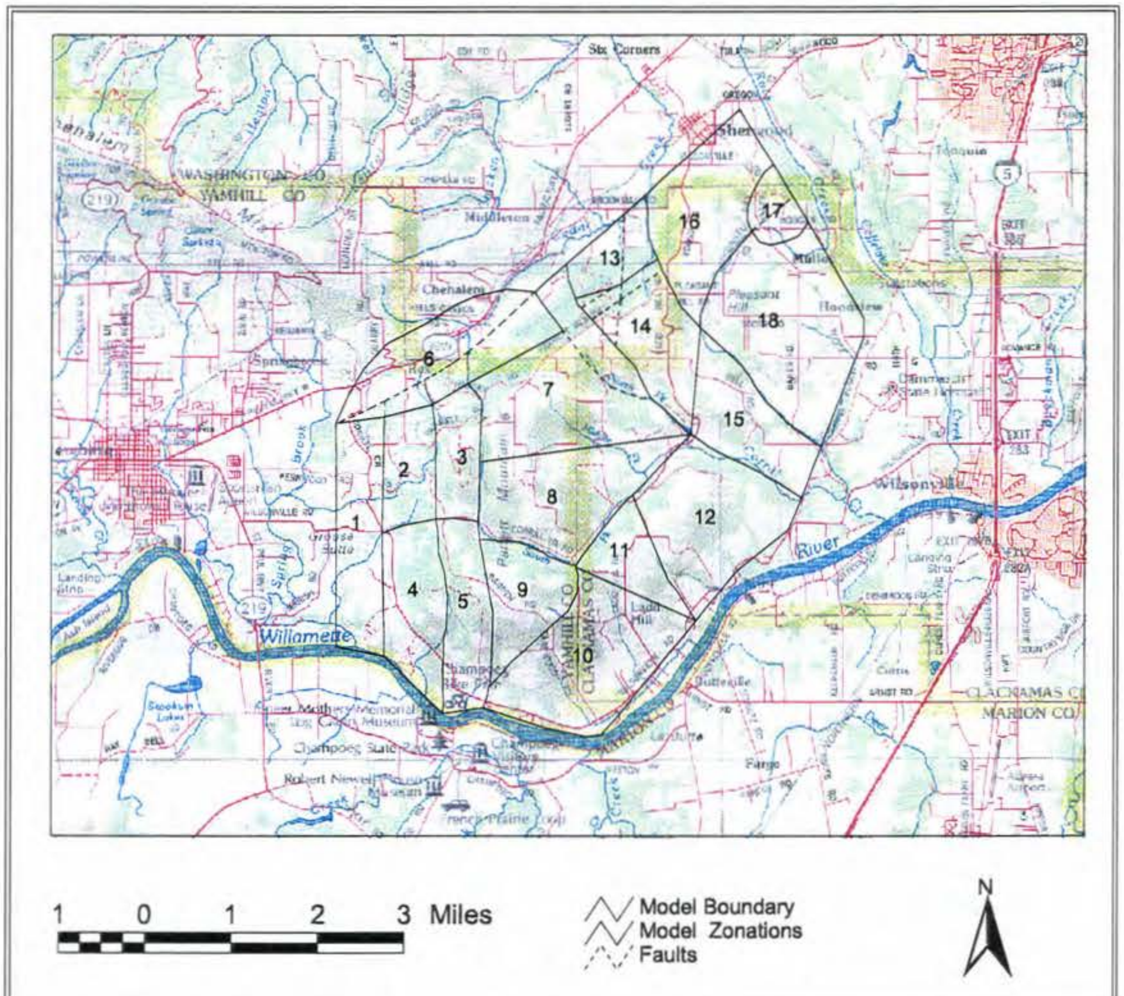


Figure 4-3b: Model 2 Zones

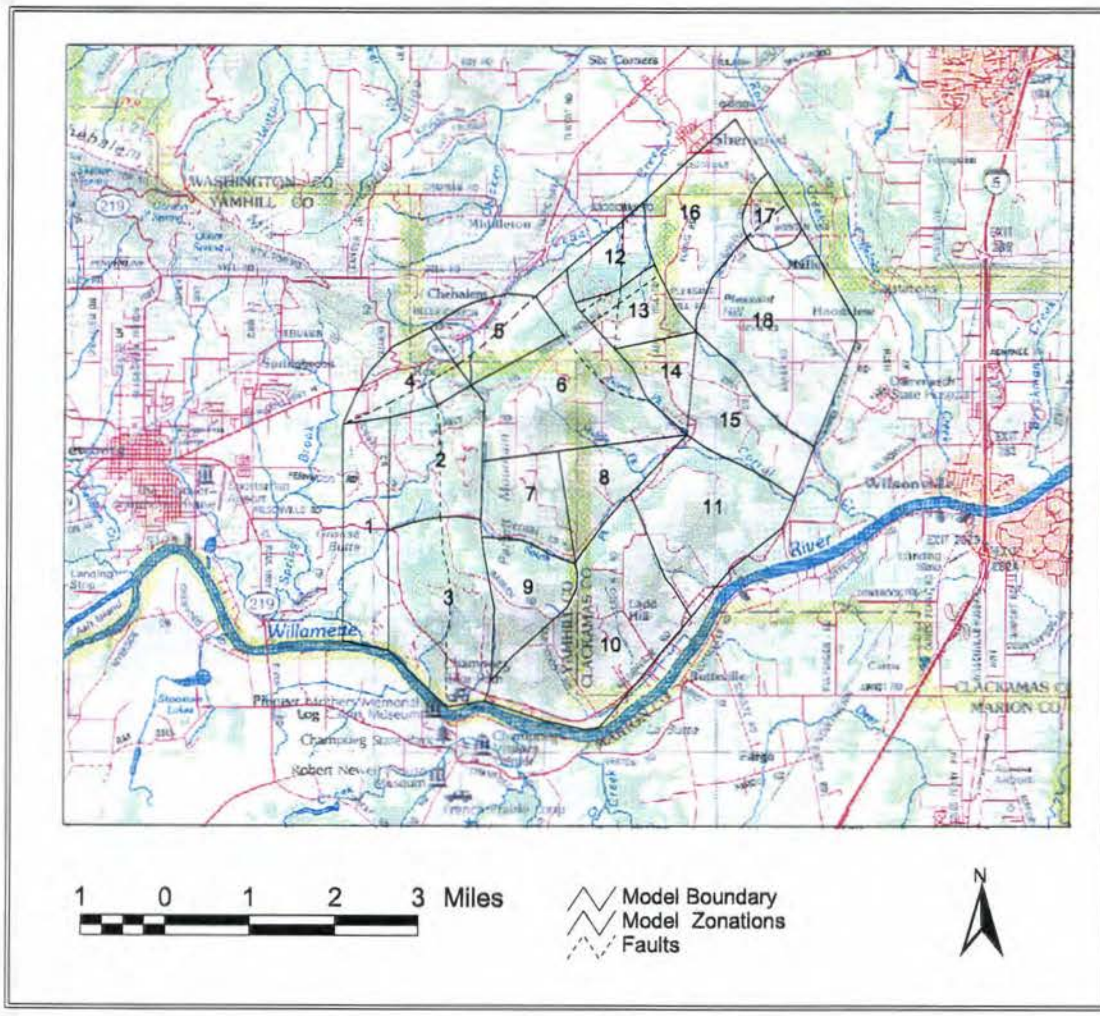


Figure 4-3c: Model 3 Zones

After hydraulic conductivity inputs were adjusted, an attempt was made to alter streambed conductance. Streams and rivers in the area were divided into three categories: the Willamette River, streams flowing over basalt, and streams flowing in Quaternary sediments. Figure 4-4 displays the streams and rivers in the Parrett Mountain area in conjunction with the surficial geology in order to differentiate the streams based on various sediment types. It was found that changes to streambed conductance resulted in small increases in model error, and that the model was relatively insensitive to streambed conductance. Ultimately streambed conductance values were left at initial inputs.

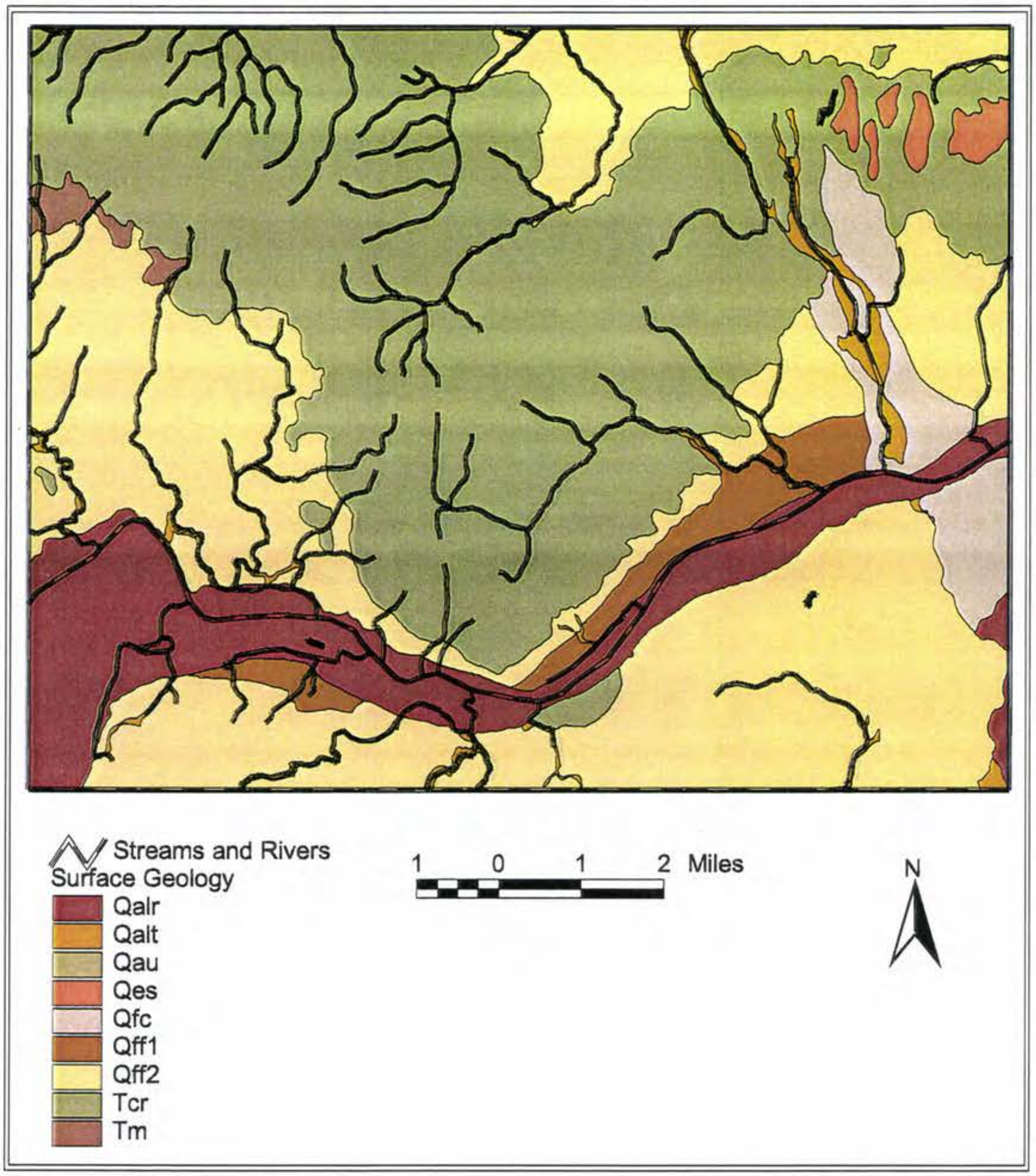


Figure 4-4: Streams and Rivers

Figure 4-5 displays observed vs. calibrated heads for the final calibrated model. Although there are deviations at individual observation points, generally calculated groundwater elevations match observed. Simulated groundwater elevation contours from Layer 1 are displayed in Figure 4-6 in conjunction with my interpretation of the water table based on shallow wells and surface water bodies. Although there are significant differences in groundwater elevations between the MODFLOW simulated water table and the interpolated water table, the groundwater flow directions for each water table match.

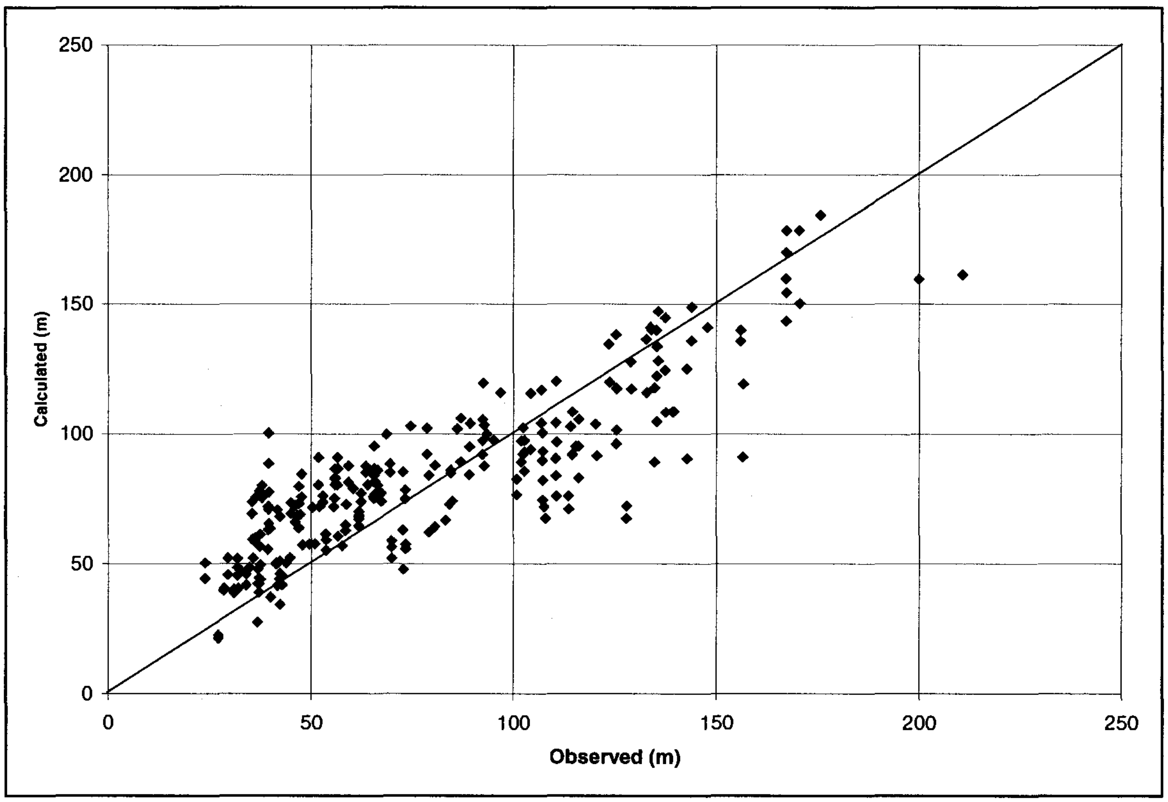


Figure 4-5: Calibrated Parameters, Observed vs. Calibrated Heads

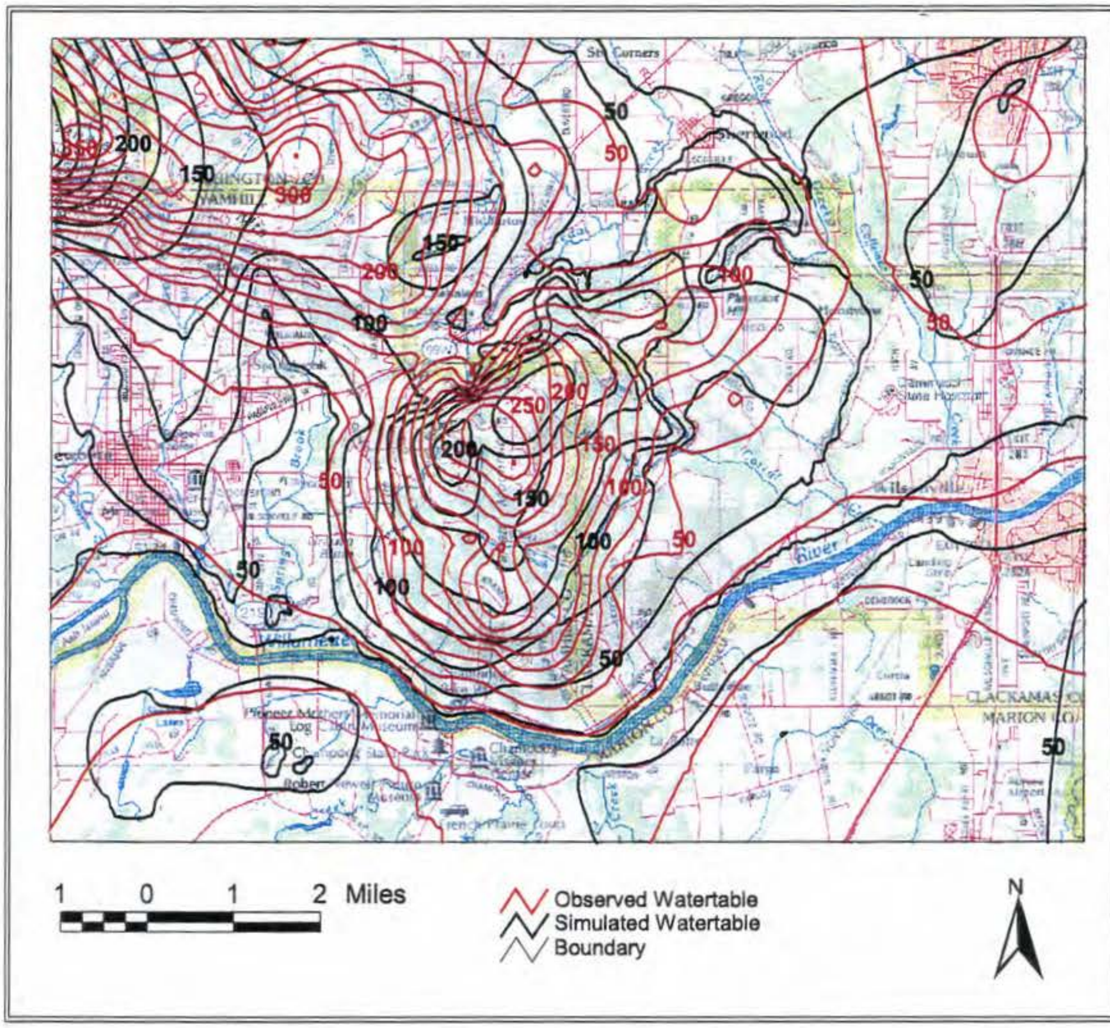


Figure 4-6: Groundwater Elevation Contours

4.2 Sensitivity Analysis

A sensitivity analysis is used to quantify uncertainty in the calibrated model caused by uncertainty in aquifer parameter estimates. A sensitivity analysis was run on the Parrett Mountain calibrated model to assess model uncertainty. Initially model parameters; leakance, streambed conductance, recharge, and horizontal hydraulic conductivity were systematically altered and changes to the model results were assessed. For each simulation one parameter was changed by a percentage amount from the original, while the remaining parameters were held constant. The error statistics were recorded from that run and the next simulation was prepared where the same parameter was altered by a different percentage amount. As part of the sensitivity analysis five model simulations were run for each parameter for a total of 20 runs. Figure 4-7 displays the graphical change in the mean absolute error as each parameter undergoes a percentage change. Based on this figure the horizontal hydraulic conductivity has the greatest impact on model error, followed by recharge, then leakance. Streambed conductance has little to no impact on model error.

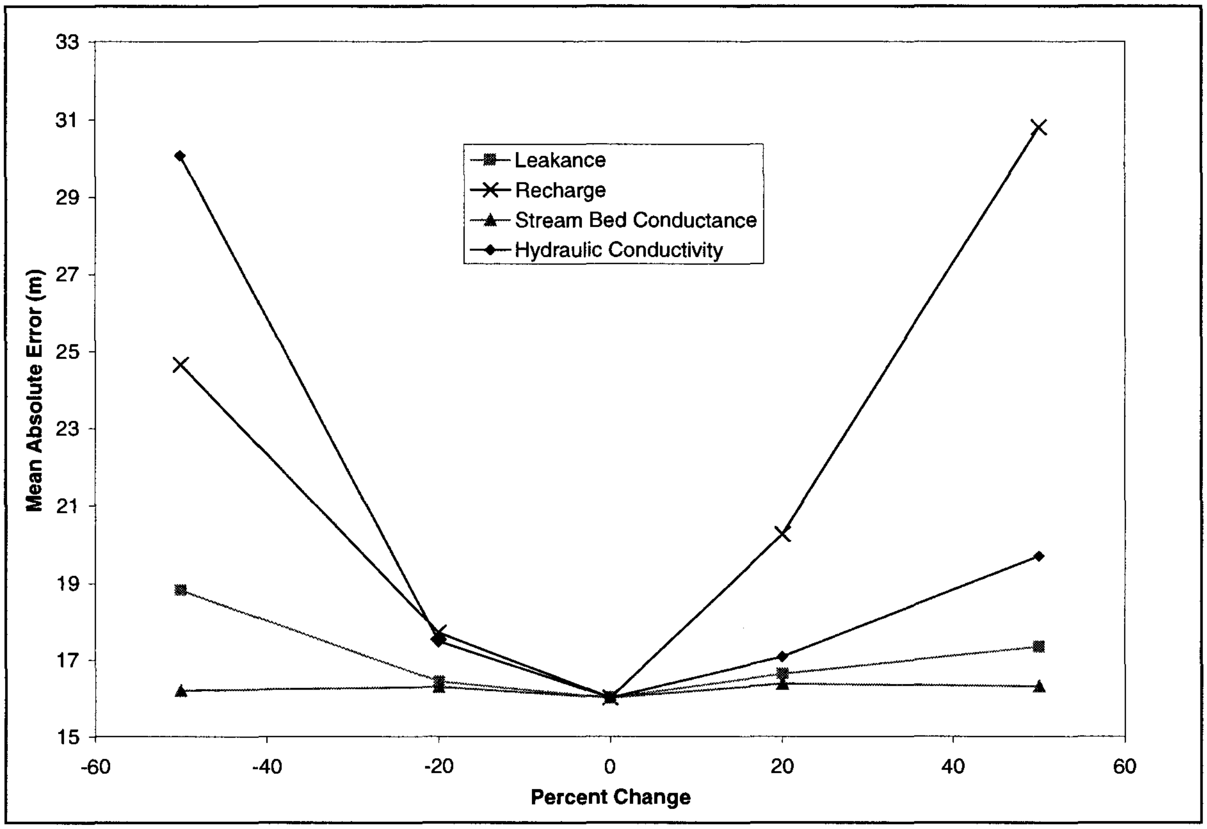


Figure 4-7: Sensitivity Analysis

As part of the UCODE parameter estimation program a sensitivity analysis was run on each model parameter. The program calculates scaled sensitivities at each observation point as a model parameter is altered by 5%, while all other parameters remain the same. The resulting change in head is recorded. Scaled sensitivity is defined below (Hill 1998, Poeter and Hill 1998):

$$ss_j = \Delta h / \Delta p \qquad (3\text{-}4)$$

where:

ss_j [T] is the scaled sensitivity;

h [L] is the simulated valued associated with the observation; and

p [LT^{-1}] is the estimated parameter.

Using the UCODE input function file, MODFLOW parameters were transformed to reflect hydraulic conductivity; vertical, horizontal, and streambed. For instance, transmissivity was calculated from horizontal hydraulic conductivity by multiplying by the layer thickness. All scaled sensitivities were calculated by altering hydraulic conductivity resulting in similar units.

Based on the scaled sensitivity results, composite sensitivities were calculated for each parameter used in the model. Composite sensitivities were calculated from the following equation (Hill 1998, Poeter and Hill 1998).

$$css_j = \left[\sum_{i=1}^{ND} \left(ss_{ij} \right)^2 / ND \right]^{1/2} \qquad (3\text{-}2)$$

where:

css_j [T] is the composite scaled sensitivity;

ss_j [T] is the scaled sensitivity at each observation point; and

ND is the number of observations.

The composite scaled sensitivities indicate the relative impact of each parameter on the model. Table 4-2 displays css values for each of the model parameters, showing that changes to stream and river bed conductance values have little impact on model results. The most sensitive parameter is Zone 10's hydraulic conductivity.

Table4-2
Calibrated Parameter Inputs and Composite Sensitivities

Zones =J	K_x [m/min]	K_z [m/min]	Anisotropy (K_x/K_z) -	Composite Scaled Sensitivities [T]
1	1.11E-04	1.11E-06	100	10
2	9.41E-06	1.18E-06	7.97	12
3	1.25E-04	1.25E-06	100	15.1
4	1.07E-03	1.07E-05	100	3.01
5	9.15E-05	9.15E-07	100	4.89
6	1.49E-06	3.09E-06	0.48	7.96
7	1.50E-04	1.50E-06	100	5.55
8	1.19E-04	1.19E-06	100	5.79
9	7.24E-05	7.24E-07	100	8.72
10	2.64E-04	2.64E-06	100	22.7
11	5.51E-04	5.51E-06	100	11.8
12	6.28E-04	6.28E-06	100	3.9
13	5.06E-05	5.06E-07	100	16.9
14	2.68E-04	2.68E-06	100	6.83
15	1.20E-03	1.20E-05	100	7.05
16	9.13E-05	9.13E-07	100	17
17	3.55E-05	3.55E-07	100	8.78
18	1.79E-04	1.79E-06	100	11.2
Streams	**Conductance m^2/min (KLW/M)**	**Parameter**		**Composite Scaled Sensitivities [min/m]**
QAL Streams	3.10E-02	c3		0.908
Basalt Streams	3.70E-07	c2		0.123
Willamette River	3.1	c1		9.73E-03

To assess the correlation of zoned parameters, sensitivities at each observation point were linearly interpolated to a 2-D grid. Figures 4-8a, 4-8b, 4-8c, and 4-8d display contour intervals of the sensitivities for changes in parameters for Zone 11 hydraulic conductivity, Zone 18 hydraulic conductivity, Zone 6 leakance, and the basalt stream bed conductance. It becomes clear that changes in zoned parameters primarily effect that particular zone, with some changes to outlying zones. Again leakance and hydraulic conductivity have significant impact on model results, while streambed conductance does not.

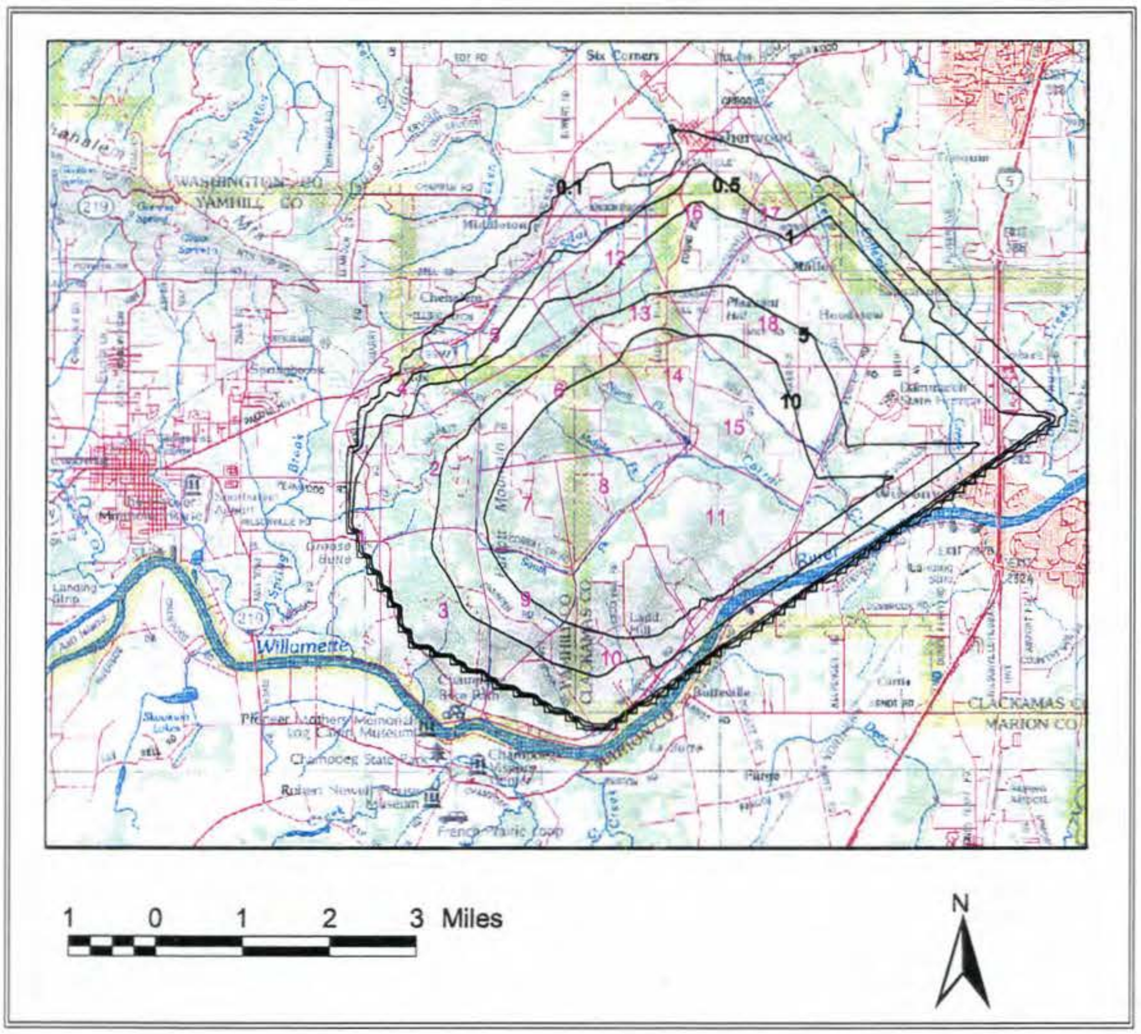


Figure 4-8a: Interpolated Sensitivities for K_x Zone 11

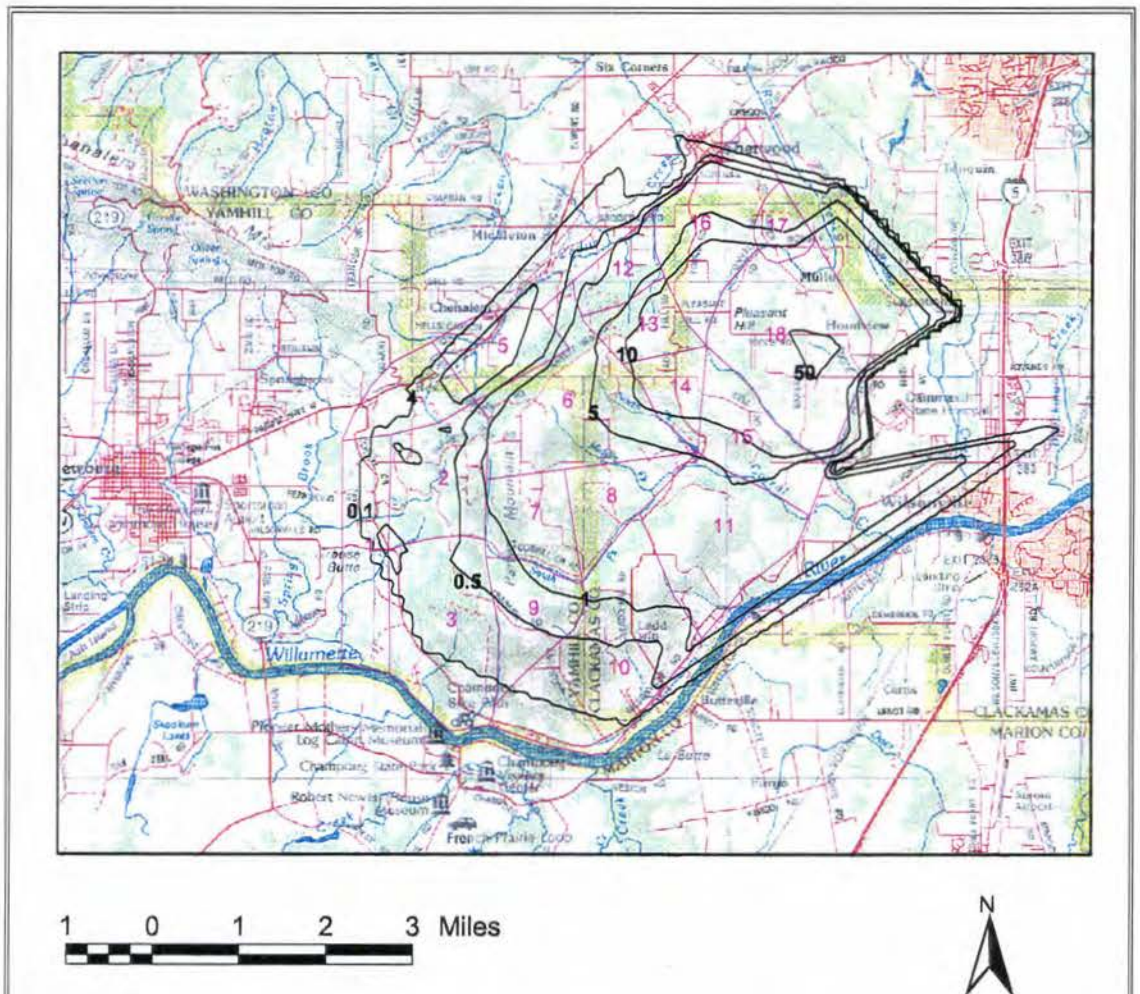


Figure 4-8b: Interpolated Sensitivities for K_x Zone 18

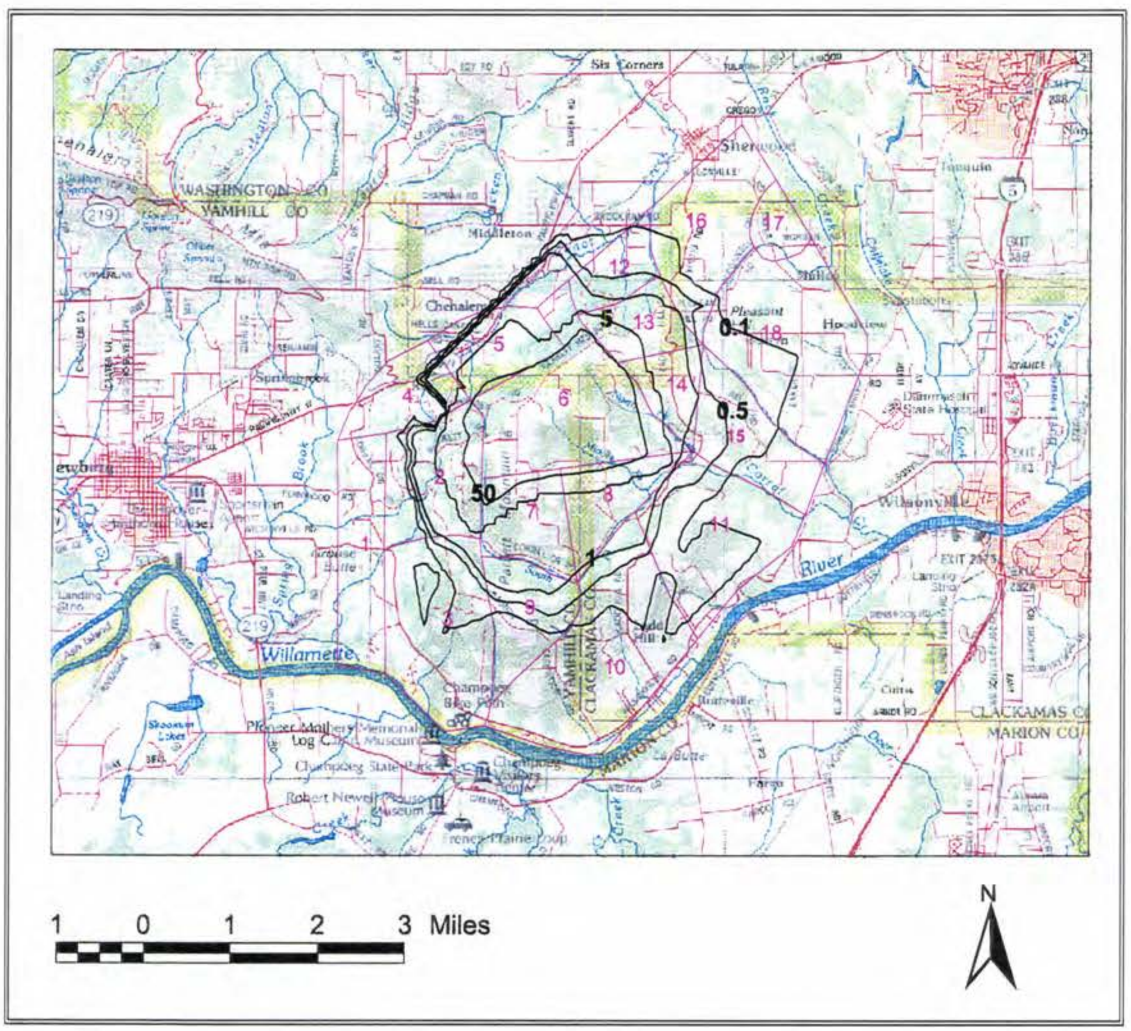


Figure 4-8c: Interpolated Sensitivities for leakance Zone 6

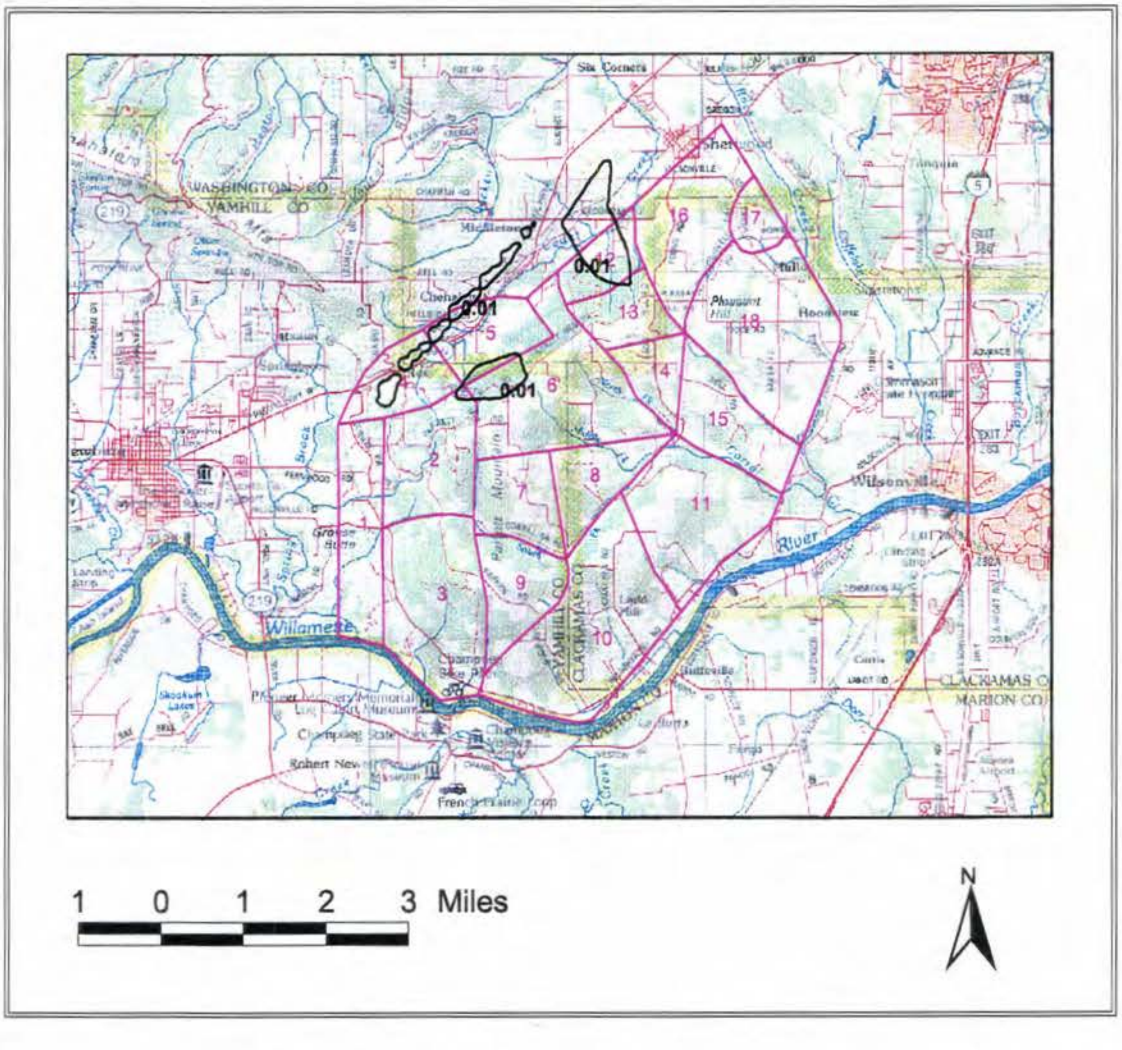


Figure 4-8d: Interpolated Sensitivities for Basaltic Streambed Conductance

4.3 Predictions

This section presents the predictive simulations based on the calibrated Parrett Mountain groundwater model. The predictive scenarios presented below are based primarily on management issues dealing with future possible groundwater uses. It is important to realize that due to the large spatial scales of this subregional model certain predictive models cannot be realistically modeled. For instance measuring the effect on one small domestic water user on a nearby user will not produce accurate or useful results. However, estimating the impact of a large scale water user at a specific location on surrounding locations can be done.

There are two predictive scenarios presented in this section. The first estimates future groundwater use by the City of Sherwood at Well Six. The second scenario is a series of simulations that estimate the relationship between general trends in population growth and impacts to groundwater.

4.3.1 City of Sherwood

In 1997 the City of Sherwood installed and began operating a groundwater extraction well located in the Northwest quadrant of the Parrett Mountain Model and screened in the basalt aquifer. This well was added to the MODFLOW well file as part of the prediction simulation. The well was assigned a pumping rate of 54 m^3/hr, which corresponds to the volume of water extracted from the well in 1997-1998 water year. The extraction rate was apportioned to the model layers based on layer thickness. Figure 4-8 shows the impact of this well on surrounding areas by displaying drawdown. At Sherwood's Well six drawdown is estimated at 22 meters. As seen from Figure 4-9, depicting drawdown versus distance from the pumping well, a drawdown of one meter is experienced approximately 1700 meters from Well 6. Based on these results the Parrett Mountain groundwater model suggests that the City of Sherwood's well may influence neighboring water wells.

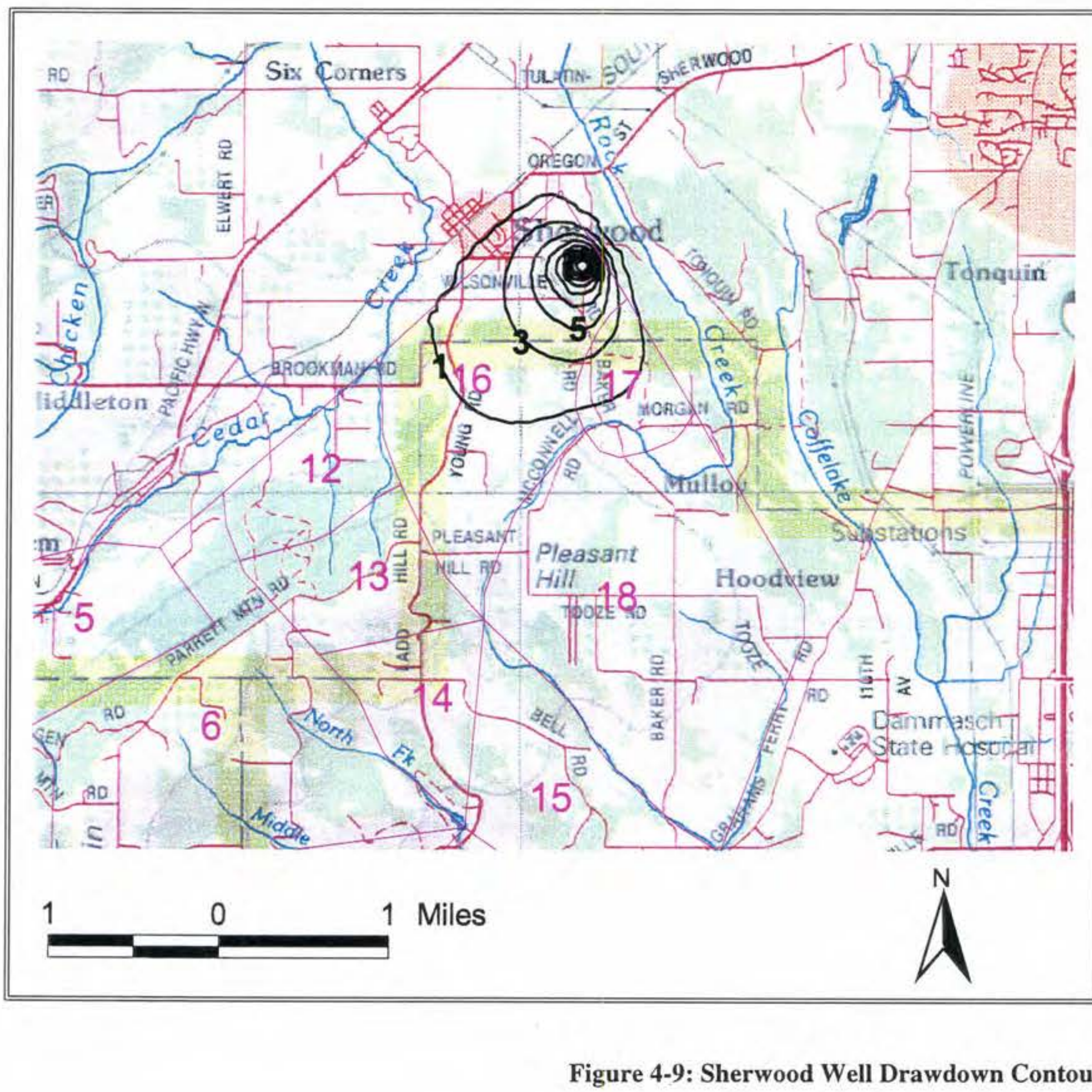


Figure 4-9: Sherwood Well Drawdown Contours

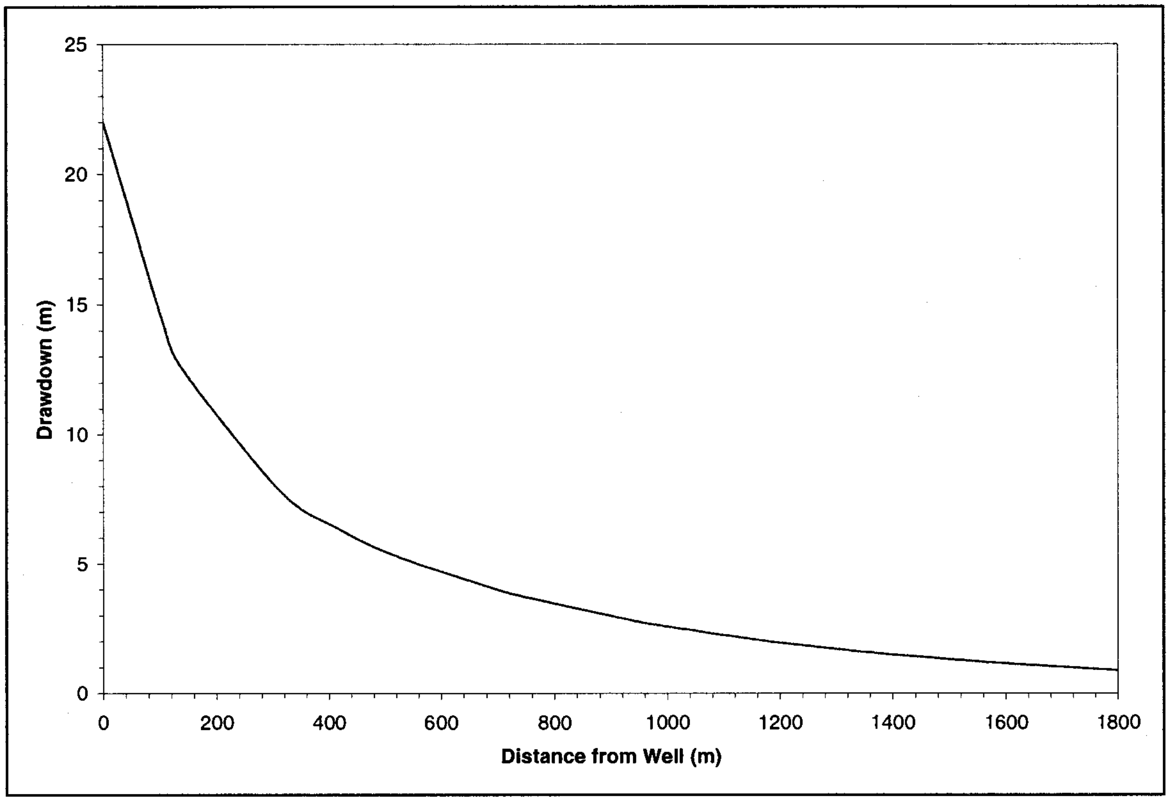


Figure 4-10: Sherwood Well 6, drawdown vs. distance from pumping well

4.3.2 Population Densities

In order to estimate the impacts of population increases on groundwater in the Parrett Mountain Region, a series of simulations were run, each with a variation in population density. Population densities were converted to pumping scenarios by assuming that all population growth took place within the study area and that pumping was uniformly distributed within the study area. The study area is 18259 acres (74 km^2) in size. By assuming 3.5 persons per dwelling, that each person uses 150 gallons per day (0.568 m^3/day), and that 50% of the extracted water is returned to the aquifer through recharge, one is able to predict pumping scenarios based on housing densities. Three simulations were run assuming housing densities of four homes per acre (4,000 m^2) (population increase of 251,120), one house per acre (4,000 m^2) (population increase of

59,405), and one house per five acres (20,000 m^2) (population increase of 8281). Figures 4-10a, 4-10b, and 4-10c display drawdown estimates for each of the four cases respectively. These simulations are not based on the population forecasts presented in Section 2.1, but instead are based on linear increases to population density, meant to demonstrate the impact on groundwater resources in the area. A comparison of Figures 4-10a and 4-10c show a significant change in drawdown levels from the smallest population increase to the largest. Simulation results based on the smallest population increase have a mean drawdown of 0.29 meters and a maximum drawdown of 3.79 meters. The simulation representing the largest population increase has a mean drawdown of 5.8 meters and a maximum drawdown of 75.8 meters. Table 4-3 displays a comparison of water needs for simulated population increases against estimated recharge based on 40% of average recharge. The information presented from these results could be useful for growth planning in the area.

Table 4-3
Estimated Water Need for Simulated Population Increases

Population Increase	Volume of Groundwater Extracted Yearly (billions of gallons)	Percent of Recharge
251,120	7	70
59,405	1.7	17
8,281	0.35	3.5

Notes:
1) Assumes groundwater extraction rate of 150 gallons per day.
2) Assumes 50% of extracted water is returned to the aquifer through recharge.
3) Assumes a recharge of 10 billion gallons per year (40% of average annual precipitation multiplied by the study area [73.0 km^2])

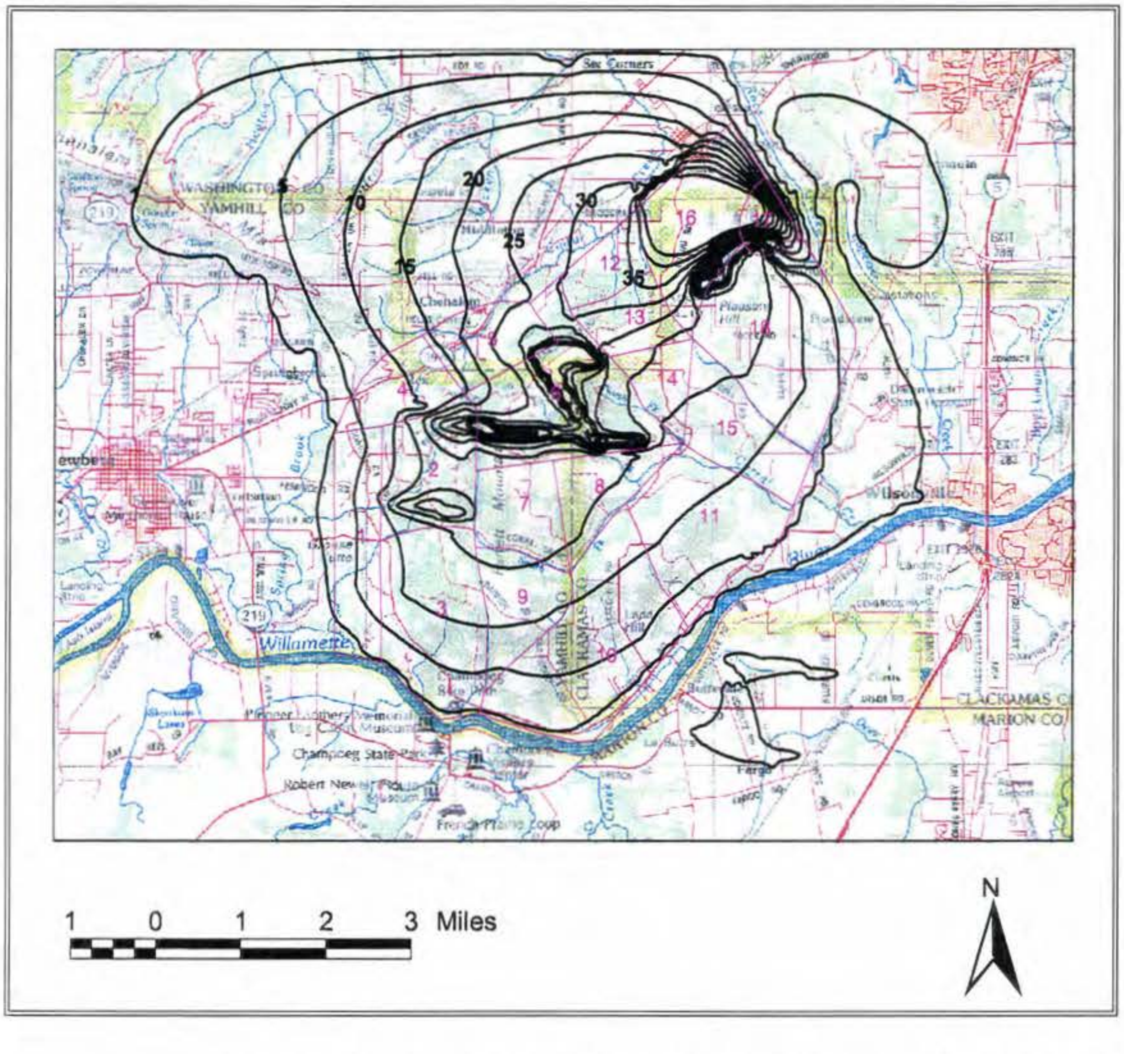


Figure 4-11a: Drawdown with Population Density Increase (4 homes per acre)

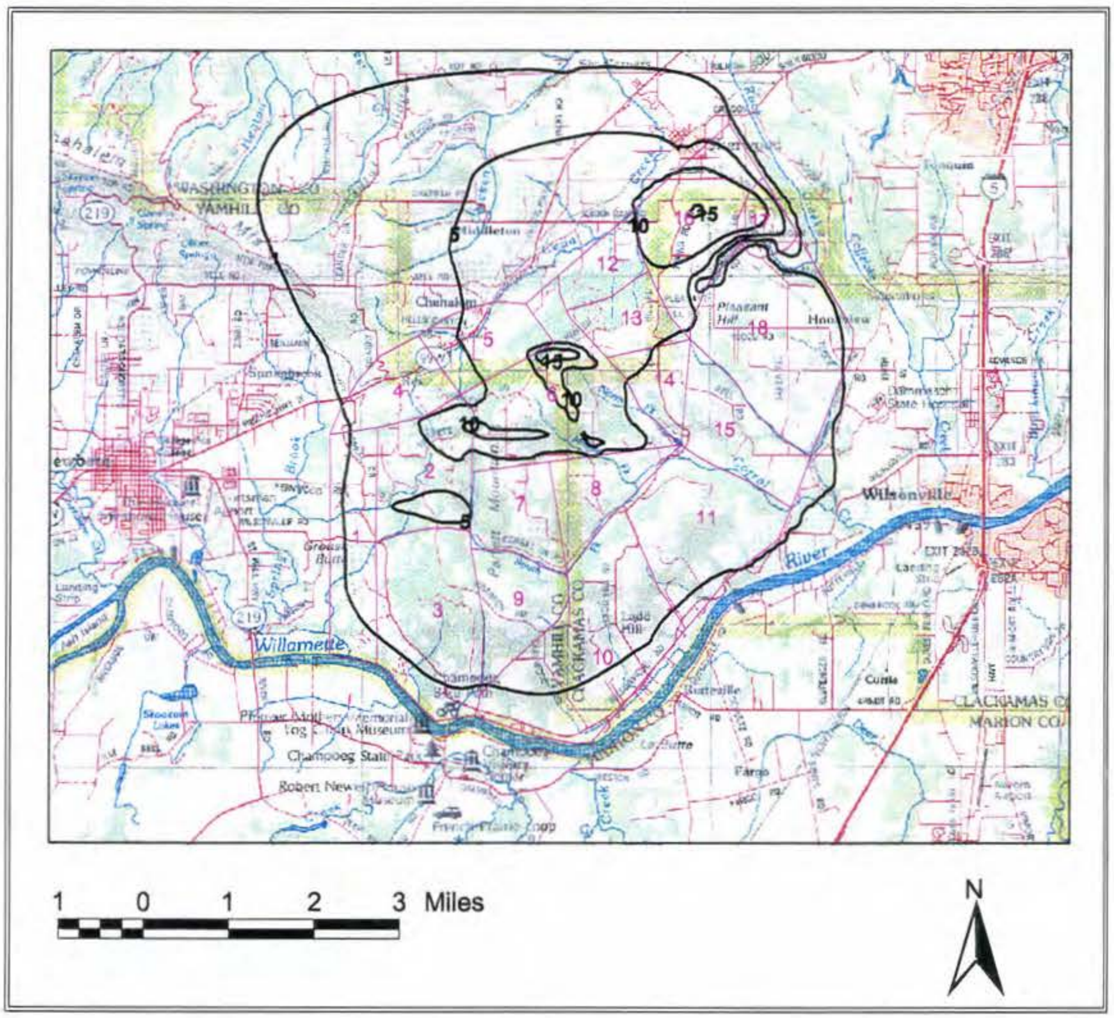


Figure 4-11b: Drawdown with Population Density Increase (1 home per acre)

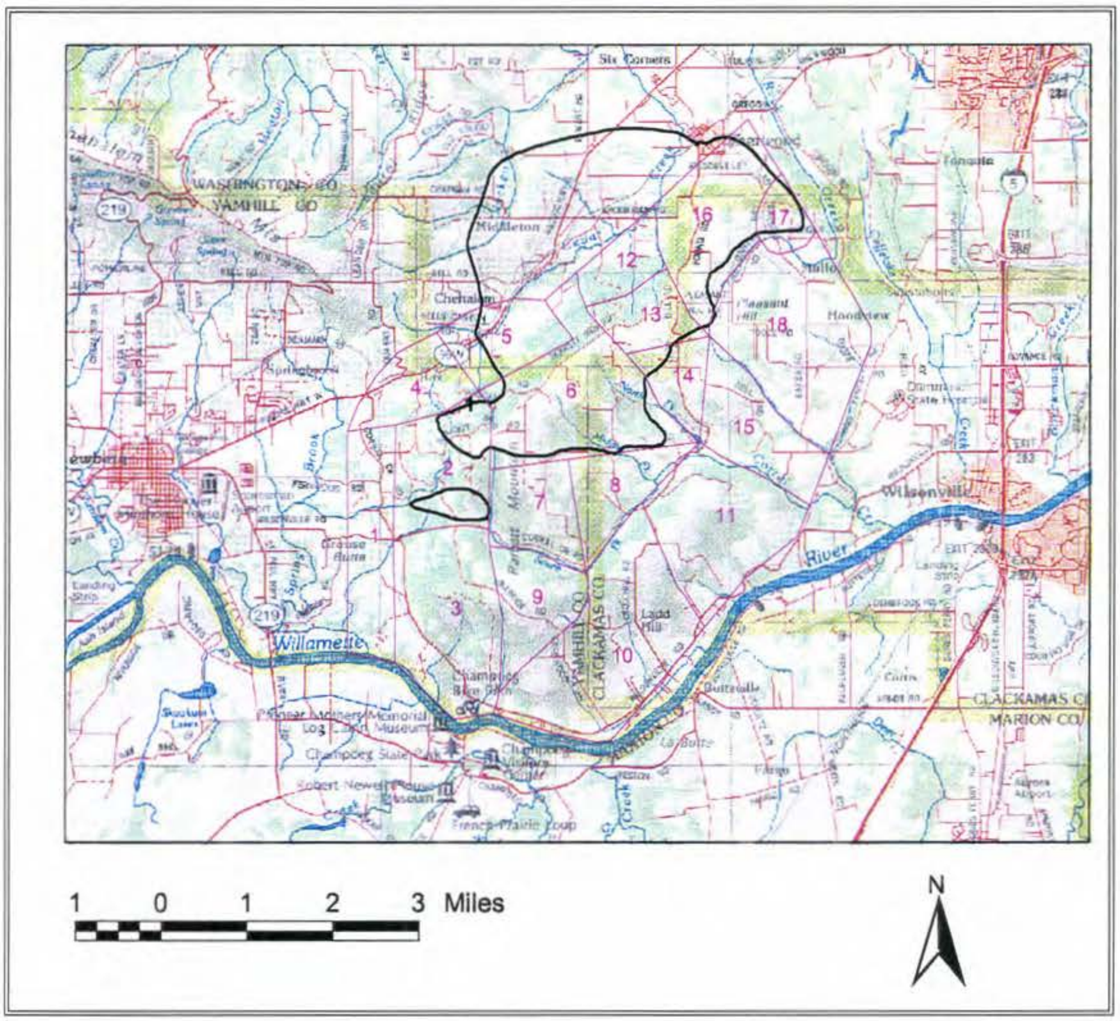


Figure 4-11c: Drawdown with Population Density Increase (1 home per 5 acres)

4.4 Model Limitations

For those using this Parrett Mountain Subregional Model for aquifer management planning or other purposes, it is important to be aware of the model's limitations. This groundwater model presents a simplified version of the actual hydrogeologic conditions present in the region. Many important hydrogeologic conditions at the site are not well known including fault and basalt flow location, anisotropy, and heterogeneity. A detailed list and description of model uncertainties is presented below.

- The CRB aquifer present in the model consists of faulted and fractured basalt. The use of MODFLOW, developed for porous media, in modeling fractured media adds uncertainties to model results. It is likely that fractured flow contributes to the wide range in waterlevel measurements present within some model zones. During calibration the hydaulic conductivity and leakance were parameterized resulting in average parameter values for the zones. Zones with large deviations in water levels will contain more error than zones without large deviations in water levels.
- The geology in the system is uncertain specifically in terms of the location of individual basalt flows. The model was constructed with knowledge of the CRB thickness and basalt top and bottom. The layers are based on arbitrary divisions and not on basalt flows. Since it is likely that interfaces between basalt flows influence groundwater flow in the region, the model dimensions may introduce uncertainties into the model.
- Each of the layers is modeled as confined, including the top most layer which conceptually should be unconfined. This was necessary to encourage model convergence.
- Vertical hydraulic conductivity at the site has not been measured. Instead an anisotropy ratio of 100 (Kx) to 1 (Kz) was assumed during model calibration. Although this is a realistic anisotropy value, others are possible. Using this ratio for anisotropy may cause errors in calibration of the horizontal hydraulic conductivity.
- Some estimates of horizontal hydraulic conductivity were derived from aquifer pump tests at individual wells, but most resulted from specific capacity tests. The resulting hydraulic conductivity data may contain inaccuracies. Furthermore the data is point specific and variable, and cannot be easily compared with the zone hydraulic conductivity values.
- Recharge resulting from precipitation was estimated by the USGS through watershed modeling. Model inputs were not altered during calibration, suggesting that any errors in recharge estimates would impact other calibrated parameters.
- Base pumping conditions are estimates of extraction rates combining irrigation and water supply, with irrigation taking up the bulk of water use. Irrigation rates were

estimated based on crop types and landuse. The methods for estimating groundwater extraction rates make assumptions and are likely to contain errors.

- Based on the observation data from wells used to calibrate the model, streambed seepage did not significantly impact model results. However there was little direct stream seepage data available for calibration. If more data were available it might be found that surface water seepage plays a more significant role.
- Boundary conditions were estimated from interpolated surface water levels based on shallow wells and surface water bodies. The model is large enough that any boundary condition error should not effect the accuracy within the study area.

Although this model contains all of the uncertainties above, it is still a useful predictive tool that can be used to assess regional groundwater impacts based on different management goals.

5. Discussion

In section 1.0 I introduced the importance and goals of the Parrett Mountain Groundwater Study, focusing on both scientific and management issues. The project goals listed in subsection 1.2 are summarized below.

- Determine whether the Equivalent Porous Media (EPM) method to modeling can be applied to the Parrett Mountain Region.
- Evaluate the hydrogeologic characteristics affecting the flow system.
- Determine whether long-term declines in water levels can be controlled.
- Develop predictive simulations that access groundwater development on the groundwater flow system.

The first two project goals improve the understanding of CRB aquifer systems, while the last two pertain to the management of the Parrett Mountain CRB aquifer system. Each of the goals listed above is discussed below to determine whether they have been met.

5.1 EPM Modeling Approach Assessment

As part of this groundwater study, I used MODFLOW to model the Parrett Mountain groundwater system. MODFLOW uses the finite difference method and assumes an effective porous medium. The Parrett Mountain aquifer system is primarily a fractured system consisting of fractured and faulted basalt and consolidated marine sediments, with some unconsolidated Quaternary sediments. Only the Quaternary sediments are a true porous medium.

A common approach to modeling fractured media is through the used of discrete fracture (DF) models. These models assume that water flows through a fracture network where the flux depends on the fracture aperture, the fracture width, the fracture length, and network interconnection. Using a DF model requires a description of the fracture network including fracture apertures and geometry. Based on the data needs for a DF model it is clear that applying a DF model to the Parrett Mountain Region is not possible.

Instead, the EPM approach was used to model the Parrett Mountain Region. The EPM approach assumes that the fractured material can be modeled as a continuous interconnected pore space. This assumption is based on the idea that a representative elementary volume for the fractured media can be defined. Essentially this means that at a certain scale a fractured network is interconnected to such a degree that it acts as a porous media. As stated in the literature review Khaleel (1989) investigated scale dependence of continuum models on Columbia River Basalt, finding that for an interconnected network with unfilled fractures and a column diameter of one meter, EPM models are equivalent to DF models at six meters.

Based on the work of Khaleel, and the successful application of the continuum models on CRB aquifers at other locations, I went forward with the EPM approach for

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Based on the work of Khaleel, and the successful application of the continuum models on CRB aquifers at other locations, I went forward with the EPM approach for modeling the Parrett Mountain groundwater system. Based on the calibration results, the EPM approach resulted in a reasonable simulation of observed heads in the flow system. There are large variations in groundwater elevations at CRB wells located in the close proximity to one another, suggesting that the EPM approach may fail locally. This may be caused by fractures and faults that impacting local groundwater conditions. However, for the scale used for the Parrett Mountain subregional model, the EPM approach is a viable method for simulating the steady state groundwater flow system. It should be noted that faults and fractures could have a larger influence on the flow system under transient conditions, thereby causing the EPM approach to be less successful for modeling the flow system.

5.2 Hydrogeologic Characteristics Effecting the Flow System

The hydrogeologic characteristics that most affect the flow system were assessed during model calibration. Based on the sensitivity analysis presented in subsection 4.2 the aquifer parameters that most affected the flow system were horizontal hydraulic conductivity, followed by recharge, and then vertical hydraulic conductivity (See Figure 4-7). It was found that altering streambed conductance had little to no effect on model calibration results.

During the calibration process it was not necessary to include major faults within the model. At early stages of calibration it was found that including low hydraulic conductivity zones at major fault locations increased model error. As a result no major faults were included in the model. Faults indirectly impacted model calibration by influencing where model zones were located, since the model zones were originally based on fault blocks. However, the model zones were altered during the subsequent calibration iterations, resulting in model zones that have little to do with fault blocks. If the major influence of faults in the area is to off-set interflow zones in the CRBs, then the lack of influence of the faults on the flow model is consistent with the EPM approach.

I was unable to determine whether the majority of the flow in the CRB occurs in the flow tops. Conceptually it seems likely that this is true, since flow tops are likely highly fractured and weathered, in comparison to basalt flow interiors, before being covered by subsequent CRB eruptions. It is probably that the more highly fractured flow tops, possibly filled with sands and silts, are more conductive than the less fractured basalt flow interior. Since I do not know the location and extent of the basalt flow tops I cannot test this theory. My limited knowledge of vertical hydraulic conductivity further hinders my understanding of the impact of flow tops on the groundwater system.

5.3 Management Issues

The final two project goals, mediation of water level declines and the development of predictive scenarios accessing the impact of groundwater development are linked with increasing groundwater demand in the region. Scenario 2, of the predictive simulations estimates drawdown based on population increases in the area (See subsection 4.3). A population increase of approximately 250,000 people, which is extremely unlikely, spread uniformly throughout the study area results in a maximum drawdown of 75.8 meters in Zone 6. A population increase of approximately 8,000 people results in a maximum drawdown of 3.8 meters in Zone 6. Based on population projections, the minimum population increase of 8,000 is the most likely scenario to occur, and should not greatly increase rates of water level decline. However, it should be stressed that the prediction scenarios are based on uniform increases in population and groundwater demand, and that concentrated growth could exacerbate the issue locally.

As shown above this Parrett Mountain Groundwater Model can be a useful, but limited predictive tool to aid in aquifer management. Although there are some uncertainties in model parameters, this model is useful in assessing the impacts of large scale groundwater demands on the flow system. Large scale groundwater demands include those incurred from general population trends, as well as municipal uses. This model should not be used to assess the impacts of local single household increases in groundwater demand.

6. Summary and Conclusions

This thesis focused on the quantitative hydrogeologic study of Parrett Mountain Region, an area located to the south of Portland. Specifically the impacts of the Columbia River Basalt Unit on groundwater flow in the region were investigated. A groundwater model was constructed to answer certain scientific questions and also to serve as a management tool to aid urban growth planning. The conceptual model for the system was based on the geologic framework prepared by Broderson (1994) and hydrogeologic data provided by the OWRD and the USGS. 1995 through 1996 time-averaged groundwater elevation data was used for model calibration with the parameter estimation software UCODE. A sensitivity analysis was conducted to determine which parameters had the most impact on model results. Using the calibrated model, two sets of prediction scenarios were run. The first involved investigating the impacts of the City of Sherwood's Well 6 on surrounding wells. The second included a series of simulations estimating the impact of growing population densities on groundwater drawdown in the region.

6.1 Scientific Issues

Based on the available data, and through the use of the Parrett Mountain model I was unable to answer all of the scientific questions posed in Section 1. What I discovered is presented below.

1. Can the Effective Porous Media (EPM) approach to groundwater modeling be applied to Columbia River Basalt (CRB) over this large of an area, resulting in faults and matrix blocks acting as a porous media?

Since I was able to gain a degree of success during calibration using MODFLOW it can be stated that CRB aquifer behaved sufficiently like a porous medium for it to be modeled with this software. Evidence suggests that an EPM model can be applied to this problem.

2. Do major faults in the area significantly influence flow?
   Although no major faults were necessary to produce the calibrated model at the subregional scale, at smaller scales it is likely that faults do play a significant role in groundwater flow. Investigating the impact of faults at smaller scales would require a more localized and more detailed model.

3. Does the majority of flow occur on basalt flow tops as some hypothesize, or does it occur vertically as well?

No information of anisotropy was available through field measurements, nor were any conclusive estimates obtained through calibration. Without information on anisotropy, I was unable to test this hypothesis.

6.2 Management Issues

The two predictive scenarios presented in Section 4 demonstrate the usefulness of the Parrett Mountain Model as a management tool. The scenario investigating the impacts of the City of Sherwood's Well Six on surrounding wells suggest that wells up to one km away from Well Six experience drawdown associated with groundwater extraction. The scenario investigating the effects of population growth on groundwater conditions gives some insight into hydrologic sustainability of Parrett Mountain groundwater resources as groundwater demand increases. Simulation results, based on assumptions of uniform population increases and uniform pumping distribution, indicate that an increase of approximately 8000 people to the study area would result in drawdowns of less than two meters throughout the model.

6.3 Future Work

To improve this groundwater model resulting in a more effective management tool and a greater understanding of fluid flow in the Parrett Mountain Region, the following three steps should be taken:

- Measure vertical hydraulic conductivity in order to improve estimates of leakance between layers;
- Measure streambed seepage rates in order to improve the understanding of surface water/groundwater interaction; and
- Construct a transient model to determine impact of storage capacity on future conditions.

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