SIMULATION OF GROUND WATER FLOW IN THE BOISE FRONT GEOTHERMAL AQUIFER

Prepared for:

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and

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ABSTRACT

Simulations of the Boise area geothermal aquifer were conducted to determine if increased injection at the City of Boise injection well would affect the temperatures and/or water levels in other primary geothermal wells. The simulations were conducted using the FEHM computer code (Zyvoloski et al., 1997) and the PEST parameter estimation code (Doherty, 2000).

The model area included the Harris Ranch, downtown Boise - Table Rock, and Stewart Gulch areas. The geothermal aquifer in this area consists of a complex series of tilted, fractured, faulted, volcanic rocks and interbedded sediments. Recharge was simulated as upward flow in fault areas and lateral flow into the model domain across the northeast boundary. Outflow included lateral flow across the southwest model boundary and discharge to wells.

The model grid represented a 3-dimensional flow system, with the finest discretization in the downtown Boise - Table Rock area. The model was calibrated to selected 1984 through 1992 water level data, and checked against 1984 through 2002 water level and temperature data.

Scenario simulations were run for 30 and 100 years from present, and consisted of (1) current pumping rates (base case), (2) a 50% increase in City of Boise withdrawals (with all increased withdrawals being re-injected), and (3) a 100% increase in City of Boise withdrawals (with all increased withdrawals being re-injected). Simulation results suggest that the hydraulic impact of increased pumping/injection, if any, will be minimal. Simulations did not predict appreciable water level declines at the observed wells associated with the increased City of Boise pumping and withdrawals over the base-case simulations. Simulations of increased withdrawals and injection showed minimal impact on inter-annual head fluctuation at the Boise Warm Springs wells. The simulations indicated a possibility of some long-term temperature declines (as much as 3ºC, or 6ºF, in thirty years). Of the wells included in the model, the only wells showing any thermal changes were the CM#1 and VA Production wells.

ACKNOWLEDGEMENTS

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This work has been guided, in part, by a Project Technical Committee. The committee consists of the following individuals:

- Chuck Brockway, Brockway Engineering (on behalf of the Boise Warm Springs Water District)
- Paul Castelin, Idaho Department of Water Resources
- Sherl Chapman / Steve Hannula, ERO Resources (on behalf of Harris Ranch)
- Kent Johnson, City of Boise
- Ken Neely, Idaho Department of Water Resources
- Deb Parliman, USGS
- Lee Liberty, Boise State University
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- Terry Scanlan, Scanlan Engineering (on behalf of the City of Boise)
- Ed Squires, Hydro Logic, Inc. (on behalf of the Terteling Family)

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1. INTRODUCTION

An extensive low-temperature geothermal aquifer system underlies the Boise area along the Boise Foothills – an area known as the Boise Front. Geothermal wells with elevated water temperatures (from about 80ºF to 170ºF) are clustered along the Boise Front in several areas, including Harris Ranch, downtown Boise - Table Rock (hereafter referred to as the "downtown – Table Rock area"), and Stewart Gulch (Figure 1-1). Thermal water from these wells is withdrawn for space heating, irrigation, and domestic purposes by a variety of private, commercial, and government users.

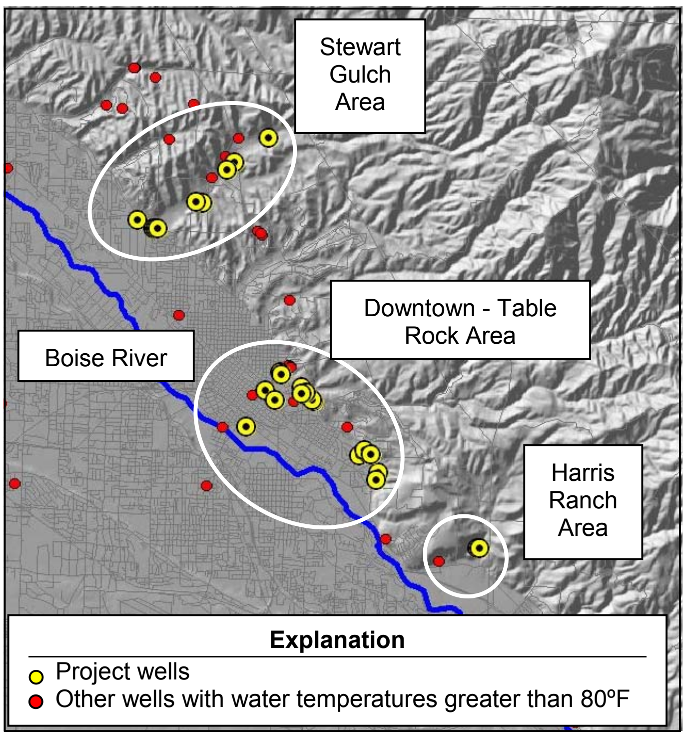


Figure 1-1: Map of the Boise Front area showing primary production areas and geothermal wells.

The motivation for this study arose from a request by the City of Boise to expand current levels of production (and subsequent re-injection) under existing water right permits. This production increase would be used to meet projected demand for geothermal heat in the downtown area. The proposed production increase led to concerns about possible water level and/or temperature changes in the geothermal system by other geothermal water users. The City of Boise and other major users therefore sought additional hydraulic, thermal, and hydrogeologic information about the geothermal aquifer system, and the development and implementation of a monitoring plan.

The primary focus of this study is on three areas: Harris Ranch, downtown – Table Rock, and Stewart Gulch (Figure 1-1). Wells in these areas generally represent the highest temperatures in the Boise Front geothermal system, generally share a common use (space heating), and have more available data than other warm-water wells. Users in these three areas expressed concern about possible effects associated with proposed increases in thermal water withdrawals (with re-injection) by the City of Boise.

1.1. Purpose and Objectives

The purpose of the overall study was to provide insight and tools for the long-term management of the Boise geothermal aquifer system. A computer model was constructed to help evaluate the feasibility of increased extraction and re-injection of geothermal water in the downtown Boise area. The purpose of the model was to simulate ground water flow and temperature in the Boise geothermal aquifer, and to evaluate various scenarios of increased geothermal production. Specific objectives of the modeling included the following:

1. Construct a model capable of matching transient water level and temperature observations in selected wells.
2. Use the model to evaluate potential hydraulic and temperature impacts on the Boise Front geothermal aquifer from a 50% increase in production by the City of Boise.

1.2. Report Organization

This report consists of (1) a general description of data used for the simulations, (2) a description of model construction, (3) a description of and results from model calibration, (4) results of scenario simulations, and (5) a summary with conclusions and recommendations. A companion report ("Hydrologic Conditions in the Boise Front Geothermal Aquifer," Petrich, 2003a) summarizes geologic and hydrologic conditions in the Boise Front geothermal aquifer. Conclusions from these reports also are presented in an executive summary (Petrich, 2003b).

1.3. Description of Data

Data used in this study were obtained from the Idaho Department of Water Resources (IDWR), U.S. Geological Survey, individual users, and private consultants. Most, if not all, of the production and water level data obtained from IDWR were collected by geothermal water users, private consultants, faculty, and students from the Boise State University (BSU) Geosciences Department, and others. Spatial data (obtained from IDWR) include political boundaries, hydrography, major roads, digital elevation data, and registered air-photo images. Well information was taken from Montgomery-Watson reports (1994a) and augmented with information collected from driller's reports and consultant's files (E. Squires, T. Scanlan). Water level data were obtained from IDWR. The sources of many of these data were geothermal users or their representatives. The IDWR data included water level data collected as part of a 1994 study (Montgomery-Watson, 1994a; Montgomery-Watson, 1994b). Production and re-injection data were obtained from IDWR. The City of Boise (Kent Johnson) supplied post-1999 production and re-injection data for the city system. The original sources of IDWR production data were geothermal users. A much more complete presentation of data used for model construction and calibration is found in the accompanying "Hydrologic Conditions in the Boise Front Geothermal Aquifer" report (Petrich, 2003a).

1.4. Previous Numerical Modeling

A two-dimensional numerical model of the Boise Geothermal Aquifer was developed by (Montgomery-Watson, 1994a; Montgomery-Watson, 1994b) and was used to address several aspects of geothermal resource management. Here, we briefly describe the modeling approach and summarize the major conclusions of the Montgomery-Watson study.

Montgomery-Watson constructed two models using the USGS MODFLOW (McDonald and Harbaugh, 1988) and HST3D (Kipp, 1986) codes. The isothermal model was constructed using MODFLOW, with cells representing 1200 ft^2. The total model domain covered approximately 27 mi^2. The northern and southern boundaries were assumed to be no-flow; the down-gradient (western) boundary was assumed to be constant head. Recharge was applied along the northeastern boundary.

Recharge rates in the model were based on expert opinion and modeling efforts in the Phase 1 study ((Montgomery-Watson, 1994a; Montgomery-Watson, 1994b). Hydraulic conductivities and storativity were adjusted during model calibration. The calibration targets were measured water levels in two wells (BLM and Kanta) for time period 1987-1992. The simulated heads matched the measured heads reasonably well, capturing the semi-annual variability (slightly over predicting winter water levels at the BLM wells and slightly under-predicting summer water levels at the Kanta well). The model also correctly captured long-term variations, including the decline measured after 1988-1989 and the increase in 1989-1992. To accomplish this calibration, a recharge rate of 2 million gallons per day was applied, and hydraulic conductivities in the downtown wellfield were kept fairly high (22-220 ft/day). Lower conductivities and storativity values typical of confined aquifers (10^{-4} or lower) resulted in over-prediction of annual variations in water levels. The reported calibrated storativity value was 3.5×10^{-3}, which the authors acknowledged to be somewhat high compared to expected values for a confined aquifer. Model performance was "verified" by comparing simulated and measured water levels at the BLM well for the 1979-1982 time period.

The thermal simulations were performed using HST3D. The parameters obtained from the calibration with the two-dimensional MODFLOW model were used to populate the three-dimensional (three layer) HST3D model. Boundary conditions between the HST3D and the MODFLOW models differed substantially because of differences between these codes. The HST3D model was only loosely calibrated to the hydrograph data.

The Montgomery-Watson simulations (Montgomery-Watson, 1994b) demonstrated that the measured temperature decline in Capitol Mall Well #2 (CM#2) from 1983 to 1993 (5ºF) could be explained by the impact of re-injection in Capitol Mall Well #1 (CM#1). The calibration to the limited thermal data was achieved by adjusting the thermal properties (presumably the thermal conductivity and the rock heat capacity) in HST3D. The thermal parameters required to achieve this match were not reported. The HST3D model was then used to predict a CM#2 temperature decline of 20ºF in 50 years and a VA Production temperature decline of 8ºF in 50 years. Almost coincident with the publication of the report in 1994, the temperatures in CM#1 stabilized along with the water level decline. From 1993 to present no additional temperature decline in CM#1 has been observed. Less severe future predictions would undoubtedly have resulted if these additional data had been available for the Montgomery-Watson model.

2. MODEL DEVELOPMENT

2.1. Introduction

A conceptual model forms the basis for numerical simulation of ground water flow. The conceptual model used for this numerical model of the Boise Front geothermal aquifer is presented in Petrich (2003a). The conceptual model includes a description of geologic setting, general aquifer characteristics, geothermal water chemistry, thermal properties, and detailed descriptions of geothermal aquifer characteristics in the downtown – Table Rock, Stewart Gulch, and Harris Ranch areas.

2.2. Code Descriptions

The modeling and calibration for this project was performed with a combination of the FEHM (Finite Element Heat and Mass) code (Zyvoloski et al., 1997) for the geothermal reservoir simulations and the PEST code (Doherty, 2000) for the parameter optimization. The FEHM code (Zyvoloski et al., 1997) was selected because of its ability to effectively model both isothermal and thermal ground water flow and 3-Dimensional (3-D) geometries. The FEHM code was developed at the Los Alamos National Laboratory, is publicly available[1], and is a principal code used in the Yucca Mountain High Level Waste Isolation Project. As such, it has undergone rigorous quality assurance (QA) testing (available on request[2]).

FEHM uses a control volume finite element method to form the discrete equations that represent the conservation of mass and energy for the simulated ground water system at each gridblock. The mathematical formulation is given in Appendix I. These discrete nonlinear equations are solved with a Newton-Raphson method for the outer nonlinear iterations and a Preconditioned Krylov method for the inner linear iterations. The control volume finite element method is identical to the familiar finite difference equations for the regular grid arrangement used for the simulations of this report. The code includes abstractions of the International Steam Tables to obtain fluid properties.

PEST (an acronym for "Parameter ESTimation") is a model-independent parameter estimator that is widely used in the calibration of environmental models, particularly ground water models. The latest version of PEST (Doherty, 2000) is particularly suited for use with the latest version of FEHM because of the special PEST interface in the latter program. This includes the ability to write model

[1] http://eesdb.lanl.gov/fehm/
[2] Contact G. Zyvoloski (gaz@lanl.gov)

outputs for which there are complimentary field observations in forms easily read by PEST, and an ability to provide PEST with internally calculated sensitivities. The latter functionality allows run-times to be reduced and/or more sophisticated parameterization methodologies to be employed than would otherwise be possible.

2.3. Model Units

The FEHM requires the use of consistent SI (metric) units. However, most ground water data collected in the study area (e.g., water level data, flow rates, recharge rates, stream fluxes, etc.) are recorded in English units. These data were converted to and reported in SI units for these simulations, unless otherwise noted. Spatial data covering the Boise Front area are maintained by IDWR in the Universal Transverse Mercator (UTM) Zone 11 and/or the IDaho Transverse Mercator (IDTM) coordinate systems, which are already based on SI units. Model results are reported in SI and English units. Time units for the model are days.

2.4. Model Grid and Boundary Conditions

Experience has shown that it is often preferable to construct a numerical model as simply as possible, and add complexity as needed. In this case, the model grid was a simple, discretized representation of a complex aquifer system. The geothermal aquifer system consists largely of fracture flow in four different geologic materials (Petrich, 2003a): (1) Tertiary basalt and interbedded and underlying sediments; (2) Tertiary siliceous volcanics (upper rhyolite) and underlying sediments; (3) Tertiary siliceous volcanics (lower rhyolite) and underlying sediments; and (4) Cretaceous granite of the Idaho Batholith. However, data accurately describing contacts between these aquifer units, especially for interbedded volcanics and sediments in the downtown – Table Rock area, are only available in some areas. The model was therefore constructed to represent the primary aquifers in each area as a single unit, with material properties varying by area. In the Stewart Gulch area, Tertiary basalt was represented as one aquifer unit. In the downtown – Table Rock area, the combination of Tertiary basalt and rhyolite zones (with interbedded and underlying sediments) were considered the primary aquifer unit. The aquifer unit simulated in the Harris Ranch area consisted of Cretaceous granite.

Quaternary sediments (Snake River Group) and Tertiary lacustrine sediments (Idaho Group) overlie much of the geothermal aquifer. Diffuse discharge may occur to these overlying aquifers, although the spatial distribution and flow rates, and the extent to which this occurs, is unknown. Upward movement of geothermal water above the Tertiary basalt probably is limited by precipitates that have formed as geothermal water encountered cooler conditions in overlying zones. It was assumed in these simulations that there was no diffuse ground water flow to or from the geothermal aquifers to overlying sediments. Thus, the top of the aquifer (a no-flow boundary) was assumed to be the upper surface of the Tertiary basalt (Figure 2-1).

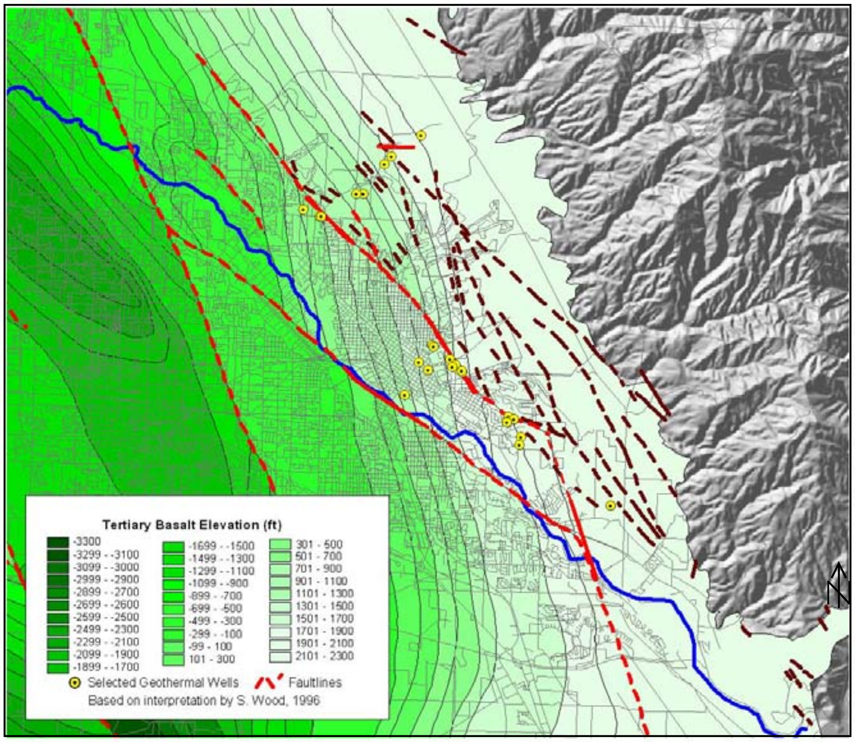


Figure 2-1: Approximate elevations of the upper surface of Tertiary basalt.

Discretization began by dividing the model domain into four primary blocks (Figure 2-2A). The blocks were defined, in part, by the presence of major faults. For instance, Block B, surrounded by the Foothills Fault, the Eagle – West Boise Fault and the Eagle – West Boise Extension, and the East Boise Fault (see Petrich, 2003a), contains the primary downtown – Table Rock wells. The aquifer in each block was assumed to have similar characteristics. The assumed aquifer thickness of each block (Table 2-1) was defined at each block corner (Figure 2-2C) based on average aggregate aquifer thicknesses (Table 2-2). The reference surface assumed to be the top of the aquifer sequence was the upper surface of the Tertiary basalt and or basalt tuff (Wood, 1996). Several wells in which open intervals did not correspond directly with the average aquifer zone depths were adjusted accordingly.

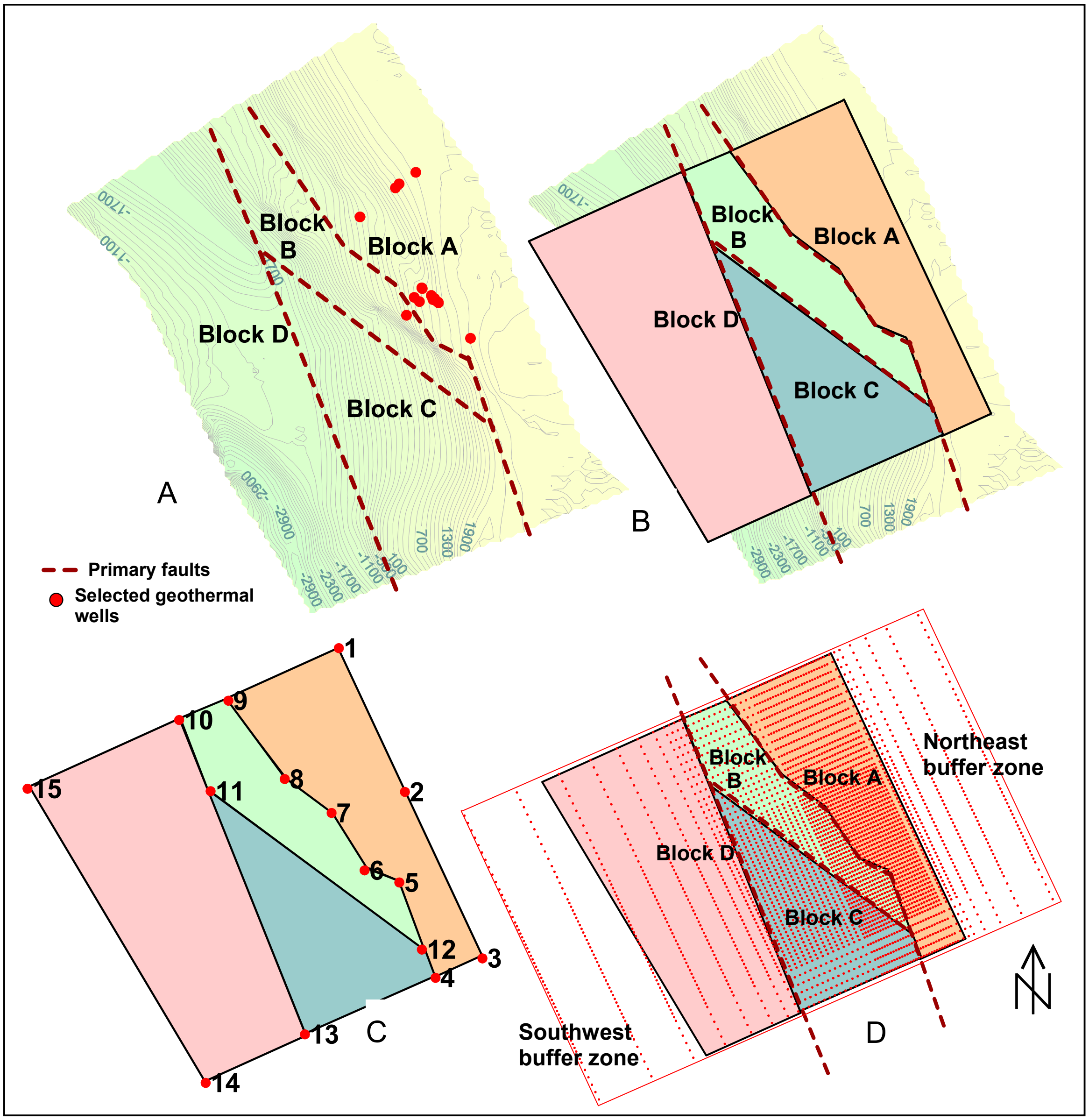


Figure 2-2: (A) Approximate elevations of the upper surface of Tertiary basalt and model block areas; (B) model blocks; (C) model block corners; and (D) model grid overlain on model blocks. Nodes outside the blocks are "buffer" cells.

The model grid was defined as a rectangular area (Figure 2-3), measuring 29.7 km x 18.9 km, extending to a depth of 2 km. The grid is most finely resolved near the downtown – Table Rock wells, because of the interest in simulating conditions in the vicinity of the City of Boise's proposed increased production and injection. The largest individual cells represent a volume of 300 x 3000 x 200 meters, and the smallest cells are 166 x 250 x 50 meters in volume. The grid was extended beyond the aquifer blocks to the northeast and southwest (Figure 2-2D) to reduce the possibility of boundary interference in the simulations. To accomplish this, two "buffer" units were included in the model (referred to as "northeast" and "southwest" hereafter). Because of the relatively large distance between these units and the area of interest, model calibrations were very insensitive to assumed characteristics of these units.

Model Block	Model Block corner ID	Estimated Elevations (ft)					Total assumed aquifer thickness (ft)	Notes
		Top of Basalt	Top of Upper Rhyolite Surface	Bottom of Lower Rhyolite Surface	Top of Granite	Model base		
A	1	2300			2200	1400	900	
	2	2300			2200	1400	900	
	3	2300			2200	1400	900	
	4	2300			2200	1400	900	
	5	2560	2462		2460	1660	900	(1)
	6	2600				1700	900	(2)
	7	1400				500	900	
	8	1163				263	900	(3)
	9	500				-400	900	
B	9	100	-500	-950		-1400	1500	(4)
	8	700	100	-350		-800	1500	(4)
	7	1500	900	450		0	1500	(4)
	6	1900	1300	850		400	1500	(4)
	5	2100	1500	1050		600	1500	(4)
	12	2300	1700	1250		800	1500	(4)
	11	-300	-900	-1350		-1800	1500	(4)
	10	-500	-1100	-1550		-2000	1500	(4)
C	11	-900				-2600	1700	
	12	2100				400	1700	
	4	2300				600	1700	
	13	300				-1400	1700	
D	10	-500				-2200	1700	
	13	100				-1600	1700	
	14	-3100				-4800	1700	
	15	-1500				-3200	1700	

(1) Used BWSWD#3 data; no basalt is present. Assumed that basalt surface is 100 feet above upper rhyolite.
(2) Used BGL#1 data.
(3) Used Silkey well data.
(4) These elevations were estimated on the following basis: average thicknesses of basalt, upper rhyolite, and lower rhyolite in block "B" wells were approximately 450 feet each. An average aquifer thickness of 1500 feet was assumed to accommodate some of the areas in which the aggregate aquifer thickness was more than the average thickness.

Table 2-1: Assumed aquifer elevations and thicknesses at model block corners.

	Thicknesses									
	Quaternary sediments and Tertiary lake sediments		Tertiary basalt and underlying sediments		Tertiary Siliceous volcanics (upper rhyolite) and underlying sediments		Tertiary Siliceous volcanics (lower rhyolite) and underlying sediments		Cretaceous granite of the Idaho Batholith	
Units	**feet**	**meters**	**feet**	**meters**	**feet**	**meters**	**feet**	**meters**	**feet**	**meters**
Average:	551	168	447	136	431	131	456	139	234	71
Maximum	1533	467	893	272	975	297	852	260	328	100
Number of project wells encounter-ing unit:	19		16		13		8		2	
Complete data in "BF Geothermal Stratsurfaces.xls."										

Table 2-2: Generalized average unit thicknesses based on selected Boise Front geothermal wells.

Lateral model boundaries were assumed to have either no-flow or constant head characteristics (Figure 2-3). The constant head boundaries (880 m and 780 m elevations at the northeast and southwest boundaries, respectively) were placed sufficiently distant from the area of interest (downtown – Table Rock) to minimize boundary influence on model results. The boundary head values were chosen so that, at least initially, the heads in the downtown – Table Rock area were reasonable compared to measured values and that the flow direction was consistent with observed head gradients (see Petrich, 2003a). The upstream head value (880m) is somewhat higher than estimates of historical heads in the aquifer prior to development (865 m – 870m). The selection of this upstream head value should not affect the results of this study, because predicted flux from the upstream boundary were primarily controlled by the permeability of the northeast buffer zone (a calibration parameter) during the model calibration process. Thus, as long as the flux direction is into the model from the upstream boundary, any reasonable value of fixed heads on the upstream boundary that is greater than the target data would be adequate. Similarly, the downstream boundaries need only to be less than target data. No-flow characteristics were assumed for the northwest and southeast boundaries. The bottom surfaces of primary faults were constructed as specified-flux boundaries. Collectively, these boundary conditions created a flow field characterized by upward flow along faults, lateral inflow from the northeast, and generally southwesterly flow to the outlet along the southwestern boundary.

All boundaries were assumed to be at a uniform and constant temperature of 80°C. This is somewhat inconsistent with observed temperature differences in geothermal wells, which range from approximately 30°C (85°F) to 80°C (175°F). However, this assumption was thought acceptable for three reasons. First, temperatures in the primary area of potential temperature changes (associated with the City's proposed production) are relatively uniform. Temperature data in the downtown area indicates that production temperatures have been constant, which suggests that the reservoir (at least in parts of the downtown – Table Rock area) is well mixed. Second, potential effects associated with increased production and injection in the downtown area associated with intrusion of cooler injected water can be evaluated as easily with a uniform temperature as with one with a thermal gradient. Third, the BGL and BWSWD wells produce water directly from the Foothills Fault; these wells have produced at constant temperature for many years under a variety of production conditions; the Foothills Fault therefore can be conceptualized as a source of constant temperature water.

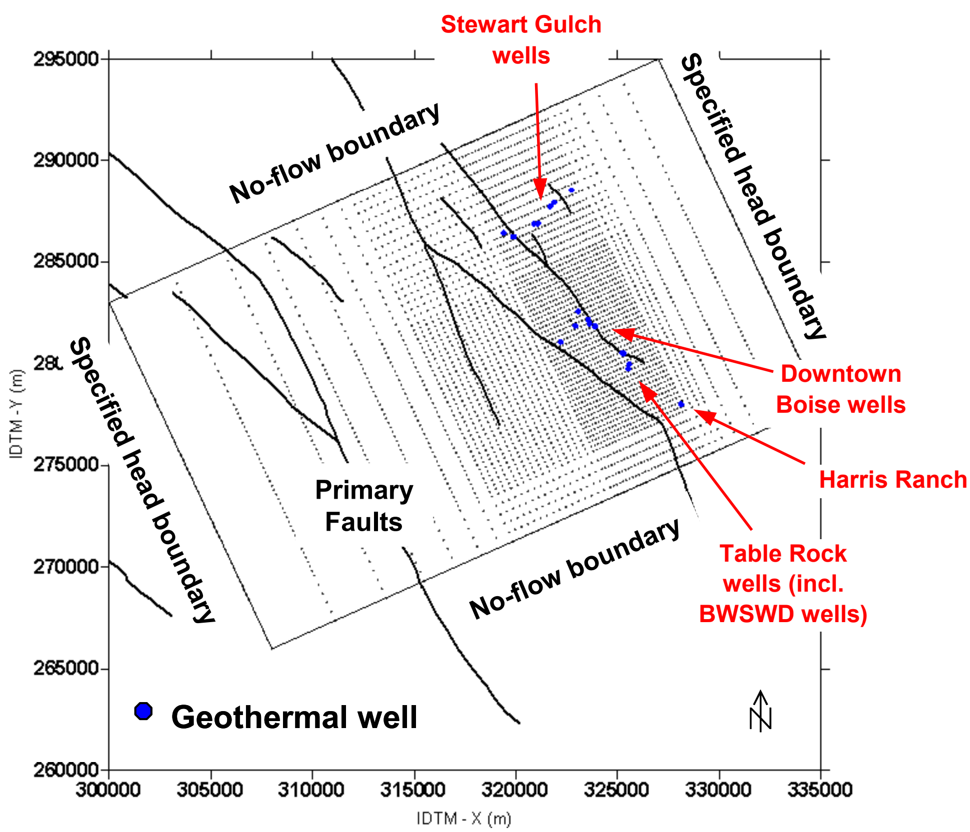


Figure 2-3: Model grid (plan view).

Primary faults were defined with separate material and boundary characteristics. Five major fault zones were delineated. All faults were assumed to have a vertical orientation, for ease of implementation and because there are insufficient data to justify a more complex geometry. Hydraulic properties were assumed to be uniform within and along each fault, with the exception of the Foothills Fault, which was divided into three distinct reaches.

The resulting zonation of the grid is shown along horizontal planes of differing depths in Figure 2-4. Because the fault blocks dip to the southwest only a portion of each block exists in each of the planes shown. The primary aquifer materials represented in Block A ("1" in Figure 2-4) consist of basalt and/or granite. The primary aquifer materials in Blocks B and C consist of basalt and/or rhyolite and interbedded sediments. Note the three different fault types for the Foothills Fault. Three cross-sectional views (Figure 2-5) are shown in Figure 2-6 through Figure 2-8. A detailed perspective of the model grid in the downtown – Table Rock area is shown in Figure 2-9.

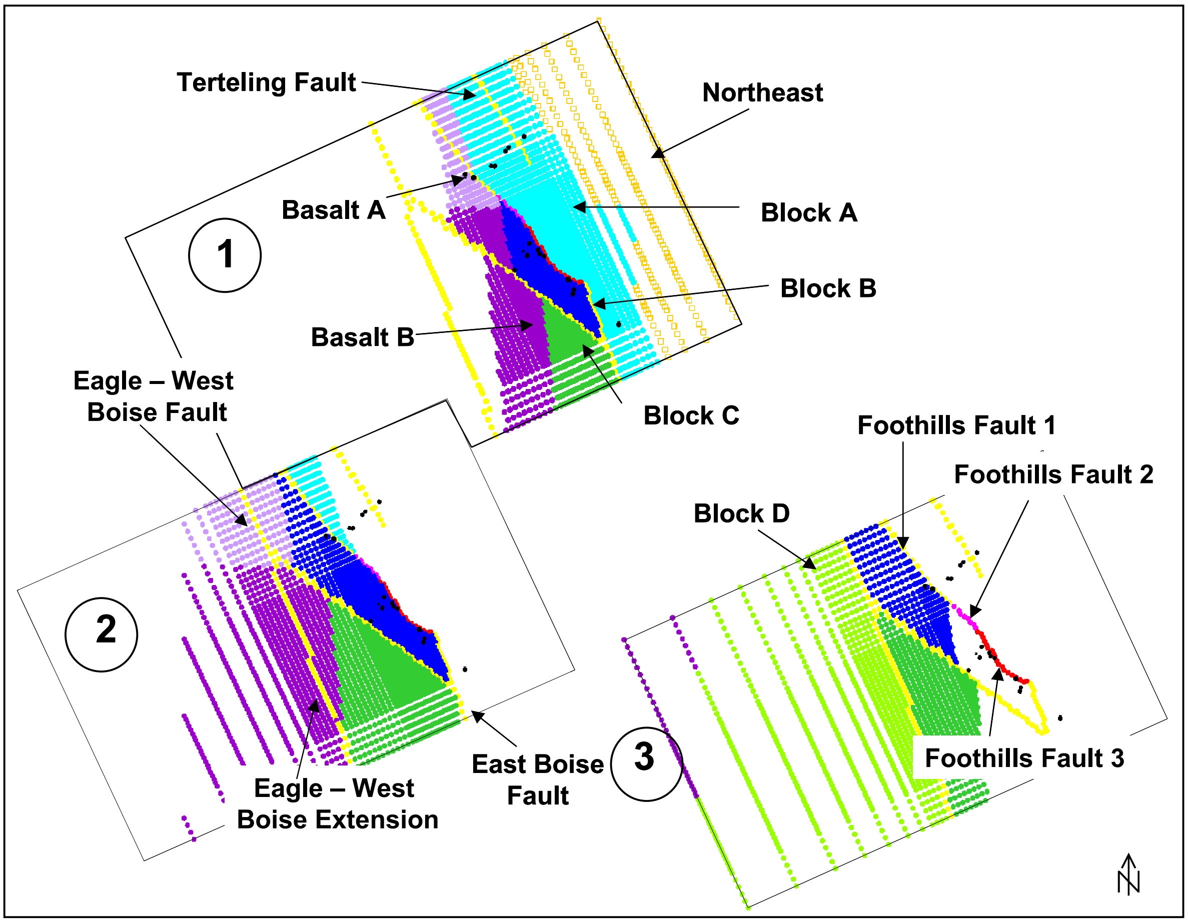


Figure 2-4: Grid representation of hydrostratigraphy at (1) 400 m above mean sea level, (2) at sea level, and (3) 400 m below sea level.

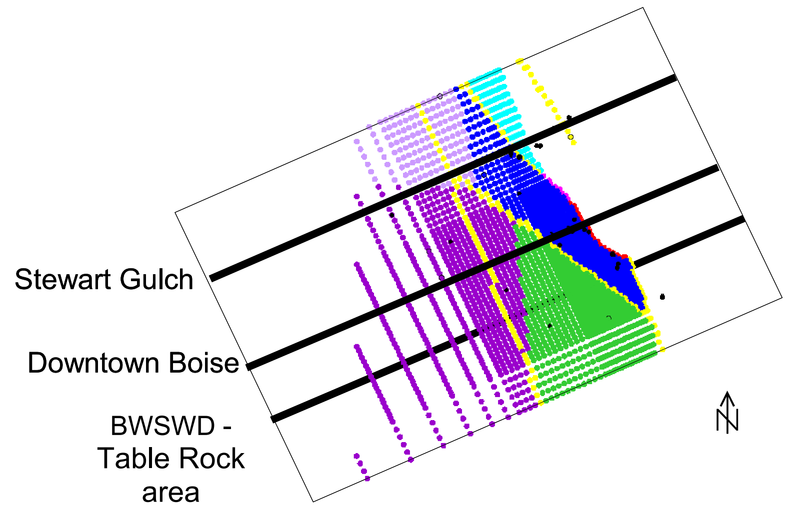
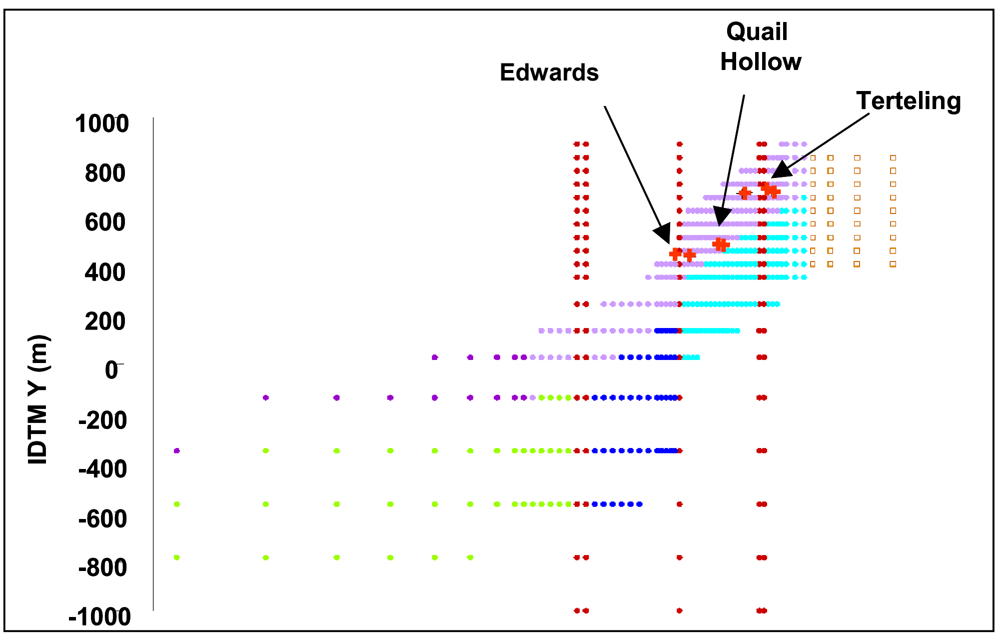
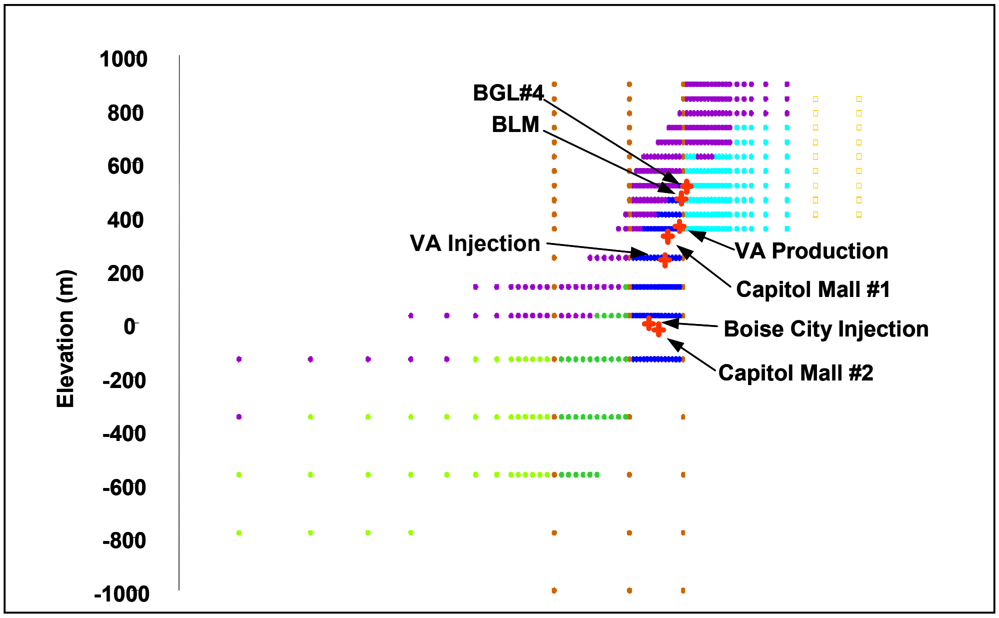


Figure 2-5: Locations of three grid cross-sections.



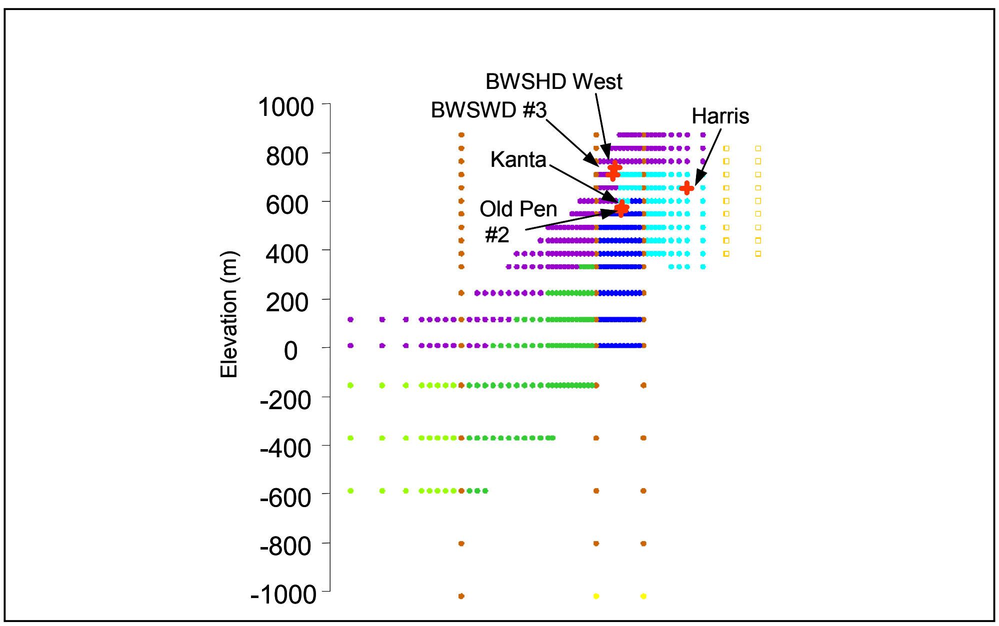
See Figure 2-4 for color references. Approximate well locations are shown at the midpoint of open interval.

Figure 2-6: Cross-section through Stewart Gulch.



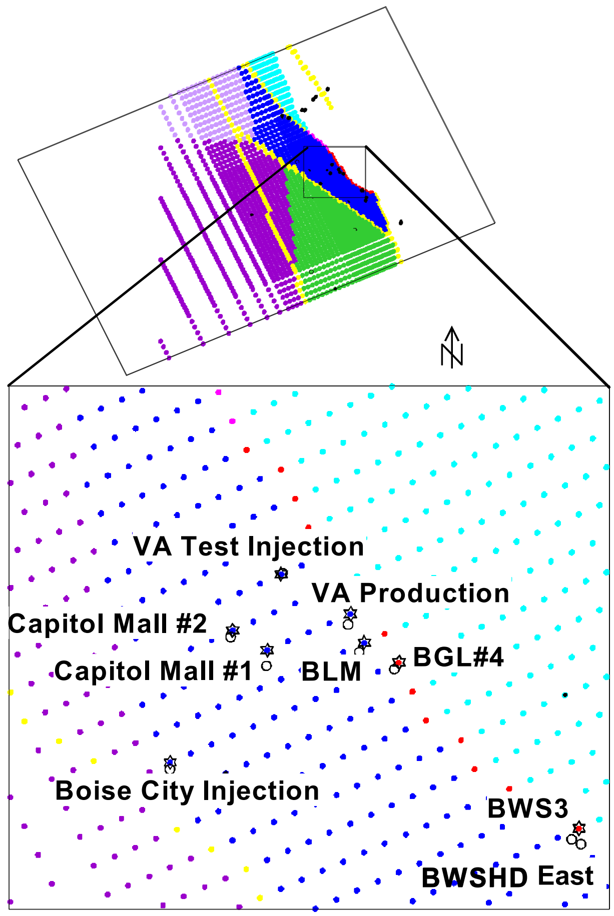
See Figure 2-4 for color references. Approximate well locations are shown at the midpoint of open interval.

Figure 2-7: Cross-section through downtown Boise.



See Figure 2-4 for color references. Approximate well locations are shown at the midpoint of open interval.

Figure 2-8: Cross-section through the BWSWD - Table Rock area.



Circles are well locations; stars are nodes where well is represented in the grid.

Figure 2-9: Close-up of numerical grid in the downtown Boise vicinity.

The three-dimensional model domain used for these simulations represents a 561-km^2 area to a depth of 2 km. A comparison of model grid characteristics with the previous model domain (Montgomery-Watson, 1994b) is provided in Table 2-3.

2.5. Initial Conditions

Initial conditions were specified to approximate aquifer conditions in 1983. The aquifer was assumed to be in steady-state equilibrium in 1983, having adjusted to long-term pumping from the BWSWD, Edwards, Silkey, and Flora wells.

The initial reservoir temperature was assumed to be a uniform 80ºC (176ºF). This assumption is consistent with observed temperatures in the downtown – Table Rock area. Assumed uniform temperatures were thought to be an acceptable initial condition because potential effects associated with increased production and injection in the downtown area can be evaluated as easily with a uniform temperature as with one with initial geothermal gradients.

Study	Dimensions	Area (km^2)	Thickness	Horizontal grid cell dimensions, (m)	Specified total inflow	
					MG/year	Kg/s
This study	3	29.7 X 18.9 (561.3 km^2)	2000m	3 km – 166 m	Calibrated parameter (see section 4.2)	
Montgomery Watson	2,3*	70	201m	402 m (1/4 mile)	730	88

Note: volume comparison = 2450:14 or 175:1
*The MODFLOW component was 2-D; the HST3D component was 3-D.

Table 2-3: Grid dimensions and comparison with the Montgomery-Watson model.

2.6. Production/Injection Wells

Production and injection wells were simulated as specified flux nodes (one node per well, placed at the approximate center of the open interval of the well – see Table 2-4). Fluxes were varied with time according to production/injection records. Annual pumping rates for the downtown – Table Rock area are listed in Figure 2-10, with tabulated values in Appendix B. Production estimates were made for the Stewart Gulch area (Figure 2-11), although these estimated rates are highly uncertain. Annual pumping data were thought to be sufficient for evaluating long-term trends (several decades), although one calibration was conducted using monthly data. For simulations presented in Sections 3 through 5, the "base case" production and injection rates in post-2002 years were assumed to be equal to 2002 rates.

Simulated water being re-injected into the aquifer was assumed to have a temperature of 45ºC. This is consistent with reported values of injection temperatures by the City of Boise ranging between 43-49ºC (110-120ºF) (Kent Johnson, *personal communication*, 2003). Some of the injection temperatures in the VA and Capitol Mall systems may vary more than this, depending on how much heat is being removed for heating. Well bore heating of the injected water was ignored, so the assumed injection temperatures may be low (several to tens of degrees Celsius, depending on the flow rate). A 45ºC injection temperature assumption therefore may make our predictions conservative.

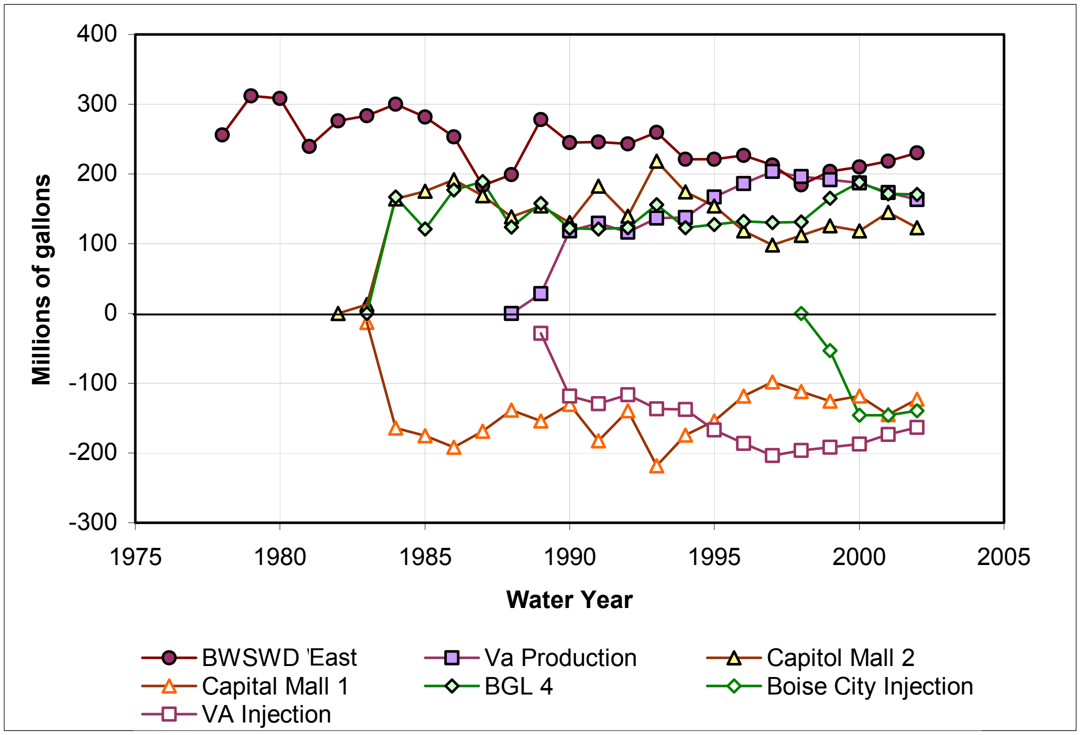
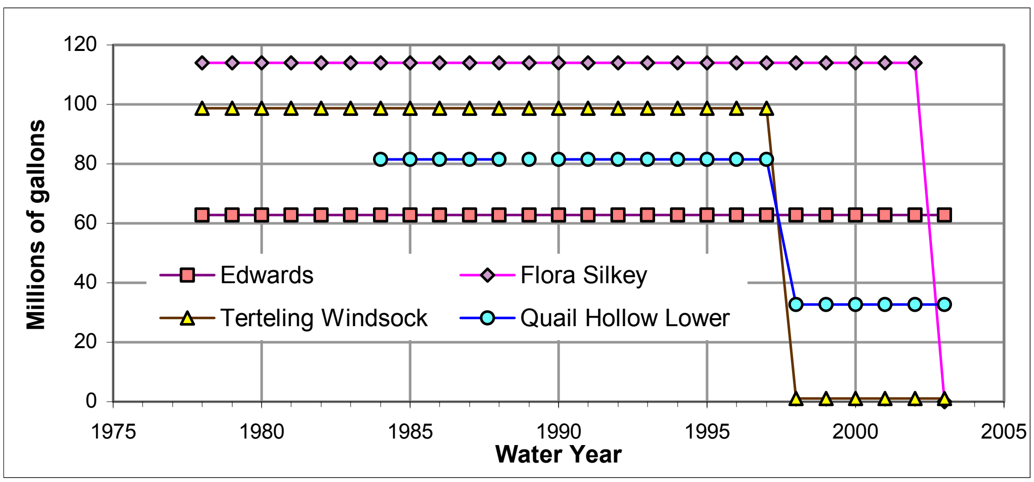


Figure 2-10: Annual production in the downtown – Table Rock area as represented in the model.



This figure does not include production from the Terteling Windsock well that began in 2002 to heat the Terteling greenhouses (using water rights formerly held by the Flora Company), nor does it include remaining minimal production at the Flora facility.

Figure 2-11: Production in the Stewart Gulch area applied in the model

Well Name	GeoWellID	X (UTM zone 11)	Y (UTM zone 11)	Z (m)	Top of casing (m)	Total depth (m)	Mid-point (m)	Unit
VA Test Injection	1674	323053.7	282571.3	829.5	269	378	323.5	Block B
VA Production	1671	323544.0	282180.5	843.5	336	386	361.0	Block B
Capitol Mall #2	1670	322661.3	282081.5	827.5	-96	48	-24.2	Block B
Capitol Mall #1	1663	322930.0	281863.3	829.6	174	296	235.0	Block B
BGL#4	1665	323890.3	281837.9	839.1	503	518	510.3	Foothill Fault 3
BWSWD[1] #2 (East)	1653	325289.7	280500.2	843.6	722	795	758.3	Foothill Fault 3
BWSWD #3	3322	325221.0	280536.1	850.3	671	786	728.8	Foothill Fault 3
Old Pen #2	1645	325515.5	279750.5	848.5	583	583	582.7	Block B
Boise City Injection	2670	322206.5	281071.1	820.4	-155	150	-2.6	Block B
BLM	1668	323627.2	281967.1	837.0	465	465	464.5	Block B
Kanta	1015	325569.7	279971.3	848.9	540	655	596.5	Block A
Harris East[2]	229	328120.4	278016.1	878.7	857	682	675.0	Block A
Edwards well	1704	319395.1	286425.6	815.7	451	451	405.0	Basalt A
Flora Silkey (shed)	1698	319858.0	286235.3	819.3	434	434	433.7	Basalt A
Terteling Windsock	1712	321689.5	287731.1	874.2	691	691	691.3	Basalt A
Quail Hollow Lower[3]	1710	320884.2	286885.7	844.4	480	480	480.2	Basalt A

[1]Boise Warm Springs Water District
[2]Actual elevation of open-interval midpoint is 769.9m; simulated elevation is lower to fit hydrostratigraphic unit delineation.
[3] Depth is unknown; simulated elevations were assigned according to depths provided for Edwards well.
All values given in meters.

Table 2-4: Well locations used for simulations.

3. Model Calibration

Model calibration is the process of adjusting model parameters so that simulated observations match measured or estimated observations as closely as possible. The goal of model calibration was to identify combinations of recharge rates and aquifer properties (permeability and storativity), neither of which is well defined by independent measurements, that could produce a reasonable match between measured and simulated heads (both spatial and temporal trends). The automated parameter estimation software PEST (Doherty, 2000) was used to achieve the best possible match between measured and observed values.

3.1. Parameters

Hydraulic parameters in this model consisted of recharge rates and aquifer intrinsic permeability and storativity in the primary aquifer blocks, primary fault zones, and buffer zones. It became evident early in the calibration process that there were more model parameters than could be supported by the calibration target dataset. Because of high correlation between parameters, PEST performed poorly and resulting calibrations were unacceptable if all parameters were allowed to vary freely. We therefore used an adaptive method of alternatively fixing insensitive parameters and freeing others during many calibration runs. Typically, PEST performed well if the total number of free parameters was reduced to four or five.

3.2. Observations

Calibration observations consisted of hydraulic head measurements. Two types of model calibration targets were used: steady-state heads and transient heads. The initial model calibration was performed using a relatively small subset of all of the available head data. The subset consisted of 1983 head data from three wells (BLM, Edwards, and BWSWD #2[3]) and transient data (1984-1992) from two wells (BLM and BWSWD #2). Model performance was judged against a larger dataset, consisting of transient data (1983-2002) for six wells (BLM, Edwards, BWSWD #2 and #3, Kanta, and VA Production) and a single measurement (2002) in the Harris West well (for well locations and hydrographs, see Petrich, 2003a). We acknowledge a potential tradeoff between using all of the available head data (which theoretically would have resulted in the lowest possible uncertainty in parameter values) versus withholding data from the calibration process to be used as a post-calibration check on model performance. We chose the latter approach to enable the testing of "predictions" using the larger dataset.

[3] Also known as the BWSWD-East well

Measured water levels at the BLM well (Figure 3-1) indicate four major stress periods in the system: (1) assumed steady-state, (2) declining heads because of increased production, (3) a new quasi-steady-state, and (4) increasing heads associated with re-injection by the City of Boise. During the calibration process, we attempted to force the model to reproduce general features of phases 1-3. The last phase, response to re-injection, was only simulated in a forward sense, apart from the calibration process.

We assumed that the measured heads in the Edwards, BLM, and BWSWD #2 wells in 1983 reflected a quasi-steady-state achieved in response to pumping at Boise Warm Springs and at Edwards well at that time. The assumption of steady-state hydraulic conditions may be questionable at Edwards well in 1983, because the estimated pumping rates increased approximately 2 years before 1983. The implications of this assumption are discussed in the results section.

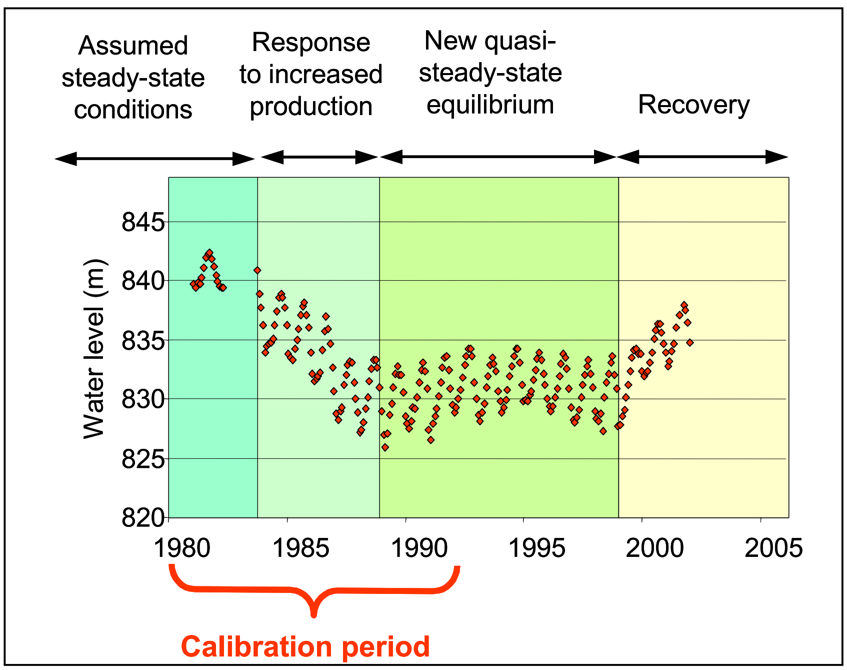


Figure 3-1: BLM hydrograph, showing responses to pumping phases and model calibration period.

Our priority in the calibration/verification process was to ensure that the model adequately reproduced measured temporal trends in response to stresses. This was because of the emphasis on exploring possible system responses to changes in production and injection. Matching spatial patterns in heads was given lower priority, partly due to questions about confidence in the spatial interpolation of head data. We assumed isothermal conditions (constant temperature of 80ºC) during model calibration to reduce computation time. We checked the validity of this assumption by running thermal simulations (with cooler re-injection water) using the calibrated parameters and confirmed that the calibration assumptions were upheld.

To focus on long-term trends, we used annual production records (Figure 2-10, Figure 2-11, and Appendix B). Single head measurements (Figure 3-2) were selected for each well to represent the recovered state after a season of pumping (i.e., "peak" water levels). The peak water levels typically consisted of late summer or fall measurements for the downtown wells and late spring water levels for the Edwards well. If there was question as to whether there were sufficient data to identify a peak water level, that year was not represented in the dataset. In some cases, this required making a judgment based on limited data. See Appendix C for individual records and inferred "peak" water levels.

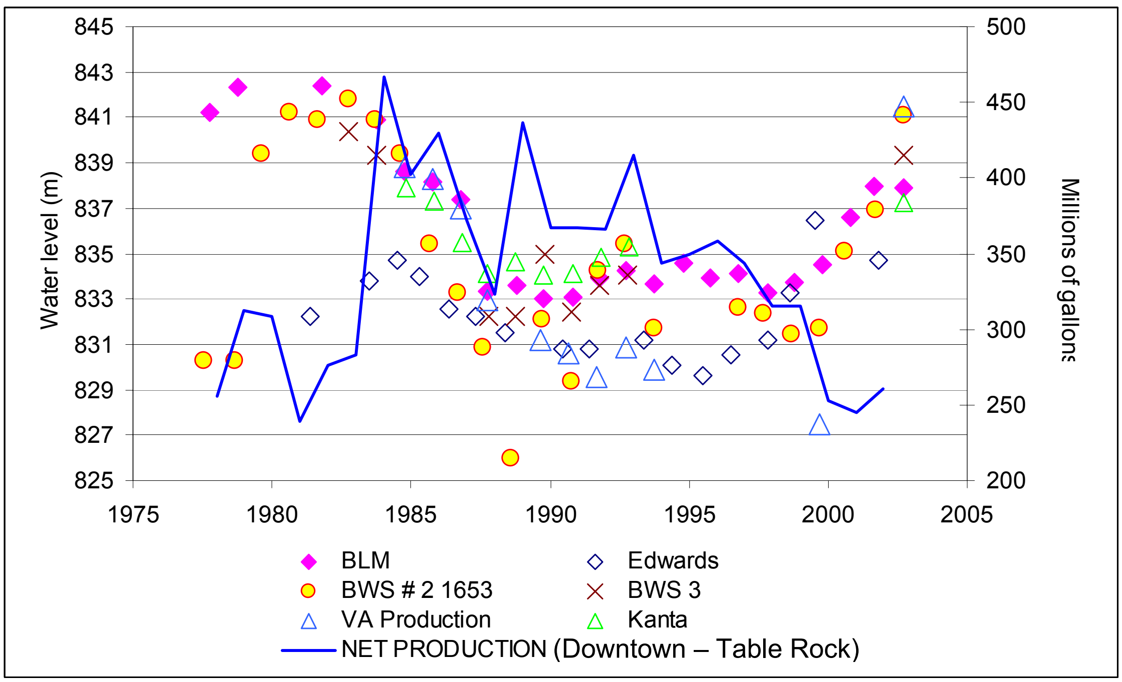


Figure 3-2: Annual "peak" water levels in selected geothermal wells, with net production in the downtown – Table Rock area.

Complete hydrographs from these wells (Petrich, 2003a) show some similar patterns. The hydrographs show a general decrease beginning in 1983 or 1984 (depending on the well location). The Edwards well hydrograph shows water level rises beginning in about 1996; water levels begin to rise in the downtown – Table Rock wells in 1999.

It is interesting to note that there are two years (1984 and 1989) in which there were significant increases in net production. The hydrograph responses to these net production increases were quite different, however. Water levels began a long decline in response to the first increase; water levels stabilize or increase in response to the second increase. As will be discussed in the calibration section, we were not able to simulate these two different responses.

This model could only be expected to reproduce water level trends in the measured hydrographs in a general sense; exact reproduction would at best be fortuitous. Sources of differences between simulated and observed values include model simplifications (i.e. homogeneous aquifer blocks, homogenous fault zones); low grid resolution (this is particularly important near a pumping well); errors with the conceptual model of geothermal ground water flow; erroneous water level and/or pressure readings; and erroneous and/or incomplete production records. Also, the model was not expected to simulate apparent incongruities (such as the differences in water levels responses to increased pumping in 1984 and 1989) when the reasons for the incongruities were not understood.

3.3. Approach

Model calibration was conducted in two steps. The model was first calibrated under isothermal conditions, followed by thermal calibration. The thermal simulations were conducted using calibrated hydraulic parameter values from the isothermal simulations. This was justified because the thermal model produced the same numerical measure of calibration as the isothermal model (within 5%). The initial calibrations were conducted in isothermal mode largely for convenience, as the FEHM code ran several times faster and used 1/3 the memory when run in isothermal mode. All of the future production scenarios were run in full thermal mode for both the hydrographs and thermal production histories.

4. Calibration Results

4.1. Comparison with Measured Hydrographs

The BLM well is one of the primary calibration targets because of its complete record, and because of its location and hydraulic connection to other downtown geothermal wells. Measured and simulated water levels in the BLM well beginning in 1983 are compared in Figure 4-1. The simulated 1983 water levels were assumed to correspond with the steady-state flow conditions (Figure 3-1); subsequent heads were assumed to be responding to annual transient production/injection rates (Figure 2-10 and Figure 2-11). The simulated heads in the BLM well reproduce some aspects of the measured trends very well: a steady-state initial head of 842 meters, an initial head drop of approximately 10 meters over 7 years (the calibration phase), and a final response to re-injection to 838 meters. A discrepancy between simulated and observed values occurs during the 1992-2000 period, when the net production increase in 1992 produced a simulated head decline of 2 meters, whereas measured water levels actually rose. This rise in BLM water levels despite a reported net production increase represents an aspect of the aquifer behavior that the model did not reproduce. Nevertheless, if model results were adjusted to account for discrepancies during this one period, the match during the response to re-injection phase would be very good.

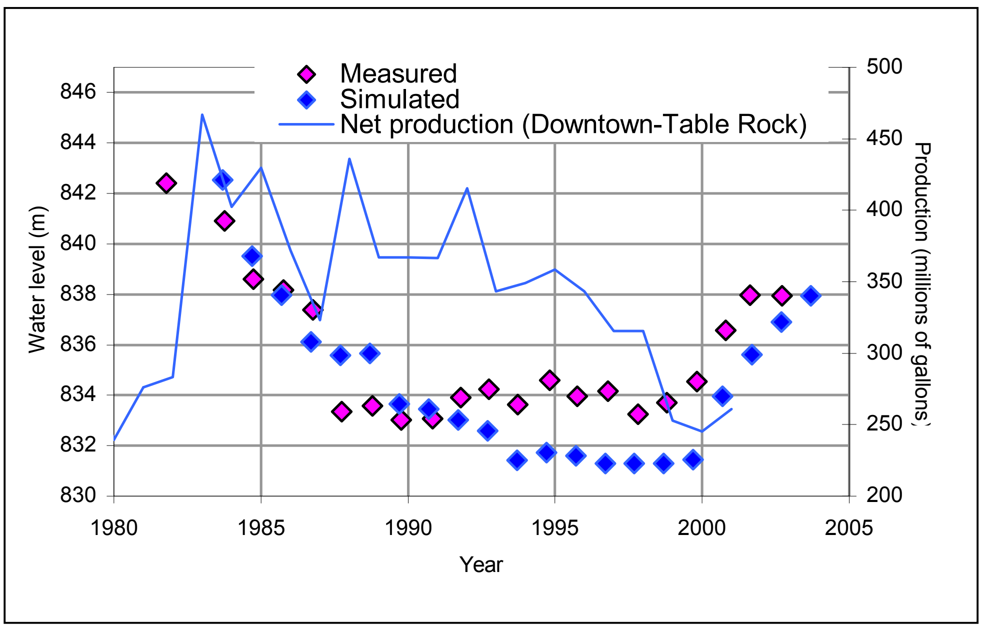


Figure 4-1: Simulated and observed water levels in the BLM well.

The comparison for the other hydrograph used in model calibration, BWSWD #2, is shown in Figure 4-2[4]. Again, general features of the hydrograph are reproduced by the model. However, the sharp decline and rebound in measured water levels in 1985 and 1990 is not captured by the model. During a period of sharp decline (1985-1987), production in the Boise Warm Springs wells decreased substantially (see Figure 2-10). Possible reasons for the apparent decline in water levels during a period of production decreases include (1) water level measurement errors, (2) production data errors, (3) local conditions (e.g., unrecorded pumping in nearby wells) not captured in model data, or (4) the decline in water levels represented a lag effect from the initiation of City of Boise production.

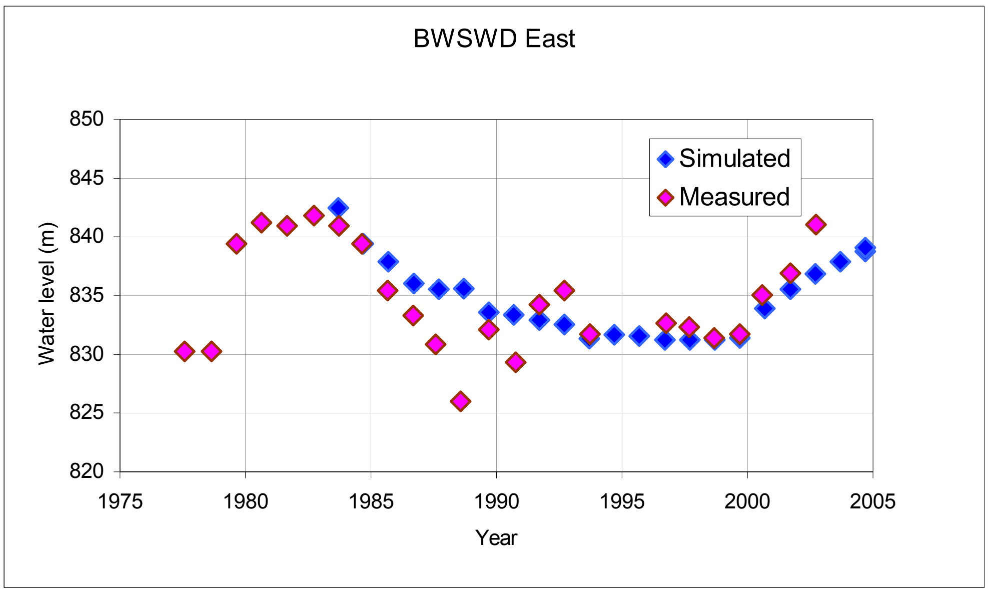


Figure 4-2: Simulated versus observed water levels in the BWSWD #2 (BWSWD-East) well.

Three other hydrograph comparisons are shown in Figure 4-3 through Figure 4-6. These wells were not used in the calibration process, but were tracked as a measure of calibration success. In all three cases, the model behavior tracks the measured behavior reasonably well. In the Kanta well, the model predicts a head decline from 1990-1995 when, in fact, measured heads rose. For reasons mentioned above in the discussion of the BLM well, there currently is no process accounted for in the model that would produce a head increase during this period.

[4] See Petrich (2003a) regarding discussion about the 1977 and 1978 "measured" data points.

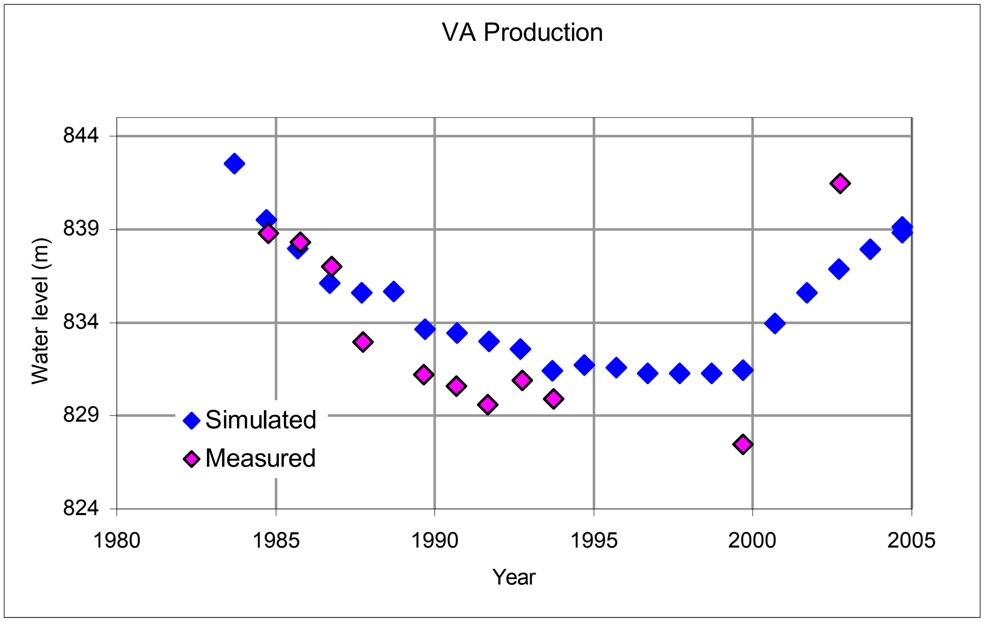


Figure 4-3: Simulated versus observed water levels in the VA production well.

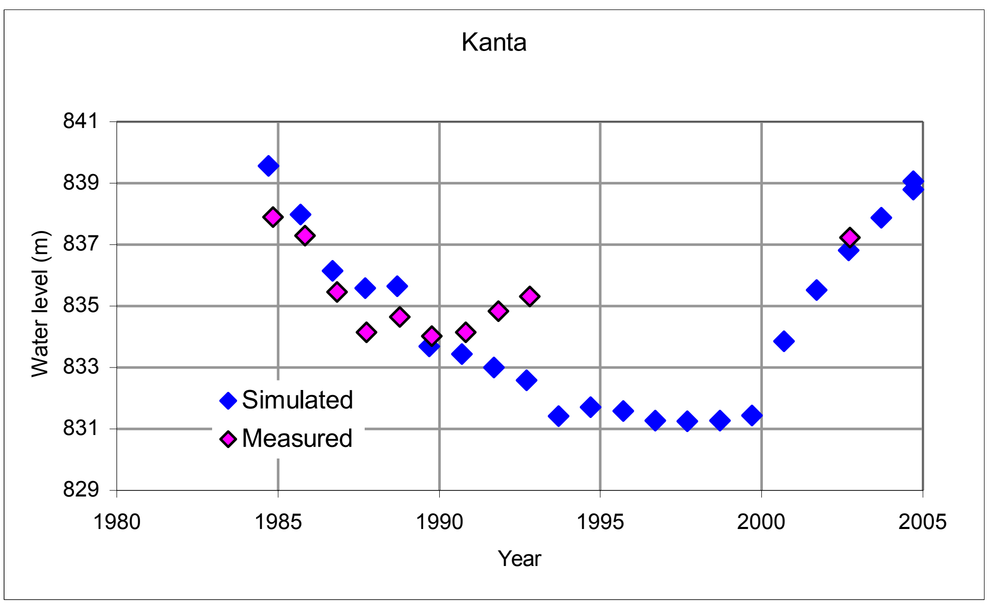


Figure 4-4: Simulated versus observed water levels in the Kanta well.

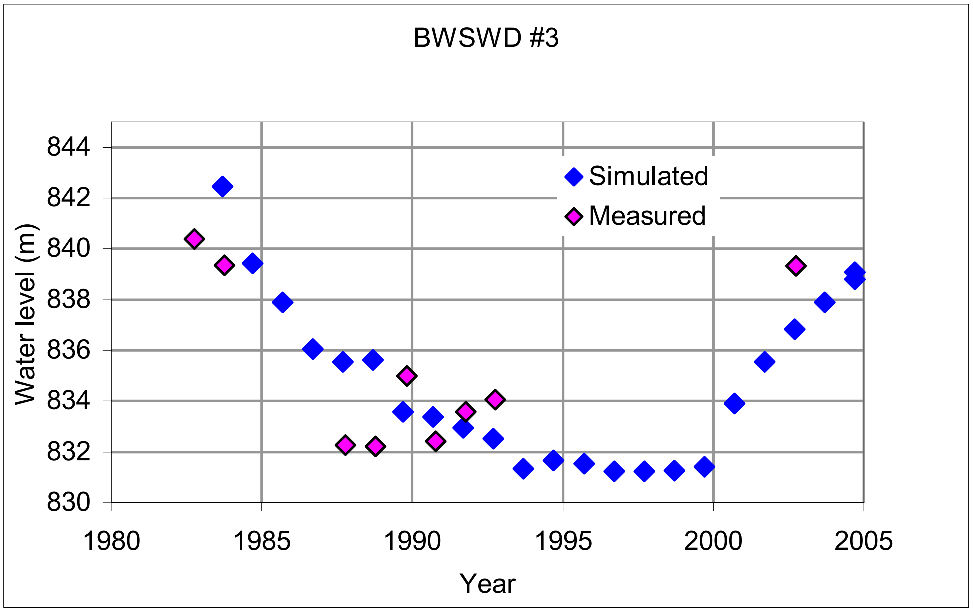


Figure 4-5: Simulated versus observed water levels in the BWSWD #3 well.

The Harris East well (Figure 4-6) was represented by a node in the model approximately 90 m lower than the actual well elevation because of the method used to define the top of the granite unit. Nonetheless, the original predicted head (Simulation "A") at the well was only 6 m too low, having dropped approximately 5 m from pumping in the downtown area. However, the original Block A permeability estimate was highly uncertain (K = -14.8 m^2)[5], so we did a sensitivity analysis for this well (Simulation "B"). For a smaller value of K (-15.8 m^2), the head at Harris East is somewhat higher and does not appear to respond to pumping in the downtown area. Because two different values of permeability provided equally well-calibrated models, we could draw no conclusions about the degree of hydraulic connection between the downtown – Table Rock area and the Harris Ranch area from these simulations.

Estimating the response (or lack thereof) of water levels in the Stewart Gulch area to stresses in the downtown – Table Rock area has been of interest in this study. Water levels and/or pressures in the Stewart Gulch area are influenced by local pumping conditions, based on general hydrograph patterns and information regarding use of wells (Petrich, 2003a). However, withdrawal data from Stewart Gulch wells are virtually non-existent. The numerical model cannot be expected to accurately simulate measured hydrographs if local production records are incomplete.

[5] Given as $\log_{10}$ values; see Table 4-1 for values in feet per day.

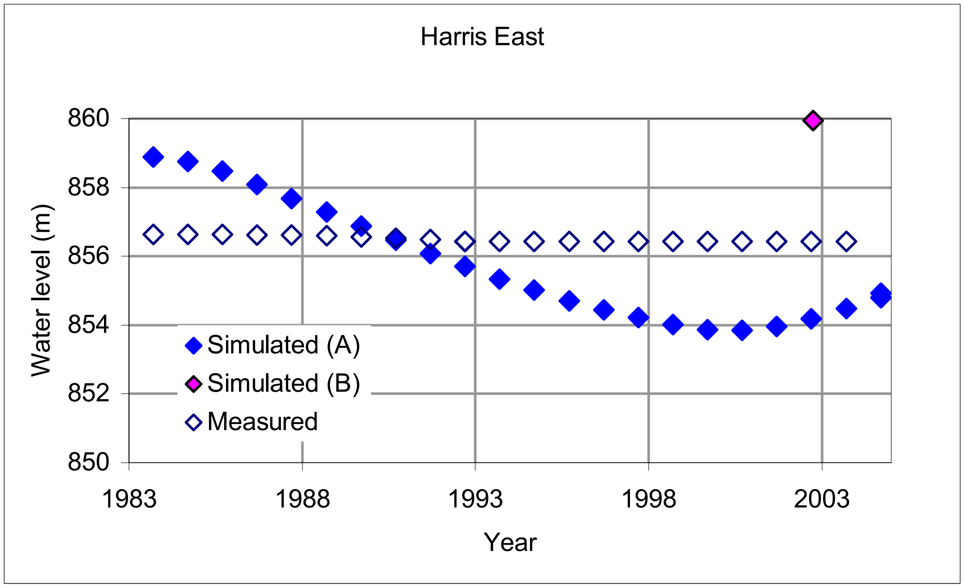


Figure 4-6 Simulated versus observed water levels in the Harris well.

However, the model can be used to evaluate a hypothetical response in the Edwards well to downtown stresses. This was done under two different scenarios: a hydraulically connected system (which assumes very high permeability values along the Foothills fault zone between downtown and Stewart Gulch) and a hydraulically disconnected system (which assumes that the Foothills fault zone has low permeability). It is important to note the connection between the downtown-Table Rock area and Stewart Gulch in the first scenario is imperfect because the two areas lie within different hydrostratigraphic units (Block B and Basalt North) and are separated by a low permeability zone within the Foothills Fault.

The two scenarios are presented in Figure 4-7. The "imperfect connection" (Simulation C) model reproduces the initial measured head well (Figure 4-7), but quickly overestimates drawdown. The hydraulic disconnect model (Simulation D) estimates the long-term declines (1985-1997) reasonably well, but under-estimates the measured head increases post-1997. One possible conclusion from this analysis is that the actual degree of connection may be between those simulated in these two scenarios. There is a high degree of uncertainty in this result; it should be re-evaluated when more complete production data in Stewart Gulch become available.

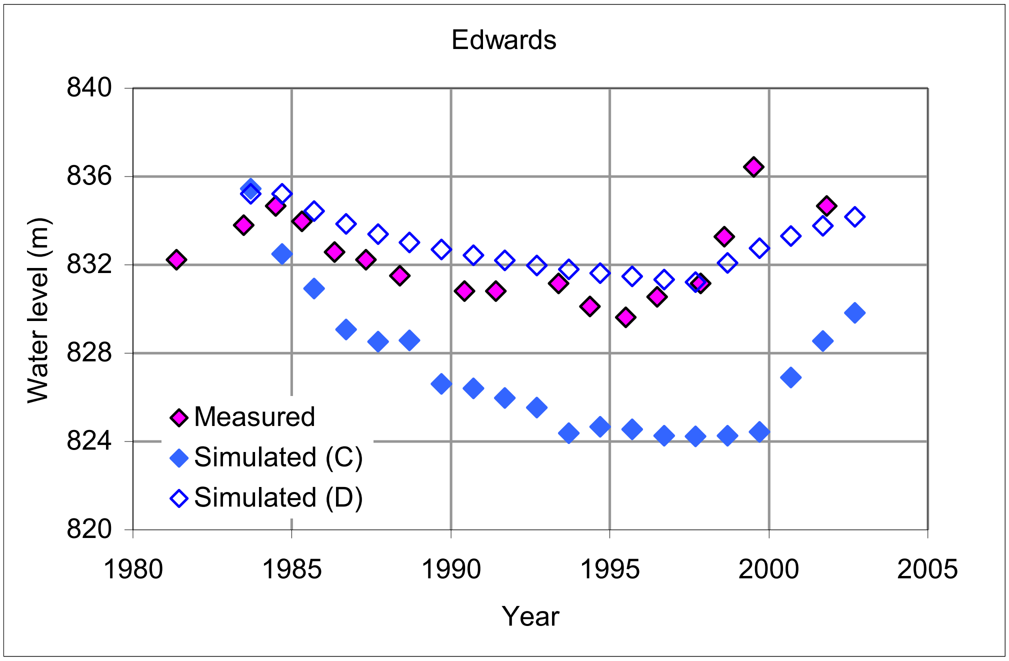


Figure 4-7 Simulated versus observed water levels in the Edwards well.

Figure 4-8 illustrates a comparison of measured versus simulated heads at the BLM well using monthly time steps. Because the aquifer parameters were derived from a calibration procedure that emphasized long-term responses, we would not expect this comparison to be perfect. The most significant discrepancy between the curves is that simulated inter-annual variability is less than that measured. Interestingly, the simulations reported by Montgomery-Watson (1994b) showed a similar difference (although somewhat less pronounced) using very different aquifer parameters. One possible explanation is that the grid resolution in both models is too large to accurately account for these short time scale responses. Nevertheless, since the emphasis of this study was to capture long-term responses of the aquifer to stress, we do not believe the discrepancies shown in this figure to be significant, as long as the model is used to simulate long-term responses to changes in stress.

4.2. Aquifer Properties and Fluxes

Table 4-1 lists the hydraulic properties resulting from the calibrated model. In general, the basalt units had low estimated permeability, the aquifer blocks had intermediate values, and the Foothills Fault zone had very high estimated permeability. The value of 87 ft/day in the downtown block (B) is somewhat lower than the high value of 220 ft/day that the previous modeling study reported (Montgomery-Watson, 1994b).

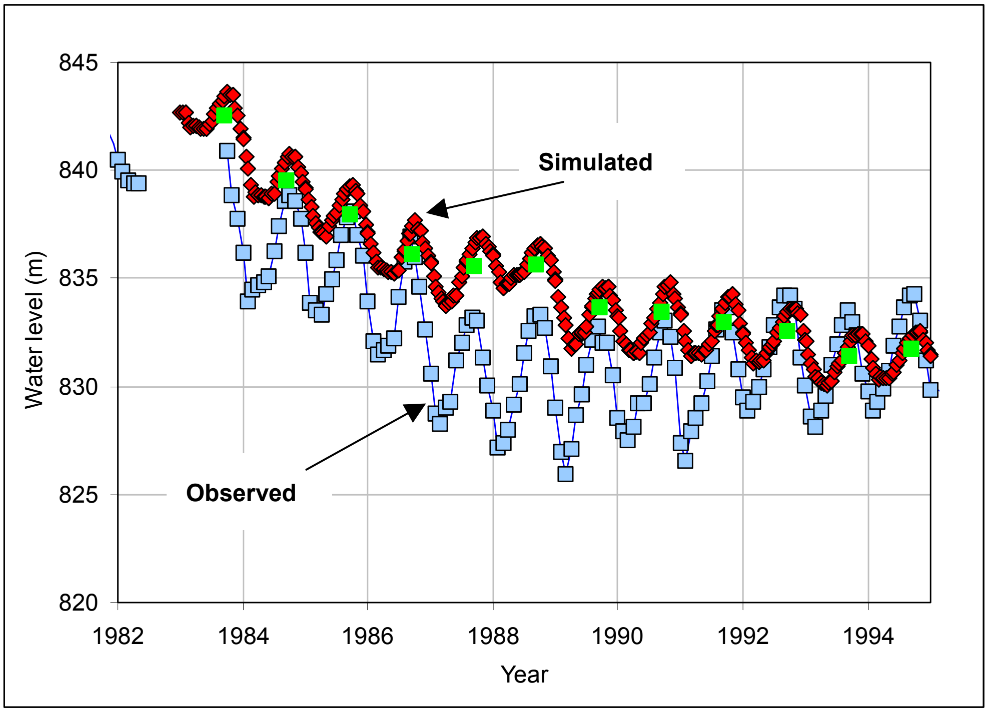


Figure 4-8: Simulated versus observed water levels in the BLM well using monthly data.

PEST consistently indicated that the calibration was very sensitive to three permeability parameters: the downtown block, the basalt unit in the vicinity of Stewart Gulch, and the northeast buffer zone. The first two are a reflection of the fact that most calibration targets were in these zones. The sensitivity to the upstream buffer zone is because this permeability controls the inflow from the lateral recharge boundary. Sensitivity to all other permeability parameters was relatively low.

The model calibration also was very sensitive to storativity parameters. Acceptable calibration could only be achieved with a storativity in Block B of $10^{-5.5}$ or lower[6]. Calibrated storativity values of the Foothills Fault zone were very low ($10^{-6.5}$). This low value is presumably the consequence of the location of the BWSWD wells in a high-conductivity flow conduit.

[6] Model results presented in this report assume $S = 10^{-7;}$ additional sensitivity runs have demonstrated that similar results can be achieved for values of S as high as $10^{-5.5}$.

	Unit	Permeability $\log_{10}$ (m^2)	Hydraulic conductivity (ft/day)
Boundaries	Southwest	-14.0	0.0278
	Northeast	-12.0	2.78
	Basalt B	-16.8	0.0000441
	Lower	-18.0	0.00000278
	Basalt A	-13.3	0.139
Aquifer blocks	A	-14.8	0.004409
	B	-10.5	88.0
	C	-15.0	0.00278
	D	-13.9	0.0350
Fault zones	Terteling	-11.9	3.50
	Foothills 1	-9.0	2780.0.
	Foothills 2	-10.2	176.0
	Foothills 3	-9.0	2780.0
	East Boise	-13.2	0.176
	Eagle – West Boise	-13.0	0.278
	Eagle – West Boise Extension	-14.0	0.0278
Storativity($\log_{10}$ dimensionless)		-6.5	

Table 4-1: Aquifer properties from calibrated model.

As described earlier, our conceptual model held that the Foothills Fault zone is a high-conductivity conduit for geothermal water. We were unable to estimate an intrinsic permeability for this fault zone using PEST, because of parameter correlation and because PEST typically reported low sensitivity for any intrinsic permeability parameter whose value became larger than $10^{-9}m^2$ (a relatively high value). This low sensitivity then compromised the performance of PEST in the calibration. We therefore fixed the permeability of the southern portion of the fault zone to $10^{-9}m^2$, which reflected our conceptual model and which allowed PEST to achieve a good calibration.

The calibration became very sensitive to fluxes in the Foothills Fault when the permeability of the Foothills fault zone was fixed, in part because of the constraints posed by the BWSWD-East well and its location in or near the fault zone. For the calibration results presented above, the total influx was approximately 308 million gallons per year (mga), with approximately half entering the model domain upward along the Fault zone (specified flux) and the other half entering as inflow from the lateral recharge boundary (constant head). In the process of testing an alternative conceptual model (see Section 5.3), we found that calibration results were insensitive to the *source* of the inflow (fault zone vs. lateral inflow); but the predicted *total* inflow was very well constrained by the calibration given the current conceptual model.

Figure 4-9 illustrates the water budget for the calibrated model. The upward fluxes along faults were specified and were constant (approximately 308 MG/yr). The majority of this flux was along the Foothills Fault zone. The inflow from the upgradient boundary was approximately equal to this, ranging from ~250 MG/year to 318 MG/yr during the peak net production time period. The total inflow (~ 600 MG/yr) is somewhat less than the total recharge assumed by the previous modeling study (730 MG/yr), even though the model extent is significantly larger. Total simulated recharge was approximately equal to net production in most years.

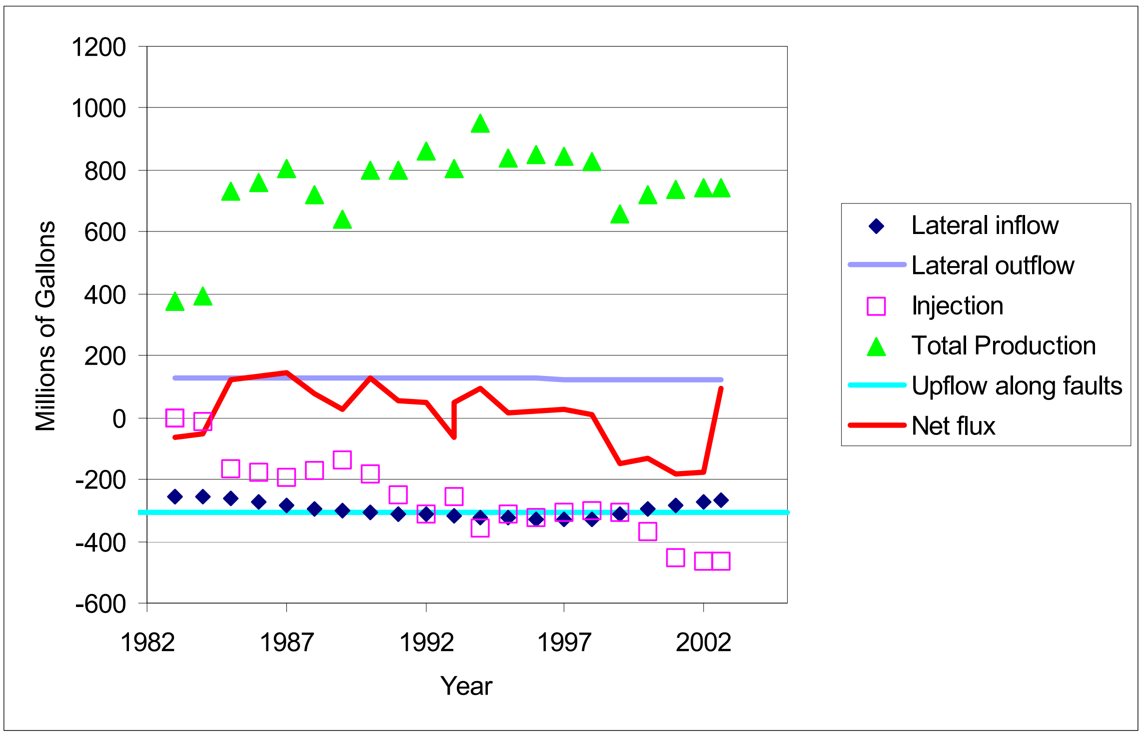


Figure 4-9: Water budget elements.

4.3. Thermal Calibration Results

The base case thermal simulation was defined with the model conditions given in Table 4-2 and with a specified temperature bottom boundary condition. The initial and boundary temperatures reflect assumptions discussed previously in this report. In general, specific heat for volcanic reservoir rocks range from 800 to 1100 J/kg-

°C and rock densities varied from 2000-2700 kg/m^3 (Tsang and Pruess, 1987, and references within). Lacking site-specific data, properties on the low end were used in the simulations as this gives the least thermal capacitance and would therefore give conservative results. The thermal conductivity is also on the low side of literature values (Brodsky et al., 1997; Sass et al., 1988), which range from 2.0-4.0 W/m-°C.

Parameter	Value
Rock Specific Heat (J/kg-°C)	800
Rock Density (kg/m^3)	2000
Thermal Conductivity (W/m-K)	2.0
Initial Reservoir Temperature (°C)	80
Boundary Inflow Temperature (°C)	80
Fault Inflow Temperature (°C)	80
Re-injection Temperature (°C)	45

Table 4-2: Parameter values for the base-case thermal simulation.

The thermal simulations produced only a very slight thermal response in CM#2 and no other thermal responses after the 23 years of simulation. The simulated temperature change in CM#2 after 20 years of production is about 0.3ºC (0.5ºF). This compares with the previous modeling study (Montgomery-Watson, 1994b) of 5ºF in 10 years.

Because the only simulated change in production temperature was in CM#2, it was of interest to investigate the extent of thermal changes near the injection well CM#1, the likely source for the temperature change. Figure 4-11 shows the simulated present day temperature in the reservoir at a depth of CM#1. It appears that the thermal perturbation from CM#2 extended almost to CM#1 (Figure 4-10).

However, CM#2 is approximately 200 m (600 ft) deeper than CM#1. It appears from the simulation that cooler water injected into CM#1 sinks near the injection – production loop (Figure 4-11). Although CM#2 is not in the plane of the contour map in Figure 4-11, its place in the fringe of the thermal perturbation is evident. Thus, the temperature decline experienced in the CM#2 well between 1984 and 1992 may be the result of mixing in the Capitol Mall injection – production loop more than a thermal decline in the larger Boise Front geothermal aquifer.

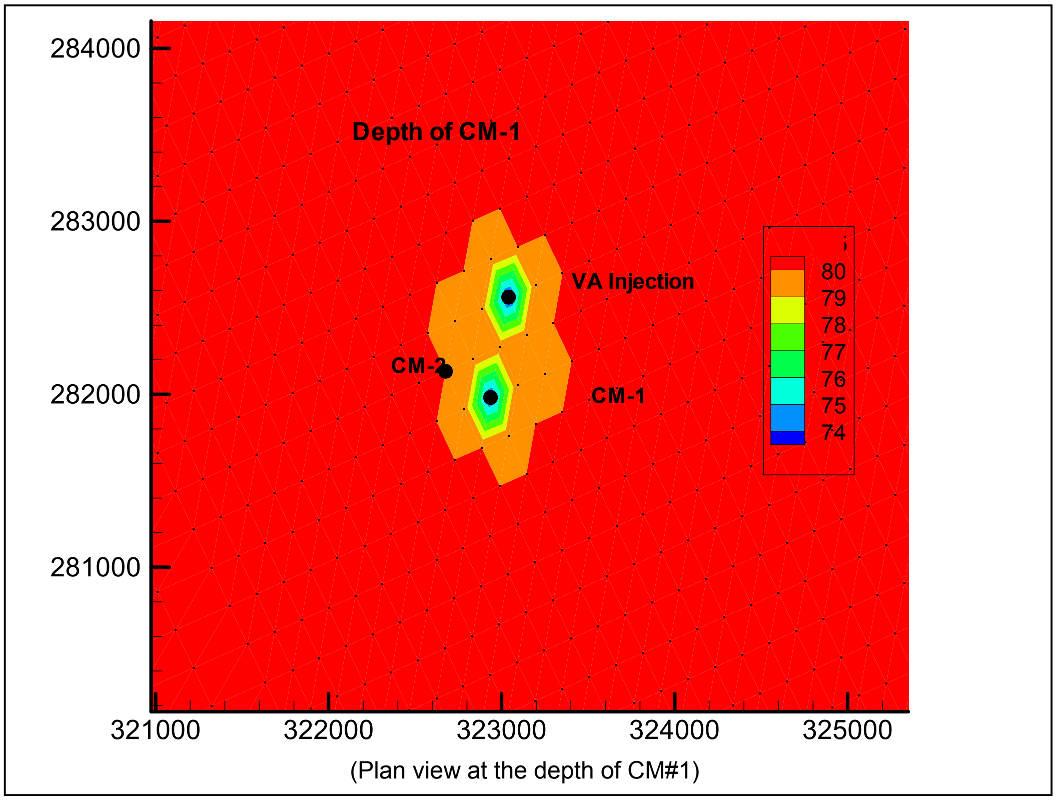


Figure 4-10: Present day simulated temperature changes (ºC) around the injection point of the well CM#1.

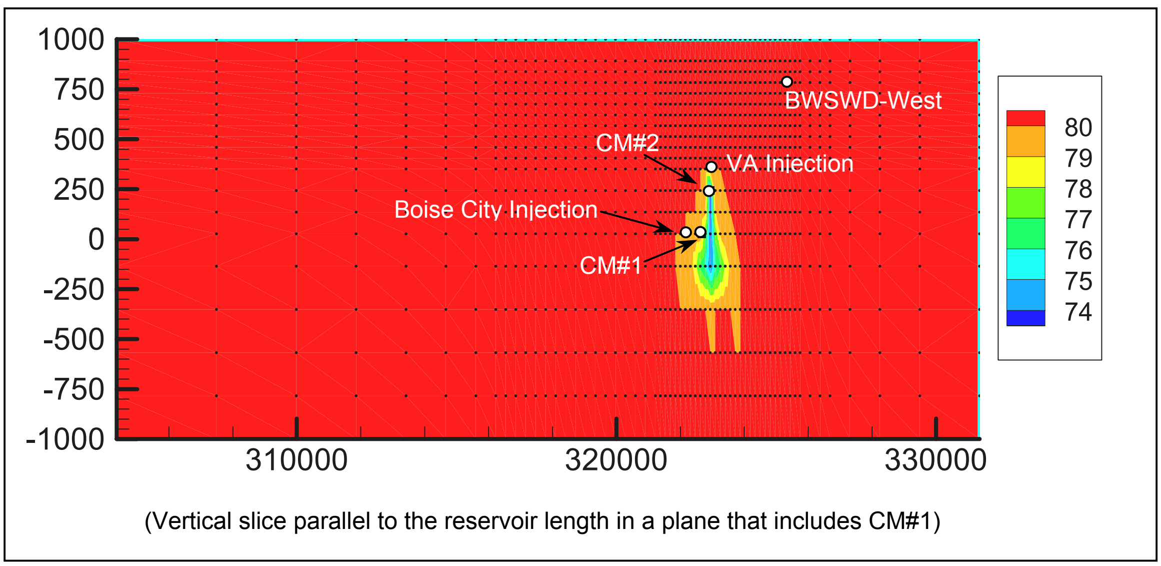


Figure 4-11: Present day simulated temperature changes (ºC) around the injection point of the well CM#1.

5. SIMULATION OF INCREASED PRODUCTION/INJECTION

5.1. Introduction

A number of simulations were conducted to evaluate possible hydraulic and temperature impacts on the geothermal system associated with increased City of Boise pumping and injection. It was assumed in all three scenarios that current production by other geothermal users would continue at current rates. The first scenario was the "base case," assuming no increased production by the City of Boise. The second and third scenarios simulated City of Boise production increases by factors of 1.5 and 2.0, respectively. It was assumed in these scenarios that the City of Boise would re-inject all of the increased production. Simulations including the increased pumping and re-injection were conducted for 30 and 100 years into the future.

5.2. Scenario Results

Results from the predictive simulations are presented in Table 5-1 and Table 5-2. The base case simulations indicated slight water level increases in most of the wells (Table 5-2) and a slight temperature decrease in CM#2 (Table 5-2). The simulation results of increased City of Boise production (150% and 200% of the 2002 rate, with all production increases being re-injected) are also given in Table 5-1. The water levels, although increasing (see below), do not change appreciably from the base case. A small thermal impact at CM#2 and a very small impact at the VA production well were simulated at 30 years in the future. No other production wells showed any appreciable change in thermal behavior. With the City of Boise production at 2.0 times the current rate, the simulated temperature impact at CM#2 after 100 years (Table 5-1) is approximately 10ºF (6ºC).

For illustration, simulated pressure, head, and temperature values for CM#2 are shown in Figure 5-1. Pressure at the well's open interval remains relatively constant, as head values slowly increase beginning in 1999, and temperature decreases.

Sensitivity calculations were carried out with respect to thermal conductivity and the bottom boundary conditions. The calculations are summarized in Table 5-2. Only minimal impact was seen in regard to the thermal conductivity. The trend was that the thermal interaction increased slowly with increasing thermal conductivity. The change of bottom boundary condition from specified temperature to no-heat-flux also impacted the thermal regime. As expected, the no heat flux bottom boundary produced the most thermal impact, although this was only 1ºF (0.5ºC) more than the specified temperature in 100 years.

	Head (m)			Pressure (mpc)		
	Present Conditions	**30 Year Prediction**	**100 Year Prediction**	**Present Conditions**	**30 Year Prediction**	**100 Year Prediction**
Current Production						
BWSWD - East	837.912	844.005	845.707	10.15	10.208	10.224
BLM	839.435	845.498	847.129	13.256	13.314	13.330
VA Production	840.002	846.054	847.701	14.292	14.35	14.366
Edwards	832.612	838.721	840.484	13.707	13.765	13.782
CM#2	842.091	848.199	849.95	17.404	17.463	17.479
1.5 X Current Production						
BWSWD - East	837.905	843.962	845.661	10.15	10.207	10.224
BLM	839.424	845.449	847.069	13.256	13.314	13.329
VA Production	839.993	846.007	847.648	14.292	14.35	14.365
Edwards	832.609	838.686	840.465	13.707	13.764	13.781
CM#2	842.088	848.162	849.918	17.404	17.462	17.479
2.0 X Current Production						
BWSWD - East	837.897	843.931	845.603	10.15	10.207	10.223
BLM	839.413	845.413	846.999	13.256	13.313	13.328
VA Production	839.983	845.972	847.584	14.292	14.349	14.365
Edwards	832.606	838.663	840.436	13.707	13.764	13.781
CM#2	842.084	848.137	849.876	17.404	17.462	17.479
1.5 X Current Production (High Thermal Conductivity)						
BWSWD - East	837.901	843.96	845.669	10.15	10.207	10.224
BLM	839.42	845.447	847.079	13.256	13.314	13.329
VA Production	839.989	846.005	847.658	14.292	14.35	14.365
Edwards	832.605	838.683	840.466	13.707	13.764	13.781
CM#2	842.087	848.165	849.934	17.404	17.462	17.479
1.5 X Current Production (Zero Bottom Heat Flux)						
BWSWD - East	837.9	843.933	845.582	10.15	10.207	10.223
BLM	839.419	845.413	846.955	13.256	13.313	13.328
VA Production	839.987	845.969	847.531	14.292	14.349	14.364
Edwards	832.604	838.665	840.424	13.707	13.764	13.781
CM#2	842.083	848.139	849.877	17.404	17.462	17.479

Table 5-1: Summary of simulated head and pressure changes associated with increased City of Boise pumping and injection.

	Temperature (ºC)		
	Present Conditions	30 Year Prediction	100 Year Prediction
Base Case			
BWSWD - East	80.00	80.00	80.00
BLM	80.00	80.00	79.93
VA Production	80.00	79.99	79.67
Edwards	80.00	80.00	80.00
CM#2	79.05	77.87	76.59
1.5 X Current Production			
BWSWD - East	80.00	80.00	80.00
BLM	80.00	80.00	79.89
VA Production	80.00	79.98	79.61
Edwards	80.00	80.00	80.00
CM#2	79.05	77.79	76.36
2.0 X Current Production			
BWSWD - East	80.00	80.00	80.00
BLM	80.00	80.00	79.87
VA Production	80.00	79.98	79.55
Edwards	80.00	80.00	80.00
CM#2	79.05	77.69	76.12
1.5 X Current Production (High Thermal Conductivity)			
BWSWD - East	80.00	80.00	80.00
BLM	80.00	80.00	79.87
VA Production	80.00	79.98	79.62
Edwards	80.00	80.00	80.00
CM#2	79.02	77.79	76.47
1.5 X Current Production (Zero Bottom Heat Flux)			
BWSWD - East	80.00	80.00	80.00
BLM	80.00	80.00	79.93
VA Production	80.00	79.98	79.61
Edwards	80.00	80.00	80.00
CM#2	79.05	77.71	75.90

Table 5-2: Summary of temperature changes associated with increased City of Boise pumping and injection.

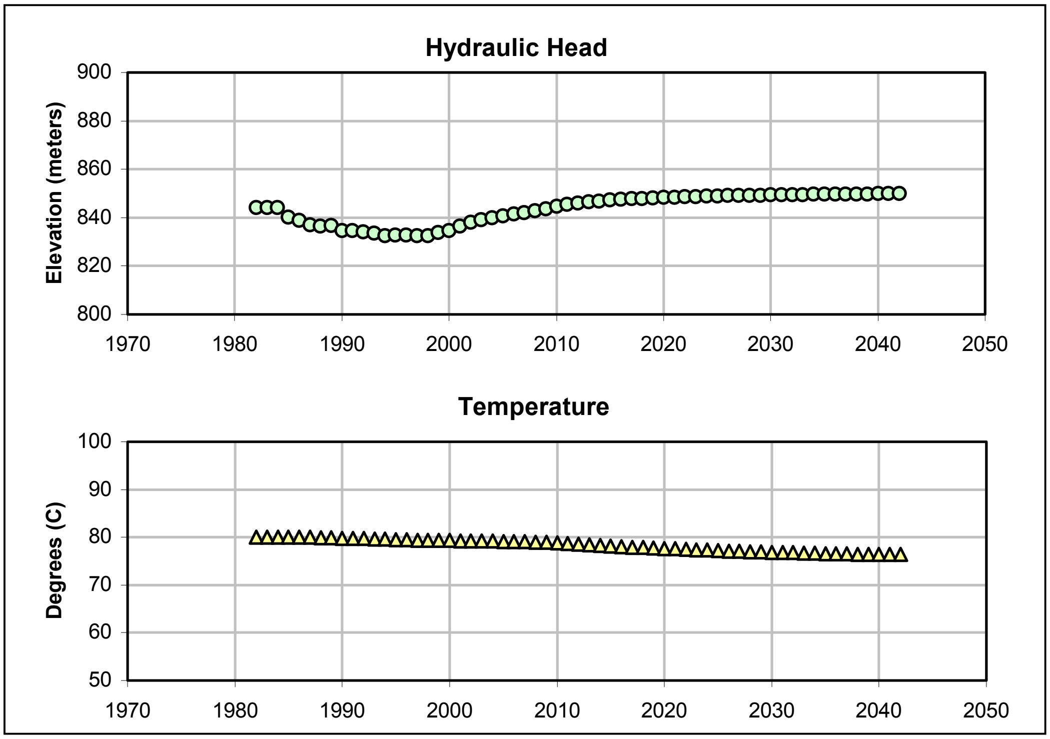
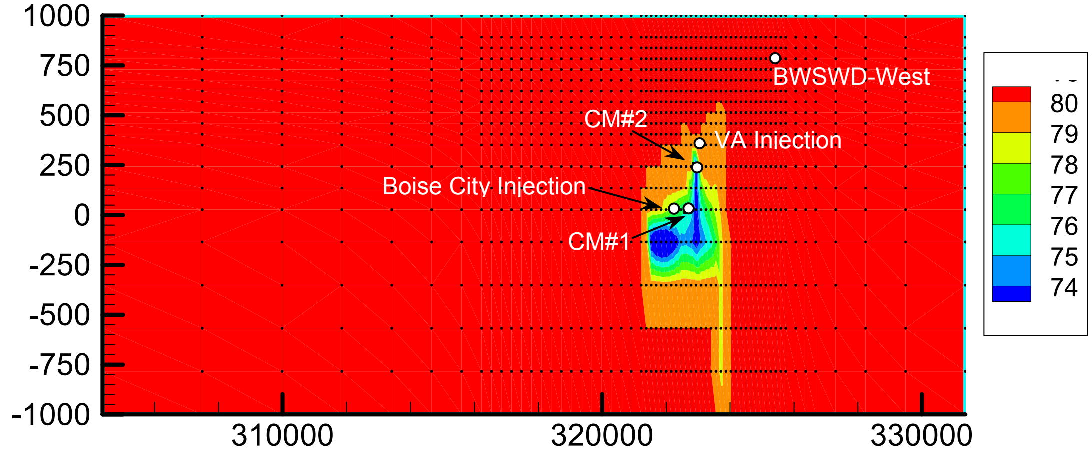


Figure 5-1: Simulated head and temperature in CM#2 (150% current City of Boise production with corresponding injection).

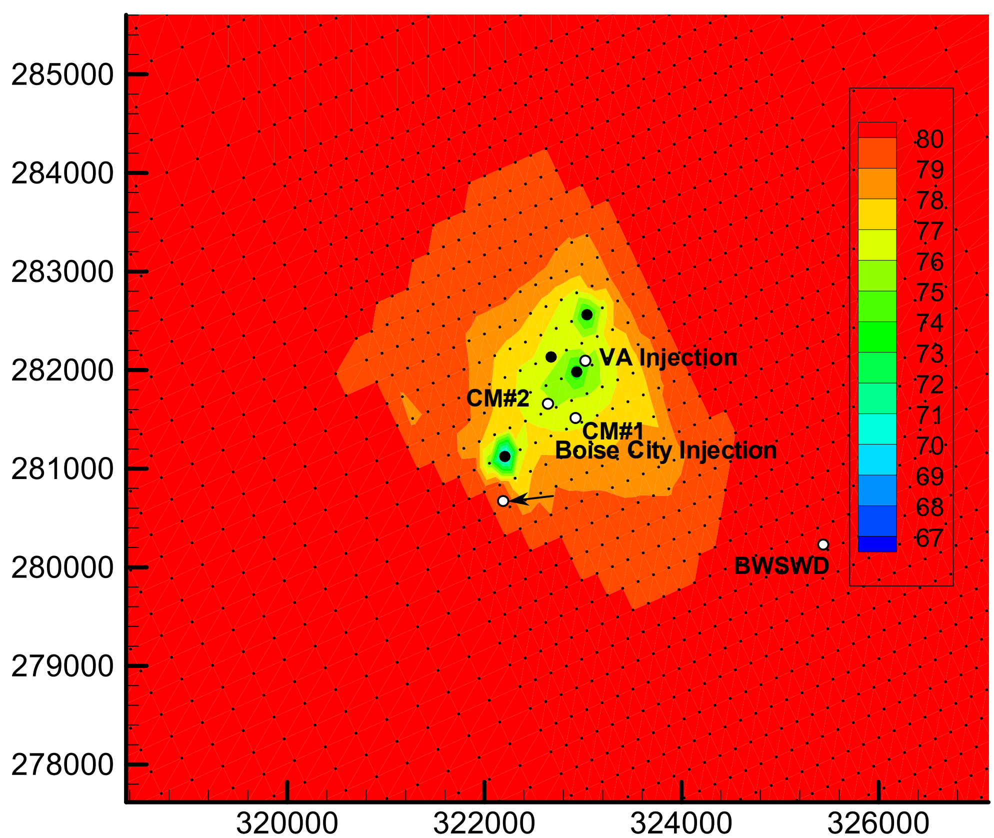
Because of the predicted thermal impact at CM#2, simulated temperatures on the vertical slice shown in (Figure 4-10) are presented for the predictive scenario based on a 50% increase in City of Boise production (with associated injection). After 100 years, (Figure 5-2) it is evident that the thermally perturbed region around CM#1 has grown, but only modestly. The blue perturbation represents the impact of the City of Boise injection.

It is of interest to consider the areal expanse of the impact of the increased City of Boise production and re-injection (Figure 5-3). The depth of the cross section is that of the City of Boise injection well. The thermal signature is pervasive throughout the downtown area, although small in magnitude. The CM#1, CM#2, and VA production wells are also shown in Figure 5-3; however, only CM#2 is located at about the same depth as the City of Boise production wells.



Cross section shows vertical slice parallel to the reservoir length in a plane that includes CM#2

Figure 5-2: Simulated temperature changes (ºC) around the injection point of the well CM#1 after 100 years of production.



(Plan view at the depth of the injection point)

Figure 5-3: Simulated temperature changes (ºC) around the injection point of the City of Boise production well.

Finally, the hydraulic head contours created by the additional production and injection are shown in Figure 5-4. Simulated head values in the region around the BWSWD West well shows a small head drop that indicates, at least locally, that the fault may not be able to supply all the water needs for the BWSWD #2 well. This suggests that there may be a component of production at the BWSWD wells that originates from the downtown production area. This part of the production would tend to draw the cooler injected water towards the BWSWD wells. However, it likely would take several centuries for the cooler pulse to reach the well.

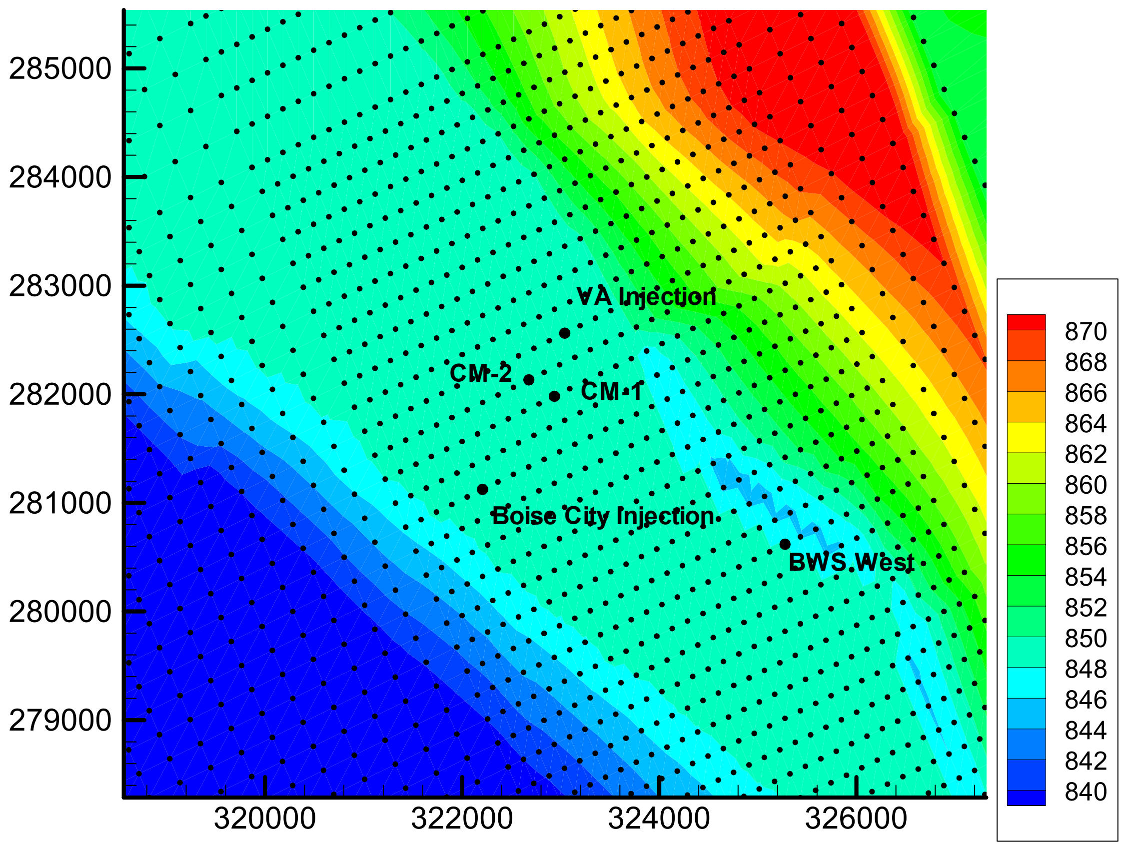


Figure 5-4: Simulated hydraulic head values (meters) associated with a 50% increase in City of Boise production (with corresponding re-injection).

5.3. Impact of Increased City of Boise Production and Injection on Seasonal Head Variations at Boise Warm Springs Water District Wells

There is some question regarding whether increased production/injection by City of Boise would increase the amplitude of seasonal fluctuations in water levels at the

BWSWD wells. This model was not designed to accurately simulate water levels in any well during pumping (because of grid dimensions) and therefore should not be used to predict seasonal fluctuations at the Boise Warm Springs well. Even at a non-pumping well (e.g., BLM well), the model underestimates the amplitude of seasonal variations by a factor of two, because the grid resolution is too coarse to adequately address questions of relatively short temporal and spatial scales.

To circumvent these model limitations, we simulated seasonal variations in water levels pre-2002 and post-2002 in the BWSWD area assuming the BWSWD wells were not pumping, and assuming a 1.5 increase in production (with corresponding re-injection) by City of Boise post-2002. The additional proposed production from the City of Boise added about 16 percent to the total production from the aquifer (105.6 kg/s Vs. 88.9 kg/s).

This simulation showed that in 2002, water levels fluctuated at Boise Warm Springs by approximately 0.6 m over the span of one year. After 2002, when simulated production/re-injection rates by City of Boise were increased by a factor of 1.5 over 2002 rates, water levels fluctuated at Boise Warm Springs by approximately 0.7 m, an increase of 16%. This simulation also suggests that increases and decreases in historical production have produced similar effects on seasonal variations in water levels in the Boise Warm Springs area, and that future impacts on this area will be within the range of those experienced in the past.

These results should be considered qualitative, given the limitations of the model to accurately represent the effects of short-term fluctuations in water levels.

5.4. Alternative Conceptualization

Several simulations were conducted to evaluate the model sensitivity to the amount of fluid flowing upwards into model domain through the Foothills Fault. In this analysis, the total amount of fluid entering the fault was fixed (492 kg/s) at twice the previous flow rate (247 kg/s) established in the calibration process (see previous sections).

A calibration was achieved that was within 10% of the original calibration based on the sum of squares of the simulation/observation differences. The primary outcome was that the additional flow in the fault resulted in less recharge flow from the northeast specified head boundaries. Only one future production scenario was run with this model; that was the City of Boise producing at 1.5 times the current rate. At 100 years in the future this alternate model simulated less thermal drawdown in CM#1 (1.3ºC versus 3.6ºC) and VA Production (0.2ºC versus 0.4ºC) than the original calibrated model. A possible reason for the difference between the two models is that the alternate model allows more of the high temperature inflow of the fault bottom than the original model. This in turn has more of an opportunity to mitigate the temperature changes occurring from injection. Alternatively, the original model, with more recharge flow entering from the lateral boundaries, probably has more 80ºC water intercepted by upstream producing wells and less available for mixing in the area of CM#1.

The elevation of the northeastern specified-head boundary was set at 880 m for all of the simulations reported in this report. However, an elevation of 900 m was also tested. A re-calibrated model with a northeast boundary elevation of 900 m yielded calibration changes within one percent of the base case.

6. MODEL LIMITATIONS

There are many assumptions, limitations, and potential errors associated with a numerical ground water flow model. Uncertainty regarding hydrogeologic characteristics, geothermal ground water flow characteristics, and flux rates into and out of the model domain may influence model results. Conceptualization errors may influence model results. Errors resulting from the misapplication of ground water flow equations may contribute to simulation error (e.g., ground water flow equations used in this model do not apply to turbulent flow, which may occur under certain conditions in fracture systems). Incorrect or insufficient discretization of space and time may contribute to simulation errors. Finally, paucity of data in portions of the model domain, and/or incorrect water level, pressure, and production data, may contribute to uncertainty in the model results.

Boundary conditions play a particularly important role in this model. Little is known of the amount and characteristics of waters that recharge the thermal aquifer. It is reasonable to assume that there are discrete sources of thermal water with different characteristics. Different recharge temperatures may be induced by varying hydraulic heads within the aquifer, or different recharge temperatures may be encountered because of processes occurring outside of the model domain. The model described in this report cannot represent these phenomena. However, that does not preclude the model from representing the anthropogenic changes from re-injection of cooler water. In other words, even though the temperatures in the aquifer and in recharge water are likely to be more complex than those modeled here, the temporal and spatial behavior of the 'overprint' of the injected water is probably adequately represented in the model.

7. CONCLUSIONS

A three-dimensional numerical model was constructed of the Boise Front geothermal aquifer system using the FEHM and PEST codes. Numerous simulations were conducted to evaluate the potential impact associated with a 50% increase in thermal water production (with all of the increased production being re-injected). The primary conclusion of these simulations is that it is unlikely that the proposed increases in production and re-injection by the City of Boise will decrease water levels, or will decrease temperatures substantially, in the downtown – Table Rock, Stewart Gulch, or Harris Ranch areas. The following specific conclusions were drawn from the simulations.

First, it appears from the simulations that the hydraulic connection between the City production and injection wells is sufficient for the proposed amount of additional production and re-injection. This is supported, in part, by rising water levels in several of the downtown – Table Rock wells, an apparent result of the re-injection that was initiated in 1999.

Second, the simulation results suggest that the average head in the downtown production area will be increasing for the near future, even if the City increases production and re-injection as proposed. This is because the net production has decreased in recent years, and the increased production and re-injection by the City of Boise will not result in an increase of net withdrawals.

Third, the City injection well is far enough removed from other users in the downtown area that the simulated thermal perturbation caused by the injected water does not appear to propagate to the other wells in the downtown – Table Rock area. However, the increased injection may produce local hydraulic changes that in turn could change the temperature mix entering individual wells. An example of this would be pulling cooler water in from lateral regions. Using the CM#2 behavior in the years 1983-1993 as a guide, hydraulic changes of 10 m (30 ft) could induce temperature changes of 5ºF. With re-injection of production water, future hydraulic changes of this size are unlikely; thus minimizing the induced thermal impact.

Fourth, there has been an ongoing question regarding the degree of hydraulic connection between the Stewart Gulch and downtown Boise areas. Two alternative conceptual models were implemented in the numerical model: partial hydraulic connection and no hydraulic connection. Neither model accurately reproduced measured hydrographs at the Edwards well. It is unclear whether this result is because of conceptual model errors or the paucity of production data in the Stewart Gulch area. It is unlikely that modeling or data analysis can be used to definitively determine the influence (or lack thereof) of withdrawals in the downtown area on wells in the Stewart Gulch area (or vice versa) given the current level of hydrologic and production data. Similarly, we could draw no conclusions about the degree of hydraulic connection between the downtown – Table Rock area and the Harris Ranch area from these simulations.

There are a number of assumptions, limitations, and potential errors associated with a numerical ground water flow model that may limit confidence in simulation results (see Section 6). Uncertainty may be exacerbated when making predictions into the distant future (e.g., 30 or 100 years).

8. RECOMMENDATIONS

There are several areas of data collection and/or investigative methods that may provide additional insight into the characteristics of the Boise Front geothermal aquifer system. These include the following:

1. Improved monitoring of geothermal water levels/pressures, temperature, and production data.
2. Field-based and/or simulated tracer tests. Bromide may be a tracer candidate depending on existing background concentrations.
3. Capture zone simulations may provide insight into potential well interference between wells.
4. Flowing and non-flowing temperature logs might provide more insight into temperatures and ground water flow associated with individual aquifer zones.
5. Exploratory drilling may help quantify hydraulic and temperature characteristics in primary faults.

9. References

Brodsky, N.S., Riggins, M., Connolly, J. and Ricci, P., 1997. Thermal Expansion, Thermal Conductivity, and Heat Capacity Measurements for Boreholes UE25 NRG-4, UE25 NRG-5, USW NRG-6, and USW NRG-7/7A, Sandia National Laboratories, Albuquerque, New Mexico.

Doherty, J., 2000. PEST - Model Independent Parameter Estimation, Watermark Computing, Australia.

Kipp, K.L., 1986. HST3D: A computer code for simulation of heat and solute transport in three-dimensional ground-water flow systems, U.S. Geological Survey Water-Resources Investigations Report 86-4095.

McDonald, M.G. and Harbaugh, A.W., 1988. A modular three-dimensional finite difference ground-water flow model. Techniques of Water-Resources Investigation of the United States Geological Survey. Book 6: Modeling Techniques.

Montgomery-Watson, I., 1994a. Boise Geothermal Aquifer Study Phase 2 Report Volume 2 (Appendices), Prepared for the City of Boise.

Montgomery-Watson, I., 1994b. Boise Geothermal Aquifer Study Phase 2 Report, Volume 1, Prepared for the City of Boise and Boise Warm Springs Water District.

Petrich, C., 2003a. Hydrogeologic conditions in the Boise Front Geothermal Aquifer. IWRRI-2003-05, Idaho Water Resources Research Institute.

Petrich, C., 2003b. Investigation of Hydrogeologic Conditions and Ground Water Flow in the Boise Front Geothermal Aquifer (Executive Summary). IWRRI-2003-07, Idaho Water Resources Research Institute.

Sass, J.H., Lachenbruch, A.H., Dudley, W.W., Jr., Priest, S.S. and Munroe, R.J., 1988. Temperature, Thermal Conductivity, and Heat Flow Near Yucca Mountain, Nevada: Some Tectonic and Hydrologic Implications. Open-File Report 87649, U.S. Geological Survey, Denver, Colorado.

Tsang, Y.W. and Pruess, K., 1987. A Study of Thermally Induced Convection Near a High-Level Nuclear Waste Repository in Partially Saturated Fractured Tuff. Water Resources Research, 23(10): 1958-1966.

Wood, S.H., 1996. Preliminary Map of the Base of the Sedimentary Section of the Western Snake River Plain. Department of Geosciences, Boise State University, Geological interpretation for the Treasure Valley Hydrologic Project.

Zyvoloski, G.A., Robinson, B.A., Dash, Z.V. and Trease, L.L., 1997. Summary of the Models and Methods for the FEHM Application - A Finite-Element and Mass-Transfer Code. LA-13306-MS, Los Alamos National Laboratory, Los Alamos, NM.

APPENDIX A. FEHM MATHEMATICAL FORMULATION

An effective continuum approach was adopted for simulating ground water flow. Based on this conceptualization, the equations governing ground water flow can be derived by combining the equations describing the conservation of fluid mass and Darcy's Law. The equations presented below are for an isotropic, isothermal medium. The conservation of fluid mass is

$$\frac{\partial A_{mass}}{\partial t} + \overline{\nabla} \cdot \overline{f}_{mass} + q_{mass} = 0 \quad \text{(Eq. 1)}$$

where

A_{mass} is the fluid mass per unit volume given by

$$A_{mass} = \phi \rho_l \quad \text{(Eq. 2)}$$

$\overline{f}_{mass}$ is the fluid mass flux given by

$$\overline{f}_{mass} = \rho_l \overline{v} \quad \text{(Eq. 3)}$$

ϕ is the porosity in the system

ρ_l is the fluid density (kg/m^3)

$\overline{v}$ is the fluid velocity (m/s)

q_{mass} is the fluid mass source (kg/s).

The velocity of the fluid can be expressed by Darcy's Law:

$$\overline{v} = -\frac{k}{\mu}(\overline{\nabla} P - \rho_l g) \quad \text{(Eq. 4)}$$

where

μ is the dynamic viscosity of the fluid

P is the fluid pressure

k is the permeability

g is the acceleration resulting from gravity.

Equations 1 and 4 can be combined to yield:

$$-\overline{\nabla} \cdot D_{mass} \overline{\nabla} P + q_m + \frac{\partial}{\partial z} g D_{mass} \rho_l + \frac{\partial A_{mass}}{\partial t} = 0 \qquad \text{(Eq. 5)}$$

which is the fundamental equation describing ground water flow. Here z is oriented in the direction of gravity and the transmissibility is given by

$$D_{mass} = \frac{k\rho_l}{\mu}.$$

Ground water flow is simulated in the site-scale SZ flow model by obtaining a numerical solution to this equation.

Conservation of fluid-rock energy is expressed by the equation

$$\frac{\partial A_e}{\partial t} + \overline{\nabla} \cdot \overline{f_e} + q_e = 0, \text{ (Eq. 6)}$$

where the energy per unit volume, A_e, is given by

$$A_e = (1-\phi)\rho_r u_r + \phi \rho_l u_l, \qquad \text{(Eq. 7)}$$

with $u_r = c_{pr} T$, and the energy flux, $\overline{f_e}$, is given by

$$\overline{f_e} = \rho_l h_l \bar{v} + K \overline{\nabla} T. \qquad \text{(Eq. 8)}$$

Here,

the subscript r refers to the rock matrix

the subscript l refers to the liquid

u_r and u_l are specific internal energies

c_{pr} is the specific heat

h_l is specific enthalpy

K is an effective thermal conductivity

T is the temperature and

q_e is the energy contribution from sources and sinks.

Equations (6) and (4) can be combined to yield:

$$-\overline{\nabla} \cdot (D_e \overline{\nabla} P) - \overline{\nabla} \cdot (K \overline{\nabla} T) + q_e + \frac{\partial}{\partial z} g D_e \rho_l + \frac{\partial A_e}{\partial t} = 0 , \qquad \text{(Eq. 9)}$$

where the transmissibility term is given by

$D_e = h_l D_{mass}$.

The FEHM software code V 2.20 is used to obtain a numerical solution to the mathematical equation describing ground water flow (Equation 5). FEHM is a non-isothermal, multiphase flow and transport code that simulates the flow of water and air, and the transport of heat and solutes, in 2-D and 3-D saturated or partially saturated heterogeneous porous media. The code includes comprehensive reactive geochemistry and transport modules and a particle-tracking capability. Fractured media can be simulated using an equivalent continuum, discrete fracture, dual porosity, or dual permeability approach. A subset of the FEHM code capabilities is used in the SZ site-scale flow model. Single-phase, isothermal flow is simulated in the SZ site-scale flow model. The control-volume finite element (CVFE) method is used in FEHM to obtain a numerical solution to the ground water flow equation over the model domain. Finite-element methods are based on the assumption that a continuum may be modeled as a series of discrete elements. For each element, equations based on a discretized form of the ground water flow equation are written that describe the interaction of that element with its neighbors. These equations describe the hydrologic behavior of the elements. This discretization leads to a set of equations that must be solved numerically to obtain the values of ground water pressure at each node throughout the model domain. The CVFE method has been used extensively in petroleum reservoir engineering (Forsyth 1989). The CVFE method treats the potentials in a finite-element approach while the control-volume aspect allows local mass conservation and upstream weighting (Verma and Aziz 1997). Quadrilaterals and triangles in two dimensions and hexahedra and tetrahedra in three dimensions are divided into volumes associated with gridblocks and areas associated with interblock distances. The gridblock volumes are the Voronoi volumes (Forsyth 1989) associated with each gridblock. Voronoi volumes are also called perpendicular bisector (PEBI) volumes. The Voronoi volume is formed by boundaries that are orthogonal to the lines joining adjacent gridblocks and that intersect the midpoints of the lines (Verma and Aziz 1997). Any point within a Voronoi volume is closer to its associated gridblock than to any other node in the grid. The CVFE method can be shown on simple elements with constant properties to be equivalent to traditional finite-element methods. The stiffness coefficients (e.g., elements of the stiffness matrix) of the traditional finite-element method can be interpreted as a linear function of the area through which the fluid passes traveling from one node to its neighbor. A stiffness coefficient uses the area of the boundary of the Voronoi volume that intersects the line joining adjacent nodes. These terms are used to form control-volume difference equations for the conservation equations. This method is not traditional because equation parameters are defined by node, not element, but the method leads to an intuitive understanding of the numerical method. In FEHM, the nodal definition of equation parameters leads naturally to a separation of the nonlinear and purely geometric parts. This separation is explained in detail in Zyvoloski (1983) and is valid over lower-order elements. The nonlinear part uses average inverse kinematic viscosity,

$$D = \frac{\rho}{\mu}\ , \qquad \text{(Eq. 10)}$$

between two nodes, which is usually taken to be the upstream nodal value. The result is a much more stable code for solving nonlinear problems while still retaining much of the geometric flexibility of finite elements. This method has been used in FEHM since 1983 (Zyvoloski 1983) and has been extensively verified (Dash et al. 1997). A harmonic weighting of the intrinsic permeability is used. Upwinding the viscosity terms is the standard way of modeling the interblock fluid fluxes. The Newton-Raphson iteration is applied to the system of equations, which is solved with a multi-degree of freedom and preconditioned, conjugate gradient methods using Generalized Minimum Residual (GMRES) or biconjugate gradient-squared acceleration techniques.

APPENDIX B. PRODUCTION/INJECTION RATES APPLIED IN SIMULATIONS FOR SELECTED DOWNTOWN WELLS (IN MILLIONS OF GALLONS)

GeoWellID	1671	1674	1670	1663	1665	2670	1653			
Year[7]	VA Production	VA Injection	Capital Mall 2 Production	Capital Mall 1 Injection	BGL #4	Boise City Injection	BWSWD West	Total Production	Total Injection	Net Extraction
Pre-1983[8]	0	0	0	0	0	0	275	275	0	275
1983	0	0	12.8	-12.8	0	0	283.5	296.3	-12.8	283.5
1984	0	0	164.6	-164.6	166.7	0	300.2	631.5	-164.6	466.9
1985	0	0	175.4	-175.4	121.4	0	281.2	578	-175.4	402.6
1986	0	0	192	-192	176.8	0	253.1	621.9	-192	429.9
1987	0	0	169.1	-169.1	188.9	0	183.1	541.1	-169.1	372
1988	0	0	138.8	-138.8	123.8	0	199.4	462	-138.8	323.2
1989	28.5	-28.5	154.4	-154.4	158	0	278	618.9	-182.9	436
1990	118.2	-118.2	130.5	-130.5	122.3	0	244.6	615.6	-248.7	366.9
1991	129.1	-129.1	182.7	-182.7	121.3	0	245.7	678.8	-311.8	367
1992	116.7	-116.7	139	-139	123.3	0	243.3	622.3	-255.7	366.6
1993	137	-137	217.9	-217.9	156	0	259.2	770.1	-354.9	415.2
1994	137.4	-137.4	174.5	-174.5	122.5	0	220.8	655.2	-311.9	343.3
1995	166.7	-166.7	154.3	-154.3	127.9	0	221.2	670.1	-321	349.1
1996	186.2	-186.2	118.7	-118.7	132.1	0	226.6	663.6	-304.9	358.7
1997	203.6	-203.6	98.6	-98.6	130.7	0	212.8	645.7	-302.2	343.5
1998	196	-196	111.6	-111.6	131.2	0	184.2	623	-307.6	315.4
1999	191.6	-191.6	125.5	-125.5	164.9	-53.6	204	686	-370.7	315.3
2000	186.9	-186.9	117.9	-117.9	188	-145.8	210.5	703.3	-450.6	252.7
2001	173	-173	144.8	-144.8	172	-145.6	218.7	708.5	-463.4	245.1
2002	163.1	-163.1	123.3	-123.3	170.7	-139.8	230.1	687.2	-426.2	261

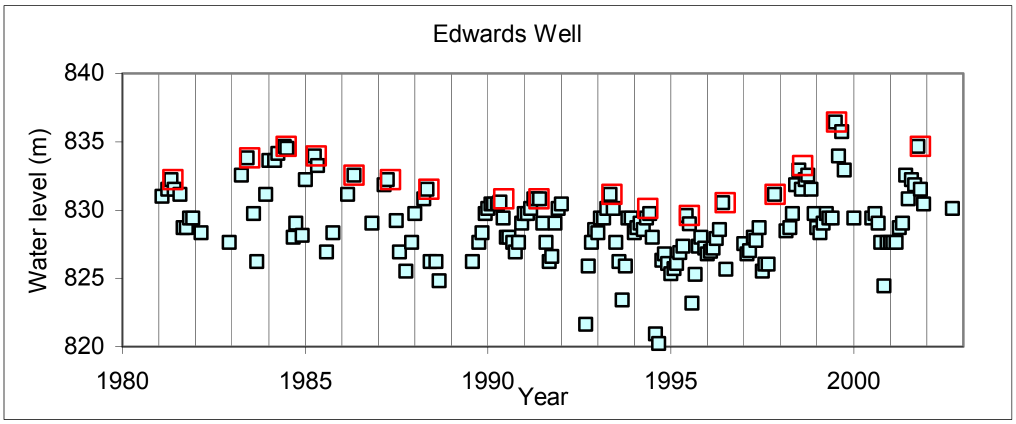
[7] Defined on water-year basis as October 1– September 30.
[8] Estimate of average annual production.

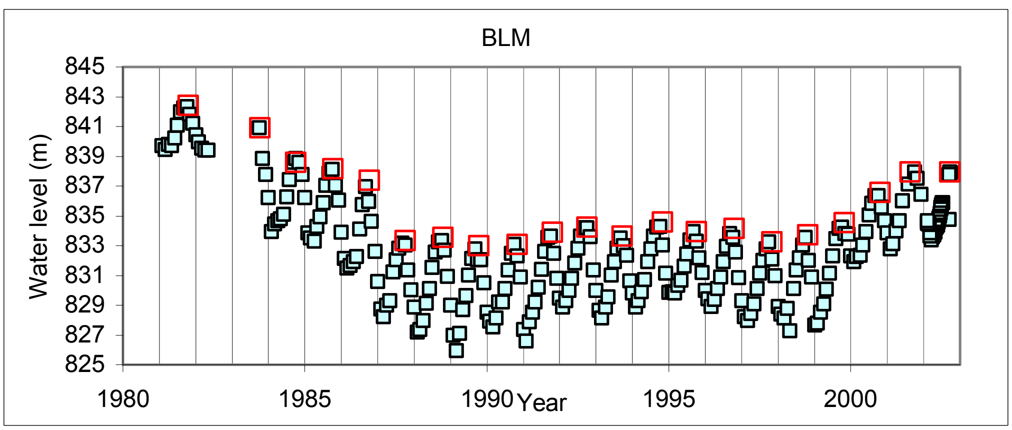
APPENDIX B (CONTINUED). PRODUCTION/INJECTION RATES APPLIED IN SIMULATIONS FOR SELECTED STEWART GULCH WELLS (IN MILLIONS OF GALLONS)

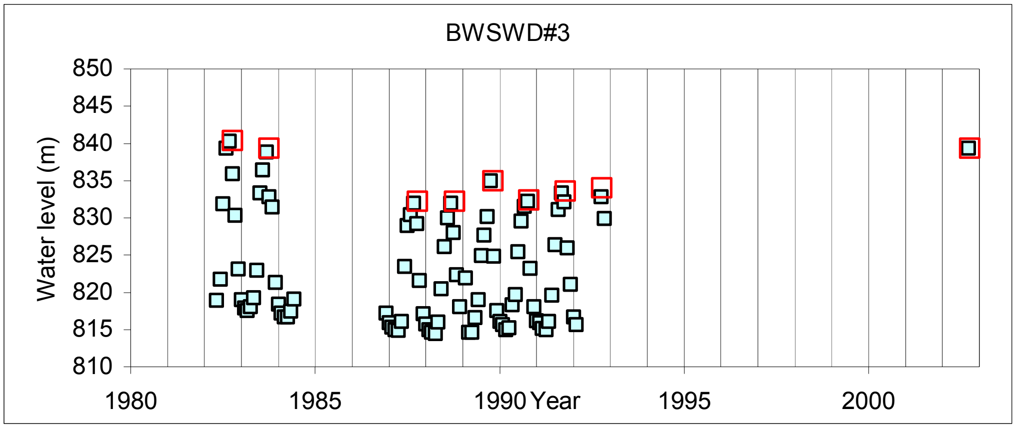
Year	Edwards	Flora Silkey, Office, and Tiegs	Terteling Motorcycle and Windsock	Quail Hollow	Total
1982	63.7	115.5	100.0	0.0	279.2
1983	63.7	115.5	100.0	0.0	279.2
1984	63.7	115.5	100.0	82.5	361.7
1985	63.7	115.5	100.0	82.5	361.7
1986	63.7	115.5	100.0	82.5	361.7
1987	63.7	115.5	100.0	82.5	361.7
1988	63.7	115.5	100.0	82.5	361.7
1989	63.7	115.5	100.0	82.5	361.7
1990	63.7	115.5	100.0	82.5	361.7
1991	63.7	115.5	100.0	82.5	361.7
1992	63.7	115.5	100.0	82.5	361.7
1993	63.7	115.5	100.0	82.5	361.7
1994	63.7	115.5	100.0	82.5	361.7
1995	63.7	115.5	100.0	82.5	361.7
1996	63.7	115.5	100.0	82.5	361.7
1997	63.7	115.5	100.0	82.5	361.7
1998	63.7	115.5	1.0	33.0	213.2
1999	63.7	115.5	1.0	33.0	213.2
2000	63.7	115.5	1.0	33.0	213.2
2001	63.7	115.5	1.0	33.0	213.2
2002	63.7	115.5	1.0	33.0	213.2
2003	63.7	0.0	1.0	33.0	97.7

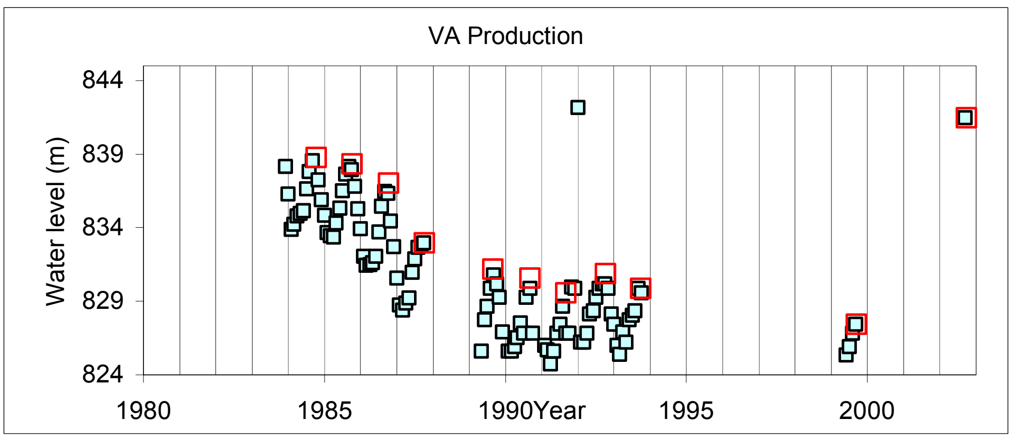
APPENDIX C: ANNUAL OBSERVATION POINTS

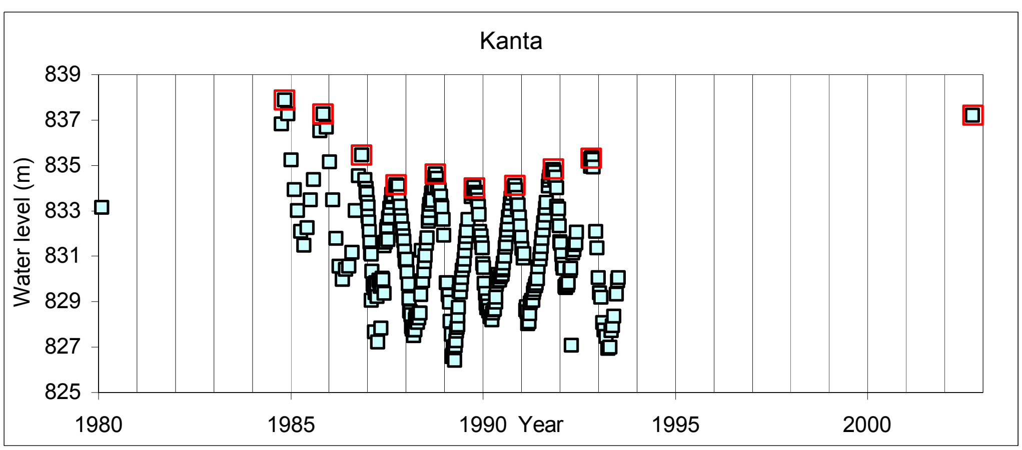
The following graphs show the selected annual observations used in the simulations of ground water flow in the Boise Front Geothermal Aquifer. Solid symbols indicate water level observations; hollow, red symbols indicate annual observation points selected for simulations. See Section 3.2 for explanation.

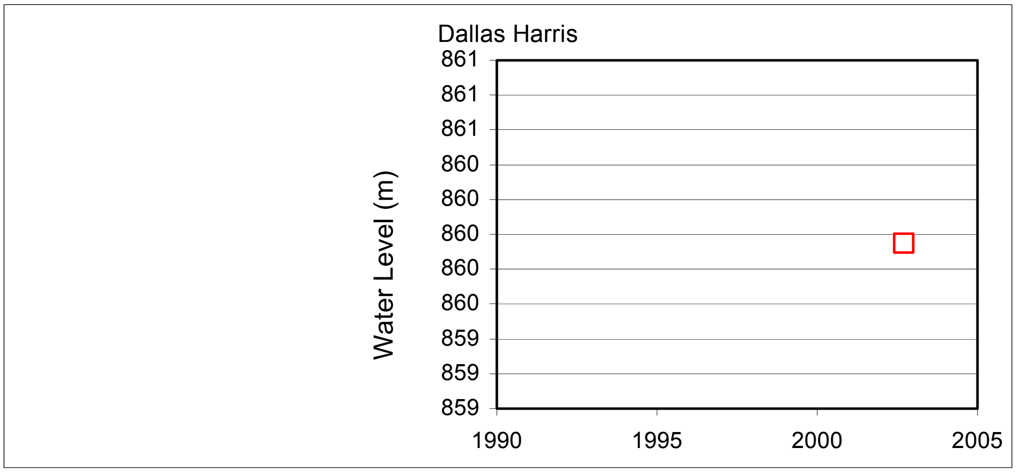




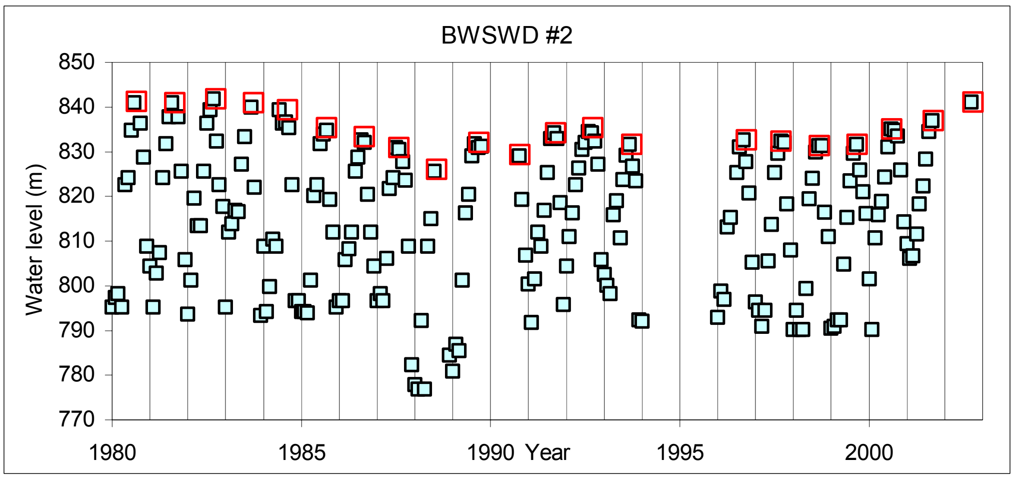

BWSWD#3
Water level (m)
850
845
840
835
830
825
820
815
810
1980
1985
1990
Year
1995
2000


VA Production
Water level (m)
844
839
834
829
824
1980
1985
1990
Year
1995
2000


Kanta
Water level (m)
839
837
835
833
831
829
827
825
1980
1985
1990
Year
1995
2000



Dallas Harris
Water Level (m)
861
861
861
860
860
860
860
860
859
859
859
1990
1995
2000
2005



BWSWD #2
Water level (m)
850
840
830
820
810
800
790
780
770
1980
1985
1990
Year
1995
2000