Mammoth Basin Groundwater Model Report

Final Report

Prepared for

Mammoth Community Water District

September 2009

WILDERMUTH™ ENVIRONMENTAL INC.

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Acronyms, Abbreviations, and Initialisms

395	Mammoth Creek Flow gage at Old Highway 395
acre-ft	acre-feet
acre-ft/yr	acre-ft per year
CDEC	California Data Exchange Center
CDFFP	California Department of Forestry and Fire Protection
CDFG	California Department of Fish and Game
cfs	cubic feet per second
CIMIS	California Irrigation Management Information System
DWR	Department of Water Resources
ET	evapotranspiration
ft^3/day	cubic feet per day
ft-msl	feet mean sea level
gpm	gallons per minute
GWMP	groundwater management plan
HCA	Hot Creek above Gorge Geyser
HCLOSE	Head change criterion for convergence
HCF	Hot Creek Flume
ka	kiloannum (thousand years)
LVHAC	Long Valley Hydrologic Advisory Committee
msl	mean sea level
MCWD	Mammoth Community Water District
OMR	Mammoth Creek gage at Old Mammoth Road
RCLOSE	residual criterion for convergence
SWRCB	State Water Resources Control Board
USGS	United States Geological Services
UWMP	Urban Water Management Plan
WEI	Wildermuth Environmental, Inc.

ES-1 Background and Purpose

The Mammoth Basin, shown in Figure ES-1, is the watershed of Mammoth Creek. The basin is located on the eastern flank of the Sierra Nevada, approximately 30 miles north of the community of Bishop and west of Crowley Lake. The Mammoth Groundwater Basin, also shown in Figure ES-1 consists of the water-bearing materials within the low-lying central portion of the Mammoth Basin. The stratigraphy of the Mammoth Groundwater Basin is generally characterized as glacial till and alluvium (shallow groundwater system) that overlay fractured water-bearing volcanics in the western portion of the basin. In the eastern portion of the groundwater basin, the same fractured water-bearing volcanics are exposed with some areas of overlying thin alluvium.

The Mammoth Community Water District (MCWD) produces groundwater from the Mammoth Groundwater Basin and diverts surface water from Mammoth Creek to meet its potable water demands for the Mammoth Lakes community. Groundwater pumping has been recorded since 1978 when the MCWD installed its first production well; the MCWD currently uses 8 wells to extract groundwater, and two more production wells are planned (Well 11 and Well 25). Over the last 10 years, from 1998 to 2008, average annual groundwater pumping has been about 1,980 acre-ft/yr.

In 1992, the MCWD initiated a groundwater monitoring program. This program was later expanded to include surface water measurements at the Lake Mary water treatment plant, discharge at Bodle Ditch, inflows and discharge at Lake Mary, discharge at Lake Mamie, discharge at Twin Lakes, and discharge at Mammoth Creek near Old Mammoth Road. Since 1993, the MCWD has prepared annual monitoring reports. These reports evaluate the groundwater level, surface flow, and water quality monitoring data collected each year. Figure ES-2 shows the surface water monitoring points, groundwater monitoring wells, and production wells that are monitored by MCWD and other cooperating entities.

In December 2004, an advisory committee was formed to provide monitoring guidance in the Mammoth Basin and to provide guidance in the preparation of a groundwater management plan (GWMP). Each entity represented on the committee had an interest in the development of groundwater resources and fully supported a management plan for future planning purposes and for the protection of local resources. In 2005, the MCWD finalized the GWMP. The purpose of the plan was to "[…] develop a management strategy for the use of groundwater within the Mammoth Basin Watershed by the MCWD." The priorities for groundwater management, per the 2005 GWMP, include obtaining sustainable yields from the groundwater basin, protecting the environment, and meeting the water supply needs of the community. A primary element of the management strategy is the effective conjunctive management of all available water resources, including surface water, groundwater, recycled water, and water conservation. This conjunctive management approach would vary the use of each resource based on the hydrologic conditions of each year or series of years.

The 2005 GWMP did not result in a single specific comprehensive management strategy, set basin-level standards for environmental impacts, or specify sustainable groundwater basin yield. However, it did recommend a series of actions that would help protect existing groundwater resources and improve the detailed understanding of basin hydrogeology in support of eventually developing specific management strategies and sustainable yield targets. These included expanded monitoring and data collection for surface water and groundwater, increased conservation, well head protection zone and recharge zone delineations, standards for well construction and abandonment, and the development of a groundwater model.

Within the GWMP (MCWD, 2005), the MCWD outlined the preparation of a groundwater model to "[…] enable the District (MCWD) to test various operational scenarios, determine areas of uncertainty, and establish locations for future monitoring wells." This document summarizes the construction and application of the first generation groundwater model for the Mammoth Groundwater Basin. The scope of work for the groundwater model study, documented herein, included the following:

- Compile and review existing historic reports and monitoring data.
- Develop and calibrate a model, based on the most refined current conceptual model of the Mammoth Groundwater Basin, to evaluate resource management alternatives.
- Simulate current and projected future groundwater pumping levels to assess potential changes to water levels and production sustainability over a wide range of climatic conditions.

The first objective involved the development of a numerical groundwater flow model that accurately represents the physical system. The physical system is better defined in the western part of the basin, and, as such, the model is more accurate in the western part of the basin than elsewhere. This is an important limitation of the groundwater model. This groundwater model was prepared so that the MCWD could use it to evaluate groundwater pumping scenarios in the future. The third objective was to apply the model to predict the sustainability of groundwater pumping under a hypothetical future groundwater pumping and surface water diversion scheme.

ES-2 Model Description

The aquifer systems in the Mammoth Groundwater Basin are complicated, and, therefore, simplification was necessary in order to create a model that could be used to test the groundwater management alternatives. A numerical computer-simulation model of groundwater flow was prepared for the Mammoth Groundwater Basin using the USGS MODFLOW-2000 model code (Harbaugh et al., 2000), which is the current standard in groundwater modeling. Figure ES-3 displays the domain of the Mammoth Groundwater Basin model. The model grid consists of 124 rows, 245 columns, and 2 layers. Horizontally, each cell has a dimension of 200 feet by 200 feet. This fine cell size was selected to model the curvature of the drawdown and to provide a model that is flexible for potential future needs. The grid cells are designated as "inactive" outside the model boundary and as "active" inside the boundary. There are a total of 24,241 active cells.

The spatial extent of the model domain was determined based on the saturated extent and thickness of the aquifer system; the extent was limited to regions where the saturated thickness was greater than about 40 feet. The saturated thickness was determined based on 1992 groundwater levels and the effective base of the aquifer. The model was calibrated over the 1992-2006 period, during which groundwater pumping averaged 1,720 acre-ft/yr.

The length of the transient stress period is three months (one quarter of a year), which was based primarily on the availability of data for calibration and the seasonal variability of the Mammoth Basin groundwater and surface water systems. Both discharge (i.e. pumping and ET) and recharge (i.e. precipitation and stream flow) show distinct seasonal features.

The groundwater model simulates the groundwater system that overlies the deeper geothermal reservoir. High temperature geothermal water is extracted from a deeper hydrothermal system for commercial power generation at the Casa Diablo Power Plant, which is currently owned by the ORMAT Corporation. Local geothermal extraction and injection operations related to existing and potential expanded future operations were not modeled as part of this study as existing publicly available studies and data do not indicate significant interaction between the upper cold water aquifer and the much deeper geothermal reservoir.

This basin-wide groundwater model, as it is currently developed and calibrated, can be used to evaluate the sustainability of groundwater pumping in the far western part of the basin. Based on the current model conceptualization and calibration, the model should not be used for any prospective analysis of surface and groundwater interaction. In fact, the MCWD will need to conduct significant new hydrogeologic characterization investigations if it desires to incorporate a reliable groundwater/surface water interaction capability into the model. Finally, this is a first generation model and can be improved as more data becomes available. At present, this model is the best tool available to the MCWD for evaluating sustainable pumping.

ES-3 Model Simulations

Two scenarios were developed to evaluate the full build-out desired yield of the basin. These model scenarios were prepared to assist in answering the following questions:

Can the Mammoth Groundwater Basin support projected long-term MCWD groundwater pumping demands?

Will changes in water levels require changes to existing wells and/or require new wells to sustain projected groundwater demand?

Two conditional pumping and diversion scenario simulations were conducted to determine the impacts of operating at a yield that supports groundwater and surface water demands at build-out. The amount of groundwater pumping and surface water diversion was varied, based on runoff year type (i.e. dry, normal, or wet). The first scenario (Current) used dry, normal, and wet year pumping rates, based on the historical average pumping rates for each year type in the calibration period. The second scenario (Build-out) used the dry, normal, and wet year pumping rates needed to meet MCWD service area build-out water demands. Table ES-1 summarizes groundwater pumping and Mammoth Creek diversions for each scenario.

The projected dry/normal/wet pumping and diversion estimates provided by the MCWD (G. Sisson, personal communication, August 5, 2008) are based on the 2005 Urban Water Management Plan (UWMP) (MCWD, 2005) and updates thereto from MCWD staff. The surface water diversion and groundwater pumping amounts listed in Table ES-1 assume a total build-out water demand of 4,600 acre-ft/yr. This is an updated total water demand for year 2025, previously listed as 4,898 acre-ft/yr in the UWMP. The surface water diversion for a normal year is the same as the value listed in the 2005 UWMP. The dry year diversion was increased from 1,677 acre-ft in the 2005 UWMP to 1,780 acre-ft, an increase of six percent. There is no prior published wet year diversion. Projected Build-out groundwater production was determined by subtracting the assumed available surface water from the total water demand (G. Sisson, personal communication, August 5, 2008).

Both conditional pumping scenarios use the same 50-year hydrology. For the period of 2007 to 2056, future recharge was estimated based on daily measured precipitation in the Mammoth Basin from 1957 to 2006. Total quarterly precipitation and its distribution within the Mammoth Basin were estimated using the same methods used to calibrate these model inputs. The intent is to determine if over a long-term hydrology (50-years), the hydrologic differences between current operations and build-out operations are acceptable.

ES-4 Simulation Results

Can the Mammoth Groundwater Basin support projected long-term MCWD groundwater pumping demands?

The model results suggest that groundwater pumping is sustainable at current levels and for build-out conditions.

Will changes in water levels require changes to existing wells and/or require new wells to sustain projected groundwater demand?

The MCWD may need to make mechanical and/or operational changes to wells as a result of production at current levels and for build-out conditions. Mechanical changes may include the lowering of pumps, deepening of wells, and/or the construction of new wells. Operational changes may include seasonal or rotational operation to manage drawdown and sustain pumping.

ES-5 Recommendations

The groundwater model and simulations presented in this report represent the best available information at this time. Ongoing monitoring by the MCWD of surface and groundwater conditions, as well as any future drilling data from production and/or monitoring wells, will add to the understanding of the hydrogeologic system and to the accuracy of model scenarios and assessments. Based on the results of this study, the following recommendations will improve groundwater modeling and the MCWD's water resources management in the future:

1) Conduct future field testing and monitoring to improve the understanding of basin hydrogeology and surface water/groundwater interactions. This effort should include a combination of one or more monitoring wells east of existing MCWD Well 24 and in the vicinity of the Mammoth Creek crossing at Highway 395 and planned "stress test pumping" of the aquifer to confirm critical hydrogeologic parameters in this area of the basin.
2) Improve the flow monitoring station at the Twin Lakes outlet. Twin Lakes outflow discharge measurements are a key boundary condition for the surface water elements of the groundwater model. Improved flow measurements would provide a more accurate boundary condition for the groundwater model.
3) Update the long-term Build-out water supply requirements as part of the 2010 Urban

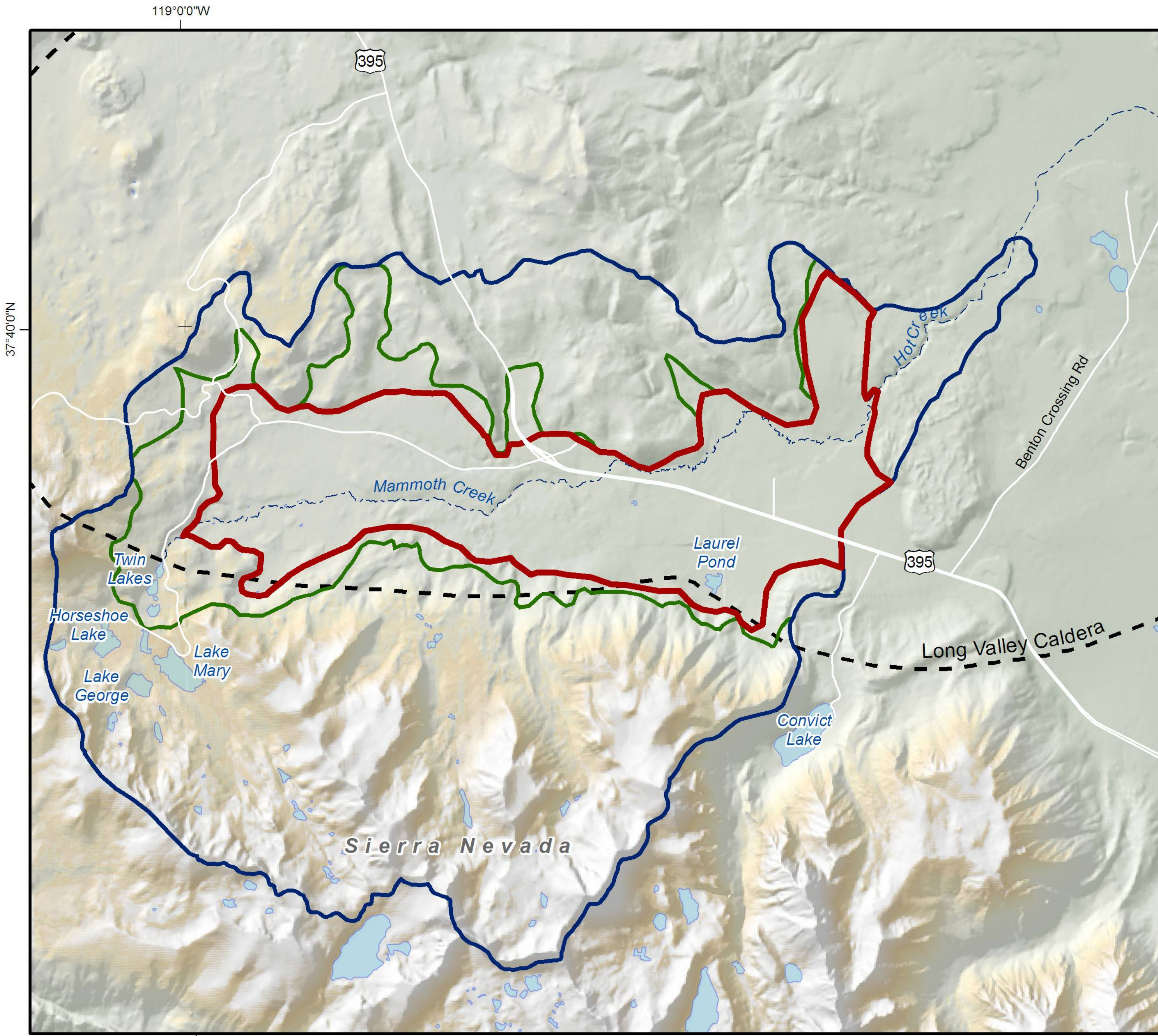
Water Management Plan update. These refined estimates of long-term supply needs should reflect the latest Town of Mammoth Lakes land use and population projections, the MCWD's updated estimates of recycled water use, and other key factors influencing long-term groundwater supply needs. The groundwater model can then be used to assess these refined pumping scenarios. For consistency with the updated 2010 UWMP, future groundwater model runs should also include specific evaluations of the standard scenarios in the UWMP, such as severe 1-year drought and 3-plus year sustained drought conditions.

4) Apply the latest long-term future Mammoth Creek diversion estimates (HDR/SWRI, 2008/09) to refine the simplified annual diversion schedule used in this study (Table ES-1). Since the completion of this groundwater modeling work, HDR/SWRI prepared daily estimates for Mammoth Creek diversions for the historic hydrology period of April 1988 to March 2008, reflecting the conditions of the MCWD's surface water rights and permits. Combining these two refined schedules of surface water availability and groundwater pumping will provide a consistent set of planning assumptions for both the groundwater and surface water modeling tools and will support the most effective operations and resource planning efforts by the MCWD.

Table ES-1
Groundwater Pumping and Surface Water Diversion for Current and Build-out Simulations[1]

Supply Source		Normal Year	Wet Year	Dry Year
Current				
Surface Water Diversion		2,425	2,760	1,677
Groundwater Pumping		1,595	1,331	1,942
	Total	4,020	4,091	3,619
Build-out				
Surface Water Diversion		2,425	2,760	1,677
Groundwater Pumping		2,175	1,840	2,923
	Total	4,600	4,600	4,600

1. G. Sisson, personal communication, August 5, 2008.



Main Features

Mammoth Hydrologic Basin

Mammoth Groundwater Basin

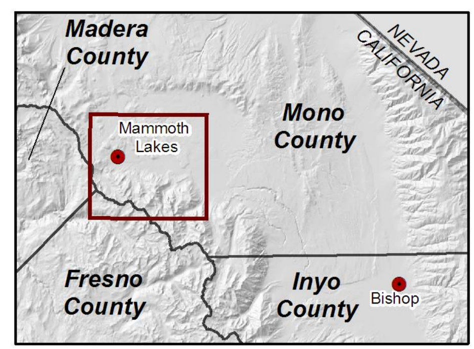
MODFLOW Groundwater Flow Model Boundary

Other Features

Caldera Boundary

Lakes

Creeks, and Streams



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0 1 2 Miles

0 2 4 KM

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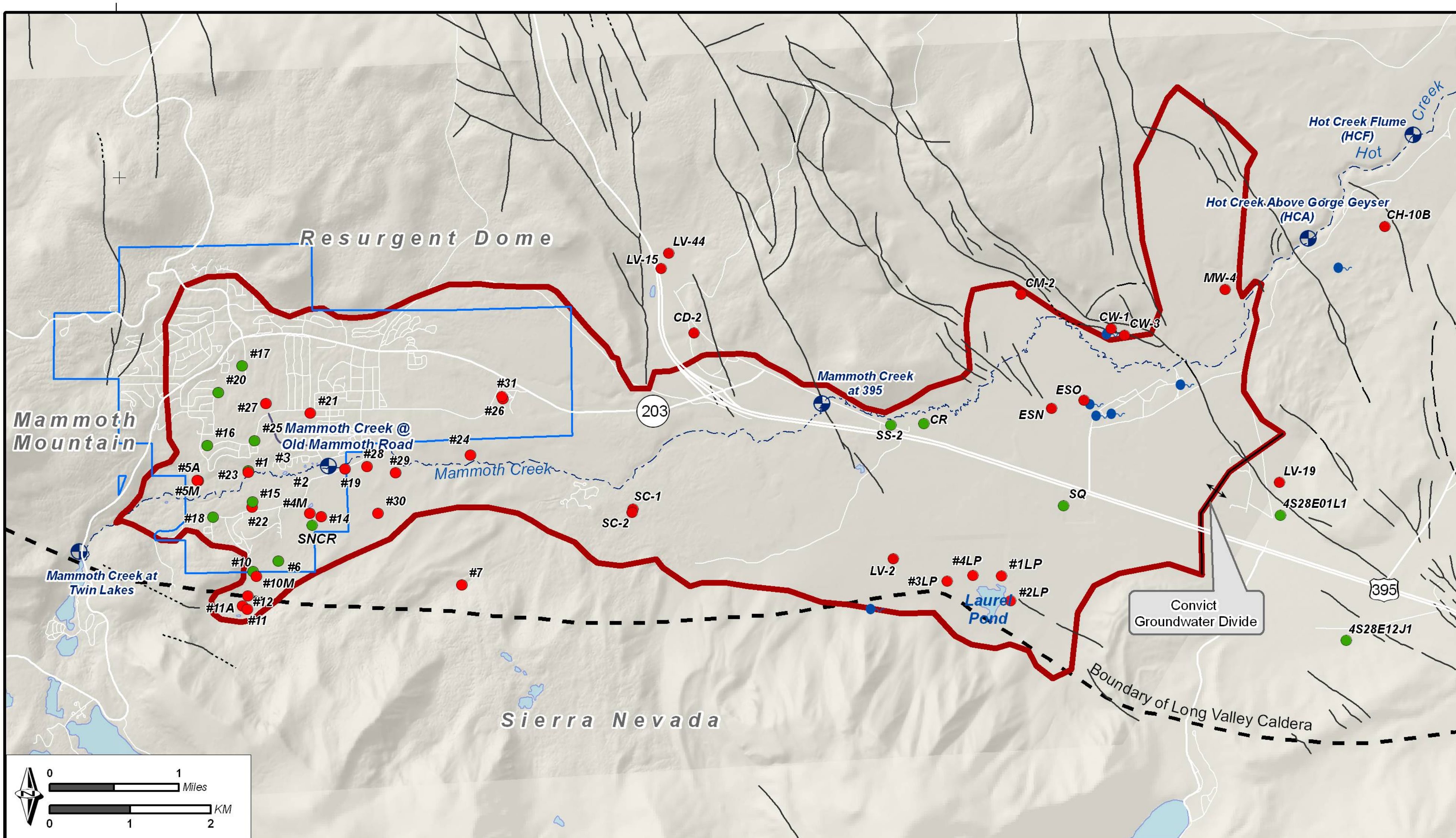
Study Area

Mammoth Basin

Figure ES-1



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Surface Water and Groundwater Monitoring Location Map

Mammoth Basin

Figure ES-2

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Surface Water Monitoring Station

Stream Gaging Station

Well Type

Monitoring Well

Production Well

MCWD Service Area Boundary

Spring

MODFLOW Groundwater Flow Model Boundary

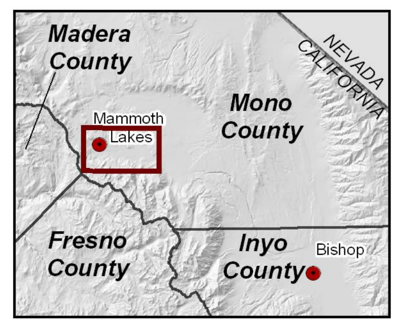
Faults

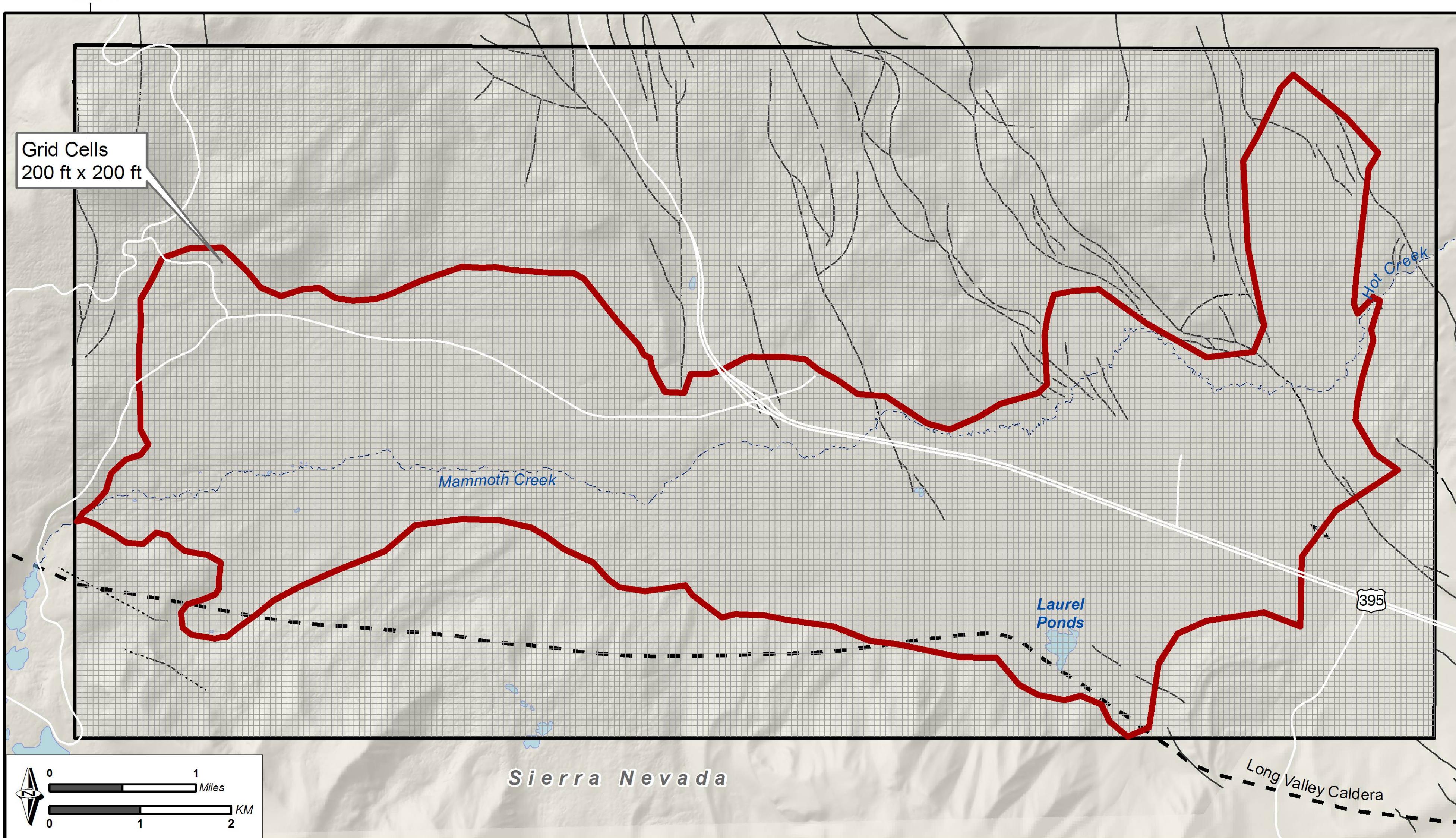
Location Certain

Location Approximate

Location Uncertain

Location Concealed





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Model Grid

MODFLOW Groundwater
Flow Model Boundary

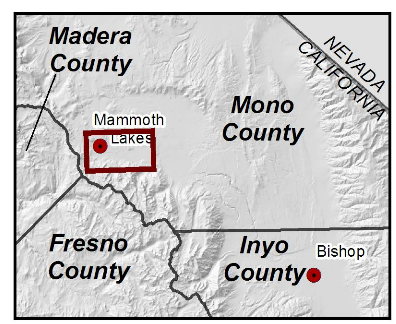
Faults

Location Certain

Location Uncertain

Location Approximate

Location Concealed



Map of Model Domain and Model Grid

Figure ES-3

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1.1 Background

The Mammoth Basin, shown in Figure 1-1, is the watershed of Mammoth Creek in the Long Valley Subunit of the Owens Hydrologic Unit of the Lahontan Drainage Province (DWR, 1973). The basin is located on the eastern flank of the Sierra Nevada, approximately 30 miles north of the community of Bishop and west of Lake Crowley. This area encompasses approximately 71 square miles.

The Mammoth Groundwater Basin, also shown in Figure 1-1, is located in the low-lying central portion of the Mammoth Basin and consists of two aquifer systems. The groundwater basin represents the water-bearing materials within the low-lying central portion of the Mammoth Basin. The stratigraphy of the Mammoth Groundwater Basin is generally characterized as glacial till and alluvium (shallow groundwater system) that overlay fractured water-bearing volcanics (deep confined groundwater system) in the western portion of the basin and exposed water bearing volcanics with some areas of overlying thin alluvium (unconfined system) in the eastern portion of the basin.

The Mammoth Community Water District (MCWD) currently produces an average of about 1,720 acre-ft/yr of groundwater (1992-2006) from the Mammoth Groundwater Basin. Groundwater pumping has been recorded since 1978 when the MCWD installed its first production well; the MCWD currently uses 8 wells to extract groundwater, and two more production wells are planned. All of the MCWD production wells are in the western portion of the Mammoth Groundwater Basin and penetrate the deep aquifer, which consists of fractured basalt with some interbedded glacial tills.

In 1992, the MCWD initiated a groundwater monitoring program and has prepared groundwater monitoring reports annually since 1993. These reports provide an evaluation of groundwater level, surface flow, and water quality monitoring data accumulated throughout the year. Currently, the MCWD maintains and monitors 19 monitoring wells. Since its inception, the monitoring program has been expanded to include surface water measurements of discharge at the Lake Mary surface water treatment plant, discharge at Bodle Ditch, inflows and discharge at Lake Mary, Lake Mamie discharge, Twin Lakes discharge, and Mammoth Creek discharge near Old Mammoth Road.

The MCWD uses groundwater and surface water diverted from Mammoth Creek to meet potable water demands for the Mammoth Lakes community. To meet anticipated future water demands, the MCWD is evaluating water resource supply alternatives similar to those outlined in their 2005 Urban Water Management Plan. A groundwater model was constructed and used to evaluate groundwater pumping (yield) and to assess potential changes to the aquifer system that may be associated with different levels of pumping.

1.2 Project Objectives

There were three objectives for this study: 1) to develop a groundwater model that can be used by the MCWD to evaluate water resource and supply management alternatives, 2) to assess long-term groundwater basin trends under current projections of future groundwater use, and 3) to estimate impacts to existing MCWD production wells and yield under the projected groundwater use levels.

More specifically, the first objective involved the preparation of a numerical groundwater flow model that accurately represents the physical system. This groundwater model was prepared such that the MCWD could continue to use it to evaluate groundwater pumping scenarios in the future, as the need arises.

The second and third objectives involved using the groundwater model to evaluate existing and future projections of groundwater use. As the MCWD updates and refines the long-term water supply needs of the community, the groundwater model will be updated and used in conjunction with future resource planning studies and tools to simulate and assess changes to the aquifer system and to help identify an acceptable long term developed yield.

1.3 Report Organization

Section 1 – Introduction: This section presents the general setting of the modeling area and the modeling objectives and provides an overview of the report's organization.

Section 2 – Hydrogeologic Setting and Conceptual Model: Section 2 describes the hydrogeologic conditions of the Mammoth Basin. Topics covered in this section include geologic setting, hydrostratigraphy, the occurrence and movement of groundwater, and groundwater levels. The data discussed herein were used to construct a hydrogeologic conceptual model of the Mammoth Basin for input to the groundwater-flow model.

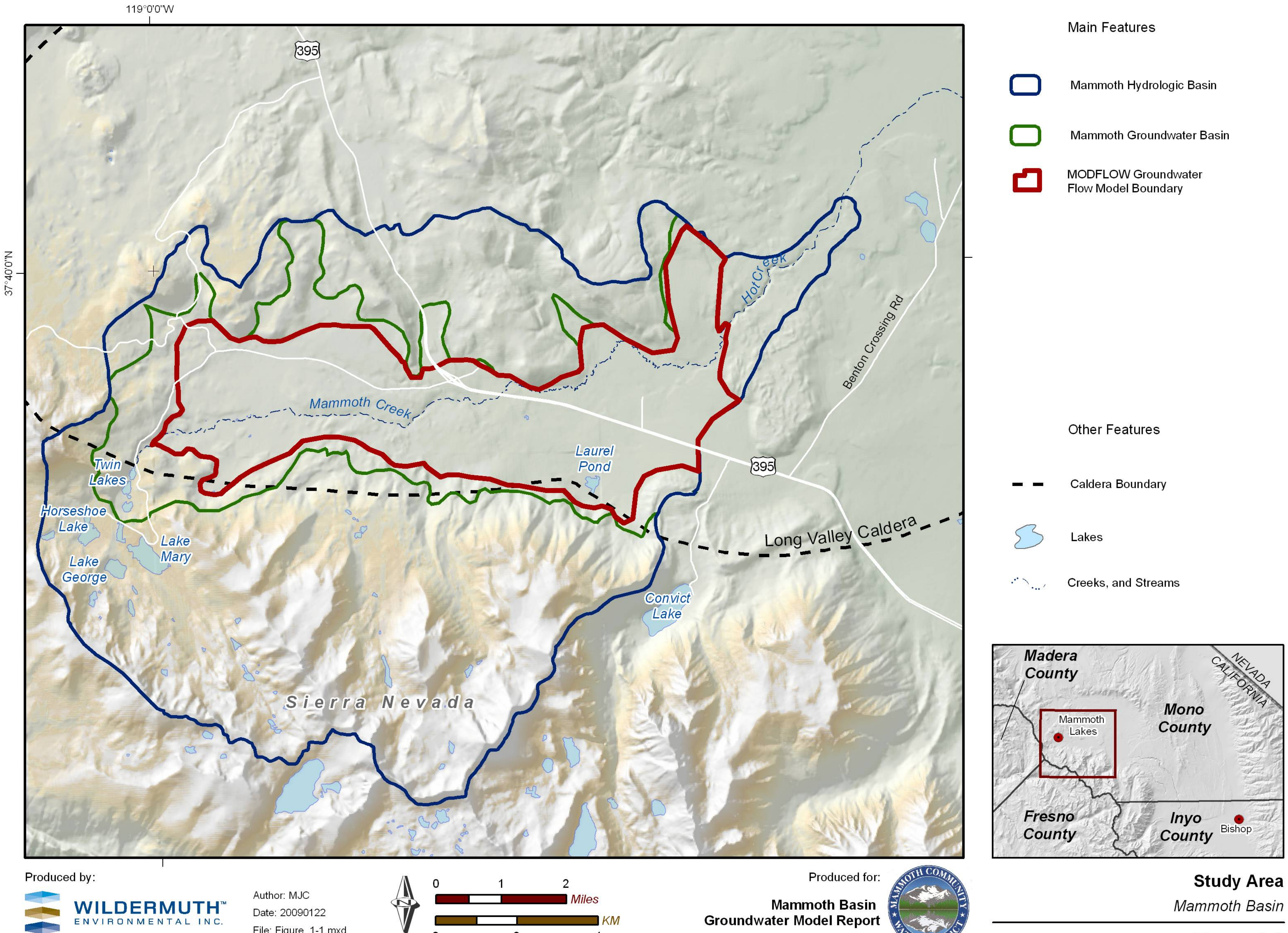
Section 3 – Water Budget: Section 3 describes inflows to and outflows from the Mammoth Groundwater Basin.

Section 5 – Model Construction: Section 5 describes how the conceptual model was translated into a numerical model. The model domain, initial conditions, boundary conditions, and hydraulic conditions are all defined. Simplifying assumptions made in the conceptual model are discussed as is the conceptual model's compatibility with the modeling objectives and function.

Section 6 – Calibration: Section 6 discusses the model calibration process and results.

Section 7 – Predictive Simulations: Section 7 describes each predictive simulation and relates the simulations to the study objectives.

Section 8 – References: Section 8 provides references for the data, computer codes, and modeling procedures utilized in this modeling effort.



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Study Area

Mammoth Basin

Figure 1-1

The Mammoth Basin watershed occupies a topographically diverse area. Surface elevations range from about 12,500 ft-msl at Bloody Mountain in the southern portion of the basin to about 6,900 ft-msl at the far eastern extreme of the basin. Surface topography ranges from flat to undulating in the Mammoth Basin to sharp and craggy in the western mountainous elevations. The topography is characterized as an alpine glaciated surface superimposed on an extrusive volcanic terrain.

2.1 Geologic Setting

The Mammoth Basin watershed straddles the southern boundary of the Long Valley Caldera. Figure 2-1 shows location of the basin and features throughout the basin used to characterize the hydrogeologic setting. Table 2-1 lists the names, owners, and coordinates of wells that contributed data to the hydrogeologic characterization of the basin. Figure 2-2 depicts the general surface geology of the project area. Over one-half of the basin is down-dropped into the Long Valley caldera, and the remaining portion is south and outside of the caldera. The Mammoth Basin is generally formed by elevated areas to the north and west, which are comprised largely of Tertiary extrusive igneous rocks; a central trough filled with Quaternary alluvial, glacial, and volcanic deposits; and an abrupt southern flank of Pre-Tertiary igneous intrusive and metamorphic rocks. The central trough area opens and drains east to the Owens River and Crowley Lake. Within the eastern portion of the basin, Quaternary lake deposits occur sporadically. Numerous faults occur in the extrusive igneous rocks along the northern flank of the basin while few faults have been mapped in the central and southern parts of the basin.

The Long Valley Caldera is a geologically active area. The United States Geologic Survey (USGS) has recorded active seismicity and crustal deformation in the area since 1980 (Howle & Farrar, 2001). Local volcanic activity provides heat for a hydrothermal system that underlies the cold water aquifer system. This system has several discharge points that create hot springs at the ground surface. A long-term hydrologic monitoring program was initiated in 1982 with the intent to document changes in the hydrologic system that are related to volcanic processes and seismicity (Howle & Farrar, 2001). In 1988, a second monitoring program was initiated. This joint program between the USGS and Mono County was implemented to provide data to the Long Valley Hydrologic Advisory Committee (LVHAC). The LVHAC was formed in 1986 to provide Mono County with advice concerning hydrologic environmental issues related to resource development in the Long Valley Caldera (Farrar & Lyster, 1990). The LVHAC program is directed at monitoring discharge changes at Mammoth Creek, springs at the Hot Creek Fish Hatchery, and springs at Hot Creek Gorge. LVHAC quarterly monitoring reports are prepared and distributed by the USGS. The data collected within these programs provided much of the data used herein.

2.2 Stratigraphy

The stratigraphy of the Mammoth Groundwater Basin is typically characterized as glacial till and alluvium (shallow groundwater system) that overlay fractured water-bearing volcanics (deep confined groundwater system) in the western portion of the basin and exposed water-bearing volcanics with some areas of overlying thin alluvium (unconfined system) in the eastern portion of the basin. All of the MCWD's production wells terminate within the deep confined system.

2.2.1 Consolidated Non-Water Bearing Bedrock

Pre-Tertiary Rocks – This complex of rocks consists of Paleozoic metasediments, Mesozoic metavolcanics, and Cretaceous intrusive rocks, including a wide variety of igneous and metamorphic types that occur exclusively in the southern part of the Mammoth Basin. Groundwater in the Pre-Tertiary rocks is generally associated with the secondary porosity of faults, joint systems, and fracture zones. The quantity of groundwater yielded from these rocks in the Mammoth Basin vicinity is usually small. The Pre-Tertiary rocks are the basement complex of the Sierra Nevada and are considered non-water bearing.

Quaternary Rhyolites – This complex of rocks includes the rhyolites of Hot Creek and Mammoth Knolls, flows associated with the Resurgent Dome, and underlying early rhyolites (Bailey, 1989). These extrusive volcanic flows tend to be porphyritic high-silica rhyolite and are light-gray to buff-gray and glassy. The quantity of groundwater yielded from these rocks in the Mammoth Basin vicinity is usually small; these rocks are also considered non-water bearing.

2.2.2 Water-Bearing Rock

Previous studies (Bailey, 1989; Lipshie, 1974; Bailey et al., 1976) have indicated the presence of more than 20 geologic rock units in the project area. For modeling purposes, these rock units can be grouped into general hydrostratigraphic units that share similar hydrogeologic characteristics. The general hydrogeologic characteristics of the exposed and underlying rock formations in Mammoth Basin are described below from youngest to oldest.

Quaternary Alluvial Deposits – These deposits primarily occur in the eastern half of the study area and are comprised of detritus derived from all other rock formations in the project area. These deposits are comprised of clay, silt, sand, cobbles, and boulders that are generally unconsolidated and range in thickness from a thin wedge to an estimated 60 feet (DWR, 1973). Permeability within this unit generally ranges from low to moderate. This unit is not considered a significant groundwater reservoir because of its limited thickness and areal extent.

Quaternary Lake Deposits – These relatively minor deposits occur in the northeast corner of the study area. This unit was formed during the upper Pleistocene epoch in a large regional lake created by the damming of the upper Owens River Valley by volcanic and glacial activity. The lake deposits are most frequently comprised of unconsolidated, fine-grained sediments of low permeability and produce only small to moderate quantities of water. The thickness of these deposits range to over 200 feet regionally. However, in the Mammoth Basin, the depths appear only to reach a few tens of feet in localized areas and, therefore, do not appear to constitute significant aquifers.

Quaternary Glacial Deposits – During the Quaternary (Pleistocene) epoch, alpine glaciation was active throughout a large area of the Sierra Nevada. Remnants of this glaciation persist today in some of the higher elevations. Features related to glaciation and glacial deposition are present in the southern and western portions of the study area. The glacial deposits are slightly to moderately consolidated, consist of clay to boulder size sediments, and locally provide groundwater to wells. Such materials were deposited during several glacial and inter-glacial intervals throughout the Pleistocene epoch and vary in thickness from a few feet to more than 250 feet.

Quaternary through Tertiary Igneous Rocks – This unit consists of lava flows, breccias, and tuffs inter-bedded with glacial debris. The types of rock primarily include basalt and andesite. These formations occur throughout the groundwater basin and outcrop in the central and eastern parts of the basin. The secondary porosity in these volcanic rocks, combined with the inter-bedded glacial sediments, produces significant aquifers. These formations comprise the majority of the water-bearing units that have been developed for groundwater production, and all MCWD wells penetrate these formations. A subset of the identified flows that comprise these formations is provided below in order of age, from youngest to oldest:

- **Mammoth Pass Andesite:** Sparsely porphyritic trachyandesitic lava and cinder containing small plagioclase and olivine phenocrysts; flows from Mammoth Pass, outcrops visible within Mammoth Creek channel, terminal ridges present at the Sherwin Creek campground near wells SC-1 and SC-2 (Bailey, 1989; Hildreth, 2006).
- **Aphyric Basalt:** Aphyric to sparsely porphyritic trachybasaltic lava and cinder containing small olivine and plagioclase phenocrysts in reddish-brown to dark-gray aphanitic or medium-gray crystalline groundmass; K-Ar ages range from 152 to 64 ka (Mankinen et al., 1986). This flow is visible east of the MCWD main offices.
- **Porphyritic Basalt:** Coarsely porphyritic trachybasaltic lava and cinder typically containing plagioclase, olivine, and augite phenocrysts in a medium to dark-gray aphanitic groundmass; some flows contain abundant plagioclase phenocrysts commonly 1 cm long (Bailey, 1989). This flow is visible near the Casa Diablo Hot Springs.
- **Town Site Andesite:** Sparsely porphyritic trachyandesitic lava and cinder containing small plagioclase and olivine phenocrysts in reddish-brown to medium-gray or black groundmass; flows commonly exhibit subhorizontal platy jointing in exposed interiors; occurs near Mammoth Pass and in west moat of Long Valley Caldera (Bailey, 1989). This flow is visible on Highway 395 just prior to (east of) the northbound exit to Highway 203 and in Murphy Gulch.

2.2.3 Effective Base of the Aquifer

Consolidated bedrock underlies the water-bearing sediments of the Mammoth Groundwater Basin and acts as the effective base of the aquifer (herein referred to as the "bottom of the aquifer"). Fracture zones in the bedrock formations below the bottom of the aquifer may yield water to wells locally, but storage capacity is typically inadequate for sustained production.

The bottom of the aquifer is depicted in Figure 2-3 by equal depth contour lines of the buried contact between the consolidated bedrock and the overlying water-bearing sediments. Due to regional geothermal resources, there have been numerous investigations to determine the vertical extent of the different geologic units. A byproduct of these investigations is the identification of the bottom of the aquifer. The contours shown in Figure 2-3 were drawn from point data that were derived from lithologic descriptions in well drillers' reports and bedrock "signatures" from borehole geophysical logs and are consistent with trends in local geophysical surveys (Cascadia Exploration Corporation, 1990; GSI, 1973; DWR, 1973). The following wells penetrate the water-bearing materials and consolidated bedrock and were used to define the effective base of the aquifer:

- MCWD Well 8 (abandoned) and Well 26 (MCWD well completion reports)
- MLGRAP No. 1 and MLGRAP No. 2 (abandoned geothermal pilot holes [Dimuent & Urban, 1990])
- OH-1 (abandoned geothermal pilot hole [Mammoth Lakes, 1991])
- SF66-31 and SF38-32 (abandoned geothermal pilot holes [Bailey, 1992])

The mapped spatial extent of the bottom of the aquifer is limited to the model domain. The model domain was determined based on the saturated extent and thickness of the aquifer system; the extent was limited to regions where the saturated thickness was greater than about 40 feet. As shown in Figure 2-3, the bottom of the aquifer forms a valley trough aligned in an east-west orientation that shallows to the east. At the western edge of the Mammoth Groundwater Basin, depth to bedrock is greatest at approximately 1,000 feet below ground surface.

2.3 Groundwater Occurrence and Movement

The physical nature of the Mammoth Groundwater Basin is described below with regard to basin boundaries, recharge, groundwater flow, discharge, distinct aquifer systems, and hydrostratigraphy.

2.3.1 Mammoth Groundwater Basin Boundaries

The physical boundaries to the Mammoth Groundwater Basin are shown in Figure 2-1 and include:

- **Sierra Nevada/Long Valley Caldera to the South:** The Sierra Nevada is composed of a wide variety of igneous and metamorphic impermeable rocks, which are not considered water bearing. In some locations, the faulting associated with the Long Valley Caldera is assumed to be the groundwater basin boundary.
- **Mammoth Mountain to the West:** The rock that comprises Mammoth Mountain is permeable and contributes underflow to the Mammoth Groundwater Basin. The geology of Mammoth Mountain is very complicated due to its dynamic state, which contributes uncertainty to the connectivity and quantity of flow from the Mammoth Mountain area. The boundary of the Mammoth Groundwater Basin was defined as the contact between Mammoth Mountain volcanics and the known water-bearing material of the Mammoth Groundwater Basin.
- **Resurgent Dome to the North:** The Resurgent Dome is comprised of volcanic bedrock and is an effective barrier to groundwater flow along the northern boundary of the Mammoth Groundwater Basin.

- **Bedrock Constriction at Hot Creek to the North and Northeast:** This boundary is the gap between the rhyolite hills near Hot Creek narrows and the outlet of the Mammoth Groundwater Basin. These hills are composed of low permeability volcanic bedrock and are an effective barrier to groundwater flow along the northern and eastern boundaries of the Mammoth Groundwater Basin.
- **Groundwater Divide to the East:** A flattened mound of groundwater exists beneath the area between the Mammoth Yosemite Airport and Convict Creek and acts as a groundwater divide between the Mammoth Groundwater Basin and the rest of the Long Valley Basin. This assumption is based on historical water level elevations in wells in the eastern portion of the basin. This mound of groundwater extends from the bedrock hills east of the airport to south of the glacial moraine near the entrance to Convict Lake. Groundwater to the west of this divide flows westward within the Mammoth Groundwater Basin, and groundwater to the east of this divide flows eastward toward Crowley Lake.

2.3.2 Groundwater Recharge and Discharge

The predominant sources of recharge to the Mammoth Groundwater Basin are:

- Infiltration from overlying stream channels and ponds
- Underflow through saturated alluvium and fractures within bordering bedrock boundaries
- Deep percolation of precipitation

In general, groundwater flow mimics surface drainage patterns: groundwater flows from areas where the majority of recharge occurs in the west and south towards the central axis of the basin and then east/northeasterly along the axis of the basin before exiting the basin through a bedrock constriction at Hot Creek. Figure 2-4 is a groundwater elevation contour map for fall 2006 that shows these general groundwater flow patterns (perpendicular to the contours). A comparison of this contour map to groundwater elevation contour maps from other periods shows similar flow systems, demonstrating that the groundwater flow systems within the Mammoth Groundwater Basin are relatively consistent over time (see Figure 2-5 [fall 2001] and Figure 2-6 [fall 1993]).

Groundwater discharge from the Mammoth Groundwater Basin occurs primarily as sub-surface underflow to Mammoth Creek and Hot Creek. The sources of groundwater discharge from the Mammoth Groundwater Basin include:

- Groundwater production from wells
- Shallow groundwater discharge to surface water and subsequent outflow from the basin via Mammoth/Hot Creek. Specifically, areas of shallow groundwater include the following:
  - Mammoth Creek and Hot Creek: the reach of Mammoth Creek where it is in direct contact with highly permeable volcanics. This reach may recharge or discharge, depending on the groundwater level.
  - Areas of high groundwater (seasonal): the southwestern and southern portions of the basin. Figure 2-7 shows areas of high groundwater.

  - Springs: A number of springs discharge to the surface in the eastern portion of the basin. Among these springs, the most significant are in the vicinity of the Hot Creek Fish Hatchery and are designated AB, CD, and 23 (see Figure 2-7).
- There is no subsurface outflow from the Mammoth Groundwater Basin except to Mammoth Creek. This assumes that there is no flow from the Mammoth Groundwater Basin into fractured bedrock north to the Resurgent Dome or north/northeast to the rhyolite hills near Hot Creek narrows and Mammoth Airport.

2.3.3 Aquifer Systems and Hydrostratigraphy

As described in Section 2.2.2, the water-bearing sediments of the Mammoth Groundwater Basin are composed of alluvium, glacial deposits, basaltic flows, breccias, and tuffs that are often inter-bedded with glacial debris. These layers and their geometries are numerous and complex, and simplification was required to develop a hydrogeologic conceptual model representative of the three-dimensional physical system. This conceptual model, which was used as an input to the numerical groundwater flow model (see Section 5), is described below.

To develop the conceptual model, three hydrogeologic cross sections were constructed across the Mammoth Basin. The plan-view locations of these cross sections are shown in Figure 2-8, and the profile-view cross sections are shown in Figures 2-9 through 2-11. Plotted on these cross sections are well and borehole data, including borehole lithology, well casing perforations, and water levels.

Cross section A-A' trends from west to east along the axis of the consolidated bedrock trough, passes through the MCWD production well field, and parallels Mammoth Creek. Cross section A-A' originates approximately at Mammoth Lakes, extends eastward to the Hot Creek Fish Hatchery, and terminates near the outlet of the basin. Figure 2-9 shows cross section A-A' in profile view and depicts piezometric levels for fall 2006. Piezometric level and well construction data were obtained from the MCWD. Production and monitoring wells are shown in their actual or relative locations along the section line. Two distinct aquifer systems exist in the area where the MCWD produces groundwater:

- In the western portion of the basin, there are two aquifer systems: 1) a deep volcanic system that is highly responsive to MCWD groundwater production and responds slowly to recharge and 2) a shallow system that is not impacted by MCWD groundwater production and responds rapidly to recharge.
- In the eastern portion of the basin, what constitutes the deep aquifer in the western portion of the basin is no longer capped by the shallow aquifer. This system, in the eastern portion of the basin, is often unconfined and has little response to MCWD groundwater production.

Cross sections B-B' and C-C', shown in Figures 2-10 and 2-11, respectively, cross the western end of the Mammoth Groundwater Basin in a north-south orientation. Similar to cross section A-A', these profile views depict piezometric levels and well construction data, which were obtained from the MCWD. Note that the alluvial and glacial deposits vary significantly in thickness.

The western shallow system is defined herein as the glacial till and alluvium that overlies the basin and is generally less than 100 feet in depth; although, there are deeper areas, such as near Well 17. The deep system consists of fractured basalts and other water yielding rock that underlies the shallow system in the west. This same deep system is an unconfined single aquifer unit in the eastern portion of the aquifer where there is no overlying glacial till but occasional overlying thin alluvium and lacustrine deposits.

Figure 2-12 shows the water level time histories of several wells perforated in the shallow system and in the deep system; shallow system wells are depicted by dashed lines, and deep system wells depicted by solid lines. The color scheme denotes shallow and deep system pairings where the piezometric levels for wells perforated in the deep system are comparable to those for wells in the shallow system. The shallow monitoring wells located in the MCWD production well area have piezometric levels that are less than 50 feet below ground surface. Shallow system piezometric level variations within the year are generally less than ten feet and follow the snow melt pattern with increasing levels in late spring and early summer and mild decreases thereafter until the next snow melt. The piezometric levels of the MCWD deep monitoring and production wells are typically more than 150 feet below the ground surface—one notable exception is Well 5A, which is perforated in the deep and the shallow aquifer. Deep system piezometric level variations within the year can be as large as 50 to 75 feet due to production stresses. The seasonal response to snow melt in the deep system appears to be dwarfed by production stresses. Over the long term, groundwater levels show the impacts of lower recharge in a dry year or dry years with accompanying larger pumping stresses as well as the impacts of increased recharge in wet years and the subsequent reduction in pumping stresses (WEI, 2003).

The piezometric level time histories for all wells with data that could be recovered for this study are plotted in Appendix A. The hydraulic impact of MCWD groundwater production does not appear to extend east of MCWD Well 24 to the springs at the Hot Creek Fish Hatchery nor does it appear to affect the piezometric levels of the monitoring wells that are perforated in the shallow system and located in the same area as the MCWD production wells. This is consistent with the findings documented in *Annual Report on Results of Mammoth Community Water District Groundwater Monitoring Program for October 2001 – September 2002* (Schmidt, 2002) and in *Investigation of Groundwater Production Impacts on Surface Water Discharge and Spring Flow* (WEI, 2003). The deep system generally shows a progressive drawdown from the summer through the fall and generally recovers during the rest of the year. There have been two periods of progressive drawdown in the deep system from 1990 through 1995 and again from 2000 through 2005. This drawdown corresponds to a drought period wherein groundwater production was increased to replace surface water supplies.

The Department of Water Resources (DWR, 1973) divided the Mammoth Groundwater Basin into eastern and western areas. The dividing point used by DWR is located near the Los Angeles YMCA Camp along the northern boundary of Section 7, T4S/R28E. For this investigation, the Mammoth Groundwater Basin was also divided into eastern and western areas, although these areas differ slightly in description. The western area was established as the groundwater basin to the eastern extent of the glacial till, or approximately 4,500 feet east of MCWD Well 24. The western area is represented by two aquifer systems. The eastern area of the Mammoth Groundwater Basin is the remaining portion of the groundwater basin and is defined as a single aquifer system.

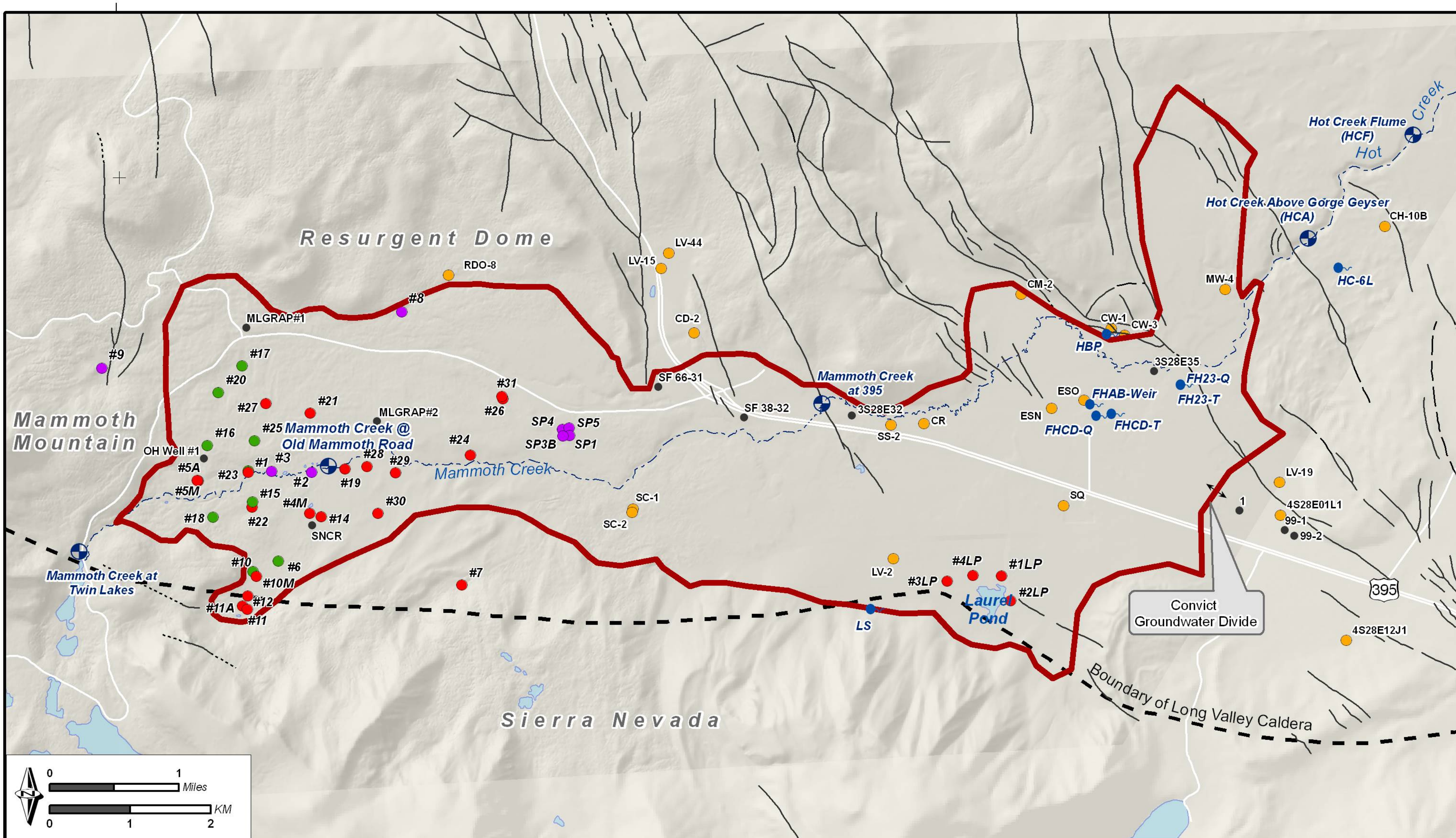
The surface area of the western portion of the groundwater basin is approximately 5 square miles. The most significant streams in the western area are Mammoth Creek and Bodle Ditch. The MCWD has constructed numerous production and monitoring wells in this area. Typically, these production wells were drilled to depths of more than 350 feet. The lithology logs of these wells indicate that inter-bedded alluvium, glacial till, and various types of extrusive volcanic rocks comprise the western basin area aquifers. Based on piezometric levels and the MCWD's pumping records, the deep aquifer system is confined to semi-confined. The highly variable nature of the subsurface lithology and the complex stratigraphic and structural conditions result in a complex aquifer system. Groundwater recharge to the western portion of the basin is derived from the deep percolation of precipitation and applied water, side boundary inflow, and from infiltration along Mammoth Creek and other tributaries. Groundwater discharge from the western area is defined as groundwater production, subsurface outflow to the eastern area, and evapotranspiration.

The surface area of the eastern portion of the groundwater basin is approximately 13 square miles. The most significant streams in the eastern area are Mammoth Creek, Laurel Creek, and Mammoth Creek/Hot Creek. Some small, non-MCWD production wells and test wells have been constructed within the eastern area. Geothermal groundwater is extracted and re-injected in the vicinity of Casa Diablo. Casa Diablo facility operations occur in the central portion of the Mammoth Groundwater Basin and appear outside or below the hydraulic influence of the MCWD wells, which are located about three miles to the west. Borehole logs for these wells indicate that the subsurface lithology is similar to that found in the western area but without as much overlying alluvium and glacial till. Recharge to the eastern area is derived from the deep percolation of precipitation, infiltration along stream courses, the recharge of recycled water at Laurel Pond, and subsurface inflows from the south, west, and north. The seasonal presence of marshes and shallow groundwater over a large area of the valley surface suggests that under normal conditions, this area is often refilled completely. The USGS has several monitoring wells in the eastern basin area. Appendix A contains hydrographs for these wells. Piezometric levels in the eastern area vary little over time in response to climatic variability and do not appear to be influenced by the large piezometric variations in the deep system in the western basin area utilized by the MCWD.

There are a number of springs that discharge to the surface in the eastern area of the basin. Among these springs, perhaps the most significant are in the vicinity of the Hot Creek Fish Hatchery, designated AB, CD, and 23 (see Figure 2-7). Discharge plots for these springs are also provided in Appendix B.

Table 2-1
Mammoth Basin Wells and Well Attributes

Well Name	Type	Depth (ft)	Owner	Easting	Northing
CD-2	Geothermal	0	Casa Diablo (CD2)	7019242	2062309
1	Destroyed	409	Hot Creek Hanger Group	7041493	2055074
99-1	Production	143	Hot Creek Hanger Group	7043336	2054270
99-2	Production	143	Hot Creek Hanger Group	7043735	2054036
CR	Production	80	Jarvis	7028618	2058601
RDO-8	Abandoned	7789	Lawr. Berkeley Lab.	7009228	2064649
ESO	Production	44	Mammoth Elementary	7035151	2059566
4S28E01L1	Production	70	Mammoth/Yosemite Airport	7043175	2054873
1	Production	382	MCWD	7001072	2056676
2	Abandoned	630	MCWD	7003662	2056625
3	Abandoned	330	MCWD	7002019	2056669
4M	Monitoring	89	MCWD	7003583	2054951
5A	Monitoring	357	MCWD	6998982	2056299
5M	Monitoring	80	MCWD	6999023	2056279
6	Production	670	MCWD	7002297	2052998
7	Monitoring	480	MCWD	7009777	2052032
8	Abandoned	563	MCWD	7007331	2063157
9	Abandoned	802	MCWD	6995098	2060869
10	Production	700	MCWD	7001272	2052583
10M	Monitoring	27	MCWD	7001399	2052376
11A	Monitoring	600	MCWD	7000839	2051173
11	Monitoring	43	MCWD	7001032	2051046
12	Monitoring	27	MCWD	7001053	2051587
14	Monitoring	520	MCWD	7004042	2054810
15	Production	720	MCWD	7001236	2055413
16	Production	710	MCWD	6999404	2057716
17	Production	710	MCWD	7000810	2060955
18	Production	710	MCWD	6999630	2054803
19	Monitoring	700	MCWD	7005009	2056754
20	Production	710	MCWD	6999850	2059877
21	Monitoring	640	MCWD	7003598	2059025
22	Monitoring	85	MCWD	7001218	2055210
23	Monitoring	65	MCWD	7001067	2056629
24	Monitoring	450	MCWD	7010135	2057320
25	Production	700	MCWD	7001315	2057916
26	Monitoring	700	MCWD	7011460	2059625
27	Monitoring	97	MCWD	7001797	2059414
28	Monitoring	100	MCWD	7005904	2056864
29	Monitoring	100	MCWD	7007072	2056599
30	Monitoring	610	MCWD	7006360	2054944
31	Monitoring	--	MCWD	7011410	2059721
1LP	Monitoring	25	MCWD	7031791	2052402
2LP	Monitoring	25	MCWD	7032152	2051399
3LP	Monitoring	23	MCWD	7029584	2052188
4LP	Monitoring	23	MCWD	7030634	2052431
SP1	Abandoned	53	MCWD	7013889	2058371
SP3B	Abandoned	42	MCWD	7014153	2058434
SP4	Abandoned	32	MCWD	7014165	2058115
SP5	Abandoned	47	MCWD	7013899	2058105
OH Well #1	Abandoned	1966	MMSA	6999253	2057194
SS-2	Production	100	Mono County. Sheriff	7027285	2058551
3S28E32	Unknown	75	Pacific Energy	7025694	2058939
3S28E35	Unknown	516	Pacific Energy	7038023	2060737
SQ	Production	125	Press Gravel	7035332	2054687
SNCR	Production	--	Snow Creek	7003666	2054469
SF 38-32	Corehole	2637	Union Geothermal	7021287	2058858
SF 66-31	Corehole	1157	Union Geothermal	7017798	2060095
4S28E12J1	Production	70	USFWS	7045844	2049772
CH-10B	Monitoring	315	USGS	7047433	2066645
CM-2	Monitoring	152	USGS	7032583	2063869
CW-1	Monitoring	805	USGS	7036261	2062481
CW-3	Monitoring	917	USGS	7036816	2062203
ESN	Monitoring	74	USGS	7033832	2059220
LV-15	Unknown	57	USGS	7017915	2064929
LV-19	Monitoring	97	USGS	7043125	2056206
LV-2	Monitoring	43	USGS	7027382	2053108
LV-44	Monitoring	80	USGS	7018225	2065551
MLGRAP#1	Abandoned	1535	USGS	7000998	2062521
MLGRAP#2	Abandoned	1610	USGS	7006310	2058695
MW-4	Monitoring	340	USGS	7040910	2064077
SC-1	Monitoring	132	USGS	7016769	2055135
SC-2	Monitoring	230	USGS	7016713	2054995



Author: MJC

Date: 20090122

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Study Area Feature Map

Mammoth Basin

Figure 2-1

Produced for:

Mammoth Basin Groundwater Model Report

MCWD Well Status and Location

- Monitoring Well
- Production Well
- Abandoned Well
- Other Wells and Boreholes

USGS Monitoring Station

- Well
- Spring
- Stream Gaging Station

MODFLOW Groundwater Flow Model Boundary

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed

Madera County

Mono County

Mammoth Lakes

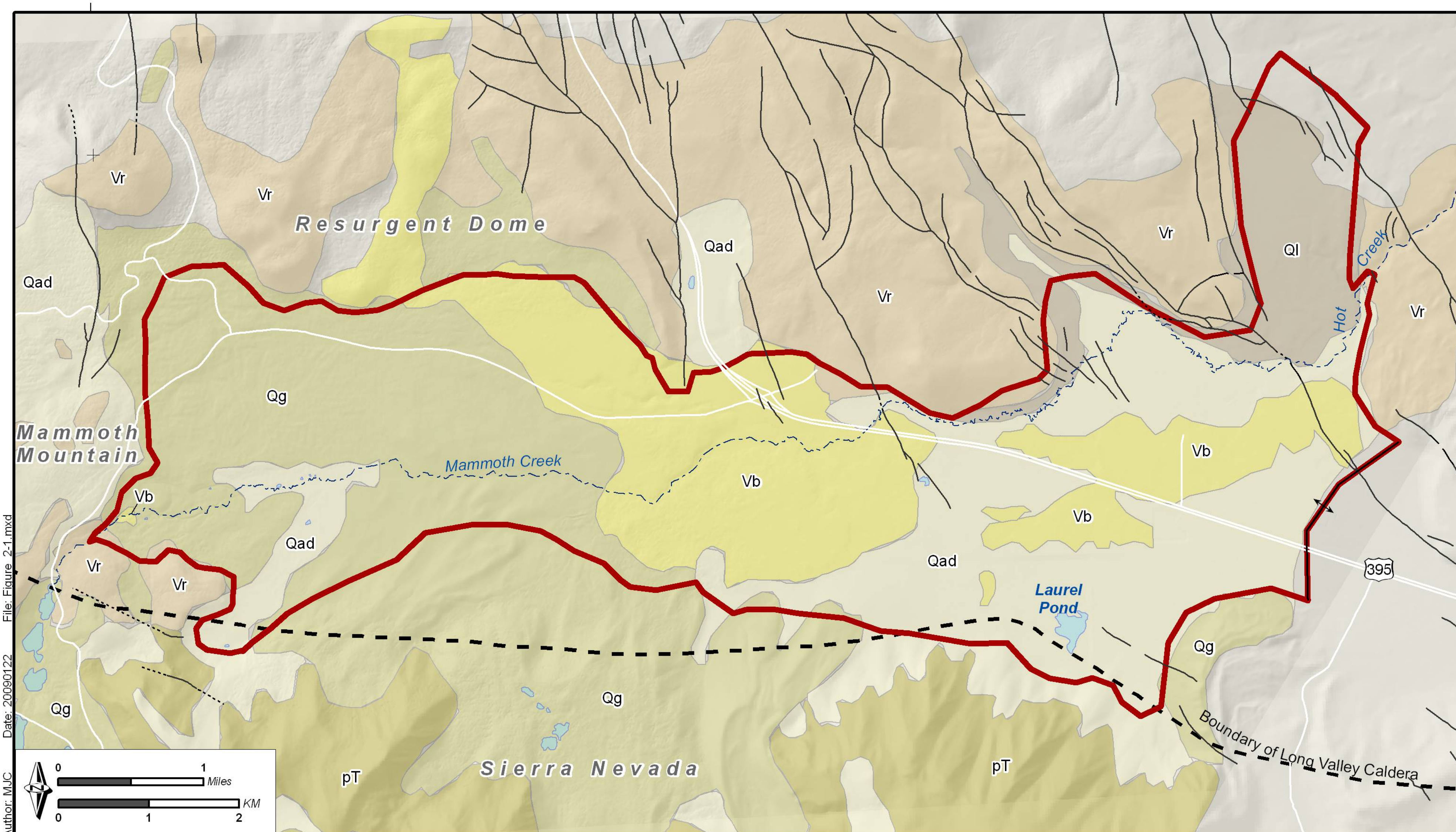
Fresno County

Inyo County

Bishop

NEVADA

CALIFORNIA



Author: MJC Date: 20090122 File: Figure 2-1.mxd

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Generalized Geologic Map

Mammoth Basin

Figure 2-2

Produced for:

Mammoth Basin Groundwater Model Report

MODFLOW Groundwater Flow Model Boundary

Geology

Qad Alluvial Deposits

Vb Basalt and Andesite

Qg Glacial Deposits

Ql Lake Deposits

Vr Rhyolite and Latite

pT Pre-Tertiary Complex

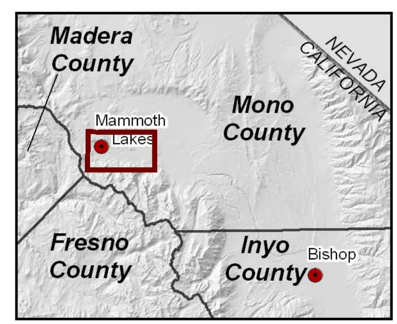
Faults

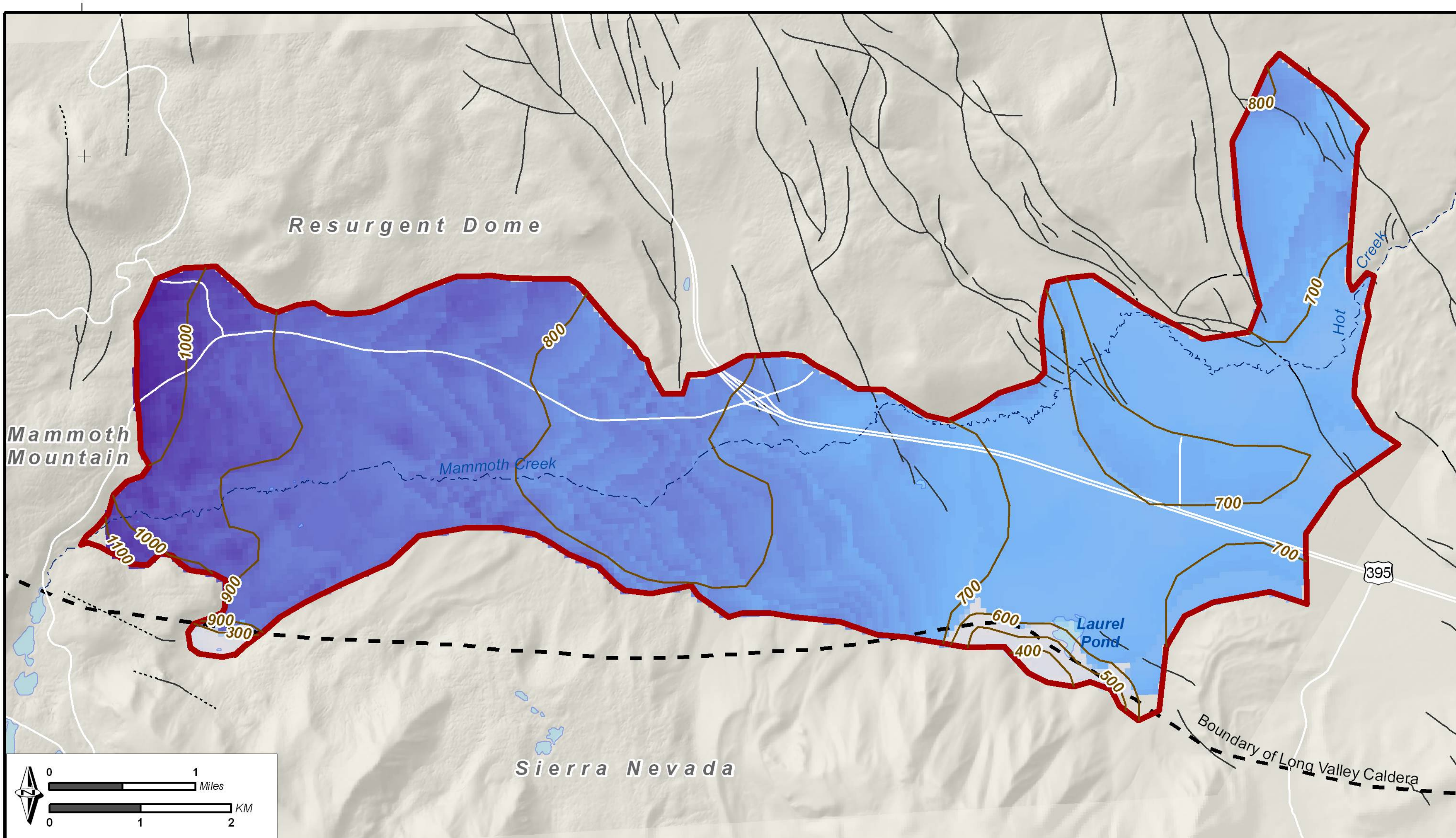
Location Certain

Location Approximate

Location Uncertain

Location Concealed





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Effective Base of the Aquifer

Depth to Bedrock

Figure 2-3

Produced for:

Mammoth Basin Groundwater Model Report

Interpolated Depth to Bedrock

1100 ft-bgs

700

300

MODFLOW Groundwater Flow Model Boundary

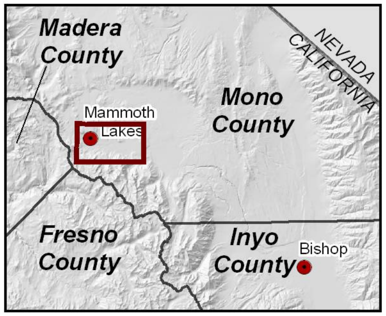
Faults

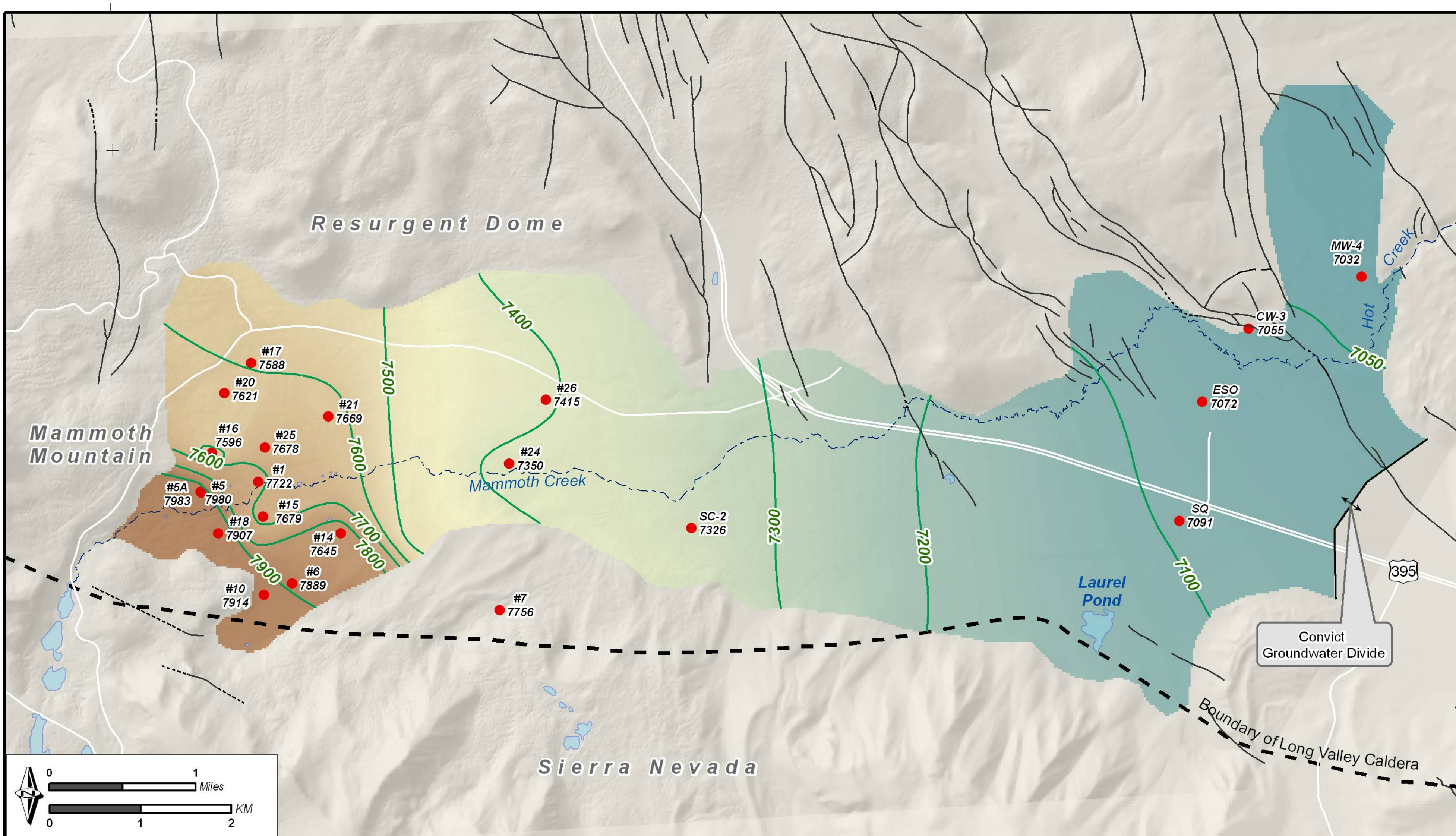
Location Certain

Location Approximate

Location Uncertain

Location Concealed





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Interpolated Groundwater Levels

7900+ feet above msl

Contours and Raster Surface 7500

7000

Well with Groundwater Level Time History

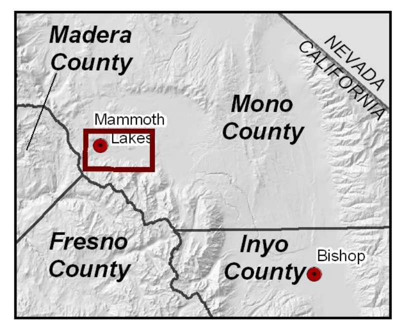
Faults

Location Certain

Location Approximate

Location Uncertain

Location Concealed



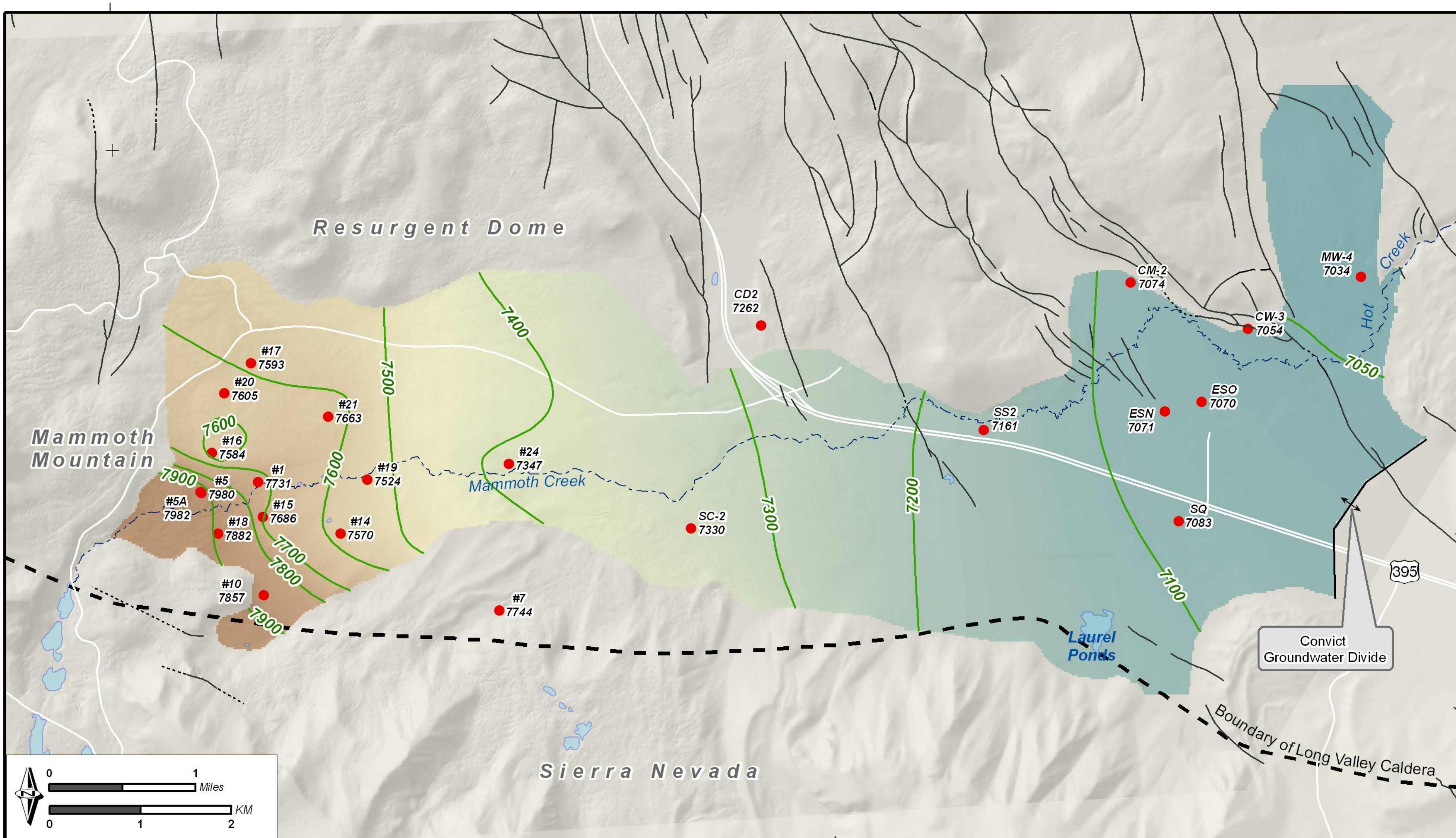
Groundwater Level Elevation

Fall 2006

Figure 2-4

Produced for:

Mammoth Basin Groundwater Model Report



Author: MJC Date: 20090122 File: Figure_2-5.mxd

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Interpolated Groundwater Levels

7900+ feet above msl

Contours and Raster Surface

7500

7000

Well with Groundwater Level Time History

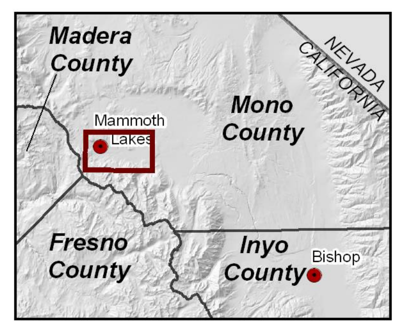
Faults

Location Certain

Location Approximate

Location Uncertain

Location Concealed



Groundwater Level Elevation

Fall 2001

Figure 2-5

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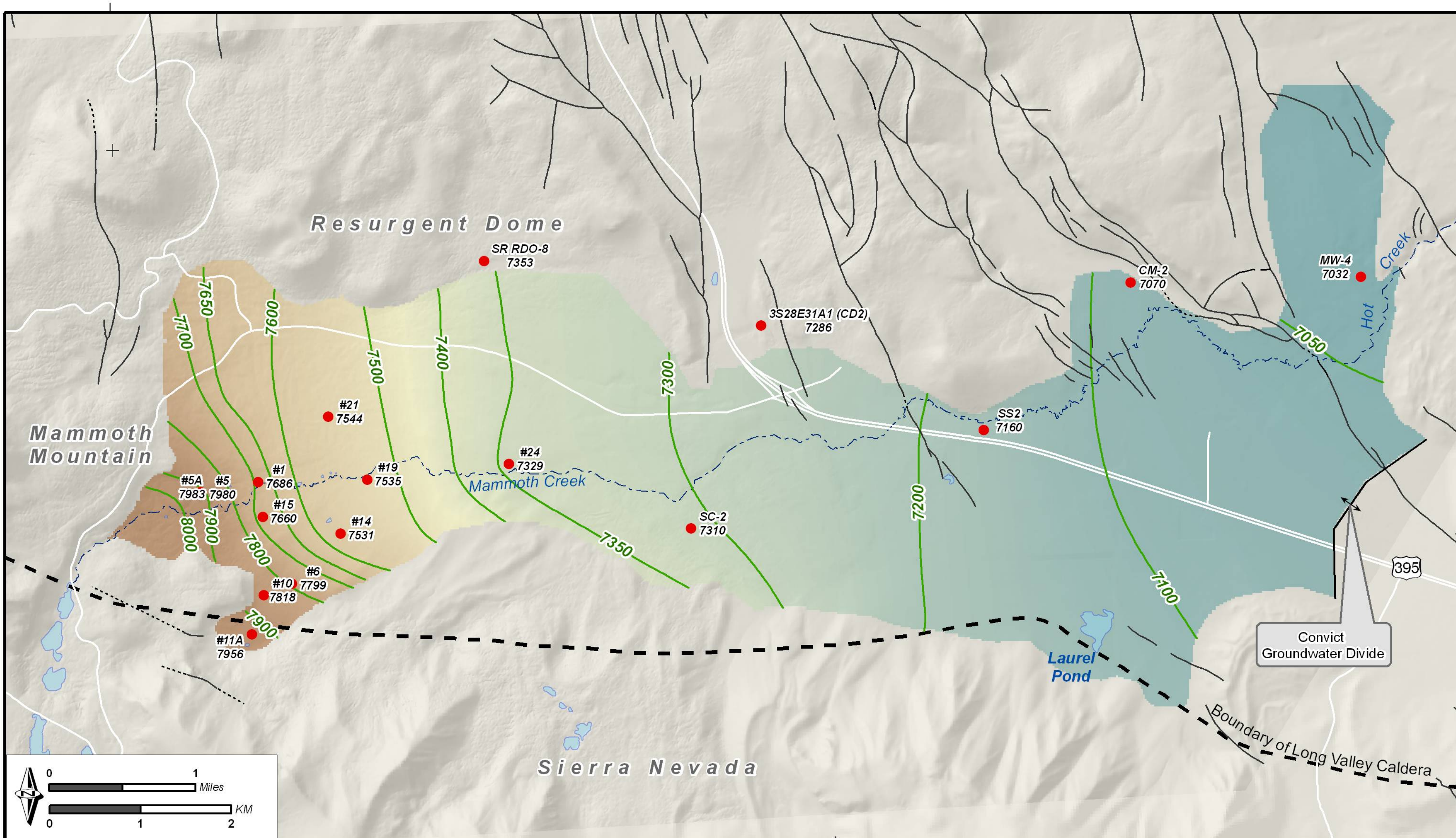
Mammoth Basin Groundwater Model Report



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Date: 20090122

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Interpolated Groundwater Levels

7900+ feet above msl

Contours and Raster Surface

7500

7000

Well with Groundwater Level Time History

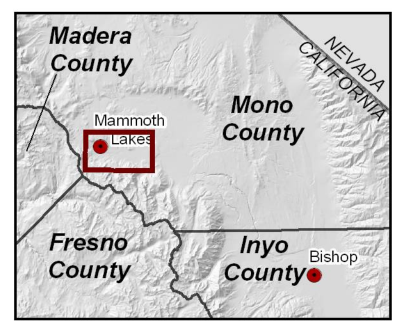
Faults

Location Certain

Location Approximate

Location Uncertain

Location Concealed



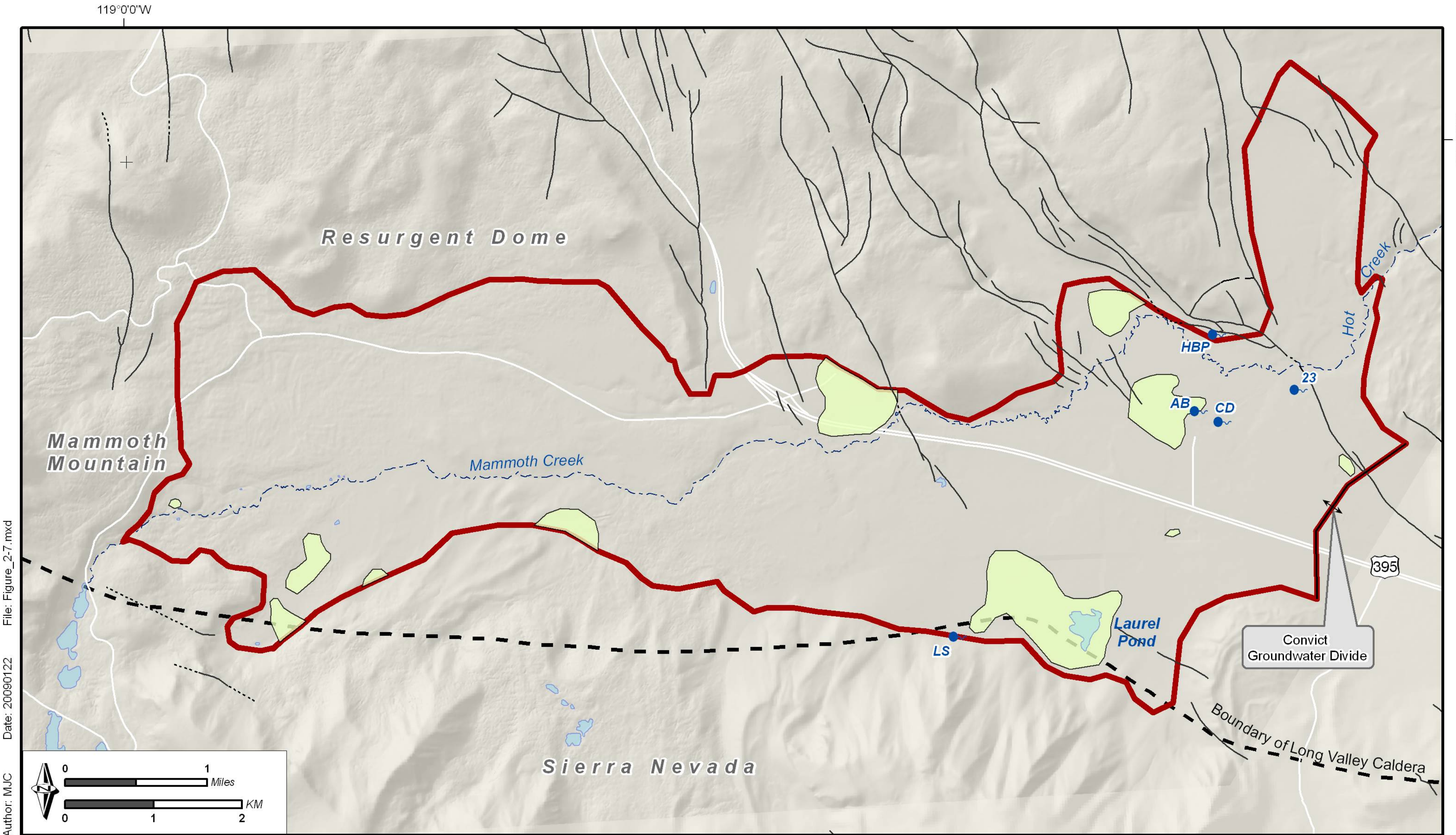
Groundwater Level Elevation

Fall 1993

Figure 2-6

Produced for:

Mammoth Basin Groundwater Model Report



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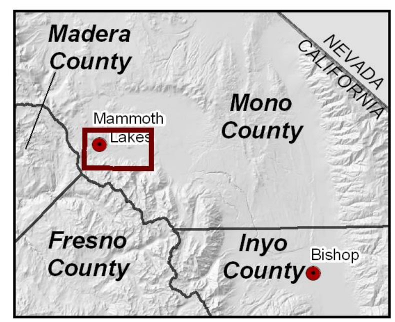
Generalized Area of Rising Groundwater

Note: These areas of rising groundwater occur after significant precipitation events.

Spring

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed

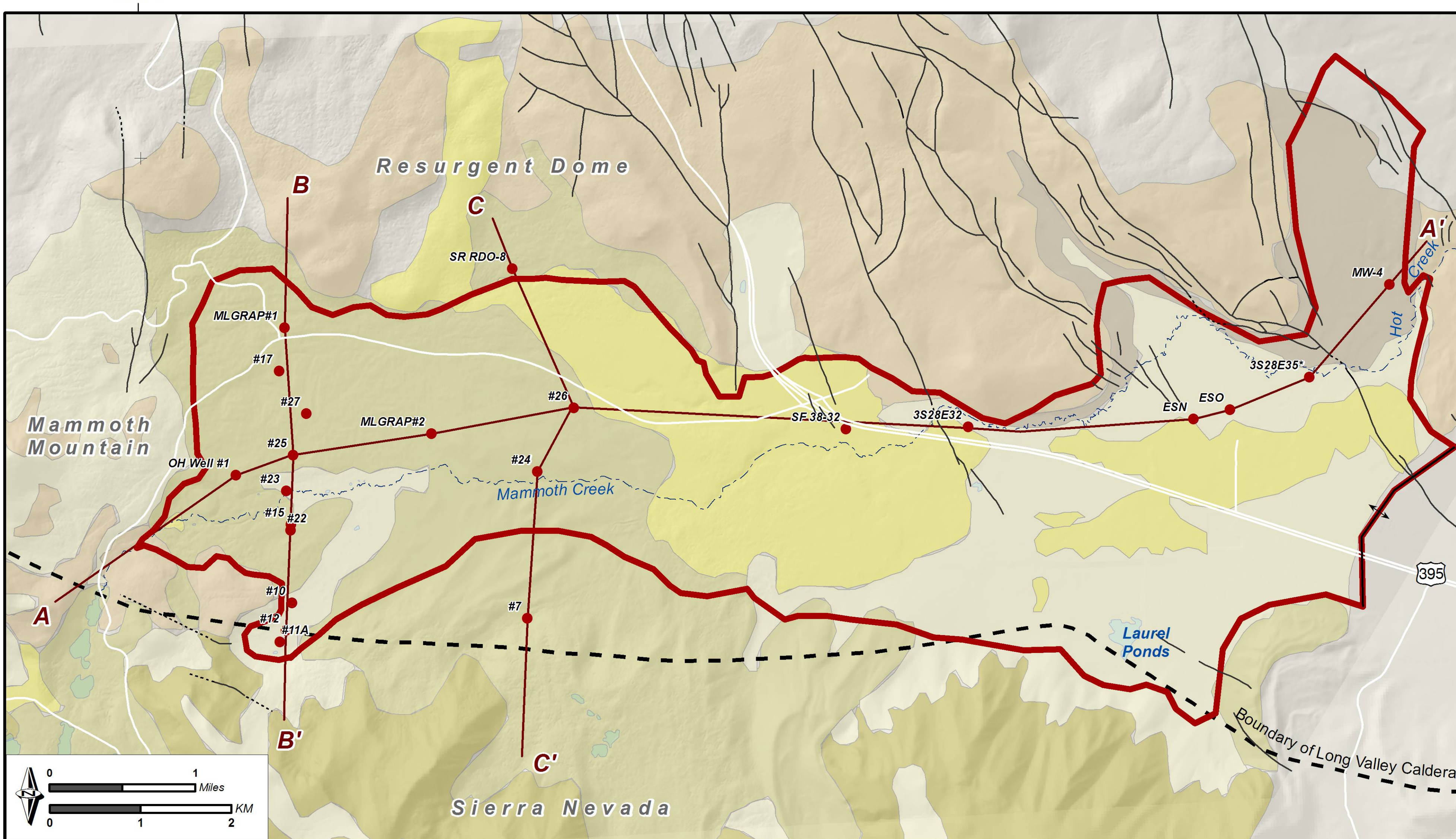


Location of High Groundwater and Groundwater Discharge

Figure 2-7

Produced for:

Mammoth Basin Groundwater Model Report



File: Figure_2-8.mxd

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Hydrogeologic Cross-Section
{Shown in Figures 2-9 thru 2-11}

Wells Used in Cross-Section
*Approximate location

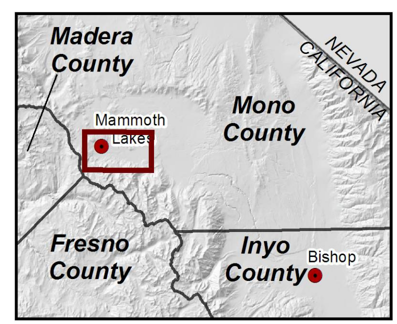
MODFLOW Groundwater Flow Model Boundary

Geology

- Alluvial Deposits
- Basalt and Andesite
- Glacial Deposits
- Lake Deposits
- Pre-Tertiary Complex
- Rhyolite and Latite
- Pumice Deposits

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed

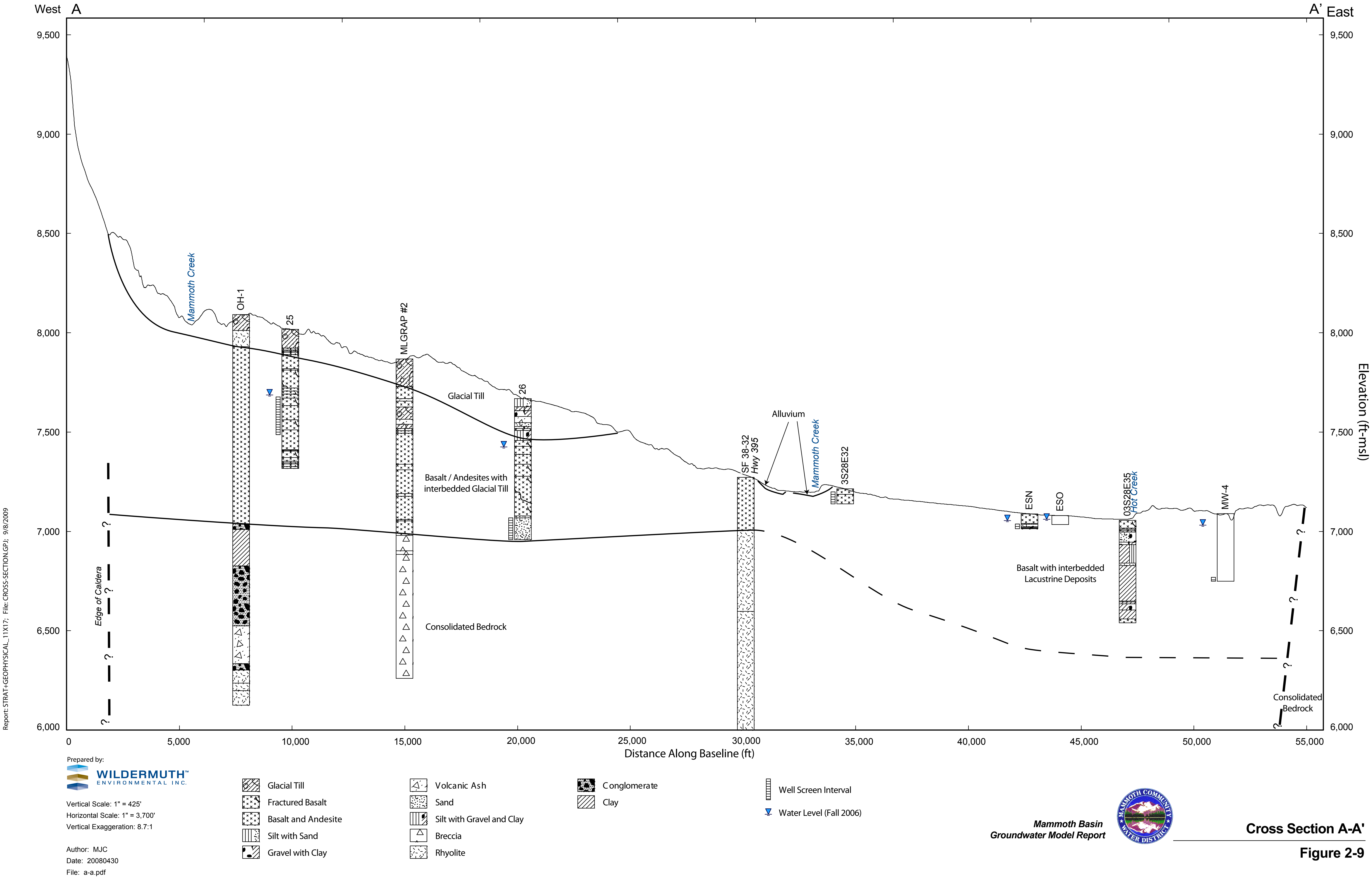


Location of Hydrogeologic Cross Sections

Figure 2-8

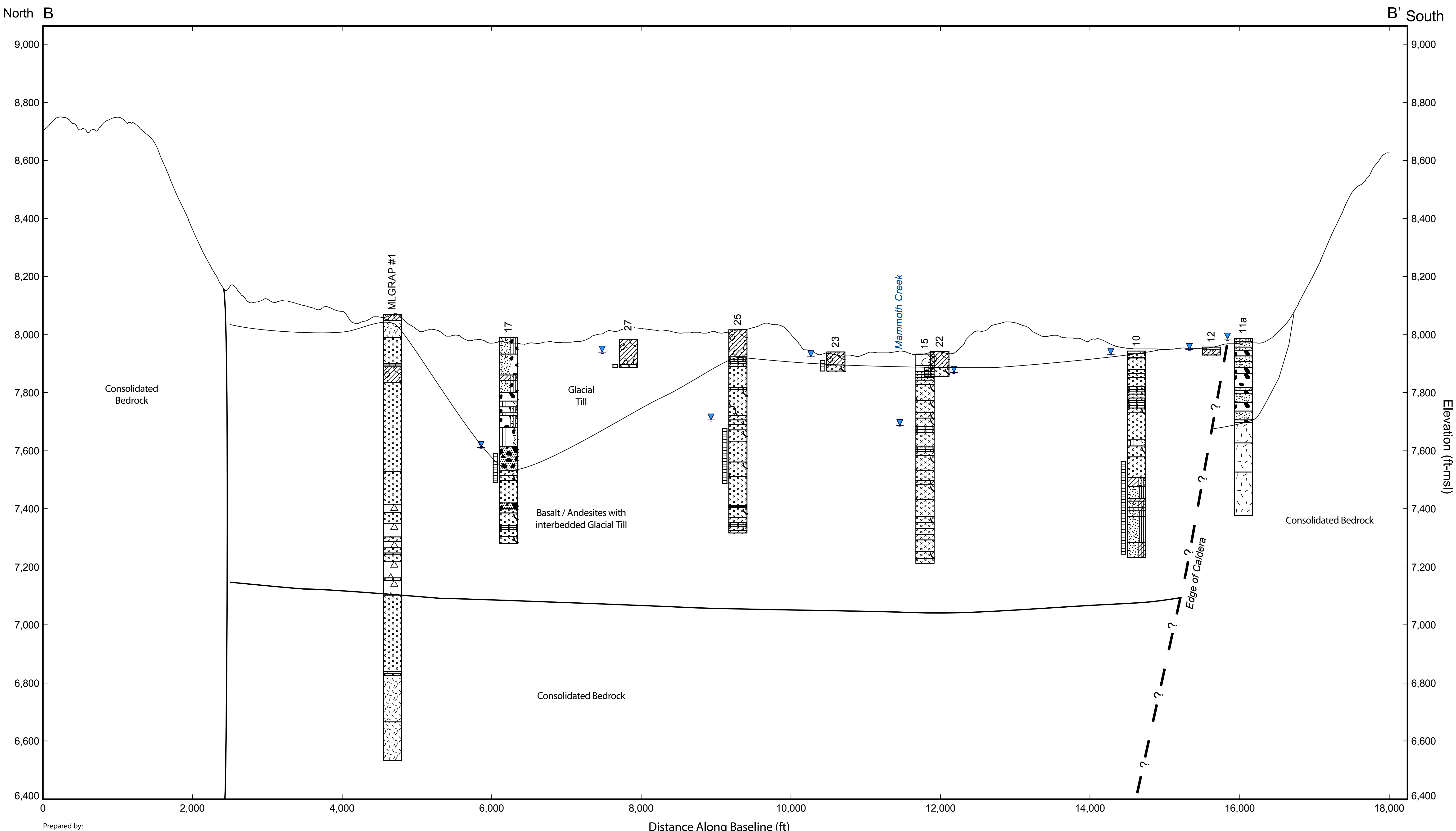
Produced for:

Mammoth Basin Groundwater Model Report



Cross Section A-A'

Figure 2-9



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Vertical Scale: 1" = 315'
Horizontal Scale: 1" = 1220'
Vertical Exaggeration: 3.9:1

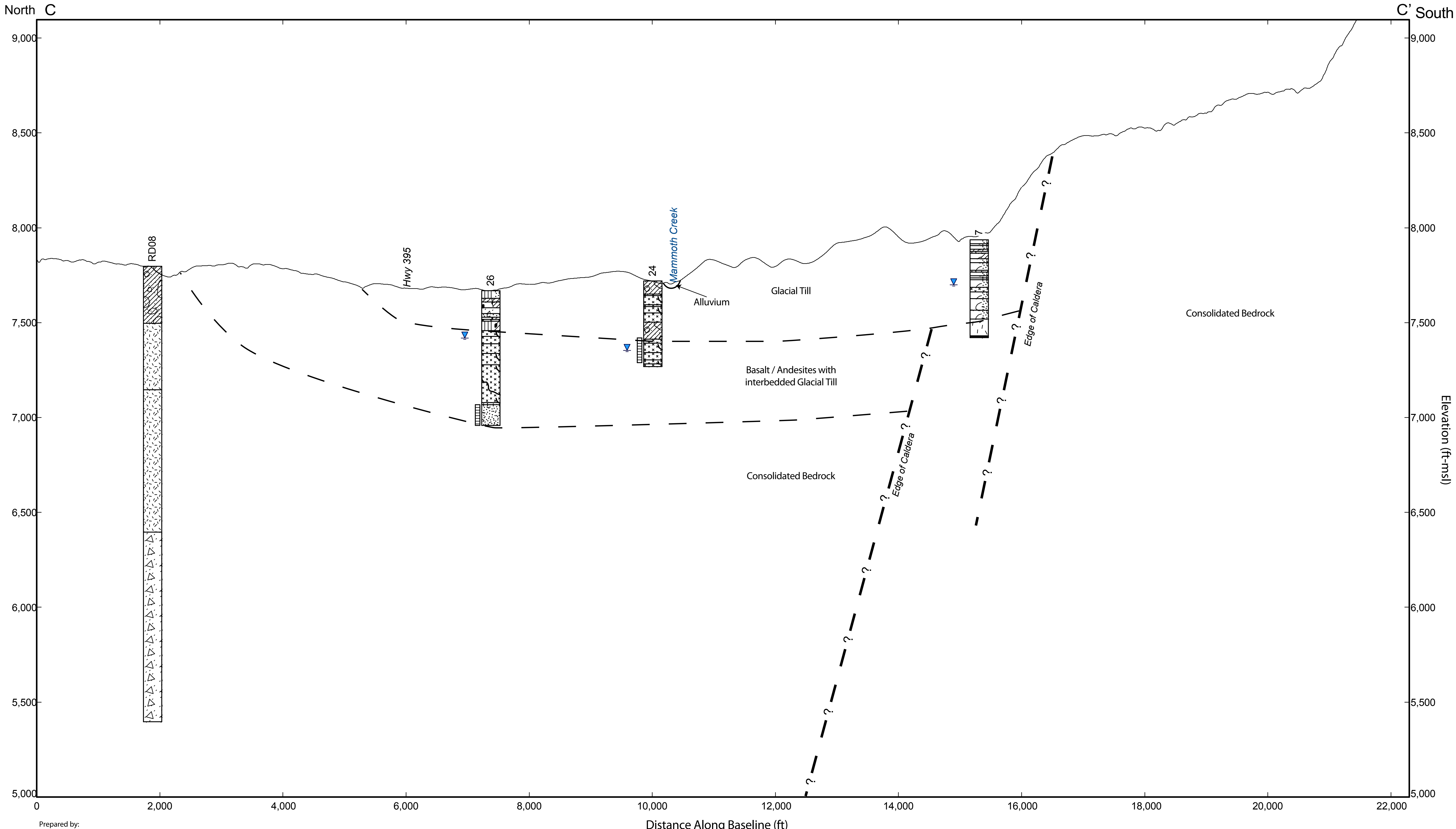
Author: MJC
Date: 20080430
File: b-b.pdf

Boulders/Cobbles with Sand
Basalt / Andesite
Fractured Basalt
Silt with Sand
Clay with Sand and Silt
Sand with Silt
Clay
Sand with Silt and Clay
Volcanic Ash
Glacial Till
Sand with Gravel
Sand with Clay
Sand
Sand with Gravel and Silt
Gravel
Well Screen Interval
Water Level (Fall 2006)

Mammoth Basin Groundwater Model Report

Cross Section B-B'

Figure 2-10



Prepared by:

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Vertical Scale: 1" = 485'
Horizontal Scale: 1" = 1490'
Vertical Exaggeration: 3:1

Author: MJC
Date: 20090126
File: c-c.pdf

Boulders/Cobbles with Sand
Clay
Sand with Gravel
Boulders/Cobbles with Clay
Sand
Basalt
Granite
Fractured Granite
Glacial Till
Fractured Basalt
Silt with Sand
Gravel with Clay
Volcanic Ash
Silt with Gravel and Clay
Rhyolite
Well Screen Interval
Water Level (Fall 2006)

Mammoth Basin Groundwater Model Report

Cross Section C-C'

Figure 2-11

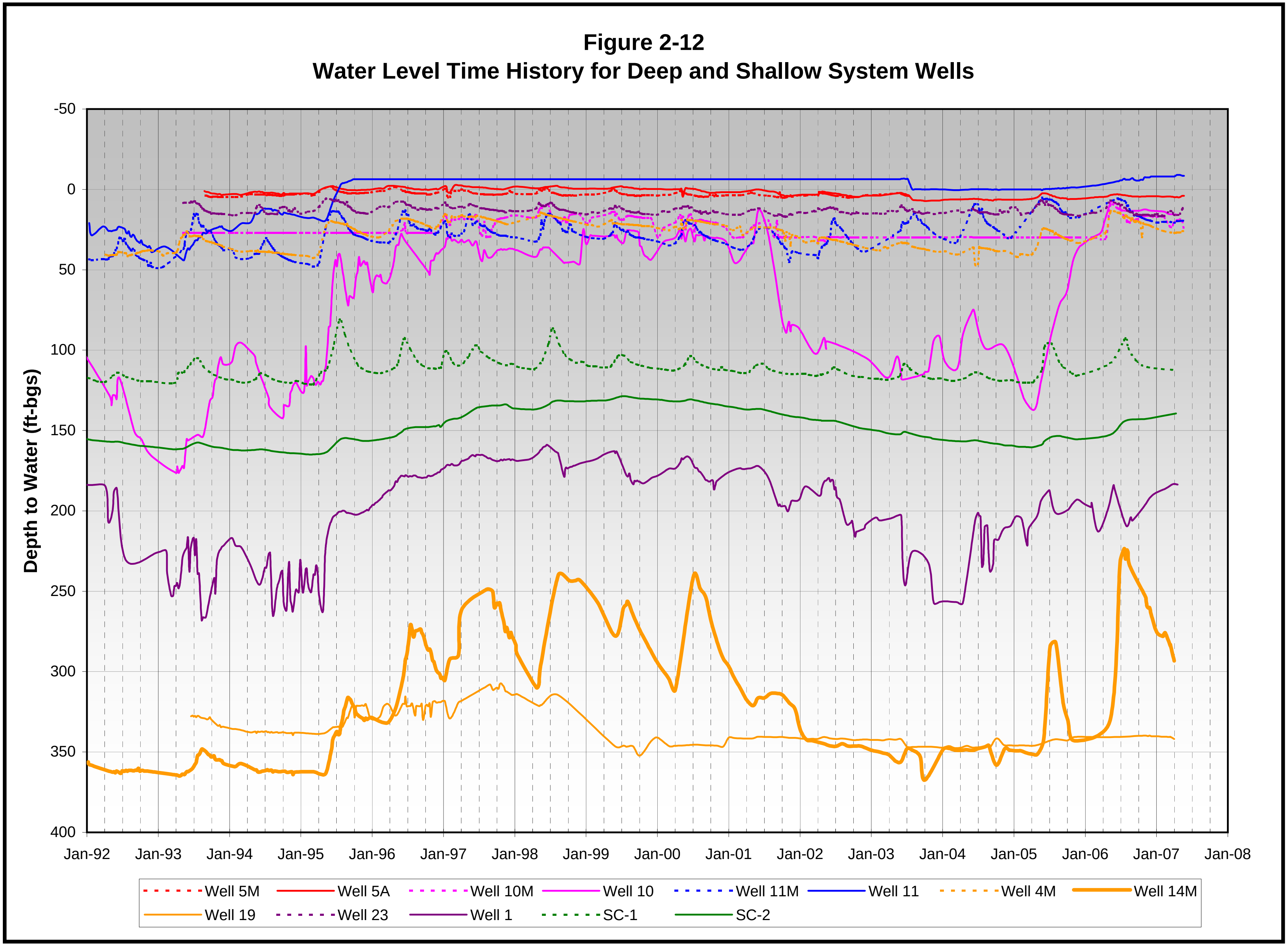

Figure2-12.xls

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The water budget is an accounting of inflows to and outflows from the groundwater system and the resultant changes of groundwater in storage. When total inflow is equal to total outflow, there is no change in groundwater storage, indicating that the aquifer system is at equilibrium, or an approximate steady state. When total inflow does not equal total outflow, there is either an increase or decrease in storage, which results in groundwater level changes.

This section discusses the groundwater budget during the calibration period, which is defined as calendar year 1992 through calendar year 2006. The values in the water budget were derived from measurements and estimates. The groundwater budget for the calibration period is summarized in Table 3-1. The average values for the calibration period are shown graphically in Figure 3-1. The water budget accounts for all Mammoth Groundwater Basin recharge and discharge components.

For this study, recharge and discharge were defined as water contributions to (recharge) and water losses from (discharge) the system. Figure 3-1 shows the components of recharge, which consist of boundary inflows, stream recharge, recharge from Laurel Pond, and the areal recharge of precipitation. The bottom half of Figure 3-1 displays the three components of discharge, which consist of evapotranspiration, discharge to streams, and groundwater pumping. Over the evaluation period, the average inflow was about 1,000 acre-ft/yr greater than the average outflow.

3.1 Recharge

3.1.1 Areal Recharge

Areal recharge was estimated from precipitation data for the Mammoth Basin. Total quarterly precipitation and its distribution within the Mammoth Basin watershed was calculated using three step-wise linear regression functions. The generated regression functions associate precipitation with three elevation categories, and each category has an associated precipitation curve. The regression functions allow for the estimation of precipitation as a function of elevation in areas that lack precipitation records. This estimation method considers elevation gradient a major contributor to the variation of precipitation.

To develop the regression function, available historic precipitation data for the Mammoth Basin were gathered from local gaging stations (Mammoth Lakes Ranger Station, Old Mammoth Road, Mammoth Pass, and Lake Mary), the California Department of Forestry and Fire Protection (CDFFP) annual precipitation map was utilized (CDFFP, 2006), and DWR's precipitation-elevation relationship was reviewed (DWR, 1973). Figure 3-2 graphically shows how the derived three step-wise functions relate precipitation to elevation.

The established precipitation-elevation relationship was used to generate a 10-meter by 10-meter precipitation grid for the entire Mammoth Basin. To generate a quarterly precipitation time series for input to the groundwater model, quarterly base precipitation values were calculated for each cell using a stepwise function, based on each cell's elevation. The calculated values were then adjusted for each cell based on the water content value of the Lake

Mary gage relative to each cell's mean. Historic precipitation data from Lake Mary (elevation 8,920 feet mean sea level) were referenced as Lake Mary has a long and continuous monthly record of precipitation. Figure 3-3 shows the annual precipitation at the Lake Mary gage. The location of the gage is shown in Figure 3-4.

3.1.2 Stream Recharge

Mammoth Creek is the primary surface water feature in the Mammoth Basin and provides recharge to the groundwater system. Stream flow at the Old Mammoth Road (OMR) gage has been recorded daily from 1992 to present, and stream flow at the outlet of Twin Lakes has been recorded from early 1994 to present, though less frequently and less accurately. Figures 3-5 and 3-6 show the measured stream flows for Mammoth Creek at the Twin Lakes outlet and OMR, respectively. A comparison of these flows indicates that measured stream flows at the Twin Lakes outlet are inaccurate during high flow periods (spring and summer), and further analysis shows that lake water levels are frequently higher than the measurement limit of the flow gage during the spring and summer, suggesting inaccuracy when flow exceeds about 31 cfs. The measurement method at the Twin Lakes outlet was altered in May 2002. However, according to the MCWD, the revised method is still inaccurate; as shown in Figure 3-5, high flows were not correctly recorded in the spring and summer of 2004 or 2005. During the fall and winter seasons, stream flows measured at Twin Lakes are quite close to those measured at OMR. In fact, the differences are so small that they are in the scale of measurement errors. Due to the inaccuracy of stream flow measurements at the Twin Lakes outlet, a relationship between flow at OMR and the Twin Lakes outlet was used to estimate flows. This relationship served as the initial estimate for the Twin Lakes outlet in the calibration process. Final flow from the Twin Lakes outlet was determined during the calibration process.

In general, stream flows are greatest in the second quarter (from April to June) with the exception of 1995 and 1998 wherein third quarter (from July to September) stream flows were greatest. The estimated average annual outflow from Twin Lakes is about 16,570 acre-ft/yr. The maximum annual inflow occurred in 1995, at 29,520 acre-ft/yr, and the minimum annual inflow occurred in 1992, at 6,570 acre-ft/yr.

Table 3-1 lists the recharge to the Mammoth Groundwater Basin from streams. These values are based on the stream characteristics, stream flow, and depth to groundwater. As shown in Table 3-1, the average annual inflow to the Mammoth Groundwater Basin from stream recharge is about 9,510 acre-ft/yr, ranging from a low of about 8,260 acre-ft/yr in 1997 to a high of about 11,580 acre-ft/yr in 1992. These values were derived from measurements and estimates that were refined in the calibration of the groundwater model.

3.1.3 Laurel Pond Recharge

With the permission of the United States Forest Service, the MCWD has discharged treated municipal wastewater to Laurel Pond since 1985. Laurel Pond is a small natural water body in the Mammoth Basin. Prior to 1985, the size of the pond depended entirely on hydrological conditions, such as local precipitation and evaporation, groundwater inflow, surface water runoff, and infiltration to groundwater.

The MCWD has measured flow to Laurel Pond since the fourth quarter of 2000. When discharge data were not available, discharge was estimated based on the quarterly relationship between total water demand and discharge to Laurel Pond. Figure 3-7 shows quarterly water demand, measured discharge to Laurel Pond, estimated discharge to Laurel Pond, and total annual discharge to Laurel Pond. In the 1992 to 2006 period, it is estimated that a total of 21,170 acre-ft of wastewater was discharged to Laurel Pond at an average rate of about 1,400 acre-ft/yr. This average discharge, which is much larger than local annual precipitation and evaporation, changed the local hydrological and hydrogeologic condition: the discharge increased the size of Laurel Pond and induced more infiltration to the groundwater system.

Estimates of recharge from Laurel Pond were based on local hydrogeology and published data (Gram/Phillips and Associates, 1982; Schmidt, 1996b; CH2M Hill, 2001) and calibrated with the groundwater model. Gram/Phillips and Associates published a study evaluating the hydraulic feasibility of effluent discharge to Laurel Pond in 1982. In 1996, Ken Schmidt and Associates prepared the first water budget for Laurel Pond to determine impacts from reducing discharge to the pond. In 2001, CH2M Hill completed a hydrologic evaluation of Laurel Pond and published an estimated water budget for the period of 1994 through 1999. The average estimated recharge from Laurel Pond estimated by Ken Schmidt and Associates was 1,170 acre-ft/yr, assuming a 65 acre pond and 1,500 acre-ft/yr of discharge to the pond. The net recharge from Laurel Pond calculated by CH2M Hill ranges from about 1,075 acre/ft in 1994 to about 1,646 acre-ft in 1998; the average rate is about 1,510 acre-ft/yr. This assumes a pond area ranging from 57 to 75 acres and from 1,125 to 1,560 acre-ft/yr of discharge to the pond. The net recharge estimated with the groundwater model from Laurel Pond to the Mammoth Groundwater Basin over the same period (1994 through 1999) ranges from about 1,300 acre-ft in 1994 to about 1,430 acre-ft in 1997 and averages about 1,350 acre-ft/yr.

Table 3-1 lists recharge to the Mammoth Groundwater Basin from Laurel Pond for the calibration period. The average recharge rate is about 1,400 acre-ft/yr. The annual recharge ranges from as low as about 1,300 acre-ft in 1994 to as high as about 1,600 acre-ft in 2006.

3.1.4 Subsurface Inflow

Subsurface boundary inflows were estimated based on a water balance and are listed in Table 3-1. The locations of boundary inflows are shown in Figure 3-8. To estimate subsurface inflow, first, total discharge from Mammoth Basin and the storage change for the 1992 to 2006 period were determined based on estimated evapotranspiration, recorded pumping, measured stream outflow, and water level changes. Second, the total amount of discharge and the storage change were subtracted from the total of all known recharge components to estimate unknown subsurface inflow. Next, quarterly precipitation time series for the seven neighboring sub-watersheds of the Mammoth Basin were calculated using the three step-wise regression functions between precipitation and elevation, and the time series precipitation data were summed for the calibration period, representing the total precipitation received by those sub-watersheds (as shown in Figure 3-8). The ratio of the estimated total subsurface inflow and the total precipitation received by the seven sub-watersheds during the calibration period represents the uniform contribution coefficient. Finally, the quarterly time-series subsurface inflows from each watershed were estimated by multiplying the precipitation of each sub-watershed by the uniform contribution coefficient.

Since precipitation is different in each watershed and varies with time, the derived subsurface inflow also varies with time. The average inflow to the Mammoth Groundwater Basin is about 17,270 acre-ft/yr. Table 3-2 shows the inflow from the seven neighboring sub-watersheds from 1992 through 2006. When the data were converted in the numerical model, the time delay between precipitation and inflow was taken into account. The delay time was set between 3 and 6 months, depending on sub-watershed size and distance to groundwater basin boundaries.

3.2 Discharge

3.2.1 Stream Outflow

In the Mammoth Basin, there is no subsurface outflow due to the rhyolite bedrock in the Hot Creek area. All of the groundwater is forced to rise up in front of the rhyolite bedrock and discharge to Hot Creek.

The USGS Hot Creek Flume (HCF) stream flow measurement station, as shown in Figure 3-4, is located downstream of the Hot Creek hot springs. Daily measured stream flow at HCF includes stream outflow from Mammoth Basin and the discharge of numerous hot springs from Hot Creek. The primary source of hydrothermal water is melted snow in the highlands around the western and southern rim of the caldera, which infiltrates to considerable depths and rises up to depths of about 1,600 to 6,600 ft-msl (USGS, 2007). Heated water flows eastward along void conduits and finally discharges as hot springs at the ground surface and in streambeds along Hot Creek. The rock layers that heat the water fed to the Hot Creek area are much deeper than the bottom of the Mammoth Groundwater Basin; thus, the hot spring water is not from aquifers within the Mammoth groundwater system. To estimate total stream outflow from the Mammoth Basin, based on measurements at HCF, the flow contribution of hot springs along Hot Creek must be known.

Discharge out of the Mammoth Basin is a key component to the water budget. As shown in Figure 3-4, the Hot Creek above Gorge Geyser (HCA) gage is closest to the edge of the groundwater model domain. Yet, this gage does not have the data history of the HCF gage. Figure 3-9 compares stream flow measurements at HCF and HCA that were recorded the same day. The stream flow difference at these two stations is the discharge flow from the hot springs. Based on the 88 measurements shown in this figure, the average difference indicates that the average hot spring flow contribution between the two gages is about 8.5 cfs with a small standard deviation. Total stream outflow from Mammoth Basin can be estimated by subtracting the hot spring contribution. Figure 3-10 shows the calculated quarterly stream outflows at HCA, which represent outflow from the Mammoth Basin.

As shown in Table 3-1, average annual outflow from the Mammoth Groundwater Basin to streams is about 23,790 acre-ft/yr, ranging from a low of about 16,120 acre-ft/yr in 1992 to a high of about 44,920 acre-ft/yr in 1998.

3.2.2 Evapotranspiration

Evapotranspiration (ET) is the combination of water loss due to evaporation from soil or open water and transpiration from plant tissue. The ET of specific plants is estimated using the reference crop and dimensionless transpiration coefficients concept (Allen et al., 1998). This concept was initially developed to estimate ET for irrigated agriculture but was later extrapolated to estimate ET for native vegetation (Steinwand et al., 2001).

In applying this concept, the ET rate of a reference crop (denoted hereafter as ET_0) is first calculated using the Penman-Monteith equation and then multiplied by a coefficient (K_c) that corresponds to the specific vegetation type:

$$ET_c = K_c * ET_0$$

Where K_c = vegetation type coefficient

ET_c = evapotranspiration

ET_0 = potential evapotranspiration

The ET calculation for the Mammoth Basin consisted of the following steps:

1. Collect and analyze ET_0 rates from the closest weather station.
2. Correct ET_0 for the elevation in the Mammoth Basin.
3. Disaggregate the basin by vegetation and land use zones, using CDFFP vegetation data (CDFFP, 2006) and Mono County land use data (Mono County, 2006).
4. Obtain transpiration coefficients from published data for similar vegetation types.
5. Calculate quarterly ET rates for each vegetation parcel using the Penman-Monteith equation.

The California Irrigation Management Information System (CIMIS) provides reference evapotranspiration rate data (ET_0) for a short actively growing grass (Shuttleworth, 1992). For this study, ET_0 rates are obtained from the weather station located in Bishop, California (37^o 21' 29"N, 118^o 24' 14" W, NAD 84, 4,170 mean sea level). This is the closest station to the Mammoth Basin (about 30 miles), and it has historical data starting in 1983.

Monthly ET_0 rates were prepared based on daily data from the Bishop station and an elevation correction (Maurer et al., 2006). These data were compared to the published CIMIS ET_0 for Zone 14 (CIMIS, 2006), which covers the Mammoth Basin. Figure 3-11 shows this comparison. Moreover, Figure 3-11 shows that the trends of both ET_0 plots are comparable with a maximum difference of 1.8 inches during the month of May.

In order to estimate the vegetation cover in the Mammoth Groundwater Basin, landscape data from the CDFFP were obtained and overlain the model area. Land use data were obtained from the Town of Mammoth Lakes (Mammoth Lakes, 2006). The final merged product consisted of eight vegetation types. Aerial photography was used to determine the existence of vegetation type combinations within the urban landscape types.

Published transpiration values (K_C) of the dominant vegetation types were collected from available literature (Merkel, 2007; Petersen et al; 1985; and FAO, 1998). Variation in seasonal plant phenology was accounted for by assigning one K_C value for each quarter of the water year. Table 3-3 lists the K_C values used for each vegetation type. These coefficients were assumed to be geographically transferable as they were initially determined for other regions. Figure 3-12 shows the distribution of vegetation cover types.

Quarterly ET_0 rates were calculated from long-term monthly average values and multiplied by the appropriate quarterly K_C for each vegetation parcel. Calculated ET, which is related to the depth of the groundwater table, is listed in the Table 3-1 and averages about 14,030 acre-ft/yr. While estimated ET accounts for a significant portion of the groundwater budget, there is significant uncertainty associated with it. The ET estimation presented herein is the best estimate for the Mammoth Groundwater Basin completed to date, but it could be improved with detailed local vegetation mapping, better documented local K_C values, and local reference ET data.

3.2.3 Groundwater Pumping

Groundwater pumping was based on records supplied by the MCWD for the Mammoth Groundwater Basin. Table 3-1 provides an annual pumping summary, and Table 3-4 shows annual pumping by well from 1992 to 2006. The average annual pumping is about 1,720 acre-ft (1,640 acre-ft for MCWD). Over the calibration period, more than 50 percent of pumping can be accounted for by Wells 10 and 15.

Table 3-1
Annual Groundwater Budget for the Calibration Period, 1992-2006[1]
(acre-ft/yr)

Year	Recharge					Discharge				Change in Storage
	From Stream	Areal Recharge	Subsurface inflow	Laurel Pond	Estimated Total Recharge	Pumping	ET	Discharge to Stream	Total Discharge	
1992	11,578	7,945	12,494	1,361	33,377	2,484	13,958	16,115	32,556	821
1993	10,594	12,301	14,765	1,454	39,115	1,744	13,990	19,844	35,578	3,537
1994	10,277	7,691	15,385	1,302	34,655	1,572	13,962	19,543	35,077	-422
1995	9,836	16,701	21,369	1,314	49,219	1,331	14,032	24,731	40,094	9,125
1996	9,061	14,453	25,519	1,411	50,443	1,115	14,064	27,515	42,695	7,748
1997	8,257	16,456	18,741	1,426	44,880	1,095	14,095	29,072	44,262	619
1998	8,263	17,462	22,145	1,326	49,195	876	14,115	29,932	44,924	4,272
1999	8,692	10,831	15,214	1,342	36,079	1,144	14,075	25,968	41,186	-5,107
2000	8,939	12,394	16,760	1,403	39,497	1,326	14,065	25,364	40,755	-1,259
2001	9,251	8,458	13,358	1,457	32,524	2,368	14,027	22,819	39,214	-6,690
2002	9,589	8,897	11,484	1,463	31,433	2,757	13,995	21,395	38,148	-6,715
2003	9,950	9,221	14,195	1,517	34,884	2,604	13,969	20,784	37,357	-2,473
2004	9,833	9,240	14,652	1,308	35,033	1,999	13,960	21,031	36,989	-1,957
2005	9,765	13,738	21,302	1,460	46,265	2,254	13,991	23,820	40,064	6,201
2006	8,750	19,834	21,624	1,630	51,838	1,143	14,072	28,867	44,082	7,757
Total	142,634	185,622	259,008	21,174	608,438	25,811	210,368	356,802	592,981	15,457
Minimum	8,257	7,691	11,484	1,302	31,433	876	13,958	16,115	32,556	-6,715
Maximum	11,578	19,834	25,519	1,630	51,838	2,757	14,115	29,932	44,924	9,125
Average	9,509	12,375	17,267	1,412	40,563	1,721	14,025	23,787	39,532	1,030

1. The values for the hydrologic components listed above are the result of various models and computations and are shown to the nearest whole acre-ft. The accuracy of these estimates is estimated to vary from plus or minus 10 to 20 percent in any given year.

Table 3-2
Annual Average Subsurface Boundary Inflows from Sub-Watersheds
(acre-ft/yr)

Year	Sub-Watershed 1	2	3	5	6	7	Total
1992	415	3,190	2,578	3,960	605	614	11,363
1993	598	4,591	3,710	5,697	871	883	16,350
1994	468	3,597	2,906	4,464	683	692	12,810
1995	799	6,135	4,958	7,614	1,164	1,180	21,850
1996	874	6,709	5,421	8,326	1,273	1,291	23,894
1997	699	5,369	4,338	6,663	1,019	1,033	19,121
1998	889	6,828	5,518	8,474	1,296	1,314	24,319
1999	546	4,189	3,385	5,199	795	806	14,921
2000	633	4,860	3,927	6,032	922	935	17,310
2001	478	3,668	2,964	4,552	696	706	13,062
2002	439	3,369	2,723	4,182	639	648	12,000
2003	502	3,854	3,114	4,783	731	741	13,726
2004	492	3,779	3,054	4,690	717	727	13,460
2005	705	5,412	4,373	6,717	1,027	1,041	19,275
2006	978	6,559	6,009	8,399	2,208	1,392	25,544
Total	9,515	72,109	58,978	89,752	14,648	14,003	259,005
Minimum	415	3,190	2,578	3,960	605	614	11,363
Maximum	978	6,828	6,009	8,474	2,208	1,392	25,544
Average	634	4,807	3,932	5,983	977	934	17,267
Average Percent of Total Subsurface Recharge	4%	28%	23%	35%	6%	5%	100%

1. The values for the hydrologic components listed above are the result of various models and computations and are shown to the nearest whole acre-ft. The accuracy of these estimates is estimated to vary from plus or minus 10 to 20 percent in any given year.

Table 3-3
Vegetation Type Evapotranspiration Coefficient

Vegetation Type[1]	Quarterly Evapotranspiration Coefficient (K_C)			
	Q1	Q2	Q3	Q4
Barren /Other[2]	0.05	0.35	0.35	0.05
Conifer Forest[3]	0.25	0.75	0.75	0.25
Hardwood Forest[4]	0.2	0.6	0.6	0.2
Shrub[4]	0.1	0.7	0.7	0.1
Water[4]	1.2	1.2	1.5	1.3
Wetland[4]	0.5	1.1	1.1	0.5
Urban[5]	-	-	-	-

1. These coefficients are assumed to be geographically transferable for the same species, as they were initially determined for other regions (Steinwand et al., 2001).

2. FAO, 1998

3. Petersen & Hill, 1985

4. Merkel & Associates, 2007

5. Urban areas were digitized for each Town of Mammoth Lakes land use classification. Evapotranspiration coefficients were assigned to each land use classification based upon the percentage of vegetation type within that classification. Urban areas outside the Town of Mammoth Lakes were assigned evapotranspiration coefficients based upon the percentage of vegetation type for the given parcel.

Table 3-4
Annual Groundwater Pumping by Well
(acre-ft/yr)

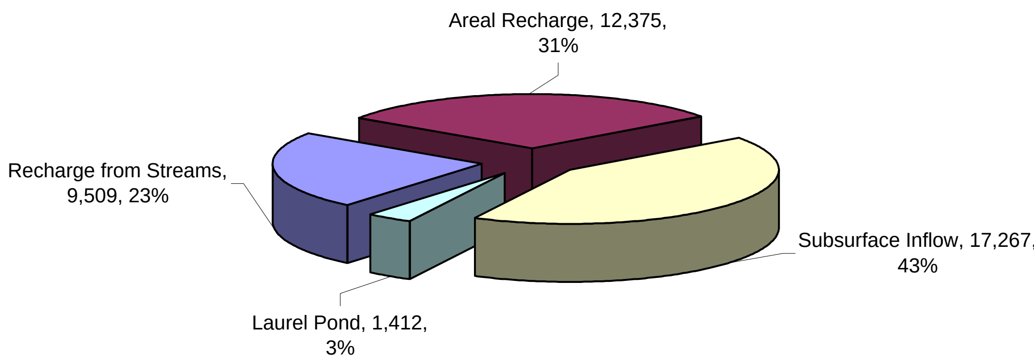
Year	Well 1	6	10	15	16	17	18	20	SC[1]	Total
1992	356	787	575	666	0	0	0	0	100	2,484
1993	142	479	607	479	0	0	0	0	37	1,744
1994	212	270	557	355	0	0	23	0	155	1,572
1995	46	228	323	329	54	44	10	132	165	1,331
1996	1	13	692	98	6	133	0	76	97	1,115
1997	13	143	347	167	56	82	0	180	108	1,095
1998	71	0	222	257	139	183	4	0	0	876
1999	72	0	136	405	104	77	28	251	71	1,144
2000	19	0	204	381	188	208	78	178	70	1,326
2001	80	111	547	570	231	425	124	246	35	2,368
2002	131	184	1,087	591	142	310	77	195	40	2,757
2003	183	454	601	806	107	172	113	81	86	2,604
2004	72	347	500	368	239	138	59	188	89	1,999
2005	188	622	576	244	100	226	53	167	77	2,254
2006	297	1	136	390	0	229	1	12	77	1,143
Total	1,883	3,638	7,108	6,105	1,366	2,226	570	1,707	1,207	25,811
Minimum	1	0	136	98	0	0	0	0	0	876
Maximum	356	787	1,087	806	239	425	124	251	165	2,757
Average	126	243	474	407	91	148	38	114	80	1,721

1. Snow Creek Golf Course production well

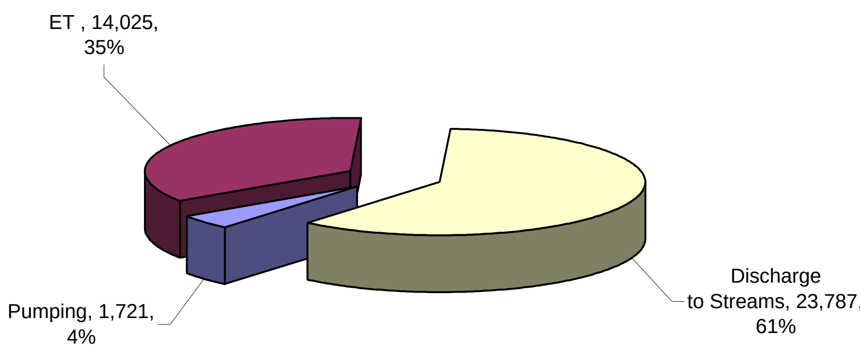
Figure 3-1

Calibration Period Water Balance Summary[1]

Calibration Period Average Recharge: 40,560 Acre-ft/yr

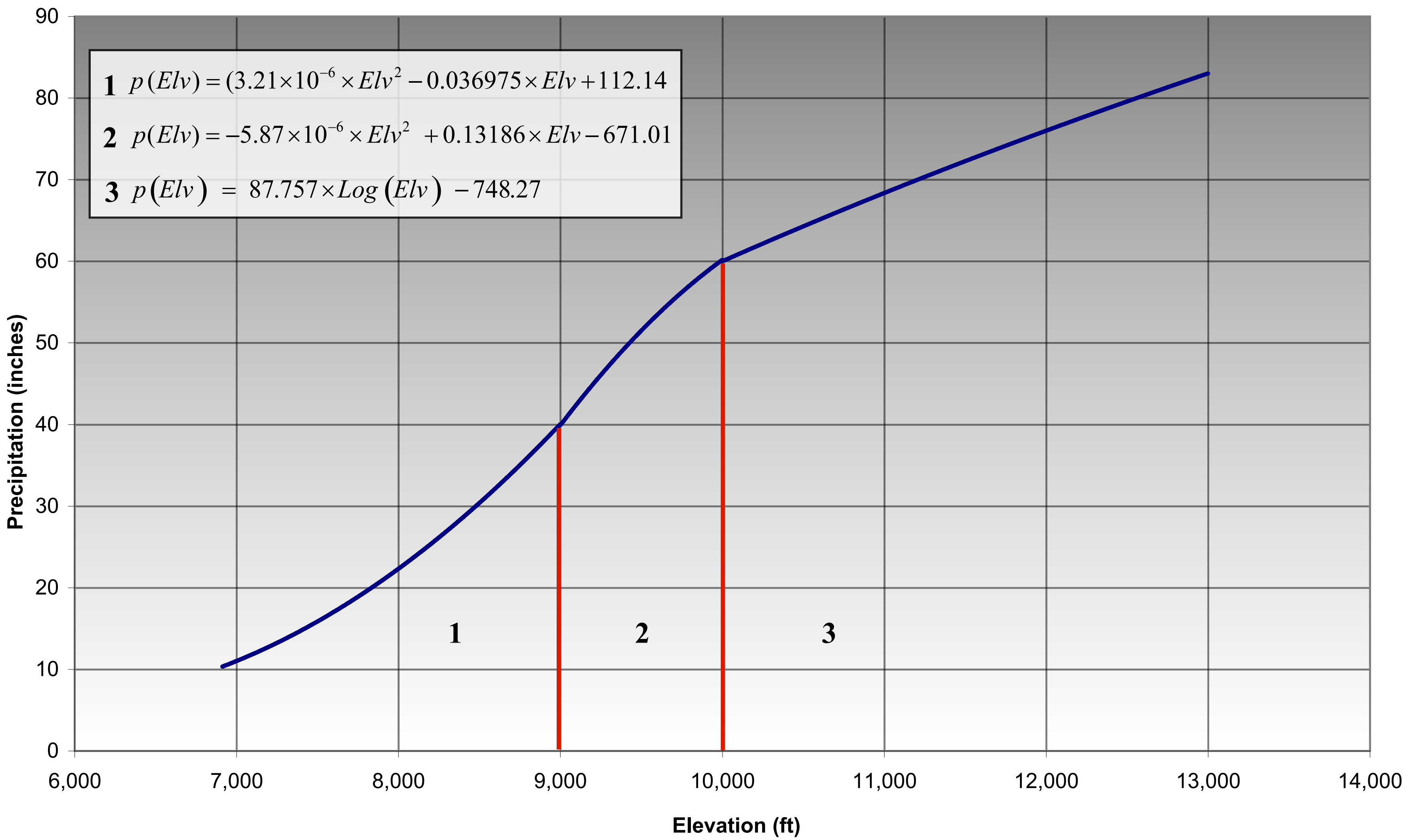


Calibration Period Average Discharge: 39,530 Acre-ft/yr



1. The values for the hydrologic components listed above are the result of various models and computations and are shown to the nearest whole acre-ft. The accuracy of these estimates is estimated to vary from plus or minus 10 to 20 percent in any given year.

Figure 3-2
Step-wise Precipitation and Elevation Functions



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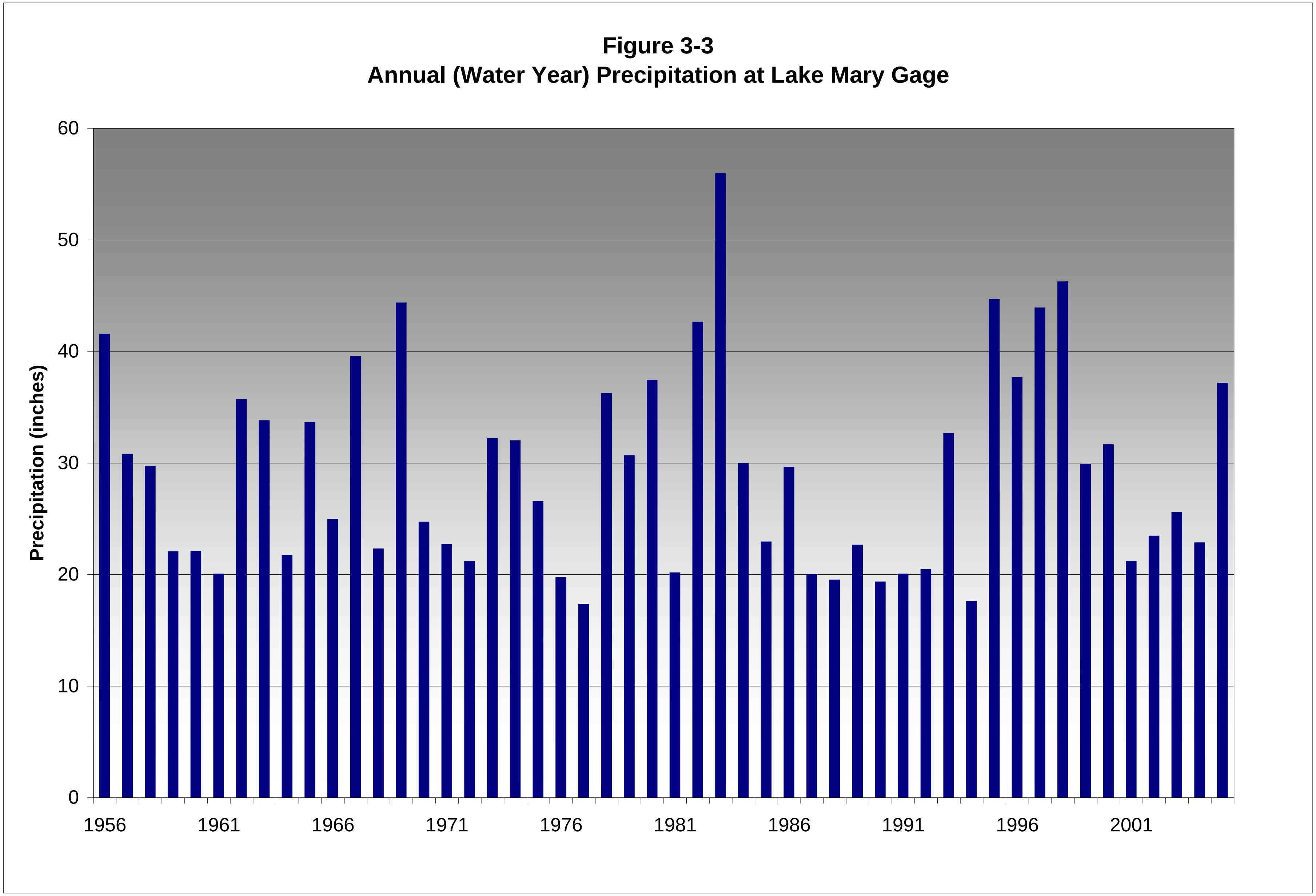

Figure3-3.xls

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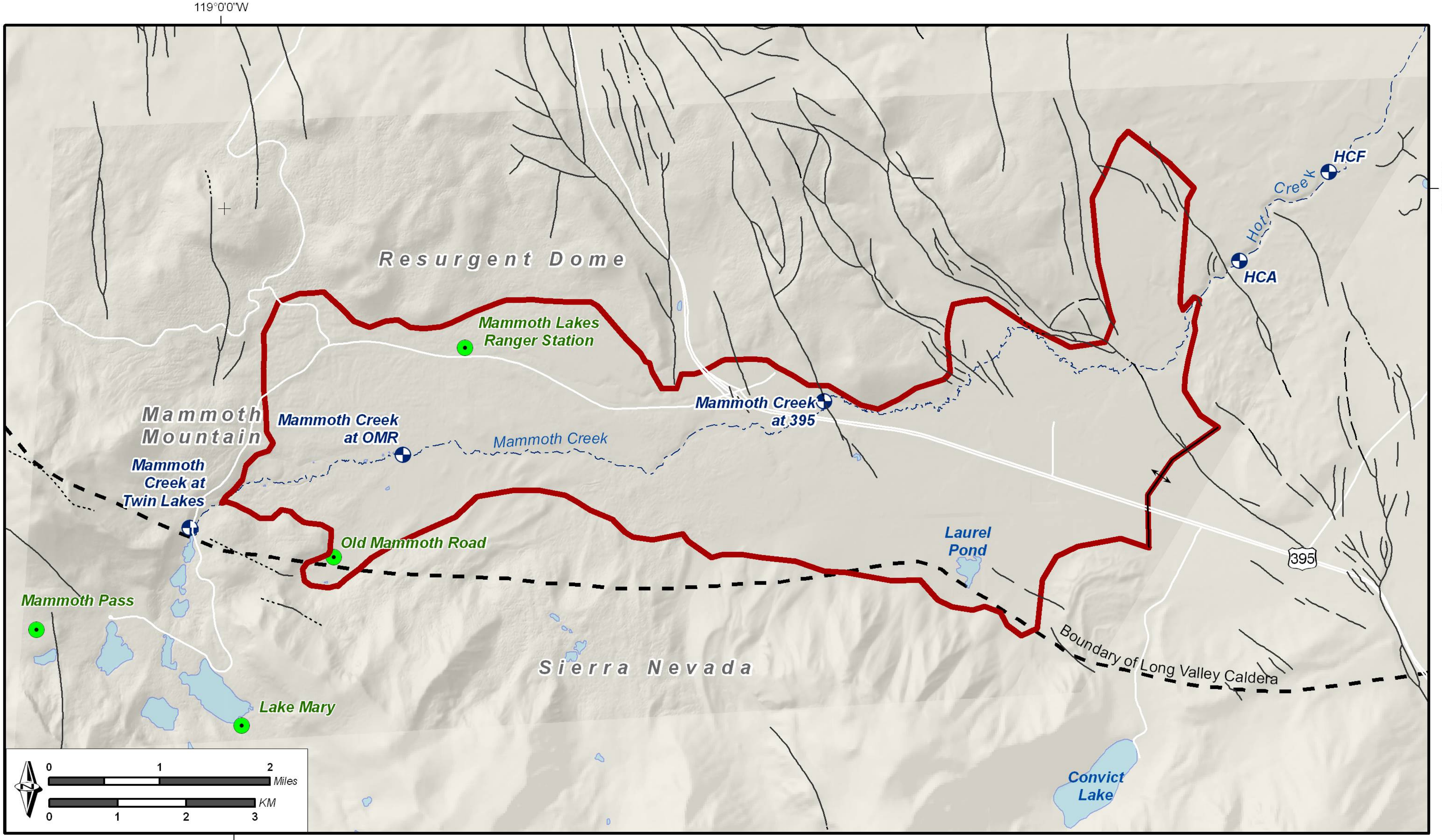

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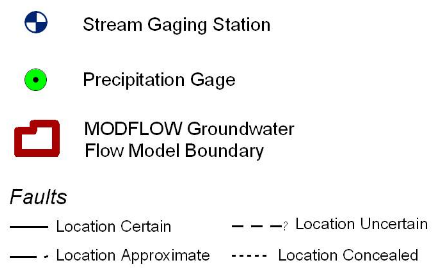
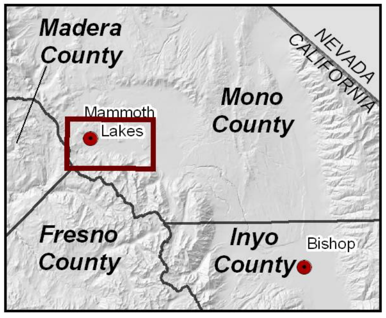




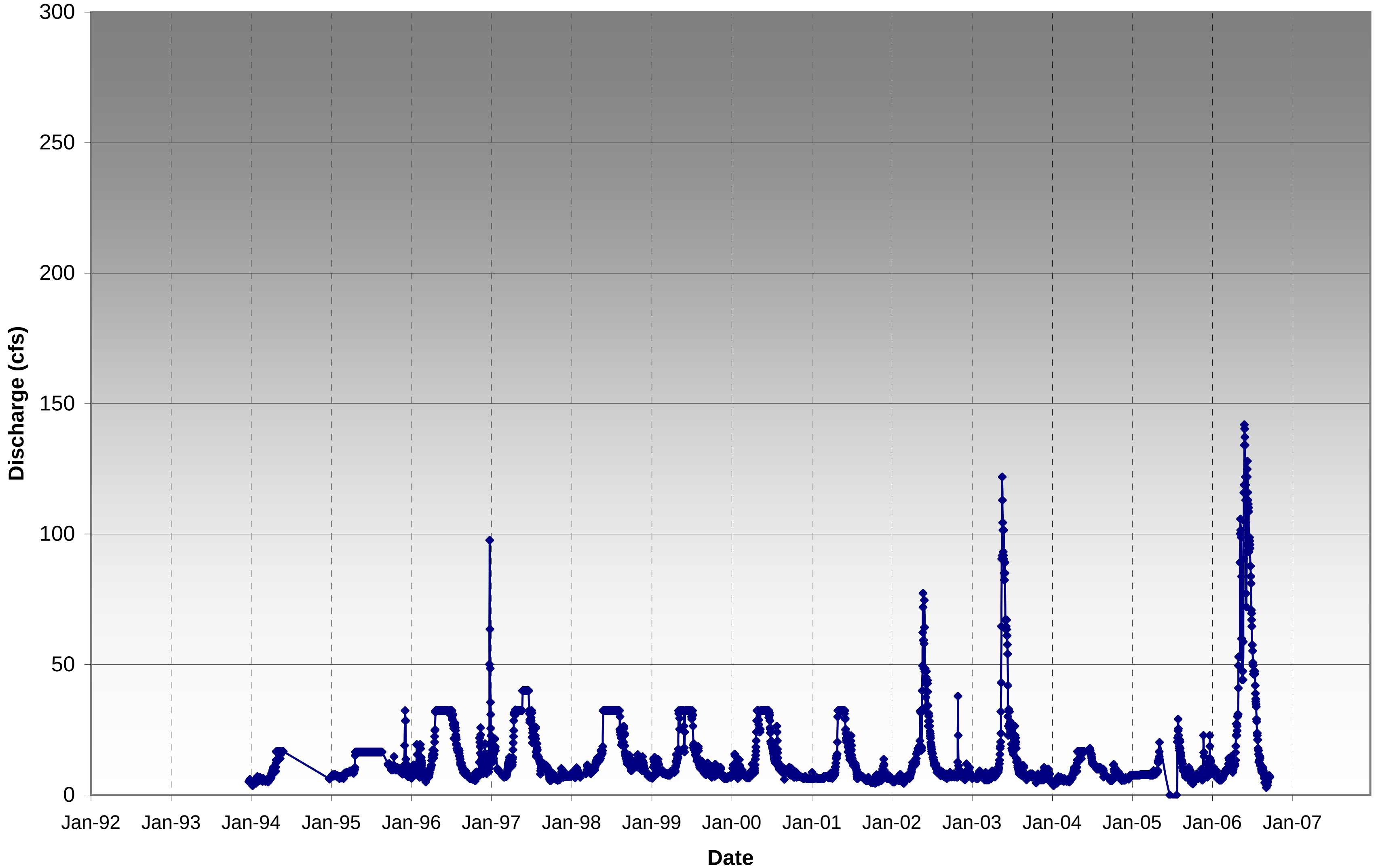
Location of Stream Flow Measurements and Precipitation Gages

Figure 3-4

Produced for:

Mammoth Basin Groundwater Model Report

Figure 3-5
Mammoth Creek Stream Flow Measurements at the Twin Lakes Outlet



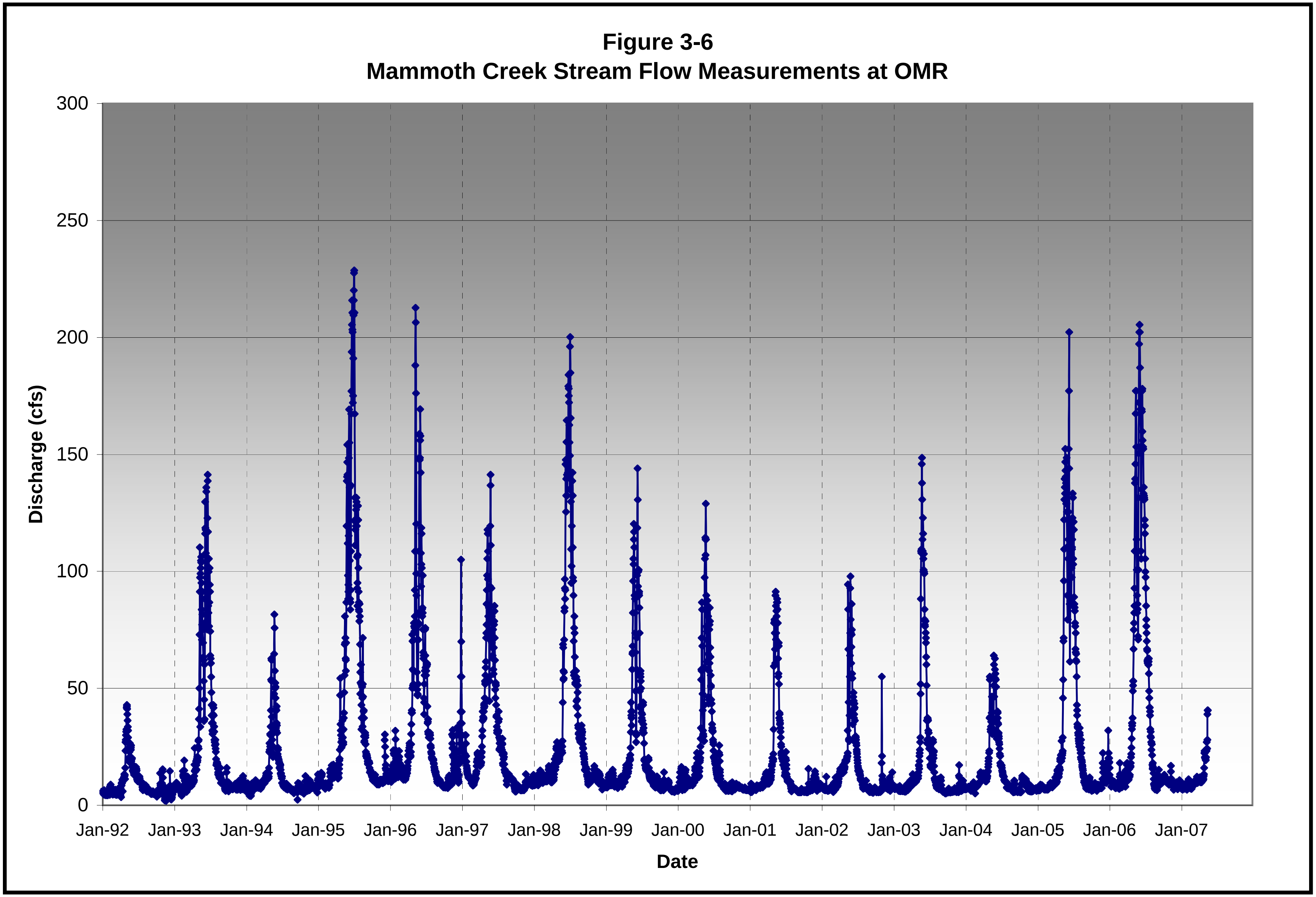
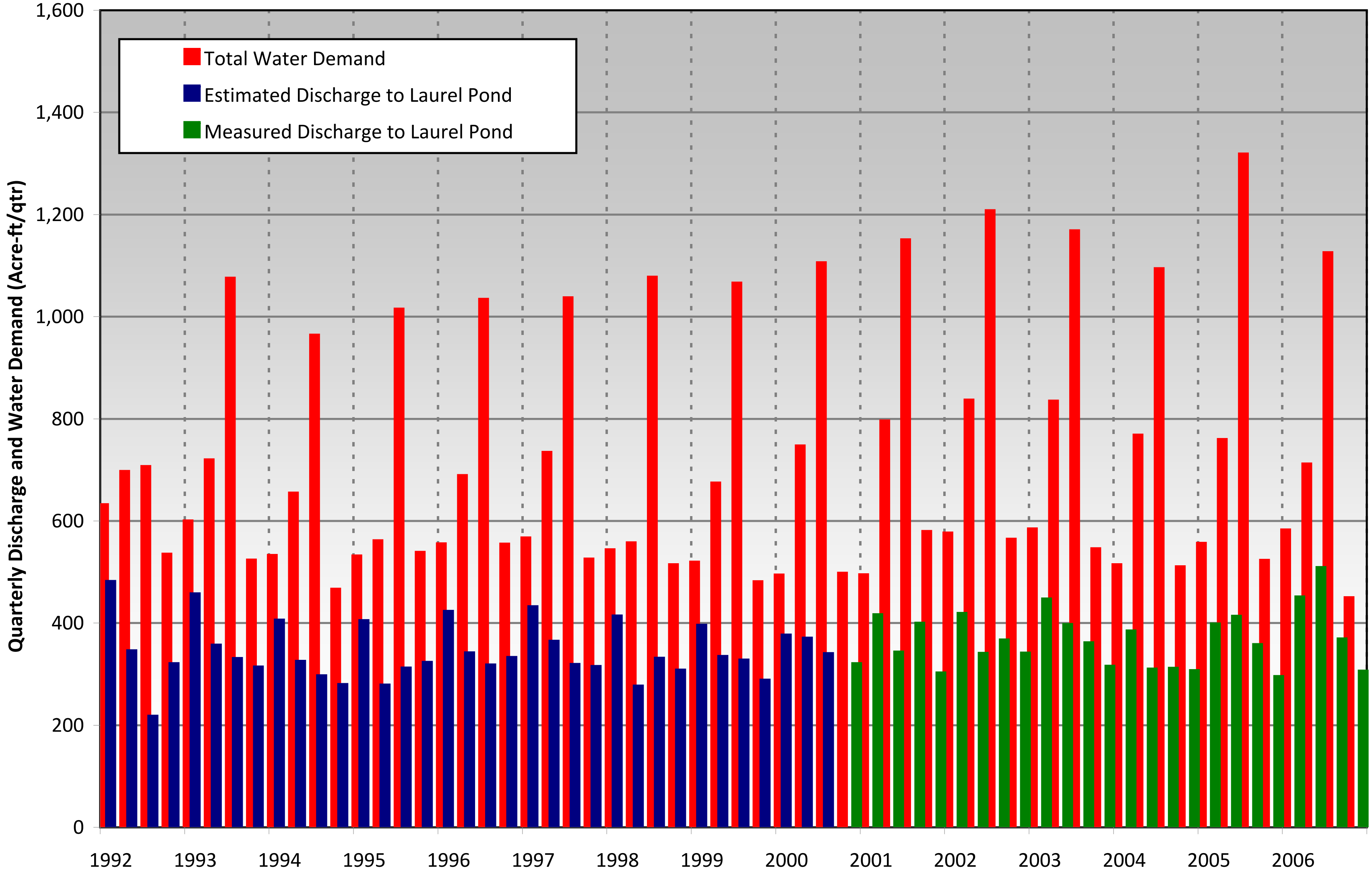


Figure 3-6
Mammoth Creek Stream Flow Measurements at OMR
Discharge (cfs)
300
250
200
150
100
50
0
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Date

Figure 3-7
Water Demand and Measured/Estimated Effluent Discharge to Laurel Pond



Note: Estimated discharge (1992 - 2000) it is based on the quarterly ratio of discharge to Laurel Pond to total water demand when Laurel Pond discharge data was available (2001-2006).

Figure3-7a.xls
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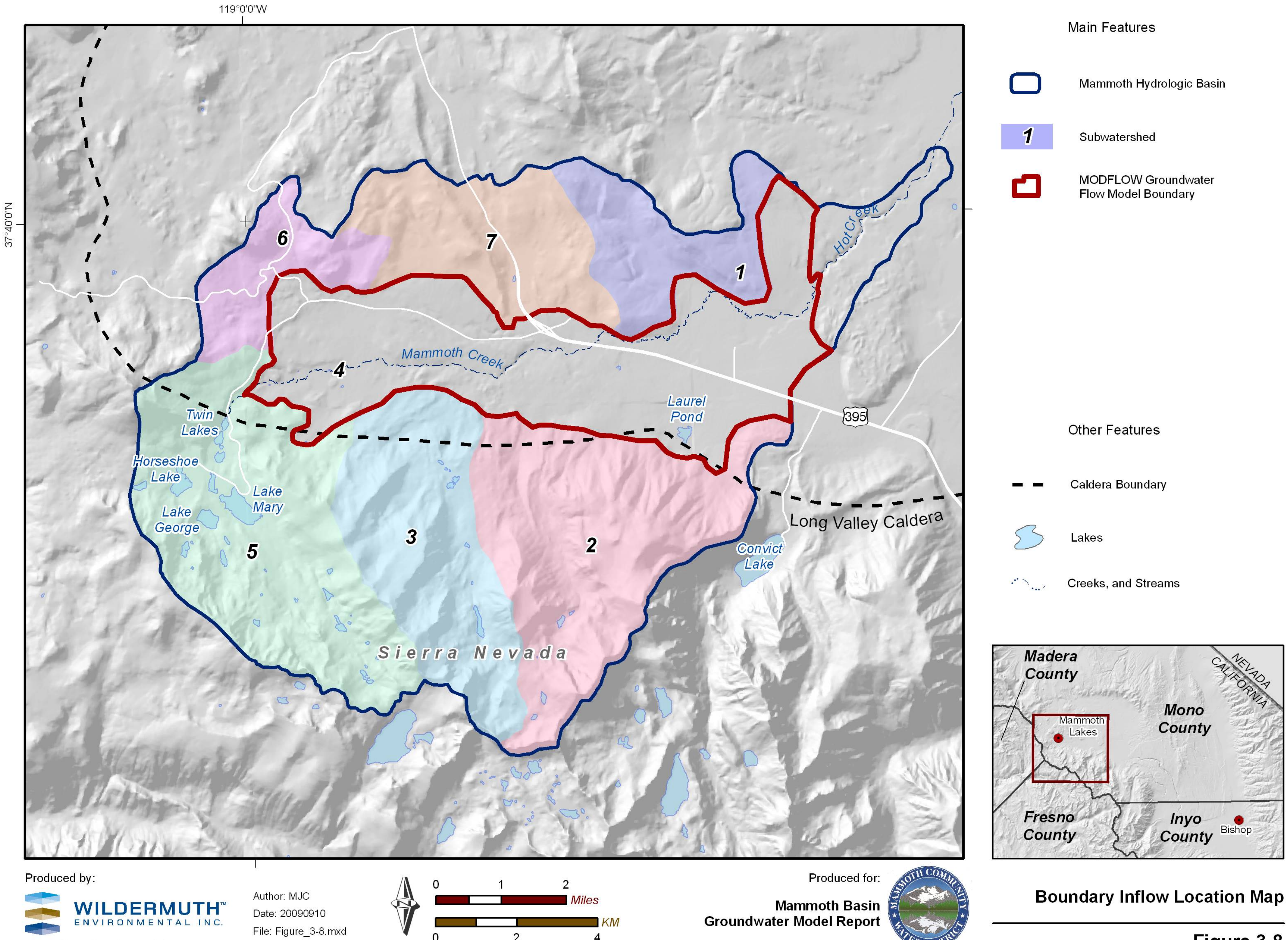

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Boundary Inflow Location Map

Figure 3-8

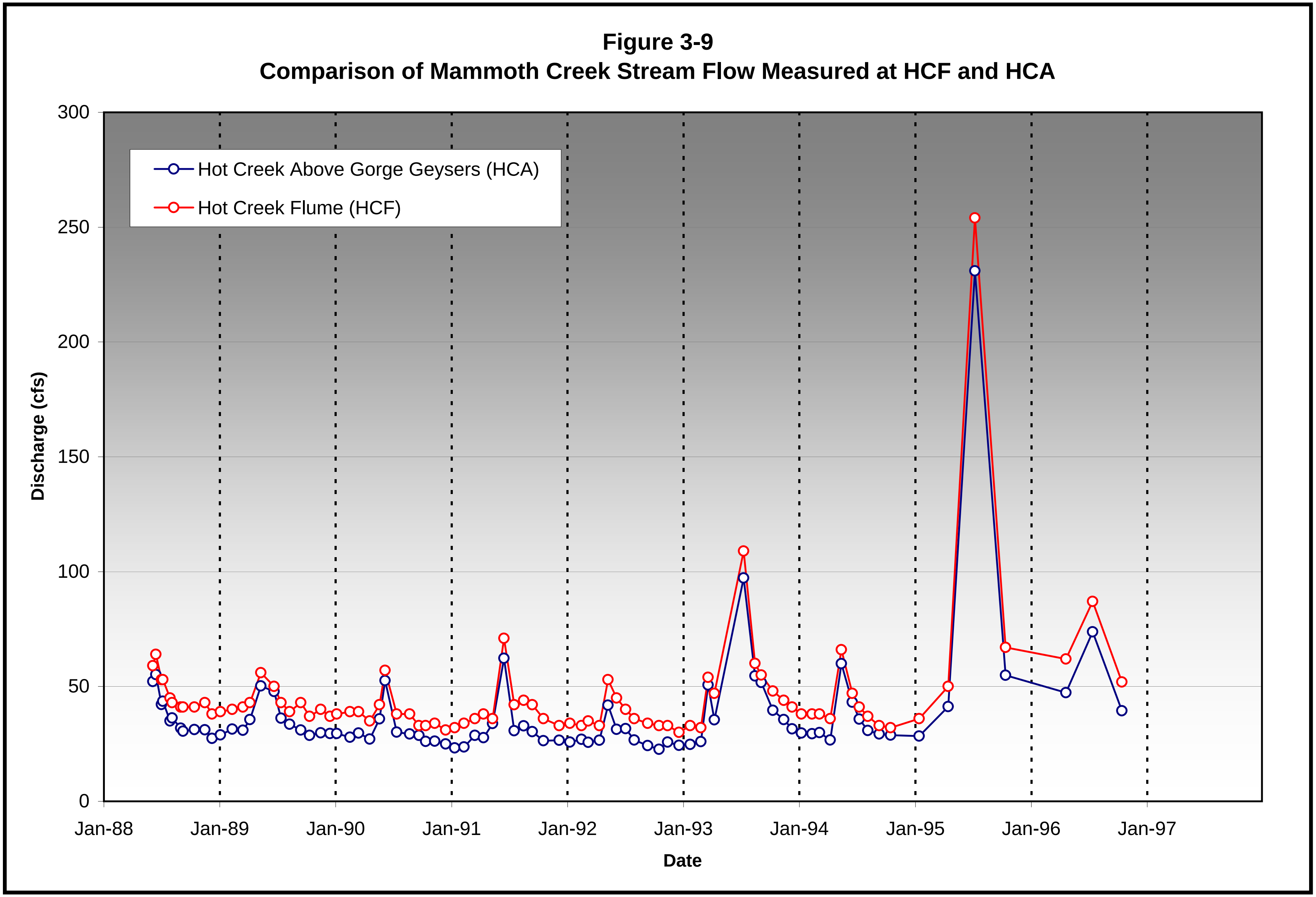


Figure 3-9
Comparison of Mammoth Creek Stream Flow Measured at HCF and HCA
Hot Creek Above Gorge Geysers (HCA)
Hot Creek Flume (HCF)
Discharge (cfs)
300
250
200
150
100
50
0
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Date

Figure 3-10
Estimated Quarterly Stream Flow at HCA

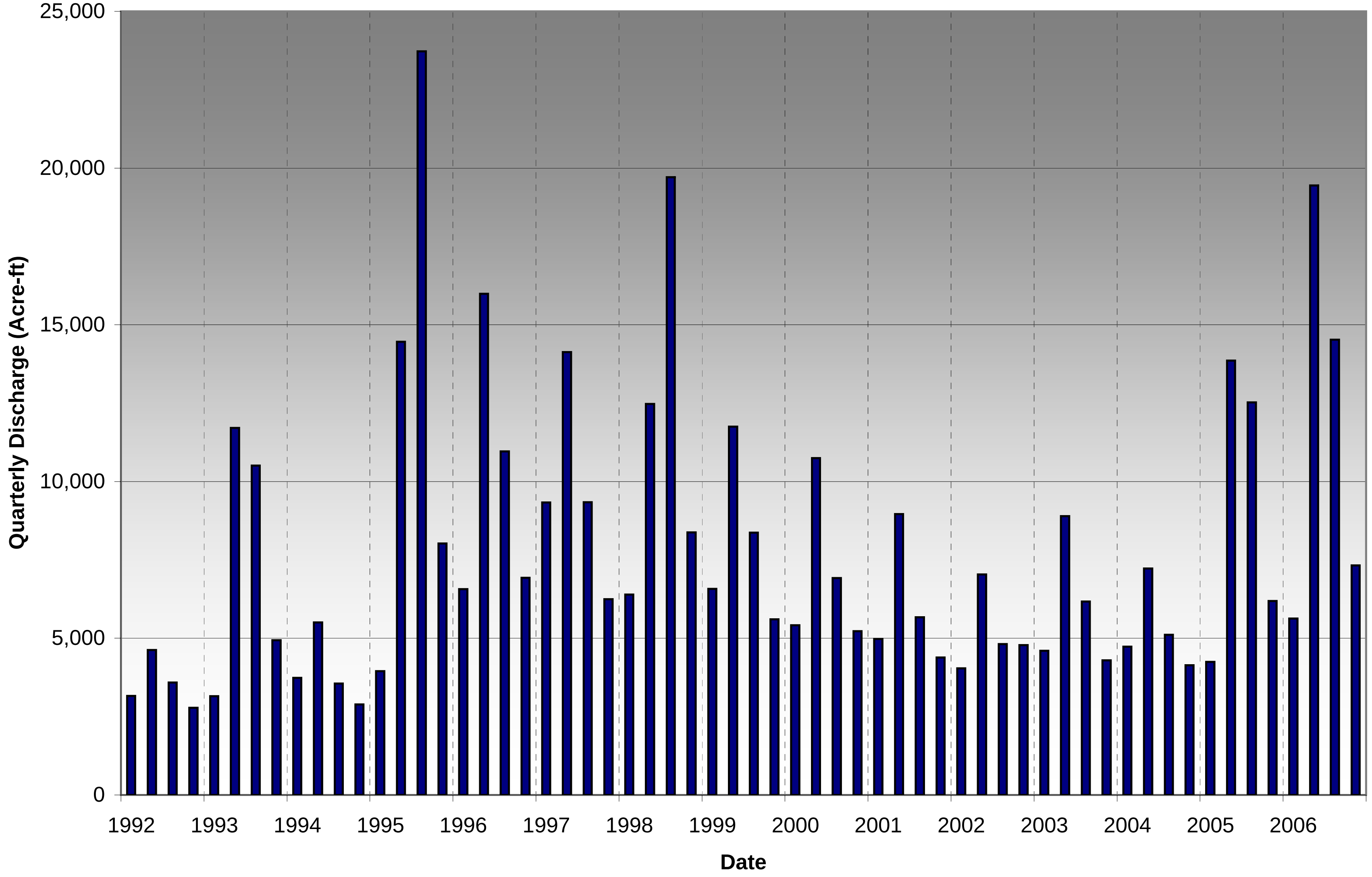
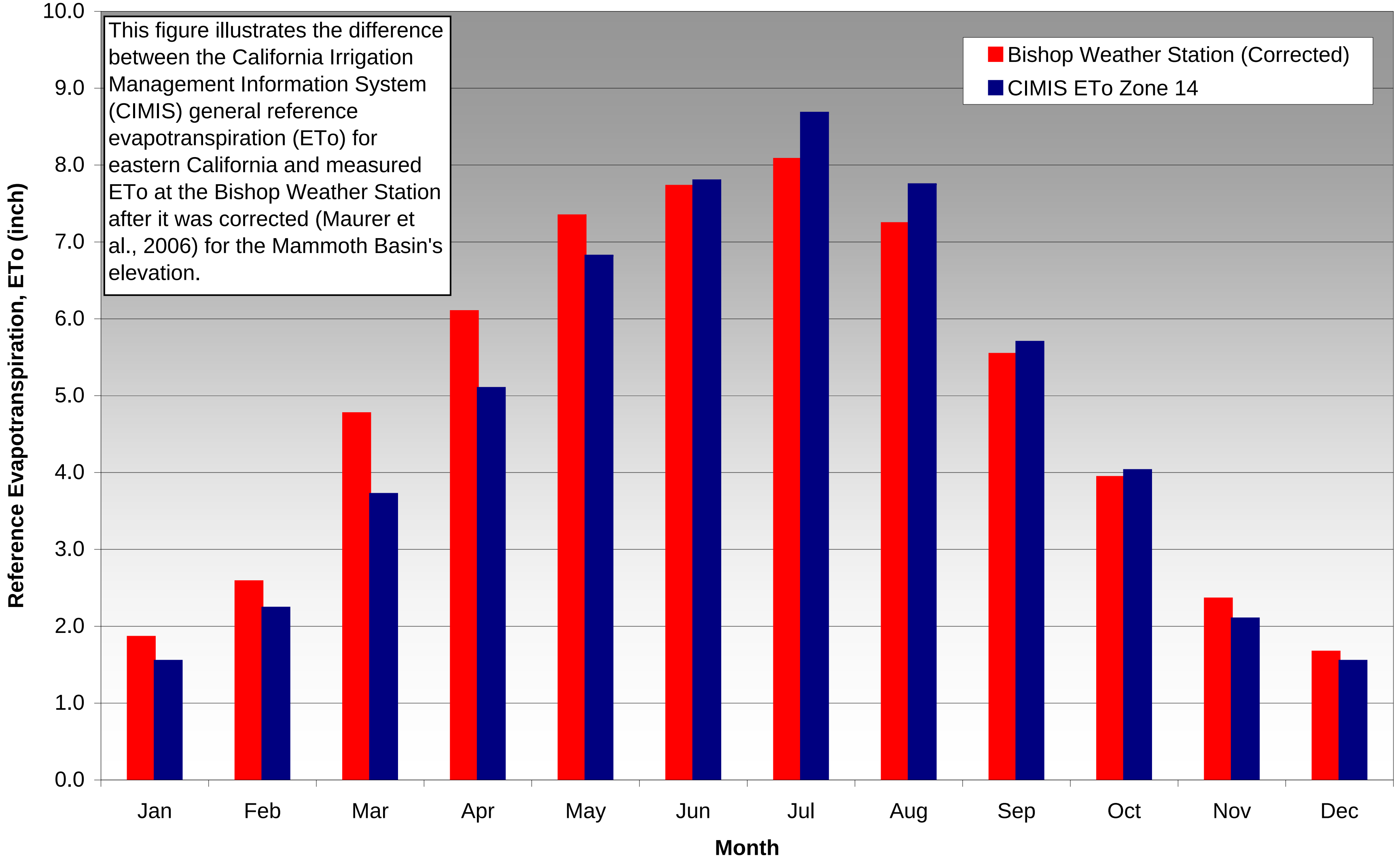
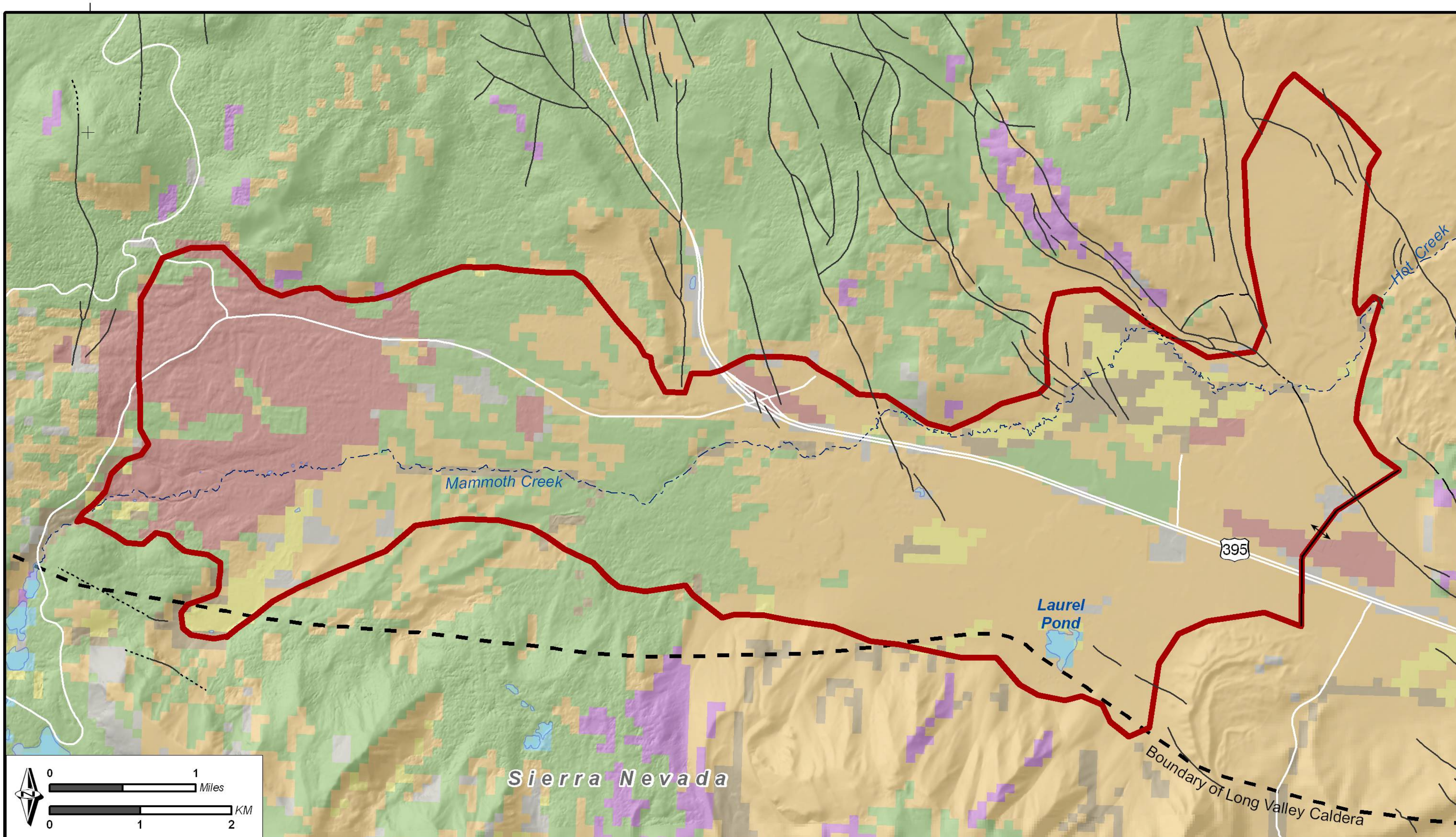


Figure 3-11
Comparison of CIMIS Zone 14 and Corrected Bishop Potential Evapotranspiration





Author: MJC Date: 20090909 File: Figure_3-12.mxd

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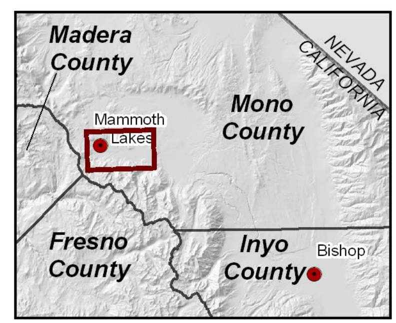
Vegetation Type

- Shrub
- Conifer Forest
- Hardwood Forest
- Conifer Woodland
- Wetland
- Barren/Other
- Water
- Mixed (Urban)

MODFLOW Groundwater Flow Model Boundary

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed



Vegetation Types

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Figure 3-12

This section describes the computer codes used in this investigation and discusses the selection criteria, assumptions, limitations, and governing equations relative to each computer code.

A groundwater flow model was prepared to represent the physical properties of the Mammoth Groundwater Basin and to test conceptual management decisions. This model employed two model codes for the purposes specified below:

- Groundwater flow: MODFLOW (McDonald and Harbaugh, 1988)
- Parameter estimation and calibration: PEST (Doherty, 2004)

4.1 MODFLOW

The USGS has developed a wide range of computer models to simulate saturated and unsaturated subsurface flow, solute transport, and chemical reactions. The most widely used of these programs is MODFLOW (McDonald and Harbaugh, 1988), which simulates three-dimensional groundwater flow using the finite-difference method. Although it was conceived solely as a groundwater flow model in 1984, MODFLOW's modular structure has provided a robust framework for the integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related models now includes capabilities for simulating coupled groundwater/surface water systems and solute transport.

MODFLOW-2000 (Harbaugh et al., 2000) was chosen for this project because 1) it has extensive publicly available documentation, 2) it has sustained rigorous USGS and academic peer review, 3) it has a long history of development and use, 4) the code is widely used around the world in public and private sectors, and 5) it can easily operate with additional simulation tools published by others due to its availability and robust framework.

MODFLOW requires several general assumptions to approximate the partial differential equations that represent flow in a system. The groundwater system must be divided up into a series of finite difference cells, each with uniform hydraulic properties. Typically, layers are identified and linked with Darcy's Law. Boundary conditions must be simplified to constant head, head dependent, or specified flux estimates. Transmissivity is calculated based on the saturated thickness of layers and hydraulic conductivity in each cell. Time must be simplified into a consistent series of discrete time units for the estimation of partial differential equations—the higher the frequency, the longer the processing time. MODFLOW also assumes all groundwater flow is laminar.

There are some limitations to the MODFLOW codes. The limitations of MODLFOW are as follows:

- MODFLOW is only capable of simulating fully saturated groundwater flow and lacks the ability to model groundwater in the unsaturated zone.
- There are limitations associated with representing a system as a finite-difference grid. This is not exclusive to MODFLOW. Most systems are more complex, and spatial discretization can often be limited by available data. Consequently, many models are

"zoned" by creating areas of like properties.

- The MODFLOW code has a steep learning curve and requires an experienced user to obtain reliable results.

4.2 PEST

PEST (Doherty, 2004), an acronym for Parameter ESTimation, is a computer code for model calibration and predictive analysis. During the calibration process, parameters are adjusted until model generated results fit a set of observations as closely as possible. PEST adjusts model parameters until the fit between model outputs and field observations are optimized in terms of the weighted least squares. PEST is not unique to groundwater flow models or MODFLOW. In fact, PEST is a public domain code that applies the Gauss-Marquardt-Levenberg algorithm. (The mathematics of PEST are further described in Section 6 of this report.) PEST has been successfully applied in many fields of the geophysical sciences, including groundwater modeling in particular. It has proven to be a robust tool and was therefore applied to the Mammoth Basin groundwater model.

PEST is prepared by Watermark Consulting and distributed as a standalone package as well as with numerous groundwater modeling packages (e.g. Groundwater Vistas and Groundwater Modeling System). The PEST software bundle was first distributed in 1994 and has since been through five major updates.

PEST was chosen for this project because 1) it reduces modeling time and significantly increases the value of modeling results, 2) it has an extensive amount of publicly available documentation, 3) it has a strong history of development, and 4) it is considered a standard in the groundwater industry and has been incorporated into most MODFLOW model processors.

This section describes how the conceptual model of the groundwater system, as described in Sections 2 and 3, was translated into a numerical model. Topics discussed herein include the model domain and grid, the assignment of hydraulic properties to the model grid, the initial conditions, and the boundary conditions.

5.1 Model Domain and Grid

The model domain and grid are shown in Figure 5-1. The model grid consists of 124 rows, 245 columns, and 2 layers. Horizontally, each cell has a dimension of 200-feet by 200-feet. This fine cell size was selected to model the curvature of the drawdown and to provide a model that is flexible for potential future needs. The grid cells are designated as "inactive" outside the model domain and as "active" inside the domain. There are a total of 24,241 active cells.

The spatial extent of the model domain was determined based on the saturated extent and thickness of the aquifer system; the extent was limited to regions where the saturated thickness was greater than about 40 feet. The saturated thickness was determined based on 1992 groundwater levels and the effective base of the aquifer.

The vertical extent of the model is comprised of two layers, representing two hydrostratigraphic layers. The discretization of these layers is discussed in Section 2. Layer 1, which represents the unconfined system, is classified as an unconfined aquifer and has a minimum thickness of 45 feet and maximum thickness of 200 feet. Layer 1 mainly consists of glacial till, alluvium materials, basalt, or a mix of all three deposits. Layer 2 is classified as an unconfined-confined aquifer and mainly consists of basalt with interbedded glacial till deposits. Layer 2 has a minimum thickness of 200 feet and a maximum thickness of 1,000 feet.

5.2 Time Discretization

The discretization of time is critical in model construction because the resolution of the model results is related to the stress period of the model. Temporal discretization includes stress periods and time steps. The length of the transient stress period is three months (one quarter of a year), which was based primarily on the availability of data for calibration and the seasonal variability of the Mammoth Basin groundwater and surface water systems. Both discharges (e.g. pumping and ET) and recharges (e.g. areal recharge and stream recharge) show distinct seasonal features. A result of using a three month time step is that all model results are estimated for a three month period; oscillations that occur on a monthly, weekly, or daily timescale are not simulated.

5.3 Hydraulic Properties

The hydraulic properties used in the model include horizontal hydraulic conductivity, vertical hydraulic conductivity, the specific yield for an unconfined aquifer, and the specific storage for confined aquifers. Although hydrogeologic systems in the Mammoth Basin are inherently heterogeneous on many scales, homogeneous hydraulic properties in each zone were incorporated into the model.

Hydraulic conductivity is the measure of a fluid's ability to flow through a medium. The value relates to fluid density (ρ), dynamic viscosity (μ), and the effective grain size (d_{10}) of unconsolidated deposits, as depicted in the following equation:

$$K = \frac{C d_{10}^{2} \rho g}{\mu}$$

Where C is a constant proportional coefficient.

The definition of hydraulic conductivity suggests that its value increases with a median grain size. For a given median grain size, hydraulic conductivity is lower in a poorly sorted medium than in a well-sorted medium because poorly sorted mediums have a smaller effective grain size. Hydraulic conductivity is generally higher in coarse-grained deposits than in fine-grained deposits.

Glacial till deposits in the Mammoth Lakes area range in size from clay to large boulders. The tills were deposited directly from glacial ice without significant sorting by running water, resulting in a small effective grain size. Consequently, hydraulic conductivity in the till is relatively low.

Alluvial materials were deposited along Mammoth Creek and in the eastern portion of Mammoth Basin. The deposits were sorted by stream flows and floods as relatively coarse materials were deposited along the streams and fine materials were deposited in the downstream plain area. The hydraulic conductivities are higher in the alluvial deposits than in the glacial tills. However, because the Mammoth Basin is located near the glacial till source area, the alluvium material has high silt content, and the hydraulic conductivity may be relatively low due to the small effective grain size.

Fractured basalt, which comprises the main lithology of layer 2, is the major groundwater aquifer of the Mammoth Basin. In some locations, when the fractured basalt is interbedded with glacial till, the fractures are partially or fully filled with till and alluvial materials. The hydraulic conductivity of the fractured basalt is much higher than that of the glacial till and alluvium.

Table 5-1 lists hydraulic conductivity estimates that were calculated using pump test data. These estimates range from 1 to 5 feet/day in glacial tills and 13 to 34 feet/day in basalts.

For numerical modeling purposes, the physical groundwater system was divided into hydrogeologically similar defined zones, each with its own hydraulic properties. The zonation in the model domain was based on sediment facies, aquifer type, and lithologic descriptions from well drillers' reports. Figures 5-2 and 5-3 show the calibrated parameter zonation for the hydraulic parameters of layers 1 and 2, respectively. A total of eighteen zones comprise the model domain, nine for each layer. Table 5-2 lists the calibrated model parameter values by zone and layer. The horizontal hydraulic conductivity values for the Mammoth Basin range from 1.4 to 26.0 feet/day. In layer 1, the hydraulic conductivity of zones 1 and 3, in which the aquifer is mainly composed of glacial till and basalt, is as low as 1.4 feet/day. The hydraulic conductivity of zone 2 in layer 1, in which the aquifer is composed of alluvium and basalt, is 7.8 feet/day. The hydraulic conductivity in layer 1 basalt ranges from 4.0 to 13.0 feet/day. The effective porosity is relatively high in the alluvium and ranges from 23 to 26 percent. In the basalt, the effective porosity is about 11 percent. The layer 2 aquifer is mainly composed of basalt, and the hydraulic conductivity values range from 5 to 26 feet/day; the effective porosity ranges from 5 to 13 percent.

5.4 Initial Conditions

Initial conditions are required to solve numerical groundwater flow problems. The initial condition for the Mammoth Basin is the groundwater level in each active cell of the model domain. The following steps were completed to generate initial conditions:

1. Prepare water level contour maps of layers 1 and 2, based on available groundwater level measurements. Initial hydraulic property estimates, well construction information, stream flow data, wet land information, and Laurel Pond surface elevations were taken into account.
2. Generate a raster or grid water level map for each layer (based on contour maps), assign an appropriate water level to each cell, and convert the data to the numerical initial condition for each layer.
3. Run the numerical model with initial condition water levels and boundary conditions for 1992. Check the goodness-of-fit, and make adjustments as needed.
4. Review high residual results, areas with large differences between simulated and measured water levels. Modify the boundary inflow if significant differences exist between simulated and measured water levels, and adjust the hydraulic parameters if necessary.
5. Repeat steps 3 and 4 until a reasonable water level distribution is obtained.

Figures 5-4 and 5-5 show the resulting initial groundwater elevations for layers 1 and 2, respectively.

5.5 Boundary Conditions

Boundary conditions for the model include areal recharge from precipitation, subsurface inflow from nearby watersheds, stream recharge and discharge along creeks, evapotranspiration, pumping, and recharge at Laurel Pond.

Table 5-3 lists the boundary conditions by geographic name, boundary type, and the MODFLOW package utilized for the boundary simulation. Figure 5-6 shows the mean boundary condition inflows for the calibration period.

5.5.1 MODFLOW Packages for Boundary Conditions

5.5.1.1 Recharge Package

The Recharge Package (McDonald et al., 2000) was used to simulate a specified flux due to precipitation distributed over the top of the model in specified units of length/time. Within

MODFLOW, these rates are multiplied by the horizontal area of the cells to which they are applied to calculate volumetric flux rates. This package was used to assign a quarterly variable flux to the piezometric surface.

5.5.1.2 Flow and Head Boundary Package (FHB)

The Flow and Head Boundary Package (Leake and Lilly, 1997) was used to specify subsurface inflows to the aquifer system from tributary areas that flank the basin. The Flow and Head Boundary Package allows MODFLOW users to specify flux or head boundary conditions that vary at times. This package was also used to specify MCWD wastewater discharge to Laurel Pond.

5.5.1.3 Evapotranspiration Package (EVT)

The MODFLOW ET Package (Harbaugh et al., 2000) was used to simulate a head-dependent flux out of the model, distributed over the top of the model in specified units of length/time. Within MODFLOW, these rates are multiplied by the horizontal area of the cells to which they are applied to calculate volumetric flux rates. This package was used to simulate evaporation and transpiration in the Mammoth Basin.

The ET Package simulates ET using the relationship between the ET rate and hydraulic head; the relationship of the ET rate to the hydraulic head is conceptualized as a piece-wise linear curve, relating the ET surface—defined as the elevation where the evapotranspiration rate reaches a maximum—and an elevation located at an extinction depth below the evaporation surface where the evapotranspiration rate reaches zero.

The ET rate for a model cell is calculated for each stress period based on its calculated head, the ET surface elevation, the extinction depth, and the maximum ET flux rate. If the elevation of the calculated head in the cell is at or above the ET surface value, the ET rate is the maximum evapotranspiration rate (high groundwater condition). If the calculated head is equal to or below the extinction depth, the evapotranspiration rate is zero (low groundwater dry condition). When the head is between the ET surface and the extinction depth, the ET rate is a linear function of the head below the ET surface. This relation is defined by the following equation:

$$Q_{ET} = Q_{ETMax}\left(1 - \frac{D}{X}\right)$$

Where Q_{ET} is the volumetric evapotranspiration rate of the active cell, Q_{ETMAX} is the maximum evapotranspiration flux rate times the area of the cell, D is the depth of the head below the ET surface, and X is the extinction depth. The depths of the head were calculated based on the ground surface elevation and the simulated groundwater table; the former remains constant over time and was extracted from a high resolution DEM. The simulated groundwater table in each cell of layer 1 varies over time.

5.5.1.4 Well Package (WEL)

The Well Package (Harbaugh et al., 2000) was used to simulate the withdrawal of water from aquifers at a specified rate during a given stress period. Well discharge is handled in the Well Package by specifying the rate (ft^3/day) during each stress period of the simulation. Negative rate values are used to indicate well discharge, and positive rate values indicate a recharging well. Well construction and screen position were taken into account in the well discharge rate calculations for each layer.

5.5.1.5 Stream Package (STR)

The Stream Package (Prudic, 1998) was used to simulate streams within the Mammoth Groundwater Basin, including surface and ground water interactions. The Stream Package routes surface flow and calculates flow to and from the aquifer based on stream stage, the piezometric surface of the aquifer, and the conductance of the stream bottom. The shift from recharge of the aquifer to discharge to the stream occurs at the point where the head in the aquifer equals the head in the stream.

Streams were divided into reaches and segments. Each reach corresponds to a single cell in MODFLOW. Reaches were grouped into segments, and each segment consists of a series of contiguous reaches where flows can be routed.

Flows between streams and the aquifer are computed using streambed conductance, the head in the stream, and the calculated head of the aquifer in each cell. Volumetric flow between a streambed and the groundwater system is computed as:

$$Q_{STR} = C_{STR}\,(h_{STR} - h(i,j,k))$$

Where Q_{STR} is the flow rate across the streambed, C_{STR} is the conductance of the streambed, h_{STR} is the head in stream stage, and $h(i,j,k)$ is the hydraulic head in the cell of row i, column j, and layer k underlying the streambed.

The conductance of the streambed is given by:

$$C_{STR} = (K_v L W)/M$$

Where K_v is the vertical hydraulic conductivity of the riverbed sediment, W is the width of the river reach, L is the length of the stream reach, and M is the thickness of streambed sediment.

However, K, W, L, and M are not individually specified. Instead, conductance of the streambed (C_{STR}) is specified. The stream segment is specified such that the conductance of the streambed in each segment remains constant but varies from one segment to another.

Figure 5-7 shows the stream segments and reaches in the Mammoth Basin. Figure 5-8 shows the streambed conductance along each reach. The streambed elevations along creeks and channels were extracted cell by cell from the 2-meter DEM. The assigned streambed elevations are about 3-10 feet below the DEM elevations, depending on location, because the center of a model stream cell is not exactly located in the middle of a stream.

The stream stage in each reach was computed using Manning's equation prior to calculating leakage to or from the aquifer. The stage for each reach was calculated using the specified inflow to the stream segment. The slope of the stream channel was first computed based on the 2-meter DEM. The stream channel slopes were then adjusted by the elevation of each neighboring reach. Manning's roughness coefficient estimates were based on the streambed characteristics of Mammoth Creek and its tributaries; the values range from 0.025 to 0.04. If no stream flow is specified into a segment, the stage for all reaches in that segment equal the top of the streambed. Leakage was iteratively computed on the basis of the computed stream stage, streambed conductance, and head for each model cell.

5.5.1.6 Preconditioned Conjugated-Gradient Package (PCG)

The Preconditioned Conjugated-Gradient Package was selected as a numerical solver in the MODFLOW 2000 model. When calibration was initiated, the convergence criteria were set with a head change criterion for convergence (HCLOSE) of 0.01 ft and a residual criterion for convergence (RCLOSE) of 10. However, these strict criteria provided only a limited improvement of the solution at the cost of a longer computation time. Considering the long computing time required with PEST inverse modeling, the MODFLOW 2000 closure criteria were relaxed to reduce computation time during the calibration without reducing the precision of the solution. The head change criterion for convergence was set to 0.1 ft (HCLOSE) and the residual criterion for convergence was set to 55.0 (RCLOSE). To be consistent, the criteria remained the same as in model calibration for all subsequent flow simulations.

Table 5-1
Estimates of Hydraulic Conductivity

Well Number	Well Depth (ft)	Perforation Range	Model Layer	Aquifer Type	Hydraulic Conductivity (ft/day)	Source
1	382	200-370	2	Basalt	**21**	Robert C. Fox 1976; Schmidt 1987
4	533	110-529	1,2	Basalt with Till and Alluvium	**1**	LeRoy Crandall and Associates 1986
5	357	60-113; 133-357	1,2	Till, Alluvium, Basalt	**2**	LeRoy Crandall and Associates 1982
10	700	136-700	2	Basalt with Till and Alluvium	**13**	Schmidt 1987
6	670	146-670	2	Basalt with Till and Alluvium	**15**	Schmidt 1992
15	720	407-720	2	Basalt	**15**	Schmidt 1992
16	710	420-470; 500-680	2	Basalt	**15**	Schmidt 1992
18	710	90-150; 240-470	1,2	Basalt with Till	**5**	Schmidt 1992
20	710	420-710	2	Basalt	**34**	Schmidt 1992
25	700	340-530	2	Basalt with Till	**4**	Schmidt 2002

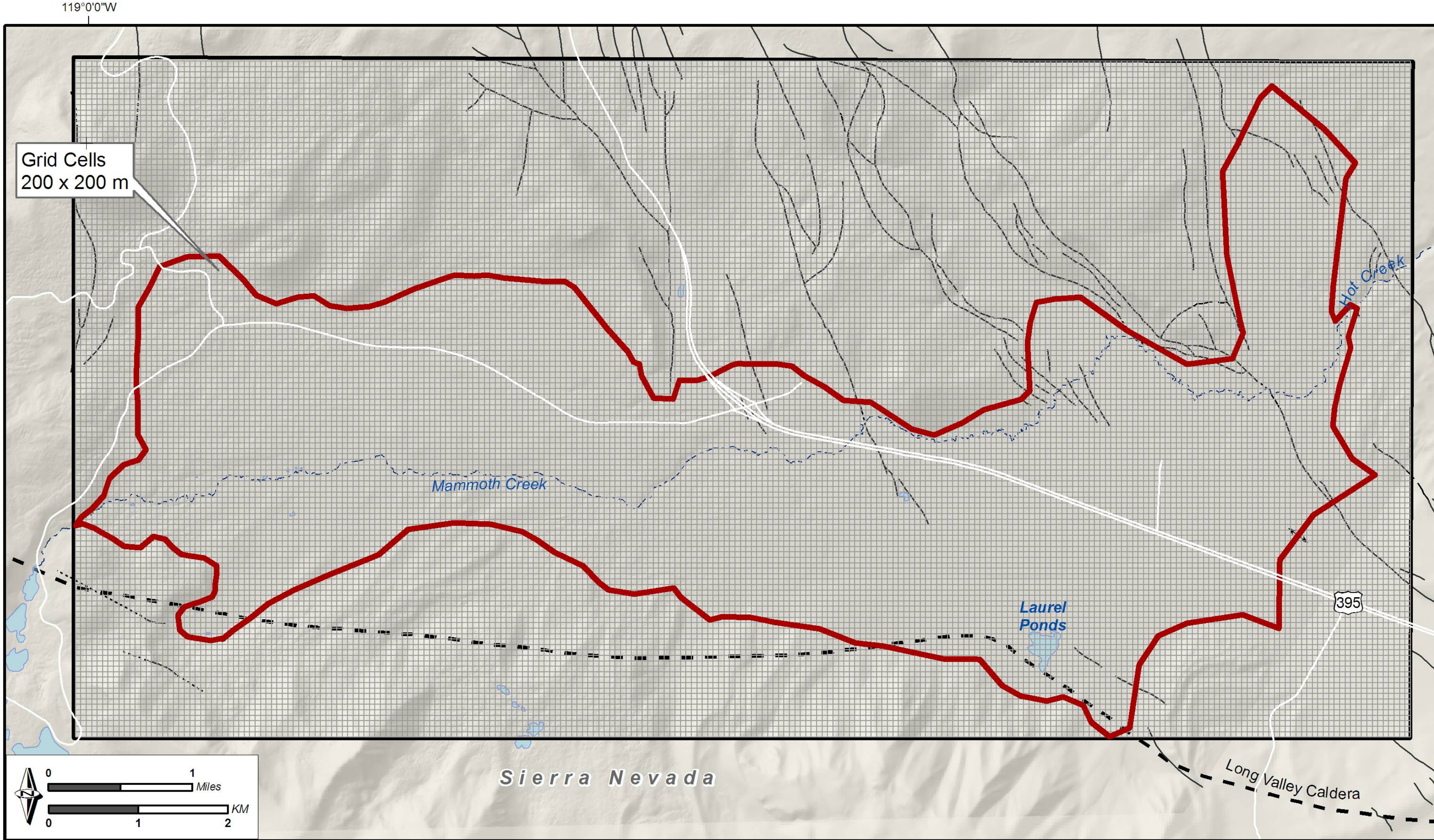
Table 5-2
Calibrated Model Parameter Values by Zone and Layer

Order	Parameter Name	Type	Layers	Zonation	Initial Estimate	Calibrated Estimate	Aquifer Lithology
1	hk1z1	Hydraulic Conductivity	1	2	7	7.8	Alluvium and Basalt
2	hk1z3	Hydraulic Conductivity	1	1,3	7	1.4	Till and Basalt
3	hk1z4	Hydraulic Conductivity	1	4	10	4.0	Basalt
4	hk1z5	Hydraulic Conductivity	1	5,8	25	13.0	Basalt
5	hk1z6	Hydraulic Conductivity	1	67,9	15	12.0	Alluvium
6	syl z1	Effective Porosity	1	2	0.14	0.23	Alluvium and Basalt
7	syl z3	Effective Porosity	1	1,3	0.14	0.1	Till and Basalt
8	syl z5	Effective Porosity	1	4,5,8	0.1	0.11	Basalt
9	syl z6	Effective Porosity	1	6,7,9	0.2	0.26	Alluvium
10	vkcbl	Vertical Hydraulic Conductivity	1,2	2	1.00E-03	7.40E-04	Alluvium, Till, and Basalt
11	vkcb3	Vertical Hydraulic Conductivity	1,2	1,3	1.00E-03	1.30E-03	Till and Basalt
12	hk2zl	Hydraulic Conductivity	2	1	25	5.0	Basalt
13	hk2z2	Hydraulic Conductivity	2	2	25	5.0	Basalt
14	hk2z3	Hydraulic Conductivity	2	3	25	11.0	Basalt
15	hk2zb	Hydraulic Conductivity	2	4,5,8	25	9.7	Basalt
16	hk2z6	Hydraulic Conductivity	2	6,7,9	20	26.0	Basalt
17	ss2zl	Storage Coefficient	2	1,2,3,	1.00E-04	1.00E-04	Basalt
18	ss2z5	Storage Coefficient	2	4,5,8	1.00E-04	1.00E-04	Basalt
19	ss2z6	Storage Coefficient	2	6,7,9	1.00E-04	1.00E-04	Basalt
20	sy2zl	Effective Porosity	2	1	0.1	0.05	Basalt
21	sy2z2	Effective Porosity	2	2	0.1	0.13	Basalt
22	sy2z3	Effective Porosity	2	3	0.1	0.13	Basalt
23	hfbl	Horizontal Barriers	1	3,4,5	1	1.00E-03	Till and Basalt

Table 5-3
Groundwater Model Boundary Conditions

Geographic Name	Boundary Condition	MODFLOW Package Applied for Condition
Subsurface Inflow from Sub-watershed 1 to Model Domain	Variable Flux	FHB[1]
Subsurface Inflow from Sub-watershed 2 to Model Domain	Variable Flux	FHB[1]
Subsurface Inflow from Sub-watershed 3 to Model Domain	Variable Flux	FHB[1]
Subsurface Inflow from Sub-watershed 5 to Model Domain	Variable Flux	FHB[1]
Subsurface Inflow from Sub-watershed 6 to Model Domain	Variable Flux	FHB[1]
Subsurface Inflow from Sub-watershed 7 to Model Domain	Variable Flux	FHB[1]
Discharge to Laurel Pond	Variable Flux	FHB[1]
Areal Recharge	Variable Flux	RCH[2]
Wells	Variable Flux	WEL[3]
Mammoth Creek and Tributaries	Variable Flux	STR[4]
Evapotranspiration	Variable Flux	EVT[5]

1. FHB - Flow Head Boundary Package - Variable flux
2. RCH - Recharge Package
3. WEL - Well Package
4. STR - Stream Package
5. EVT - Evapotranspiration Package



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Model Grid

MODFLOW Groundwater Flow Model Boundary

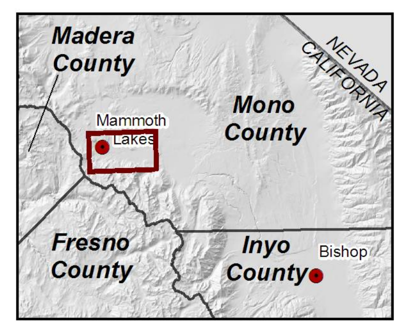
Faults

Location Certain

Location Approximate

Location Uncertain

Location Concealed



Map of Model Domain and Model Grid

Figure 5-1

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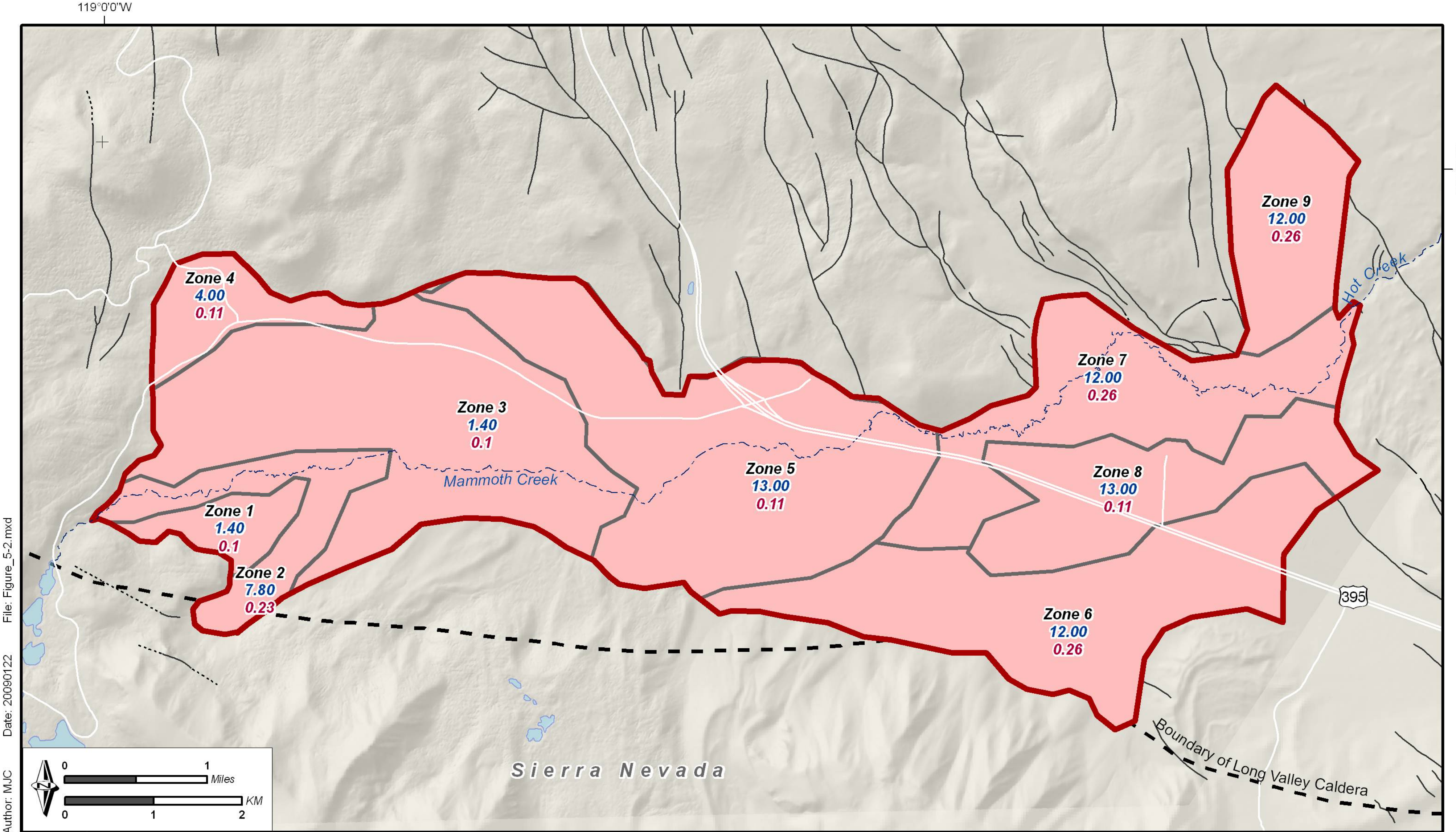

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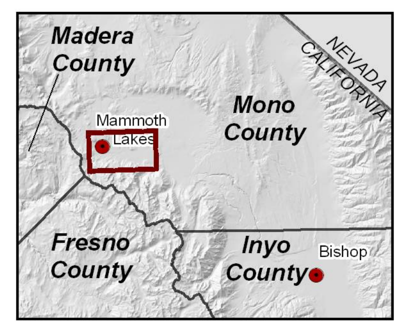
Zone 8
13.0
0.11
Model Zone
Mean horizontal hydraulic conductivity (ft/day)
Mean Effective Porosity

MODFLOW Groundwater Flow Model Boundary

Faults
Location Certain
Location Approximate
Location Uncertain
Location Concealed



Model Zonation

Layer 1

Figure 5-2

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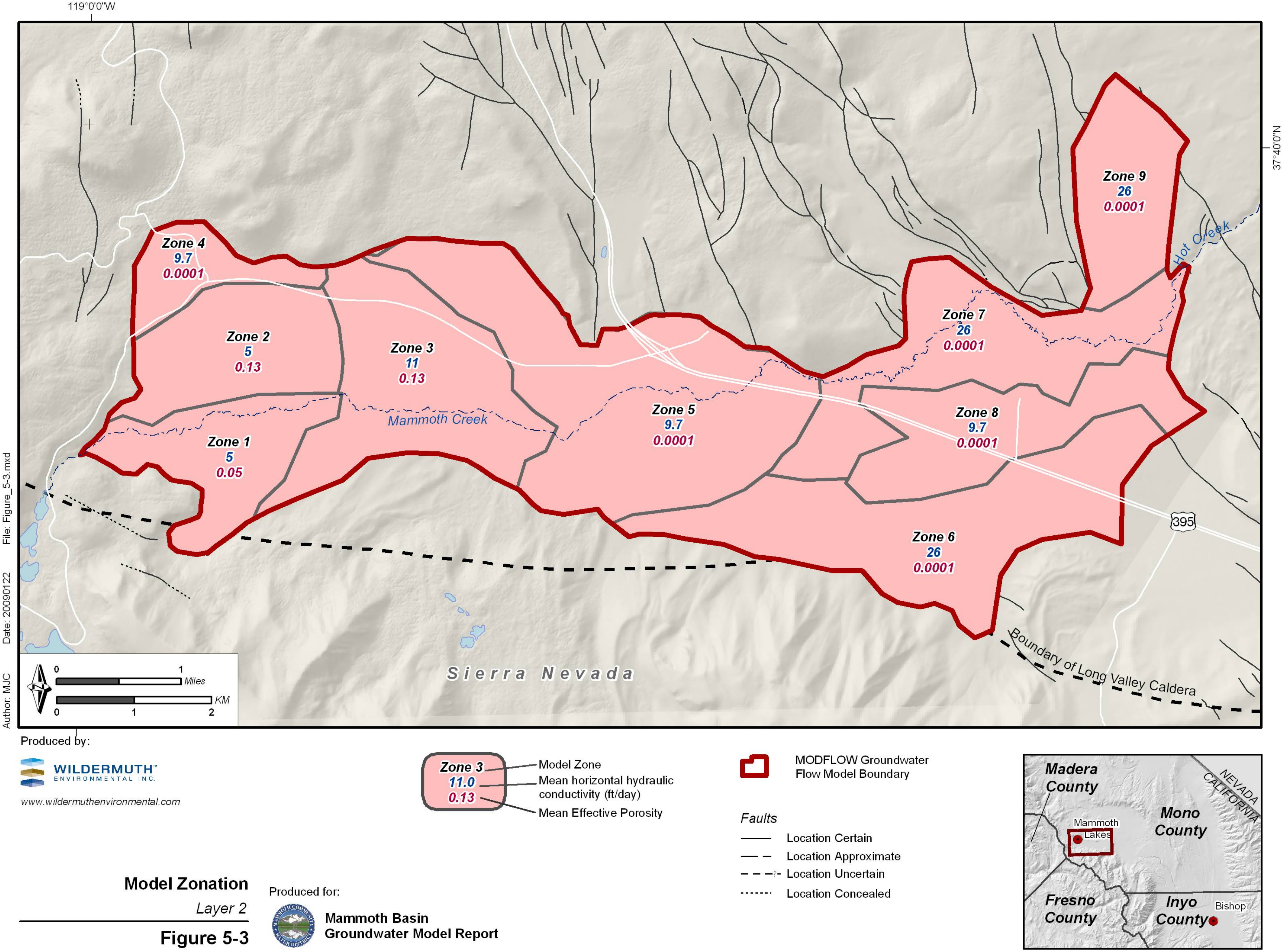

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Model Zonation

Layer 2

Figure 5-3

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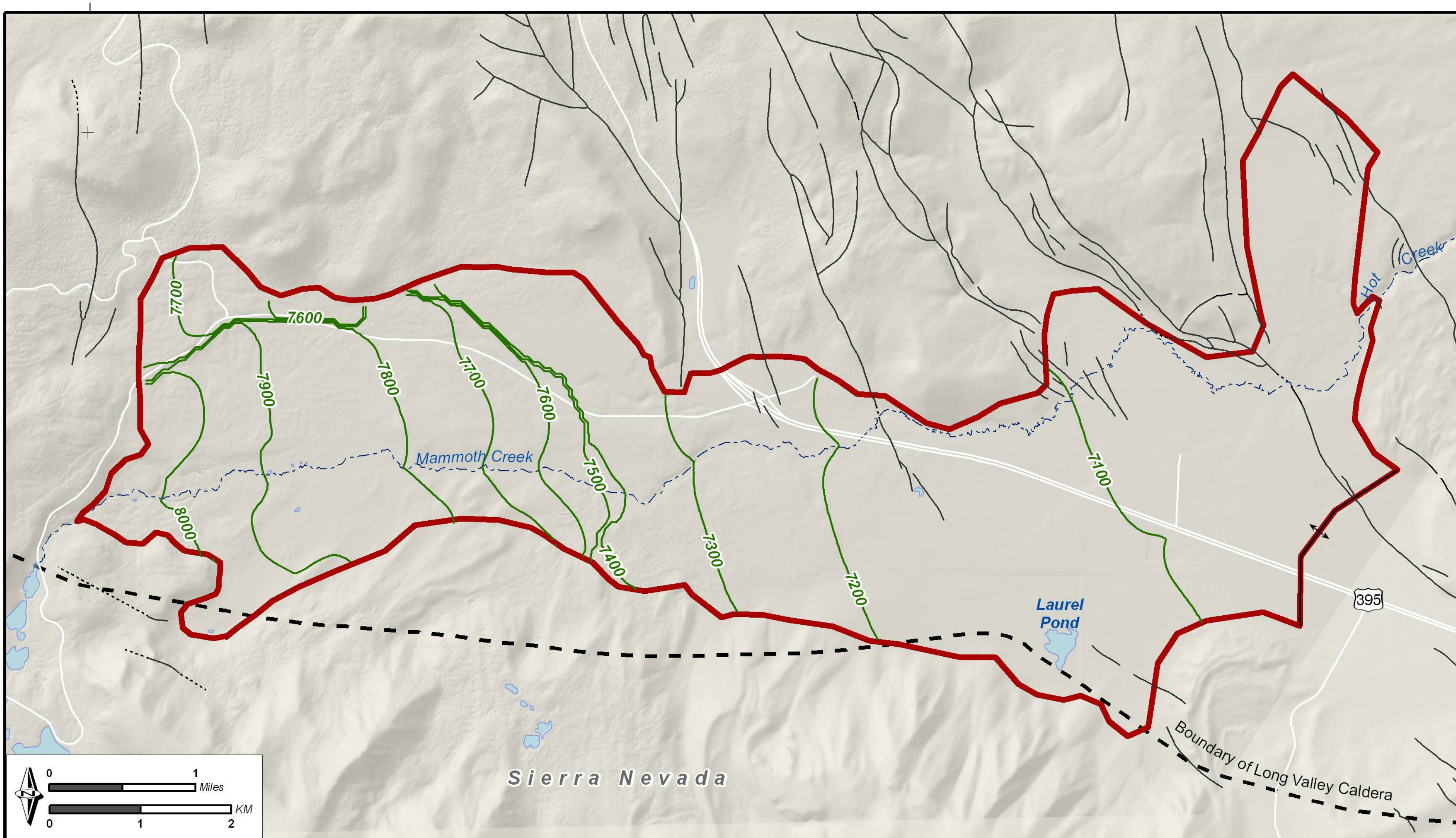

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Groundwater Elevation Contours

Initial Condition Water Level in Layer 1 -- 1992

Figure 5-4

Produced for:

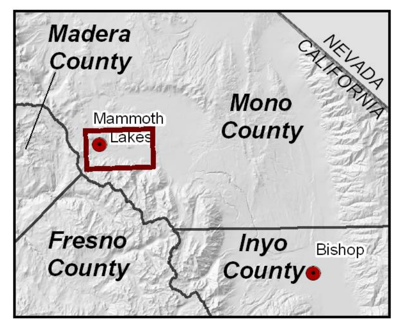
Mammoth Basin Groundwater Model Report

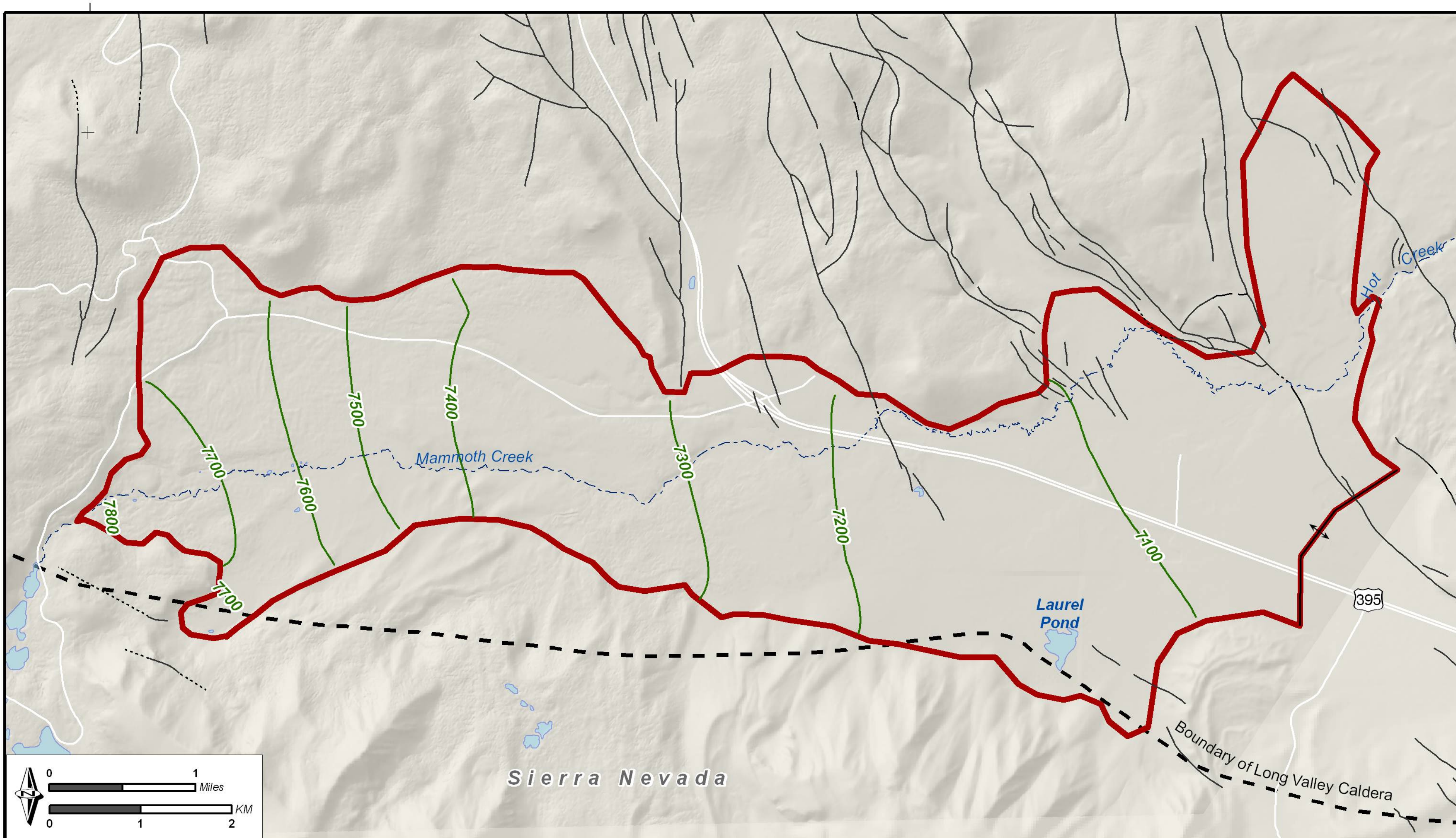
7500 Groundwater Elevation Contours (feet above mean sea-level)

MODFLOW Groundwater Flow Model Boundary

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed





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7500 Groundwater Elevation Contours (feet above mean sea-level)

MODFLOW Groundwater Flow Model Boundary

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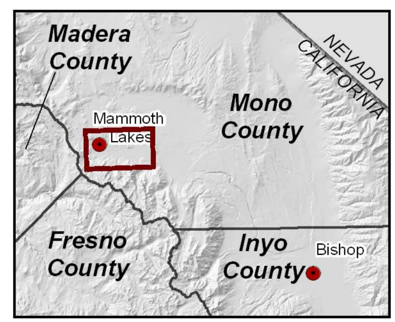

Groundwater Elevation Contours

Initial Condition Water Level in Layer 2 -- 1992

Figure 5-5

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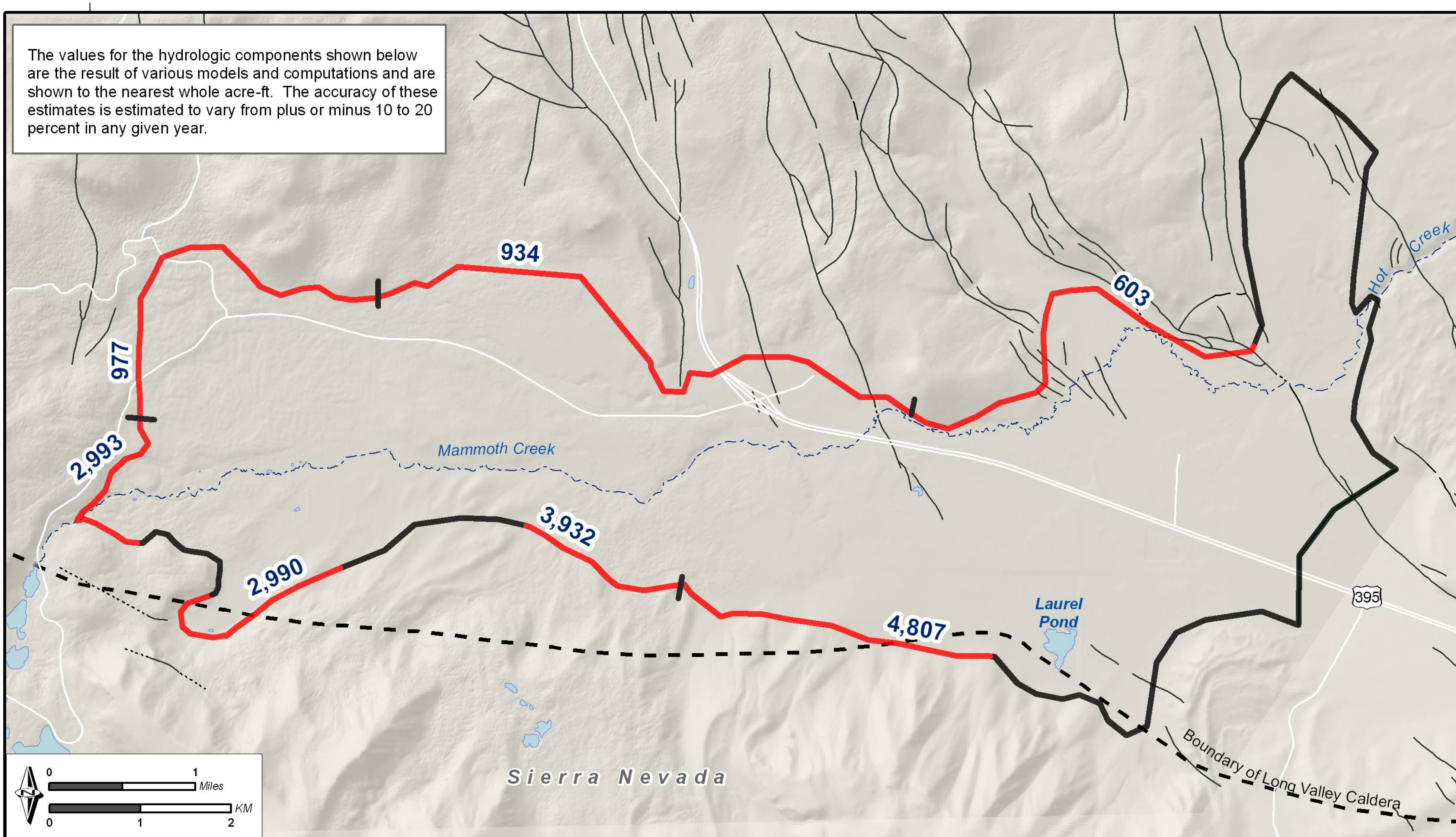
Mammoth Basin Groundwater Model Report



Author: MJC Date: 20090122 File: Figure_5-5.mxd

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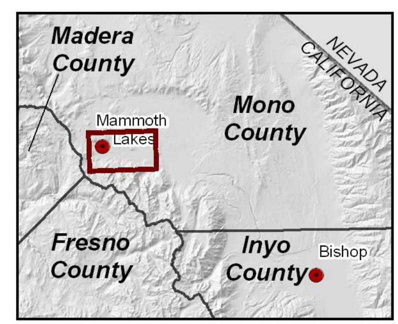
No Flow Boundary	
Variable Flux Boundary	
4,807	Mean Annual Inflow (acre-feet)

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed



Model Boundary Conditions

Figure 5-6

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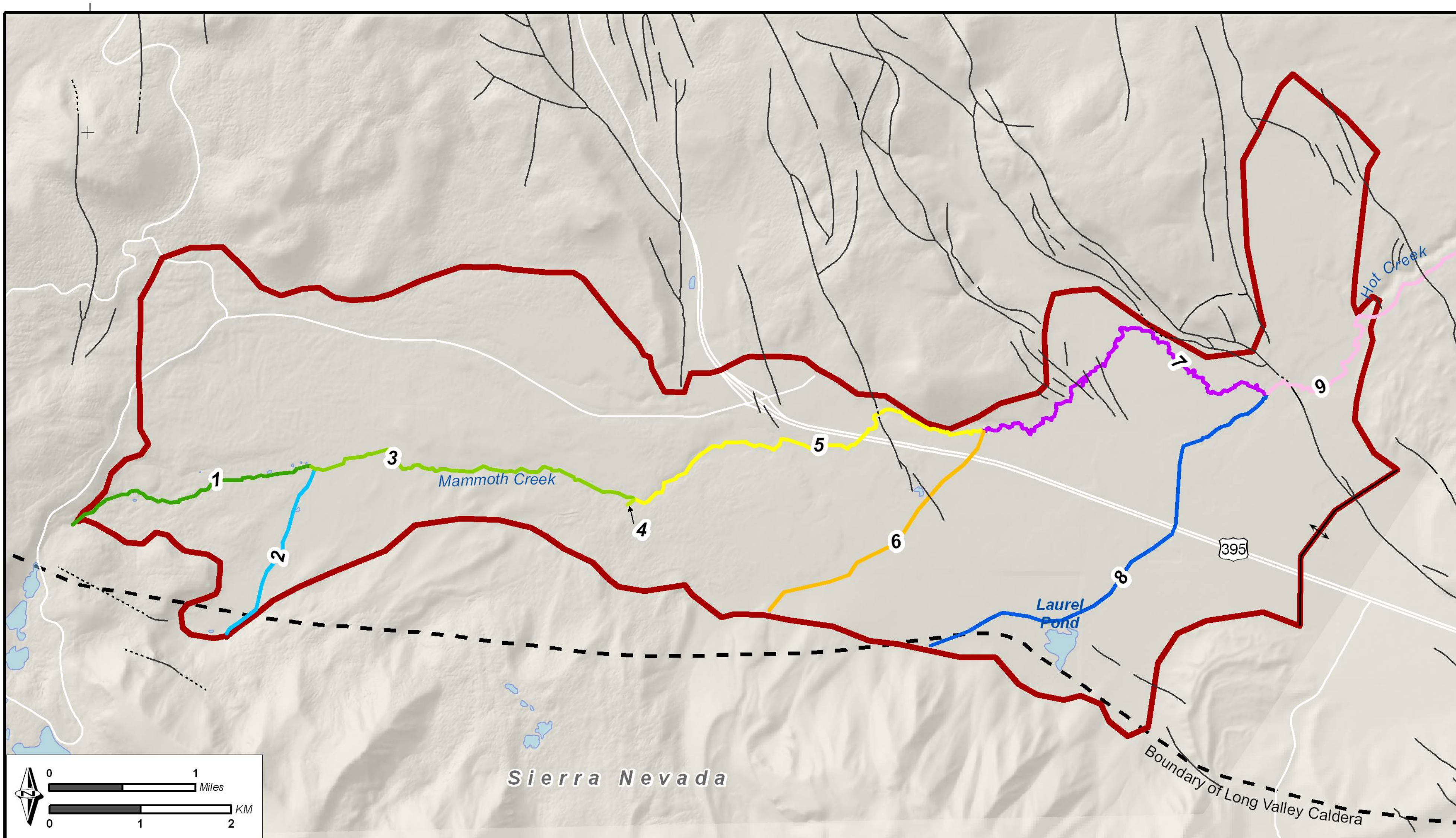

File: Figure_5-7.mxd
Date: 20090122
Author: MJC

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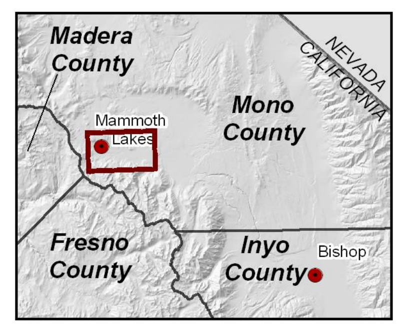
Reaches

1	Mammoth Creek	5	Mammoth Creek
2	Snow Creek	6	Sherwin Creek
3	Mammoth Creek	7	Mammoth Creek
4	Basalt Creek	8	Unnamed Creek
		9	Mammoth Creek

MODFLOW Groundwater Flow Model Boundary

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed

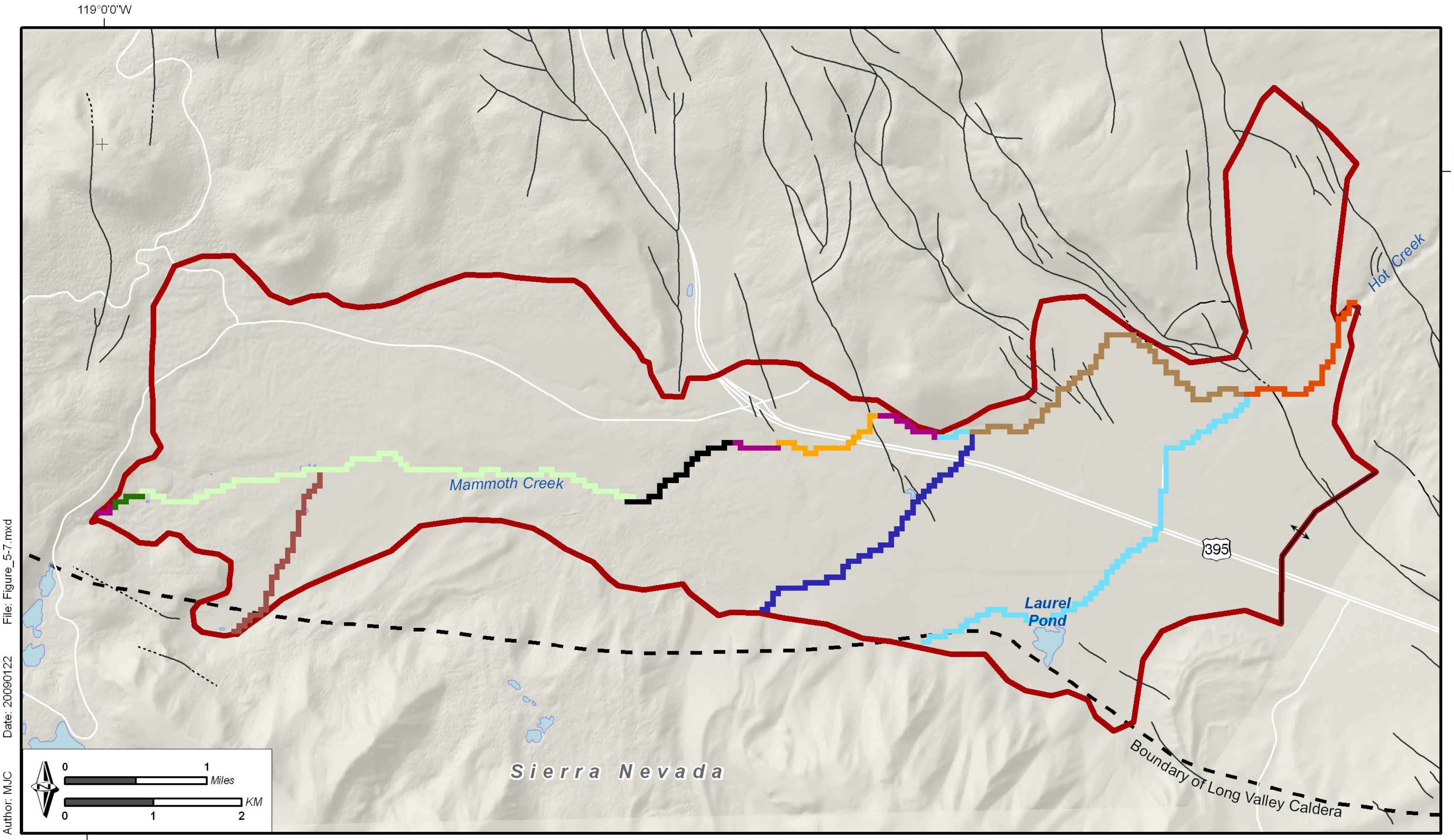


Model Stream Reaches

Produced for:

Mammoth Basin Groundwater Model Report

Figure 5-7



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Conductance of Streambed

Figure 5-8

Produced for:

Mammoth Basin Groundwater Model Report

Conductance of the Streambed

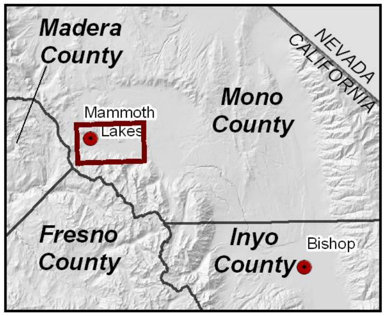
{ ft^2/day }

1,000	6,000
1,500	7,500
2,000	9,000
3,000	10,000
4,500	22,500

MODFLOW Groundwater Flow Model Boundary

Faults

- Location Certain
- Location Approximate
- Location Uncertain
- Location Concealed



Section 6 – Model Calibration

The purpose of model calibration is to estimate the best set of hydraulic and storage parameters for a numerical groundwater flow model. Reliability is vital for any groundwater flow model, and model reliability increases as model errors decrease. The main sources of modeling errors include inconsistencies or errors in the model conceptualization process and uncertainty in model parameters.

The conceptual model is the most important element in numerical modeling because errors in a model's structure are difficult to identify and correct. To minimize inconsistencies or errors in the conceptual model, a considerable effort was put forth in its development. Specific examples include:

- Construction of an appropriate model structure – the groundwater flow model is a simplification of the real system. In the Mammoth Groundwater Basin, groundwater storage in the glacial till of the western portion of the basin is insignificant, considering the scale of the entire basin; as such, this perched aquifer can be ignored. However, this would significantly affect surface water discharge. The perched aquifer was therefore included in the conceptual model even though such inclusion would increase the difficulty of solving the numerical model.
- Careful differentiation of water level information – several wells are screened within multiple aquifers. Water levels in the perched glacial till aquifer are much higher than those of the basalt aquifer with the exception of artesian conditions. Consequently, water level contour maps drawn without the differentiation of aquifers would result in a misinterpretation of groundwater discharge and water levels in the Mammoth Groundwater Basin. Water level map preparation, localized water level evaluation, and flow system characterization were done with a precise understanding of well construction.
- Investigations of geology and hydrogeology – these investigations included analyses of all available well completion reports, well construction data, and all available well pumping records.

A model's structure (i.e. layering and geometry) is not adjusted in the calibration process; calibration is the process of adjusting model parameters to produce the best match between simulated and observed groundwater system responses (e.g. water levels at wells). In this process, model parameters are adjusted with manual methods or automatic parameter-estimation techniques to match observed water levels at wells. Automatic parameter estimation is also termed inverse modeling. Numerical inverse methods are widely used in hydrology and are discussed in numerous scientific publications and books. Milestone papers include those of Neuman (1973), Yeh (1986), and Carrera and Neuman (1986a, b, and c). Inverse modeling was utilized for the calibration of the Mammoth Basin groundwater flow model.

Both MODFLOW-2000 (Harbaugh et al., 2000) and PEST (Doherty, 2004) provide a means to automate parameter estimation and further evaluate a model.

This section describes the procedure for calibrating the Mammoth Basin groundwater flow model; defines the objective function, the minimization algorithm, and the sensitivity analysis;

and discusses the selection of calibration data, the residual analysis, and model validation.

6.1 Model Calibration Procedure

PEST (Doherty, 2004) was used to assist in the calibration of the Mammoth Basin groundwater flow model. The major steps in the model calibration process include:

1. Preliminary Forward Modeling: Calibration starts with forward modeling. First, a developed conceptual model is converted to a numerical model. Numerical conversion includes the definition of model aquifer geometry, the assignment of initial and boundary conditions, discretization in space and time, and the selection of hydraulic parameter zonation and heterogeneity. Next, forward modeling is conducted to check for water balance problems and possible errors caused in the process of conversion. Lastly, modeling results are reviewed to see whether the developed numerical model is capable of simulating the groundwater system's behavior under specifically measured conditions. Forward modeling was solved using the MODFLOW-2000 groundwater model.
2. Sensitivity Analysis: The next step is to determine which model parameters should be calibrated. The model parameters must be MODFLOW-2000 input parameters, which may include the hydraulic properties of the aquifer, boundary conditions, or any other aspect of the model that can be parameterized. It is unnecessary to adjust all of the model parameters in the calibration process, and not all of the selected parameters should be subjected to each iterative-optimization process. In general, reducing the number of estimated parameters can significantly simplify inverse modeling, but this comes at a cost: it might sacrifice the model's reliability. The selection criterion for deciding which parameters should be subjected to inverse modeling should not be subjective. Instead, it should depend on the importance of the parameters, which can be measured by parameter sensitivity. Model parameters with high sensitivity coefficients are the most important in reducing model errors, and these parameters should be determined as accurately as possible. Thus, a pre-sensitivity analysis is conducted to examine the importance of model parameters before inverse modeling commences. Parameter sensitivity varies in each iterative optimization process, and sensitivity analyses should be conducted in all steps of the calibration processes.
3. Selection of Calibration Data: These data points are important for the success or failure of model development. Information about the model parameters is drawn from groundwater system measurements. Model output and measured data are compared only at discrete points in space and time—the calibration data points. The differences between measured and computed system responses at the calibration points are termed residual vectors. Calibration is the process of minimizing the sum of the squared weighted residuals by updating model parameters.
4. Forward Modeling: A MODFLOW-2000 simulation is performed with current parameter values.
5. Parameter Estimation: The calculated and measured system responses (water levels and stream flows) are compared using the sum of the squared weighted residuals, which is also known as the objective function. PEST uses the Marquardt-Levenberg method to minimize the objective function. Details of this method are given in the PEST user's manual (Doherty, 2004). The purpose of the minimization algorithm is to

find the minimum of the objective function by iteratively updating the model parameters. There are a number of strategies for updating model parameters, as discussed in the papers of Neuman (1973, 1986a, b, and c), Finsterle and Najita (1998), and Sun and Yeh (1990). The value of the objective function decreases iteratively with the progress of calibration. The simulation is repeated with updated parameters, using the minimization algorithm. The calibration of Mammoth Basin groundwater flow model was guided by parameter sensitivity analysis. The objective function, sensitivity analysis, and minimization algorithm are discussed in detail later in this report.

6. Repeat steps 4 and 5 until no further decrease in the objective function can be achieved.
7. Analysis of Residuals: If the measured data are not properly reproduced by the model (i.e. if the final residuals are large or exhibit system errors), the resulting parameters are likely to be inadequate or highly biased. Another possibility is that inconsistencies and/or errors exist in the conceptual model. And, a good match does not necessarily imply that all of the estimates are reasonable.

6.2 Sensitivity Analysis

Parameter sensitivity measures the impact of a small parameter change on the calculated system response. If a small hydraulic parameter change results in a large change in the simulated water levels of the model domain, the parameter is regarded as highly sensitive. PEST calculates sensitivities for values of hydraulic head throughout the model using the Jacobian matrix. Because certain parameter values, such as storage coefficients and hydraulic conductivity, differ greatly in orders of magnitude and are therefore incomparable for parameter sensitivities, PEST scales the elements of the Jacobian matrix by the magnitude of the parameter value to make parameter sensitivities comparable with one another. This feature allows for measuring the sensitivity of a calibration point and for measuring the importance of parameters.

Parameter sensitivity changes during each optimization process. Table 6-1 lists the model parameter sensitivities, relative sensitivities, and sensitivity rankings of the first optimization. Specifically, this example suggests that the effective porosities in zones 4, 5, and 8 (basalt aquifer) of layer 1 are very sensitive and are an important parameter. Other sensitive parameters include the horizontal hydraulic conductivity in zones 1 and 3 (glacial till and basalt) of layer 1, the vertical hydraulic conductivity in zone 2 (alluvium and basalt) of layer 1, the horizontal hydraulic conductivity in zone 4 (basalt aquifer) of layer 1, the vertical hydraulic conductivity in zones 1 and 3 (glacial till and basalt) of layer 1, the horizontal flow barrier between zone 3 (glacial till) and zones 4 and 5 (basalt), the effective porosity in zone 3 of layer 2, the horizontal hydraulic conductivity in zone 2 of layer 1, the horizontal hydraulic conductivity in zones 5 and 8 (basalt) of layer 1, and the effective porosity in zones 1 and 2 of layer 2.

Model parameter sensitivity analyses were used to determine which parameters are important and whether they should be subjected to the optimization process. This process allows for the most efficient use of computer processing time and results in reasonable calibration results.

6.3 Selection of Calibration Data

The calibration period is calendar year 1992 through 2006. Calendar year 1992 was selected as the calibration start point based primarily on the availability of continuous groundwater level records and stream flow records for stations OMR, 395, and HCF.

The developed numerical model was calibrated using water-level measurements and historic surface water flows. The calibration data or points are observable variables at discrete points in space and time for which measured data are available. While the physical system response is continuous in space and time and would be described by an infinite number of variables, actual measurements are sparse and limited. From the available measurements, a subset of all water level and surface water flow records was selected based on the following principles:

1. Measurement locations with time-series data should have sufficient sensitivities.
2. Calibration wells should be evenly distributed in space, if possible.
3. Measurements should be distributed relatively evenly over time, if possible.
4. Unreasonable and abnormal water level or stream flow measurements should be removed from the calibration data during the calibration data selection process.

A total of over 754 water-level measurements from 14 different wells were used in the model calibration, and a total of 180 stream flow measurements were used to calibrate streambed conductance. Figure 6-1 shows the location of the selected calibration wells and stream flow stations in the Mammoth Basin. Table 6-2 lists the owners and local names of those wells.

6.4 Calibration Results

Two fundamental criteria were implemented in the model calibration process: 1) the final estimated parameters must be reasonable, not only in their values but also in comparison to other parameters in space, and 2) the model should reasonably reproduce observed variables. In other words, simulated model responses, such as simulated water levels and simulated stream flows, should yield good matches to observed data. To achieve this, the sensitivity analysis described above had to be conducted during each optimization process; the sensitivity analysis in each optimization was used to guide the appropriate optimization direction and to obtain reasonable calibrated parameters. In addition, a residual analysis was conducted to further check if the physical system was properly represented by the model.

6.4.1 Analysis of Calibrated Parameters and Goodness of Fit

The best-estimated parameters were determined by matching the model to the calibration data set using PEST. If a model does not reasonably match the calibration data, the estimated parameters are meaningless because the underlying model is erroneous. Nevertheless, obtaining a good match does not guarantee that the estimated parameters are within a reasonable range or that the inverse modeling is solved in a reasonable way.

The best-estimated parameters resulted in a good match to the observed data and a reasonable estimate of aquifer property values. Table 6-3 lists the model parameter best estimates in comparison to the initial estimates. First and foremost, all final parameter estimates are within a reasonable range, based on hydrogeologic unit type and geological location. For example, the estimated hydraulic conductivity of layer 1 ranges from 1.4 feet/day to 13.0 feet/day, and the estimated hydraulic parameters of layer 2 range from 5 feet/day to 26.0 feet/day. Furthermore, the estimated parameters are comparable to each other without violating reasonable values. For example, the hydraulic conductivity estimate is about 1.4 feet/day in the glacial till aquifer (zones 1 and 3 in layer 1), which is less than the hydraulic conductivity (7.8 feet/day) of the alluvium deposits (zone 3 in layer 1). The estimated effective porosity in the glacial till is about 10 percent (zones 1 and 3 in layer 1), which is also less than those of the alluvium deposits (23 percent in zone 2 of layer 1 and 26 percent in zones 6, 7, and 9 of layer 1). And, the calibrated model yields good matches between simulated and measured water levels. Figure 6-2 is a plot of the modeled versus the measured heads for all calibration wells. All of the points that are distributed closely around the diagonal line indicate good performance of the inverse modeling and the robustness of the developed groundwater model. The points that deviate from the diagonal line are randomly distributed, indicating no trends. Figures 6-3 through 6-16 contain the simulated and measured water level plots for the calibration wells for the 1992-2006 calibration period. Inverse modeling significantly improved these matches in comparison to the simulation without calibration. With the application of inverse modeling, the sum of weighted head residuals dropped from 4.86×10^6 to 3.39×10^5.

The water level calibration plots (Figures 6-3 through 6-16) are one example of the many tools used to evaluate the calibration of the model. Calibration plots are useful indicators for success, as they show transient calculated water levels compared to measured water levels at a single location. Overall, these plots show a good relationship match, indicating that the general trends within the aquifer are simulated well.

That said, a strong relationship between simulated and measured water levels does not imply a good match in every well. Some wells did not match as closely as others. For example, the amplitude of simulated water level fluctuation in Well 1 is not as high as the measured amplitude, indicating that the simulated drawdown drops less than the measured drawdown during pumping events; on the other hand, the simulated water level does not rise as high as the measured water level when pumping decreases. This may suggest that the fractured aquifer system in the Well 1 area is so complex that it is difficult to model using the zone homogeneous model. As noted in the conceptual model discussion, multiple basaltic flows that are aggregated together have been observed in layer 2.

The goodness-of-fit for simulated and measured stream flow at OMR, 395, and HCA was also evaluated. The comparison of simulated and measured stream flows further suggests that the developed groundwater flow model can reproduce the salient features of the water system in the Mammoth Groundwater Basin. Figures 6-17 through 6-19 compare measured and simulated stream flow at these three stations. Figure 6-20 is a plot of the measured versus simulated discharge for all surface water calibration locations during the calibration period. All of the points that are distributed closely around the diagonal line indicate good performance of the inverse modeling. The majority of points that deviate from the diagonal line are randomly distributed. There is a slight trend to the over-prediction of low discharge at the Highway 395 gage. During the calibration period, the total simulated stream flows are slightly higher (about 5 percent) than measured flows at OMR. The same results are observed at station 395; the total simulated flows are slightly higher (about 4 percent) than measured flows. And, at HCA, the simulated stream flows are slightly less (about 2 percent) than measured flows. Surface water contributions to the streams from direct runoff and interflow are computed outside of the groundwater model and included as input to the groundwater model. Thus, some part of the goodness-of-fit as well as the difference between observed and estimated surface discharge cannot be attributed to the groundwater model.

6.4.2 Residual Analysis

Residual analysis is critical in evaluating the performance of inverse modeling and calibration. Minimizing the objective function using the Levenberg-Marquardt algorithm may lead to the best-estimate parameters for a given groundwater flow model. However, this does not imply that a real groundwater system is properly represented by a model. If a conceptual model fails to reproduce the salient features of a system, the given calibrated model may not be able to match observed data as expected. Residual analysis reveals potential trends in the residuals—indicating that there is a systematic error in the model or the data—and points out aspects in the model that need to be modified.

Statistics on hydraulic head residuals aid in the evaluation of model calibration. The mean of the residuals is expected to be close to zero. A large positive or negative mean indicates that data are systematically under-predicted or over-predicted by the model. The standard error in the regression is the square root of the calculated error variance. If the model fits the observations in a way that is consistent with the assigned weighting, the calculated standard error of the regression will equal 1.0. Smaller values indicate that the model fits the observations better than was indicated by the assigned weighting. A large variance or standard deviation either indicates that the data were nosier than expected or that there is a trend in the residuals. The skewness of residuals characterizes the degree of asymmetry in the distribution. Kurtosis compares the peakedness or flatness of the distribution relative to the Gaussian distribution. A distribution with Kurtosis greater than 3 is relatively peaked and less than 3 is relatively flat. A large difference between the mean and the median is indicative of a robustness problem; that is, the distribution is likely to be heavy-tailed and asymmetric.

Figure 6-21 shows the frequency residual distribution, and Figure 6-22 shows the frequency density residual distribution and the Gaussian distribution based on the residual's mean and the standard distribution. Table 6-4 lists hydraulic-head residual statistics. These data illustrate that the mean of residuals is around -0.87, which is very close to zero, with a standard deviation of 21.2. The value of skewness indicates that the residual is almost symmetrically distributed. In the residuals distribution of the model, the Kurtosis was greater than 3, which means that there are more residuals around zero. In short, the calibrated model does not show systematic error.

The residual distribution is statistically random and shows little spatial trend when observed in map form. Figure 6-23 shows each calibration well and its mean residual by geographic location. Well 6 in the western portion of the basin has a mean residual greater than 20 feet, which might be attributed to historical data collection. Nonetheless, this well is proximate to wells with very small mean residuals, indicating little spatial trending.

Table 6-5 lists residual errors, classified by percentage group. This table indicates that about 93 percent of the residual errors are less than 40 feet, about 87 percent of the residual errors are less than 30 feet, and nearly 80 percent of the residual errors are less than 20 feet.

6.5 Limitations on the Use of the Model

The conceptual model used in the Mammoth Basin groundwater model is a simplification of the physical system. Simplification is required because the physical system is much more complicated than can be simulated and because information on the geology and hydrology is insufficient to develop a precise description of the physical system. Consider Figure 2-1, which illustrates the model boundary and shows, among other features, the locations of wells constructed in the model area. As this figure shows, the production wells are located in the far western end of the basin; there are no production wells in the center or eastern part of the basin. Also, please note that the groundwater level time series data for wells east of MCWD Well 24 show no response to the seasonal drawdown observed in MCWD production wells. This implies that there is little or no hydraulic continuity between MCWD production wells and the groundwater system east of the MCWD wells, as demonstrated in *Investigation of Groundwater Production Impacts on Surface Water Discharge and Spring Flow* (WEI, 2003).

Figure 2-8 shows the locations of the surface geology and the three hydrogeologic cross sections used to develop the conceptual model. This figure suggests that hydrogeology is reasonably known in the western part of the basin in the MCWD well field area and substantially less understood east of the MCWD well field. Cross section B-B (Figure 2-10) is reasonably well supported by borehole lithology, groundwater level data, and water quality data. Cross sections A-A' and C-C' (Figures 2-9 and 2-11, respectively) are very speculative. East of cross section B-B', cross section A-A' has only three wells to describe the lithology of the 4-mile segment between cross section B-B' and Highway 395. East of cross section B-B' the conceptual model becomes substantially more speculative than near and west of cross section B-B'. In short, the conceptual model is reasonably well defined in the far west; however, east of the MCWD well field, confidence in the conceptual model is substantially less. Where that confidence breaks down is about a mile or two east of the MCWD well field.

The model is acceptably calibrated in the far western part of the basin and can be used with confidence to predict groundwater basin responses in the MCWD well field area. The model should not be used to predict groundwater basin responses more than a mile or two east of the MCWD well field until additional information is developed to improve the understanding of the groundwater system.

Table 6-1
Model Parameter Sensitivity and Ranking

Order	Parameter Name	Type	Layer	Zone	Current Value	Relative Sensitivity	Ranking
1	hk1z1	Hydraulic Conductivity	1	2	7.00E+00	2.12E+00	8
2	hk1z3	Hydraulic Conductivity	1	1,3	7.00E+00	2.49E+00	2
3	hk1z4	Hydraulic Conductivity	1	4	1.00E+01	2.45E+00	4
4	hk1z5	Hydraulic Conductivity	1	5,8	2.50E+01	2.03E+00	9
5	hk1z6	Hydraulic Conductivity	1	67,9	1.50E+01	1.80E+00	12
6	sy1z1	Effective Porosity	1	2	1.40E-01	6.46E-01	23
7	sy1z3	Effective Porosity	1	1,3	1.40E-01	8.61E-01	21
8	sy1z5	Effective Porosity	1	4,5,8	1.00E-01	2.76E+00	1
9	sy1z6	Effective Porosity	1	6,7,9	2.00E-01	7.80E-01	22
10	vkcb1	Vertical Hydraulic Conductivity	1,2	2	1.00E-03	2.48E+00	3
11	vkcb3	Vertical Hydraulic Conductivity	1,2	1,3	1.00E-03	2.28E+00	5
12	hk2z1	Hydraulic Conductivity	2	1	2.50E+01	1.07E+00	20
13	hk2z2	Hydraulic Conductivity	2	2	2.50E+01	1.63E+00	18
14	hk2z3	Hydraulic Conductivity	2	3	2.50E+01	1.63E+00	17
15	hk2z5	Hydraulic Conductivity	2	4,5,8	2.50E+01	1.37E+00	19
16	hk2z6	Hydraulic Conductivity	2	6,7,9	2.00E+01	1.65E+00	16
17	ss2z1	Storage Coefficient	2	1,2,3,	1.00E-04	1.78E+00	13
18	ss2z5	Storage Coefficient	2	4,5,8	1.00E-04	1.71E+00	15
19	ss2z6	Storage Coefficient	2	6,7,9	1.00E-04	1.78E+00	14
20	sy2z1	Effective Porosity	2	1	1.00E-01	1.93E+00	10
21	sy2z2	Effective Porosity	2	2	1.00E-01	1.92E+00	11
22	sy2z3	Effective Porosity	2	3	1.00E-01	2.18E+00	7
23	hfb1	Horizontal Flow Barriers	1	3,4,5	1.00E+00	2.21E+00	6

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Table 6-2
Model Calibration Wells

Owner	Name	Layer		Row	Column	Well Depth	Screen Top	Elevation[1]
		From	To					
MCWD	1	1	2	76	28	382	200	7,939
MCWD	4M	1	1	85	40	89	69	7,885
MCWD	5A	1	1	78	18	112	57	8,039
MCWD	6	1	2	95	33	670	146	7,916
MCWD	11M	1	1	104	27	43	5	7,974
MCWD	14	2	2	86	42	520	100	7,881
MCWD	17	2	2	55	27	710	400	7,991
MCWD	23	1	1	76	28	65	30	7,940
Mono County Sheriff	SS-2	1	1	72	159	100	-	7,182
Press Gravel	SQ	1	1	93	199	125	27	7,109
USGS	SC-1	1	1	87	106	132	40	7,488
USGS	SC-2	2	2	88	106	230	215	7,486
USGS	MW-4	2	2	47	228	340	320	7,089
Mammoth Elementary	ESO	1	1	68	199	44	-	7,079

1. Elevation based on digital elevation model.

Table 6-3
Initial and Final Model Parameter Values

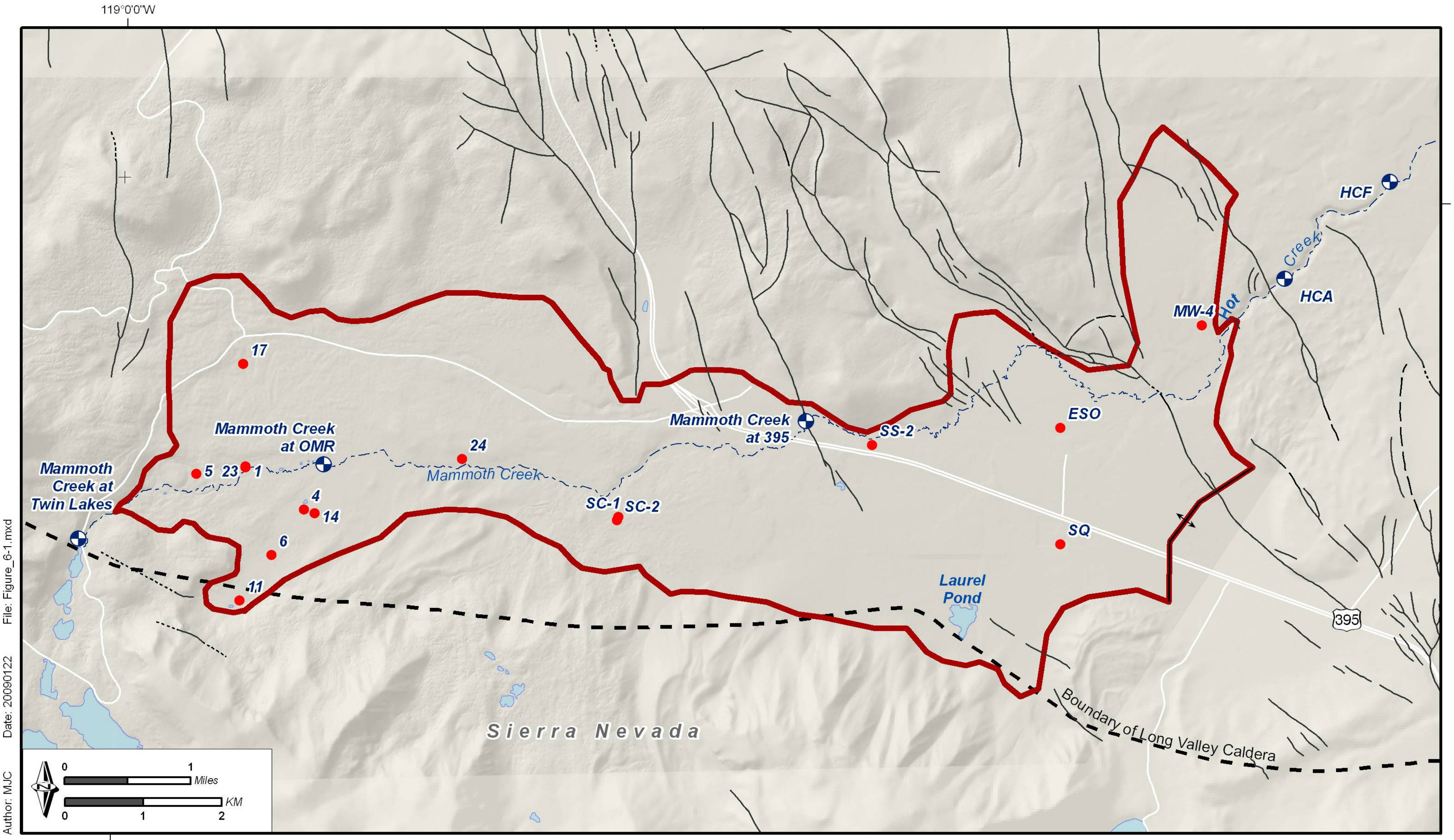
Order	Parameter Name	Type	Layers	Zonation	Initial Estimate	Calibrated Value	Aquifer Lithology
1	hk1z1	Hydraulic Conductivity	1	2	7	7.8	Alluvium and Basalt
2	hk1z3	Hydraulic Conductivity	1	1,3	7	1.4	Glacial Till and Basalt
3	hk1z4	Hydraulic Conductivity	1	4	10	4.0	Basalt
4	hk1z5	Hydraulic Conductivity	1	5,8	25	13.0	Basalt
5	hk1z6	Hydraulic Conductivity	1	67,9	15	12.0	Alluvium
6	syl z1	Effective Porosity	1	2	0.14	0.23	Alluvium and Basalt
7	syl z3	Effective Porosity	1	1,3	0.14	0.1	Glacial Till and basalt
8	syl z5	Effective Porosity	1	4,5,8	0.1	0.11	Basalt
9	syl z6	Effective Porosity	1	6,7,9	0.2	0.26	Alluvium
10	vkcbl	Vertical Hydraulic Conductivity	1,2	2	1.00E-03	7.40E-04	Alluvium, Till, and Basalt
11	vkcb3	Vertical Hydraulic Conductivity	1,2	1,3	1.00E-03	1.30E-03	Glacial Till and Basalt
12	hk2zl	Hydraulic Conductivity	2	1	25	5.0	Basalt
13	hk2z2	Hydraulic Conductivity	2	2	25	5.0	Basalt
14	hk2z3	Hydraulic Conductivity	2	3	25	11.0	Basalt
15	hk2zb	Hydraulic Conductivity	2	4,5,8	25	9.7	Basalt
16	hk2z6	Hydraulic Conductivity	2	6,7,9	20	26.0	Basalt
17	ss2zl	Specific Storage	2	1,2,3,	1.00E-04	1.00E-04	Basalt
18	ss2z5	Specific Storage	2	4,5,8	1.00E-04	1.00E-04	Basalt
19	ss2z6	Specific Storage	2	6,7,9	1.00E-04	1.00E-04	Basalt
20	sy2zl	Effective Porosity	2	1	0.1	0.05	Basalt
21	sy2z2	Effective Porosity	2	2	0.1	0.13	Basalt
22	sy2z3	Effective Porosity	2	3	0.1	0.13	Basalt
23	hfbl	Horizontal Barriers	1	3,4,5	1	1.00E-03	Glacial Till and Basalt

Table 6-4
Descriptive Statistics of Hydraulic-Head Residuals

Statistic	Residual
No. of observations	754
Minimum	-57.29
Maximum	92.29
Frequency of Minimum	1
Frequency of Maximum	1
Range	149.58
1st Quartile	-12.77
Median	-1.79
3rd Quartile	7.49
Mean	-0.87
Standard Deviation (n)	21.18
Standard Deviation (n-1)	21.19
Skewness (Pearson)	1.35
Skewness (Fisher)	1.36
Skewness (Bowley)	-0.08
Kurtosis (Pearson)	4.29
Kurtosis (Fisher)	4.32
Standard Error of the Mean	0.77
Lower Bound on Mean (95%)	-2.39
Upper Bound on Mean (95%)	0.64
Standard Error (Skewness-Fisher)	0.09
Standard Error (Kurtosis-Fisher)	0.18
Mean Absolute Deviation	14.04
Median Absolute Deviation	9.62

Table 6-5
Descriptive Statistics of Residual Intervals

Lower Bound	Upper Bound	Frequency	Relative Frequency	Density (Data)
-100	-90	0	0.000	0.000
-90	-80	0	0.000	0.000
-80	-70	0	0.000	0.000
-70	-60	0	0.000	0.000
-60	-50	1	0.001	0.000
-50	-40	19	0.025	0.003
-40	-30	25	0.033	0.003
-30	-20	38	0.050	0.005
-20	-10	145	0.192	0.019
-10	0	210	0.279	0.028
0	10	184	0.244	0.024
10	20	61	0.081	0.008
20	30	21	0.028	0.003
30	40	18	0.024	0.002
40	50	8	0.011	0.001
50	60	2	0.003	0.000
60	70	4	0.005	0.001
70	80	10	0.013	0.001
80	90	6	0.008	0.001
90	100	2	0.003	0.000



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Calibration Well

Stream Gaging Station

MODFLOW Groundwater Flow Model Boundary

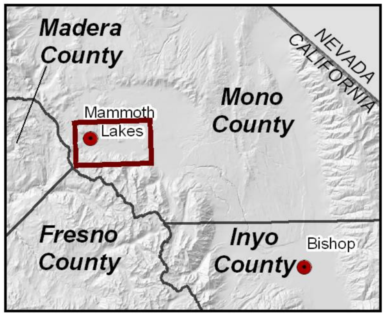
Faults

Location Certain

Location Approximate

Location Uncertain

Location Concealed



Map of Calibration Wells and Stream Gages

Figure 6-1

Produced for:

Mammoth Basin Groundwater Model Report

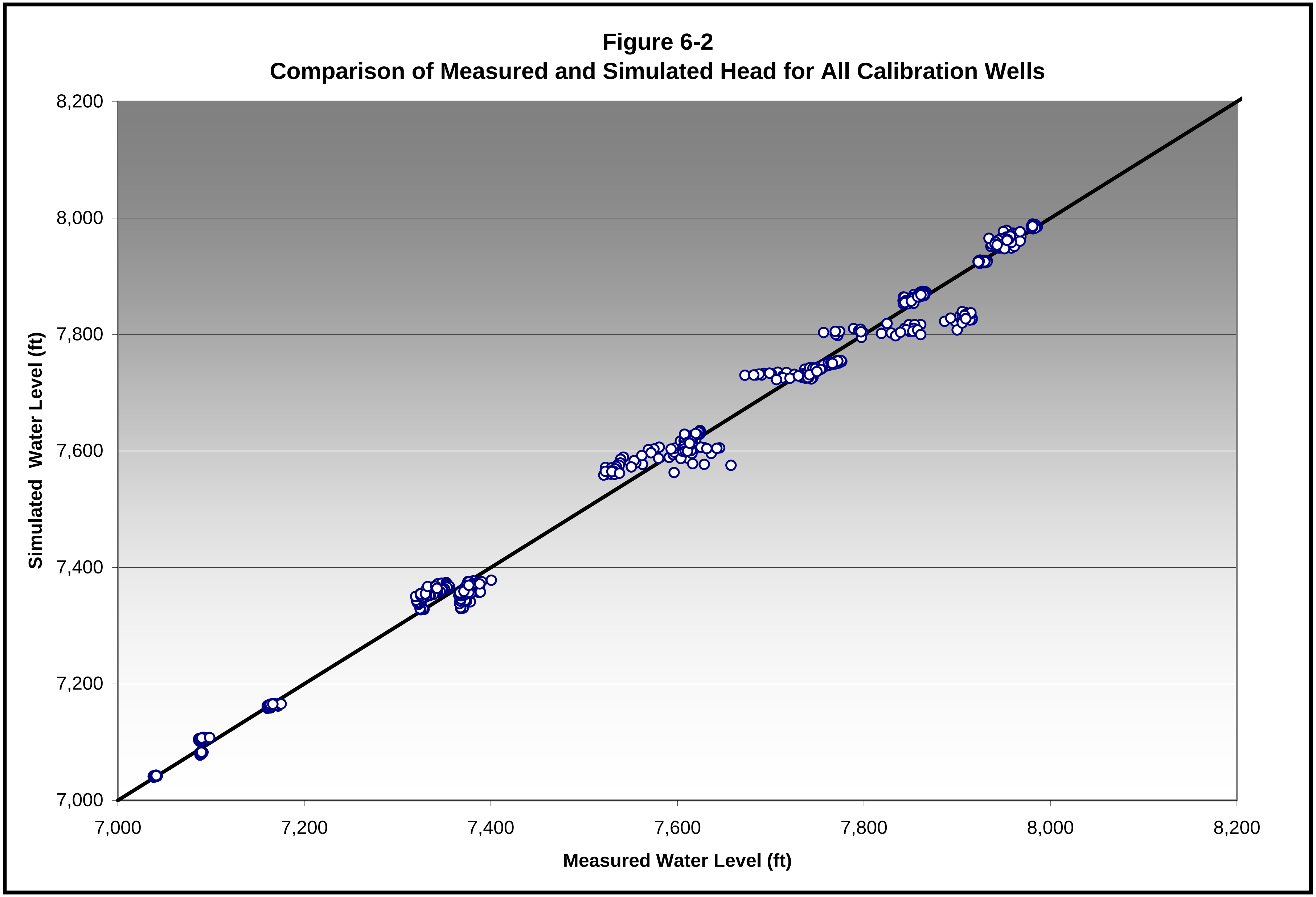


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Figure 6-3
Comparison of Measured and Simulated Groundwater Levels in Well 1

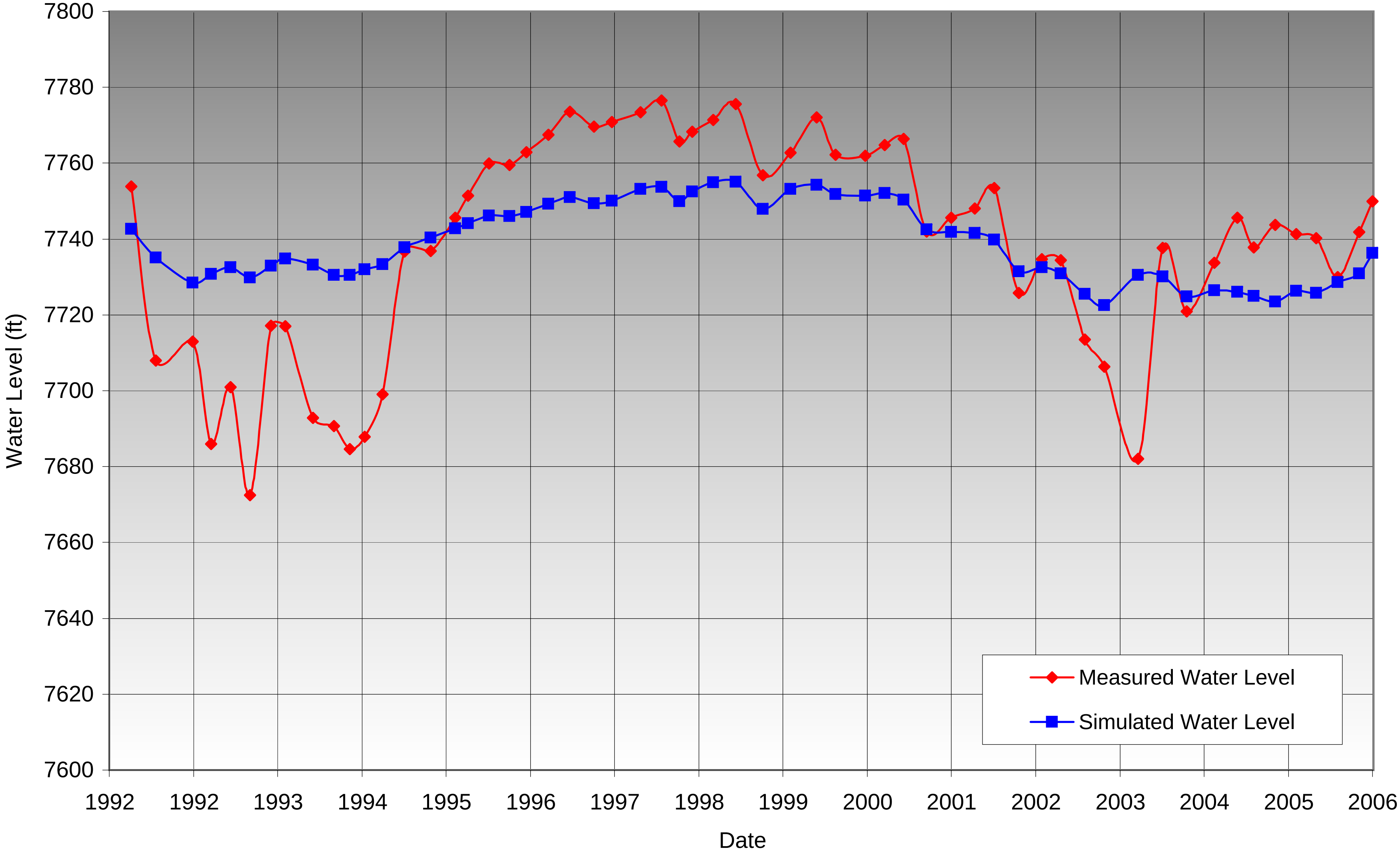

Figure6-3 through 6-16.xls -- 1_1
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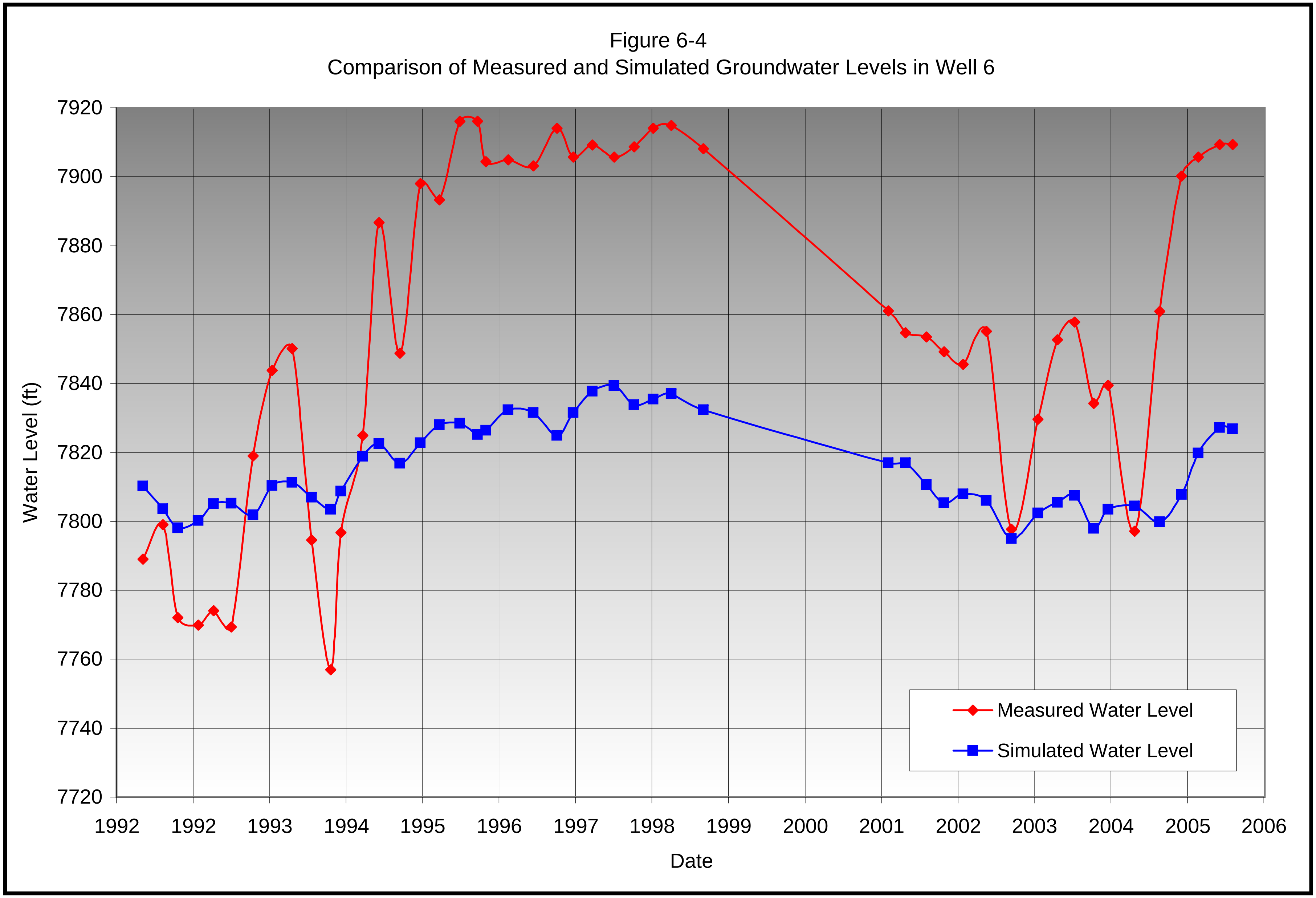

Figure6-3 through 6-16.xls -- 6_2
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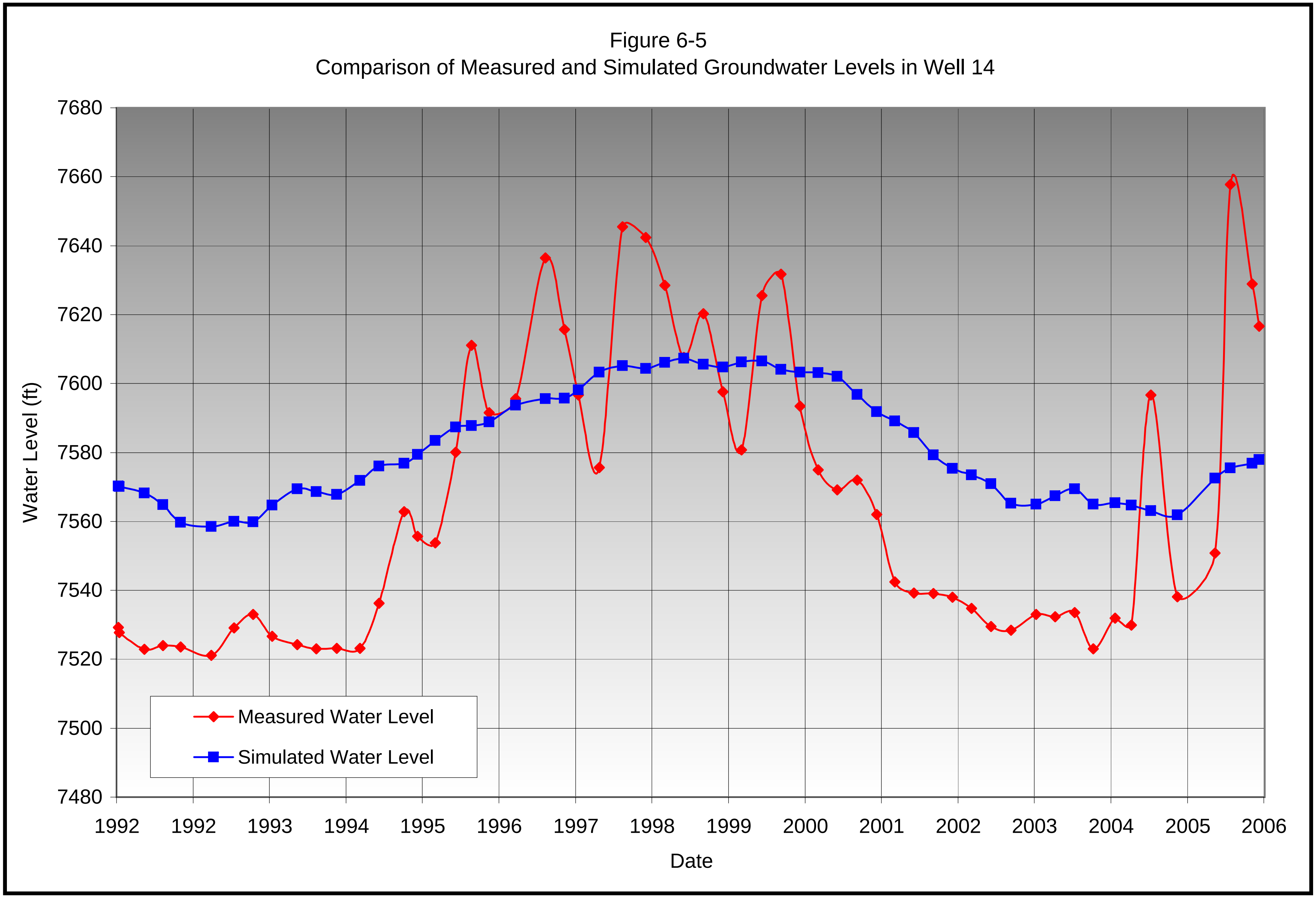
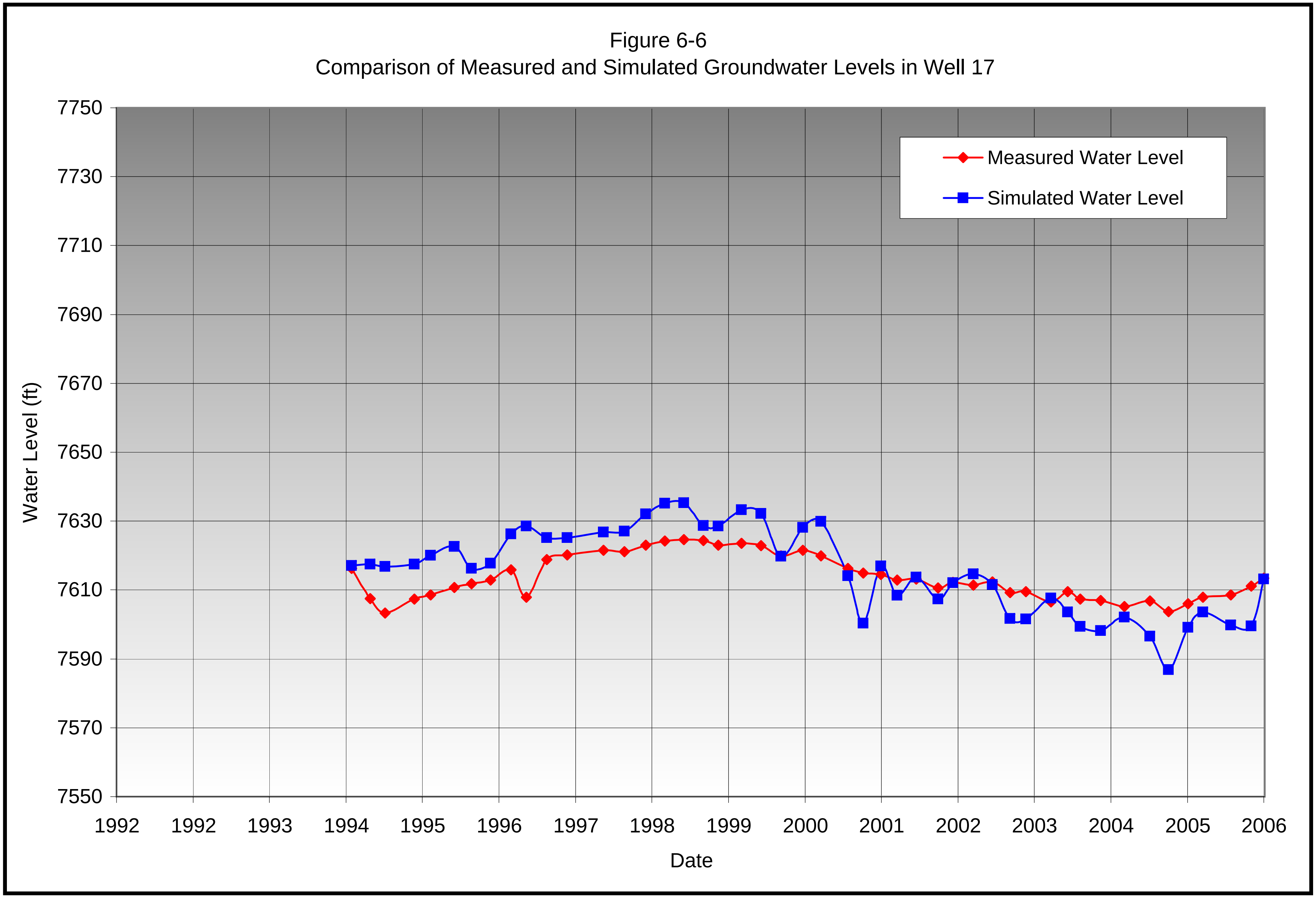


Figure 6-5
Comparison of Measured and Simulated Groundwater Levels in Well 14
7680
7660
7640
7620
7600
7580
7560
7540
7520
7500
7480
Water Level (ft)
Measured Water Level
Simulated Water Level
1992
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Date



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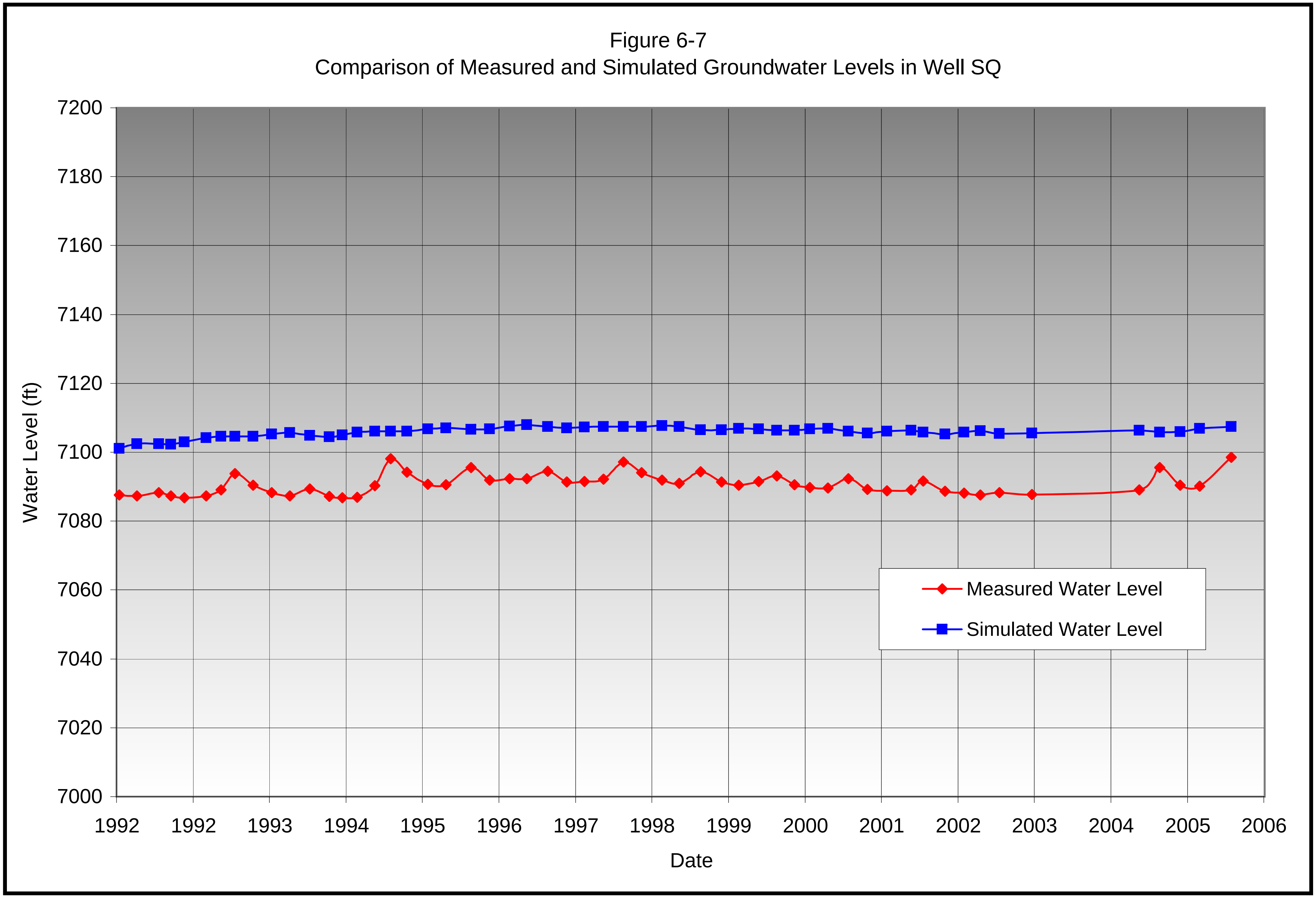

Figure6-3 through 6-16.xls -- SQ_5
9/10/2009 -- 10:25 AM

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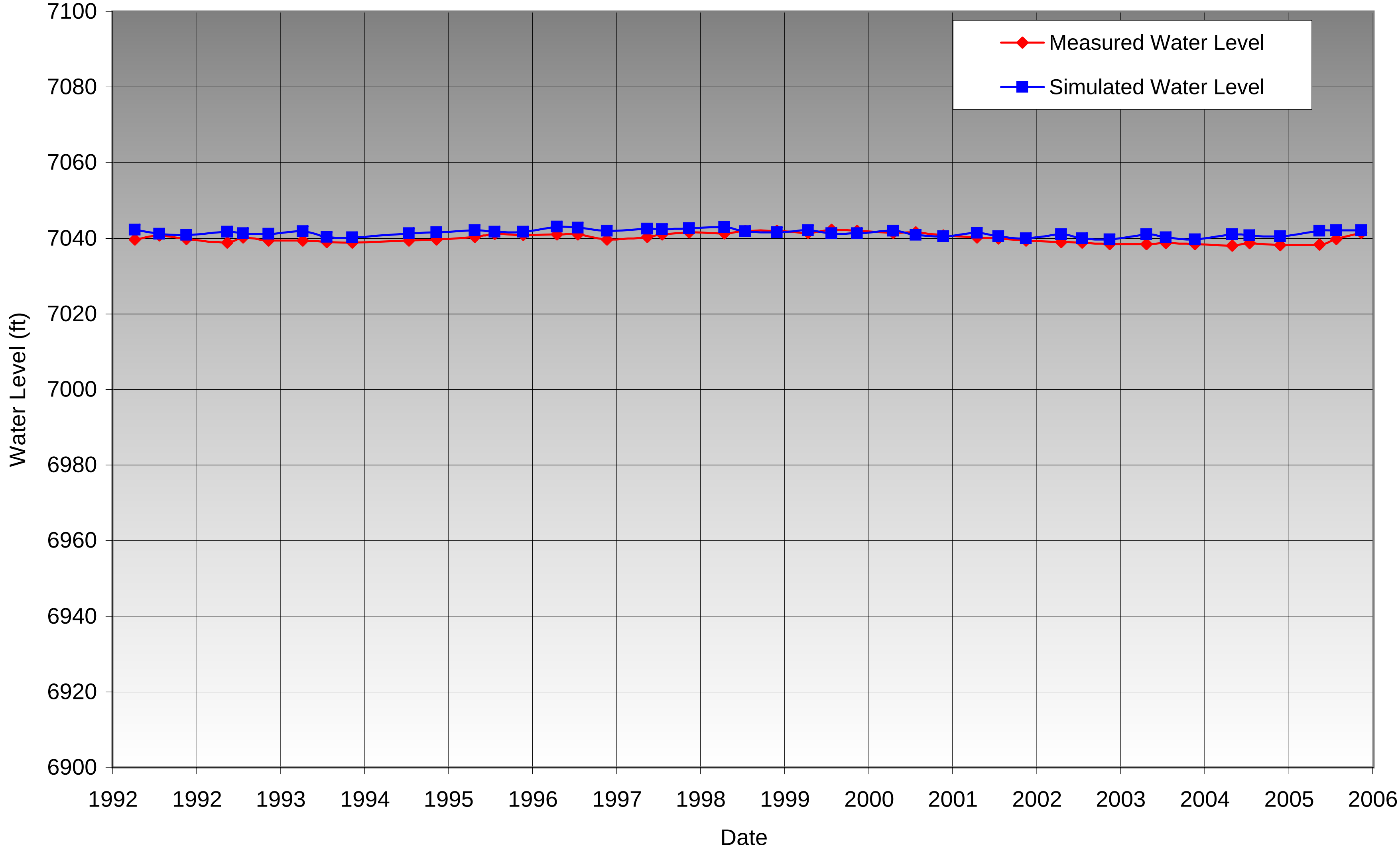
Figure 6-8
Comparison of Measured and Simulated Groundwater Levels in Well MW-4



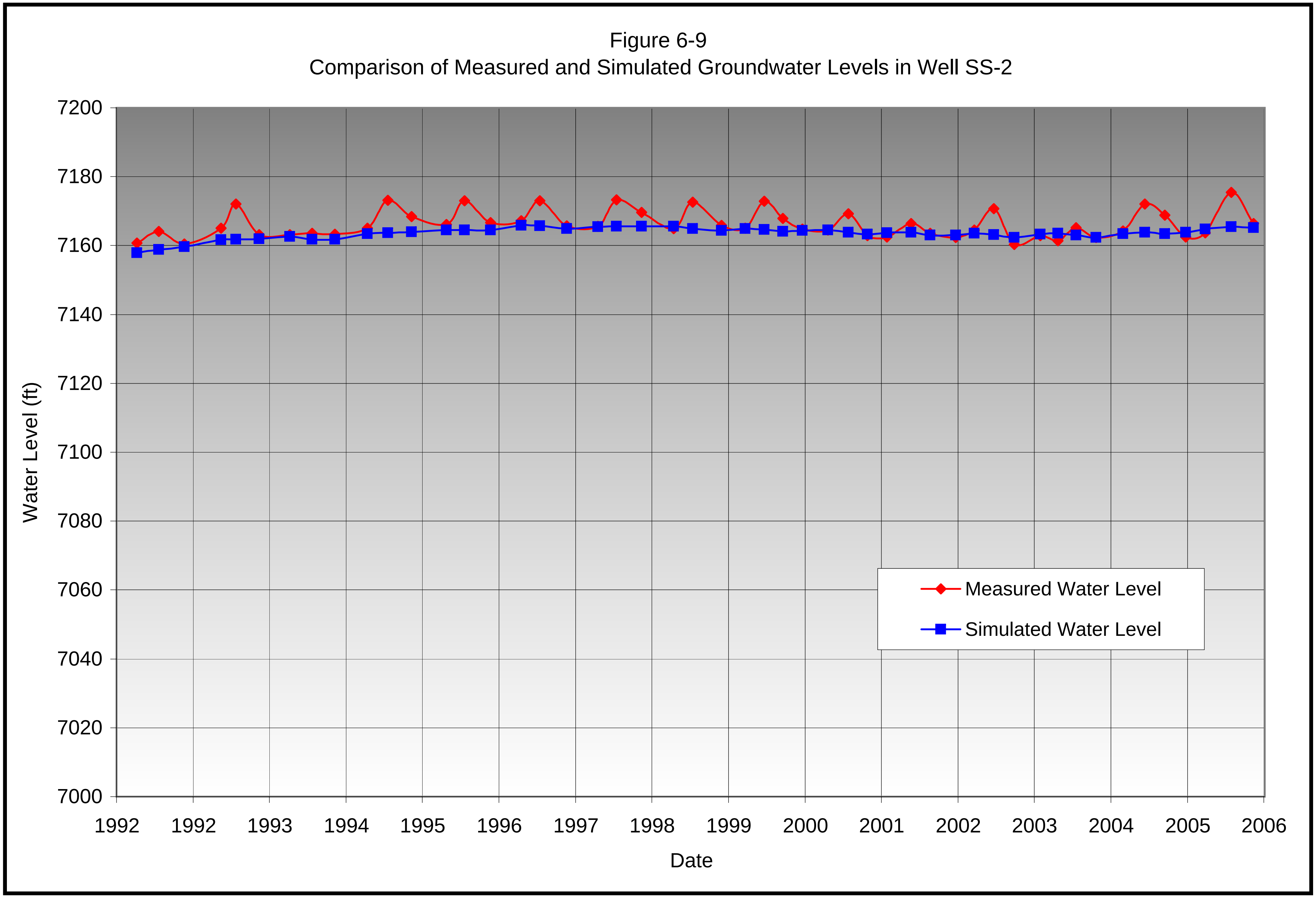


Figure 6-9
Comparison of Measured and Simulated Groundwater Levels in Well SS-2
7200
7180
7160
7140
7120
7100
7080
7060
7040
7020
7000
Water Level (ft)
1992
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Date
Measured Water Level
Simulated Water Level

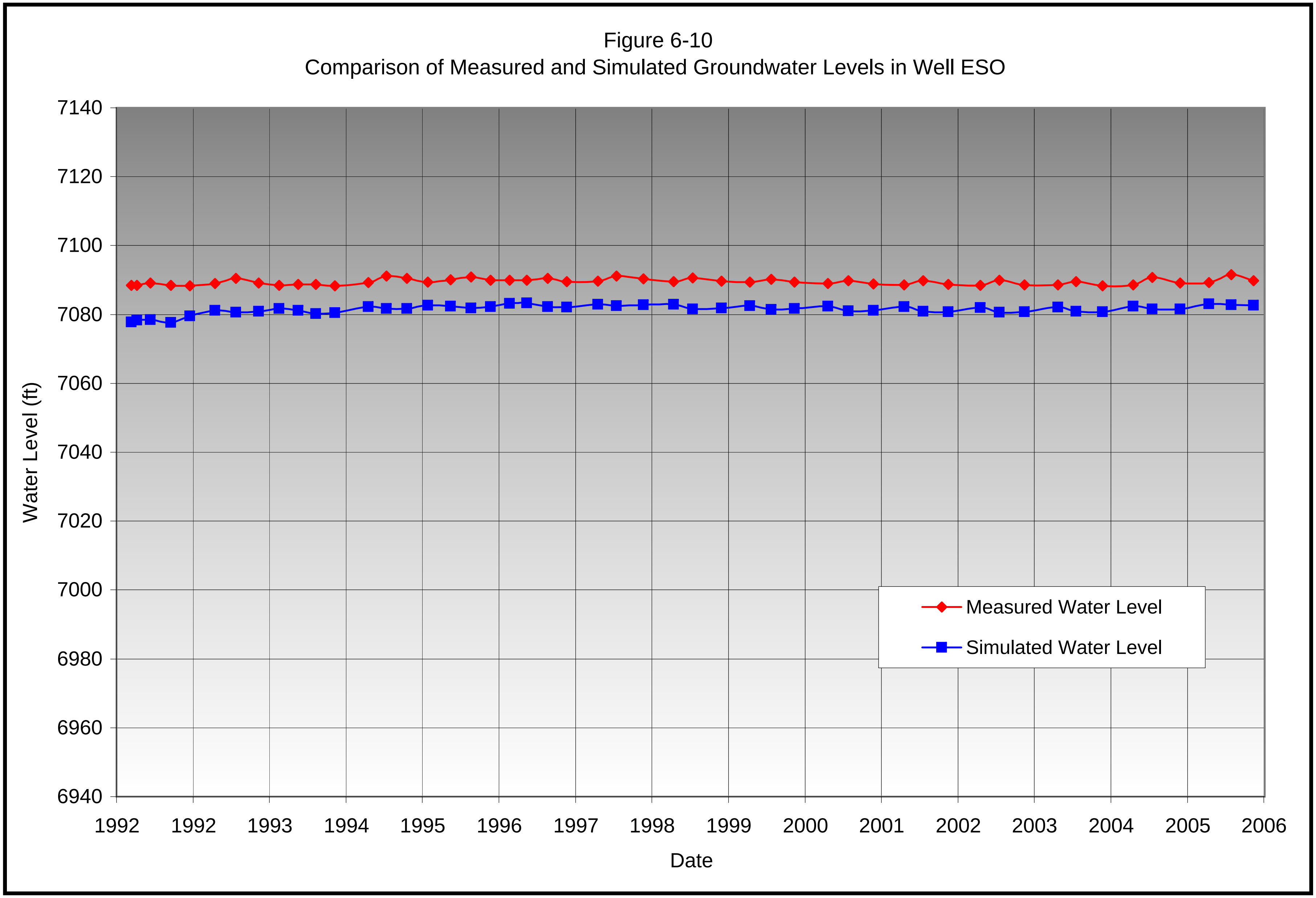


Figure6-3 through 6-16.xls -- ESO_8
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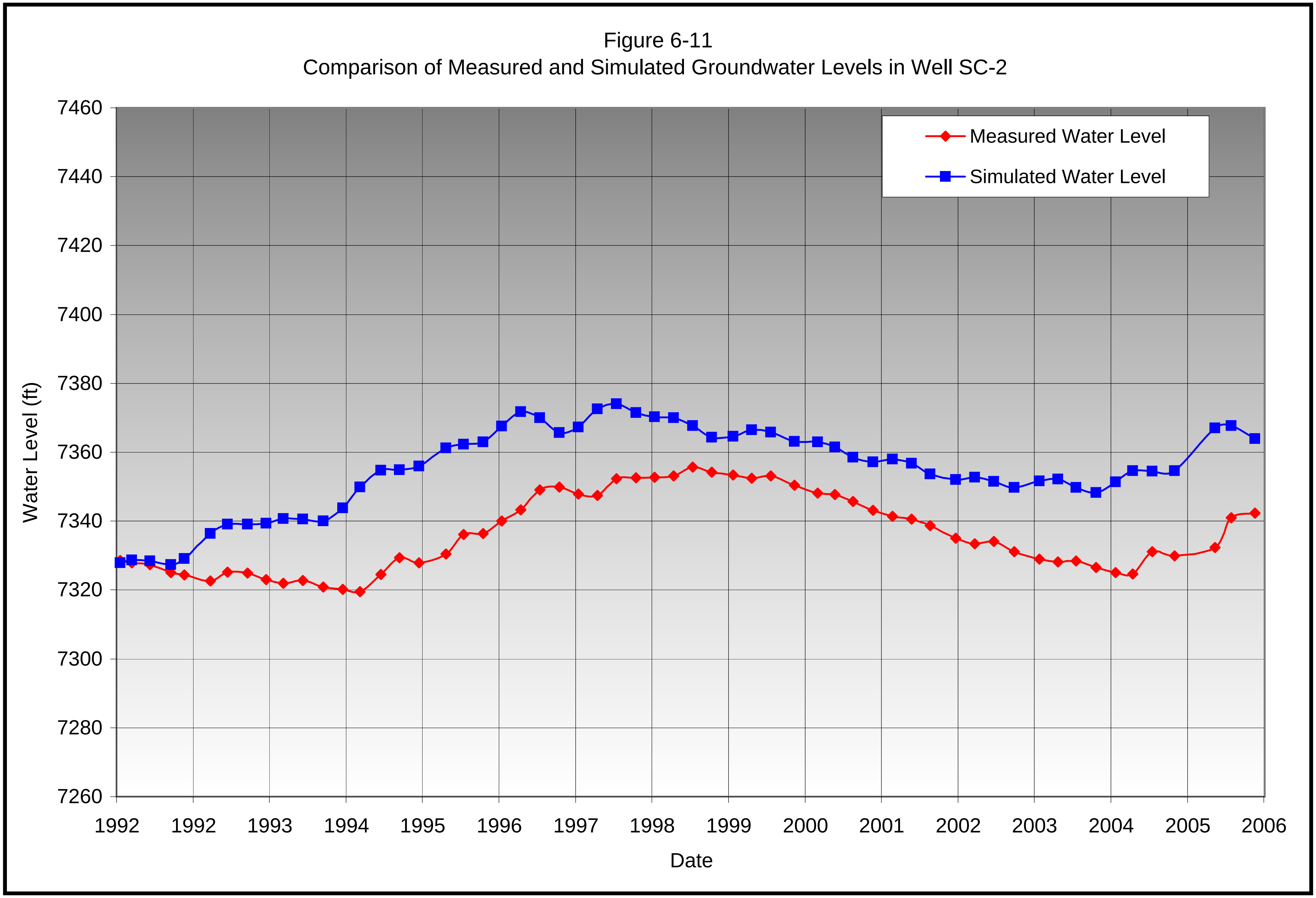

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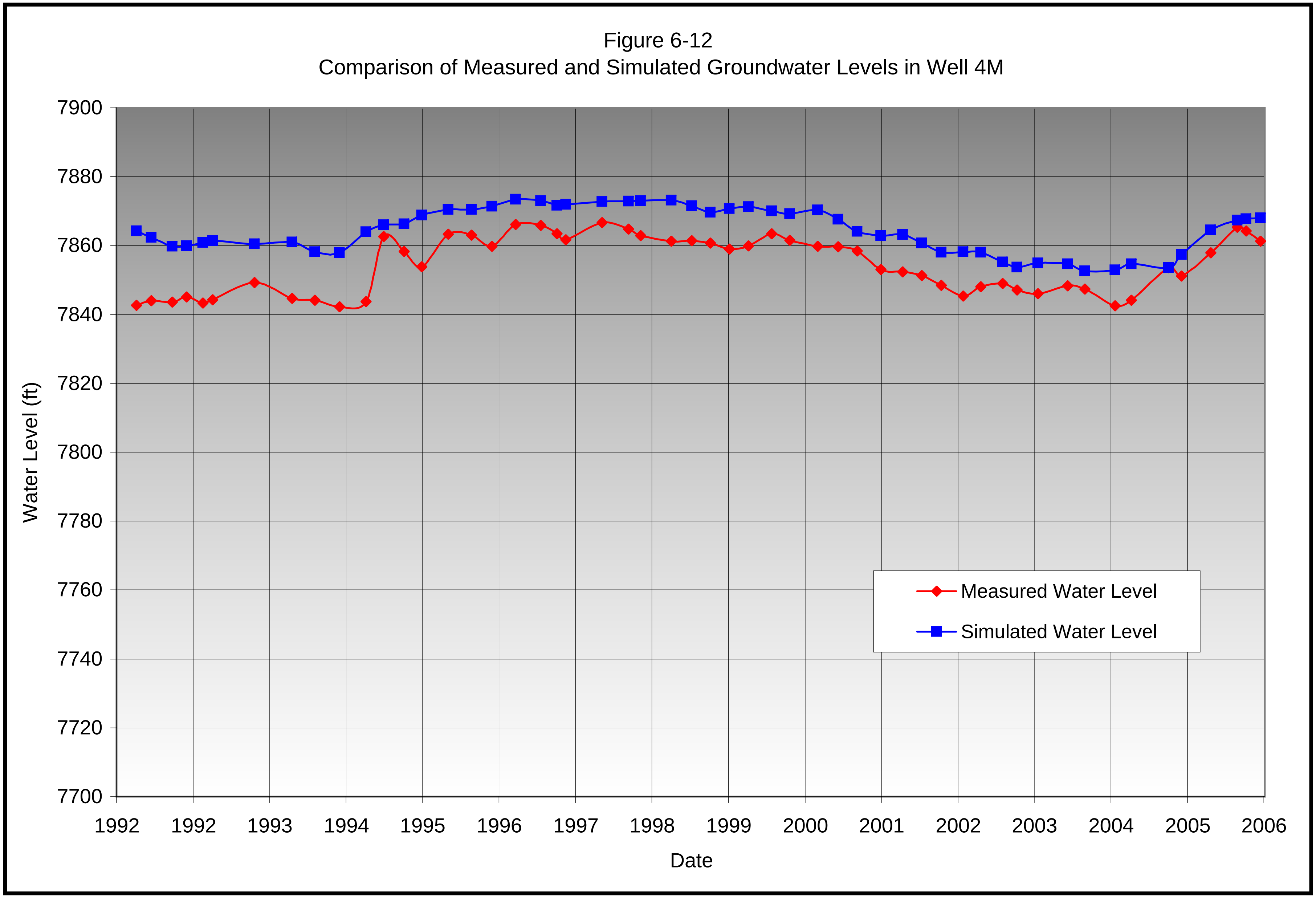

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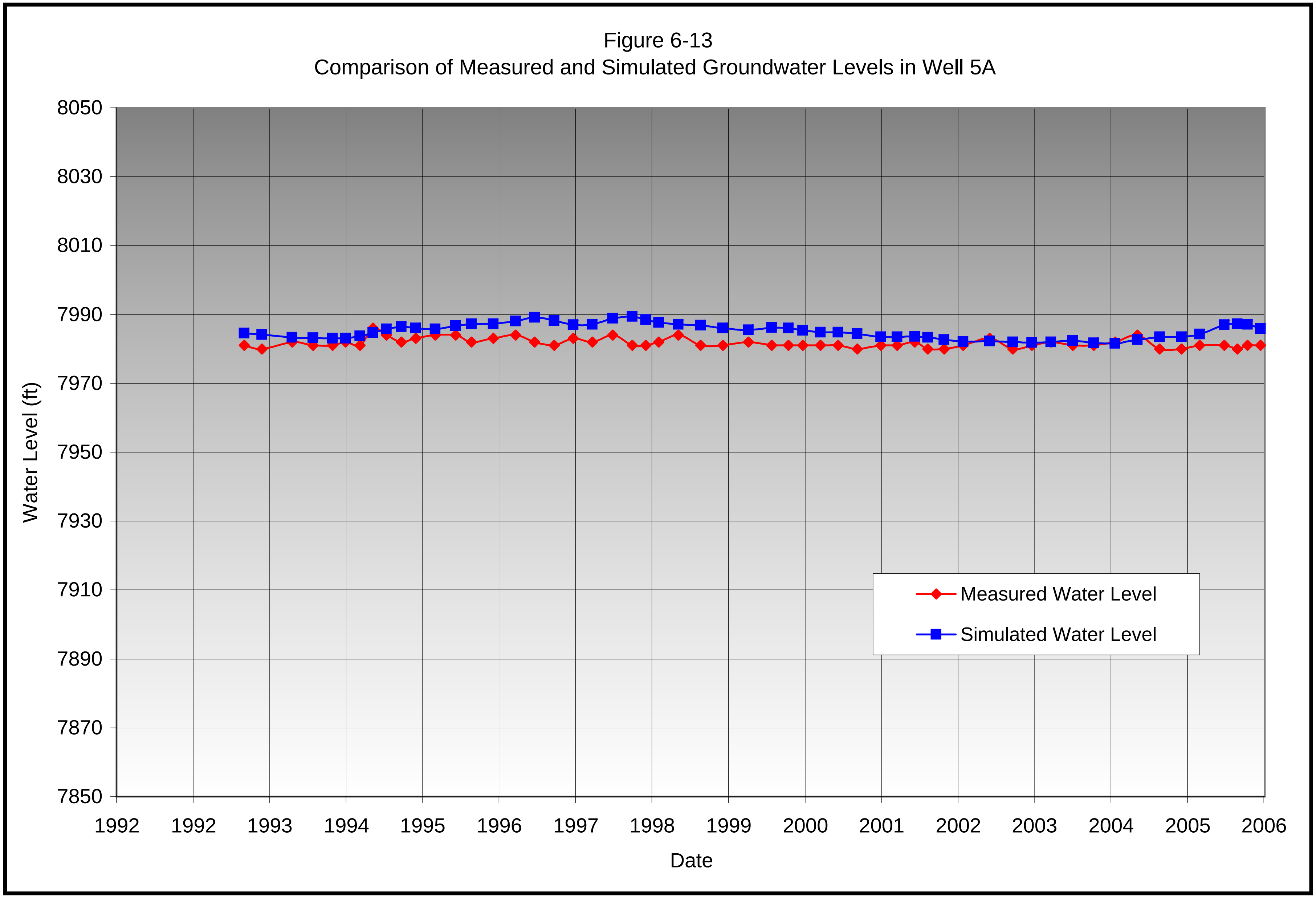

Figure 6-13
Comparison of Measured and Simulated Groundwater Levels in Well 5A
Water Level (ft)
8050
8030
8010
7990
7970
7950
7930
7910
7890
7870
7850
1992
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Date
Measured Water Level
Simulated Water Level

Figure 6-14
Comparison of Measured and Simulated Groundwater Levels in Well 11M

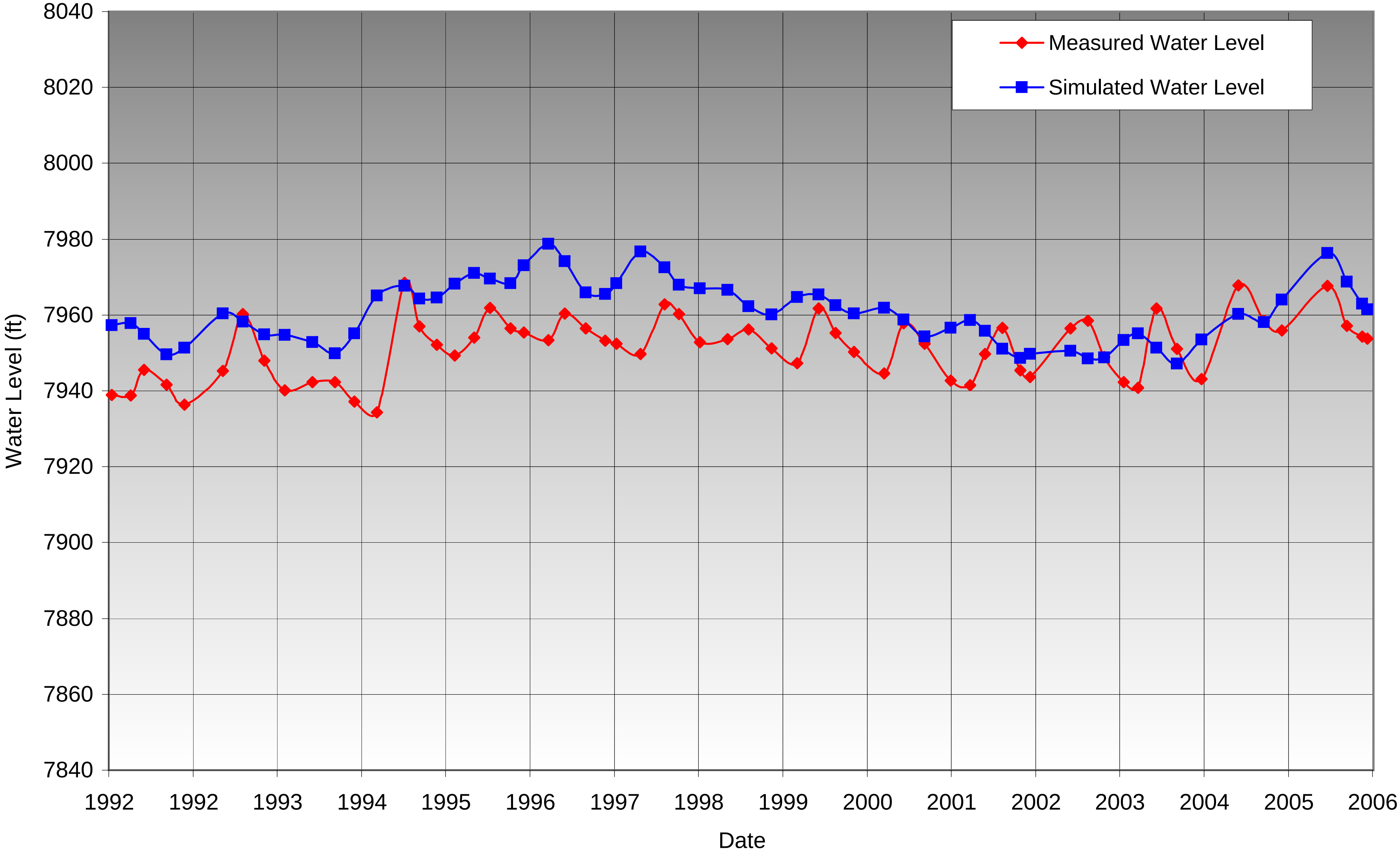

Figure 6-15
Comparison of Measured and Simulated Groundwater Levels in Well 23

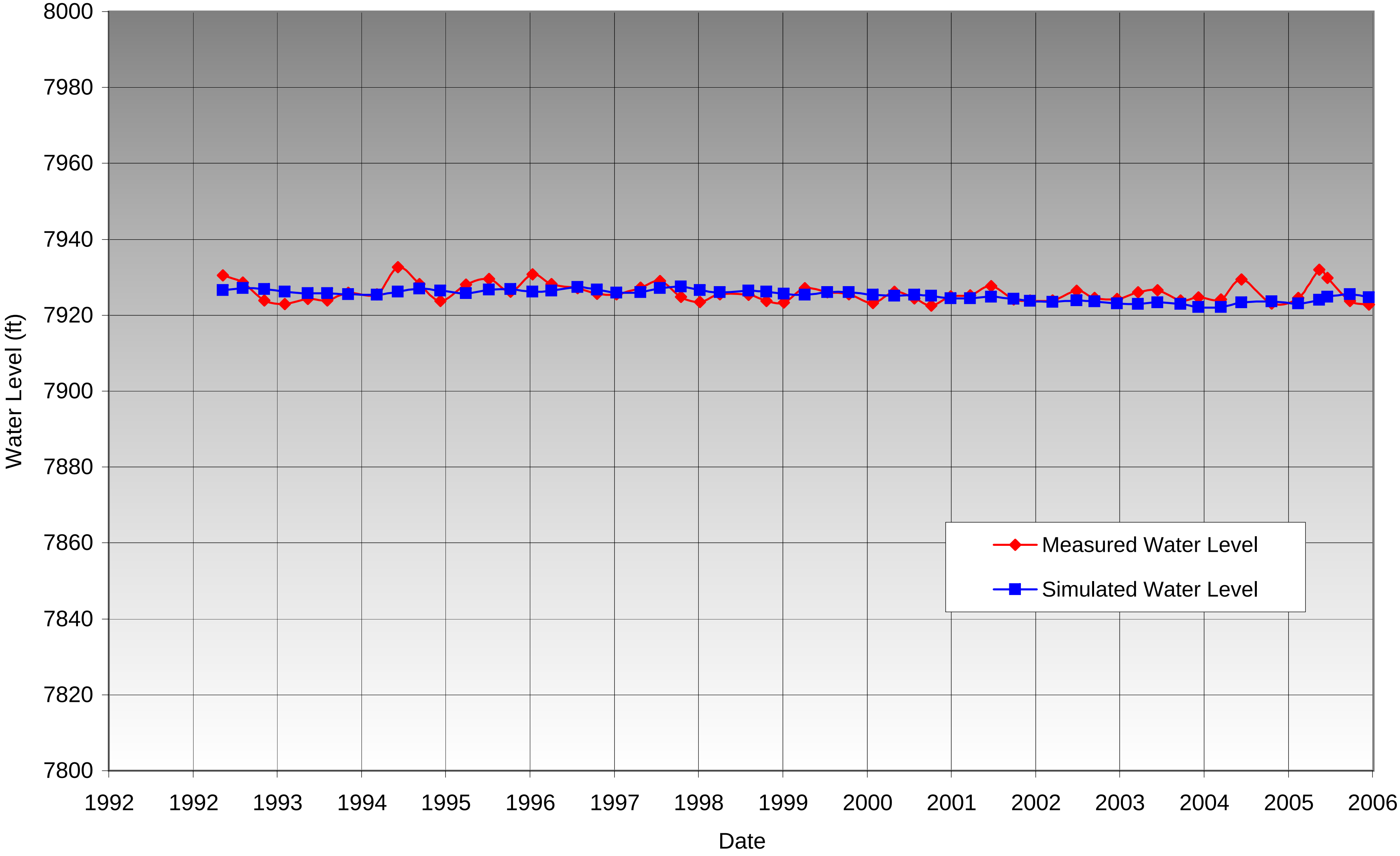

Figure 6-16
Comparison of Measured and Simulated Groundwater Levels in Well SC-1

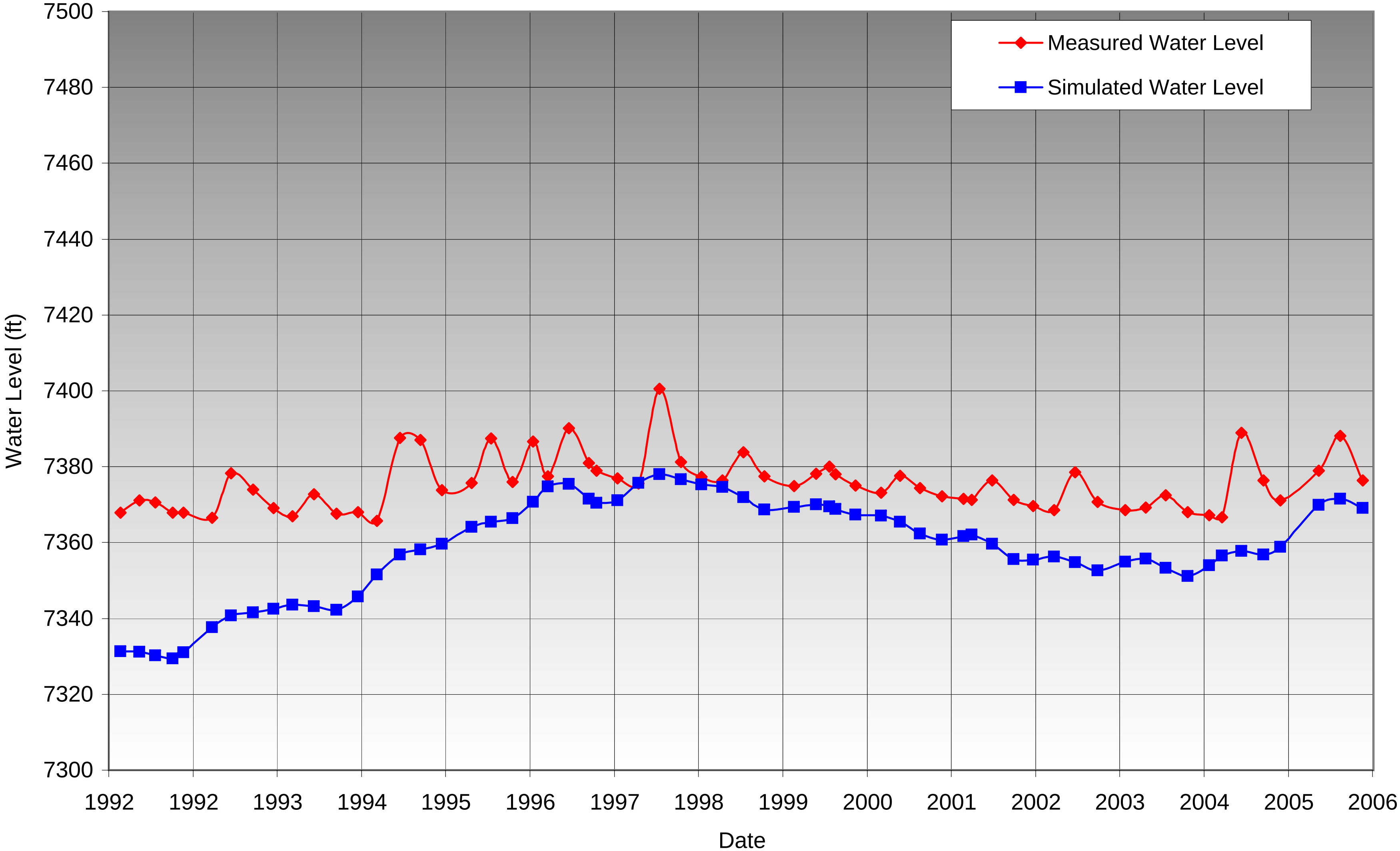

Figure6-3 through 6-16.xls -- SC-1_14
9/10/2009 -- 10:25 AM

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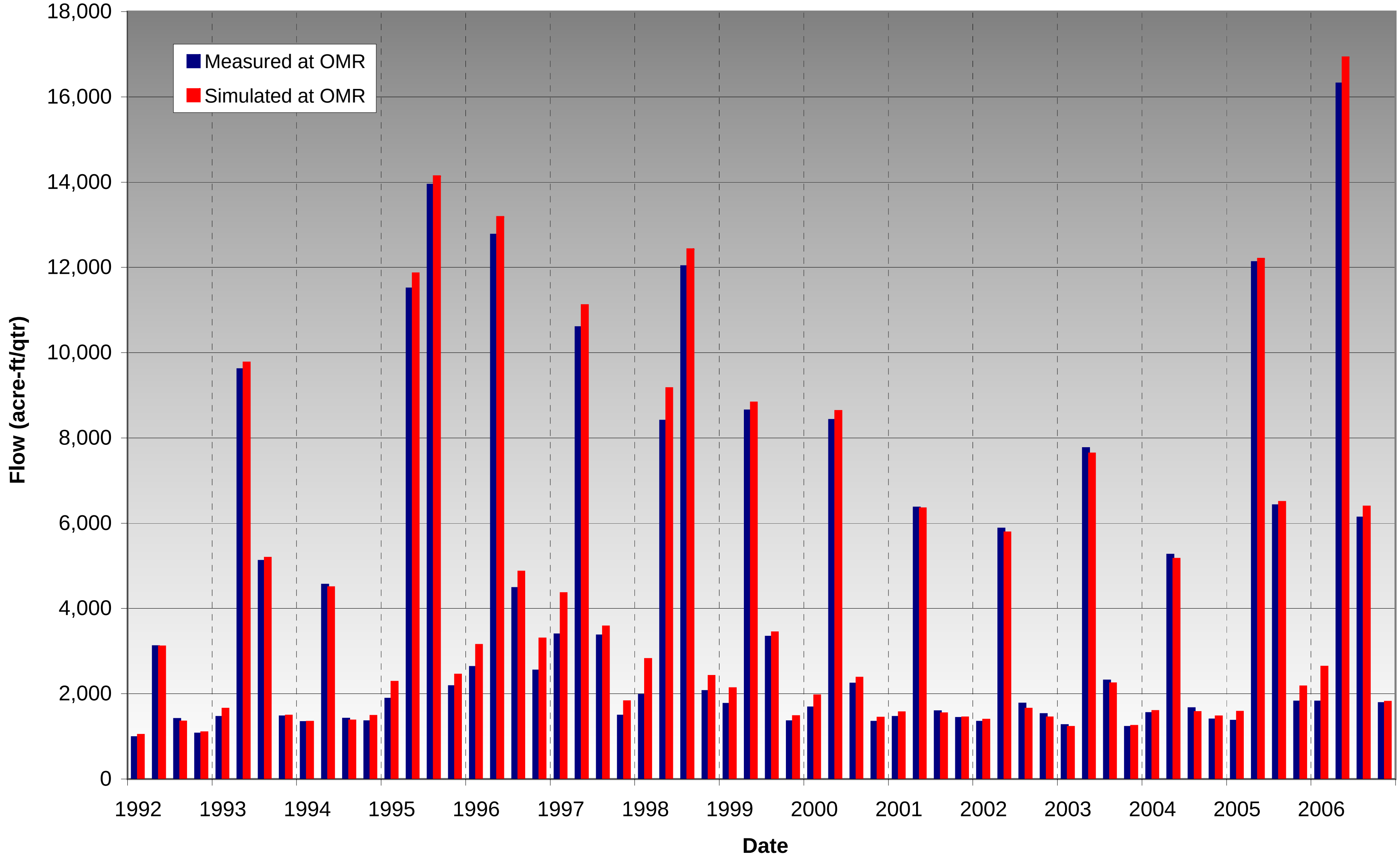
Figure 6-17
Comparison of Measured and Simulated Stream Flow at Old Mammoth Road



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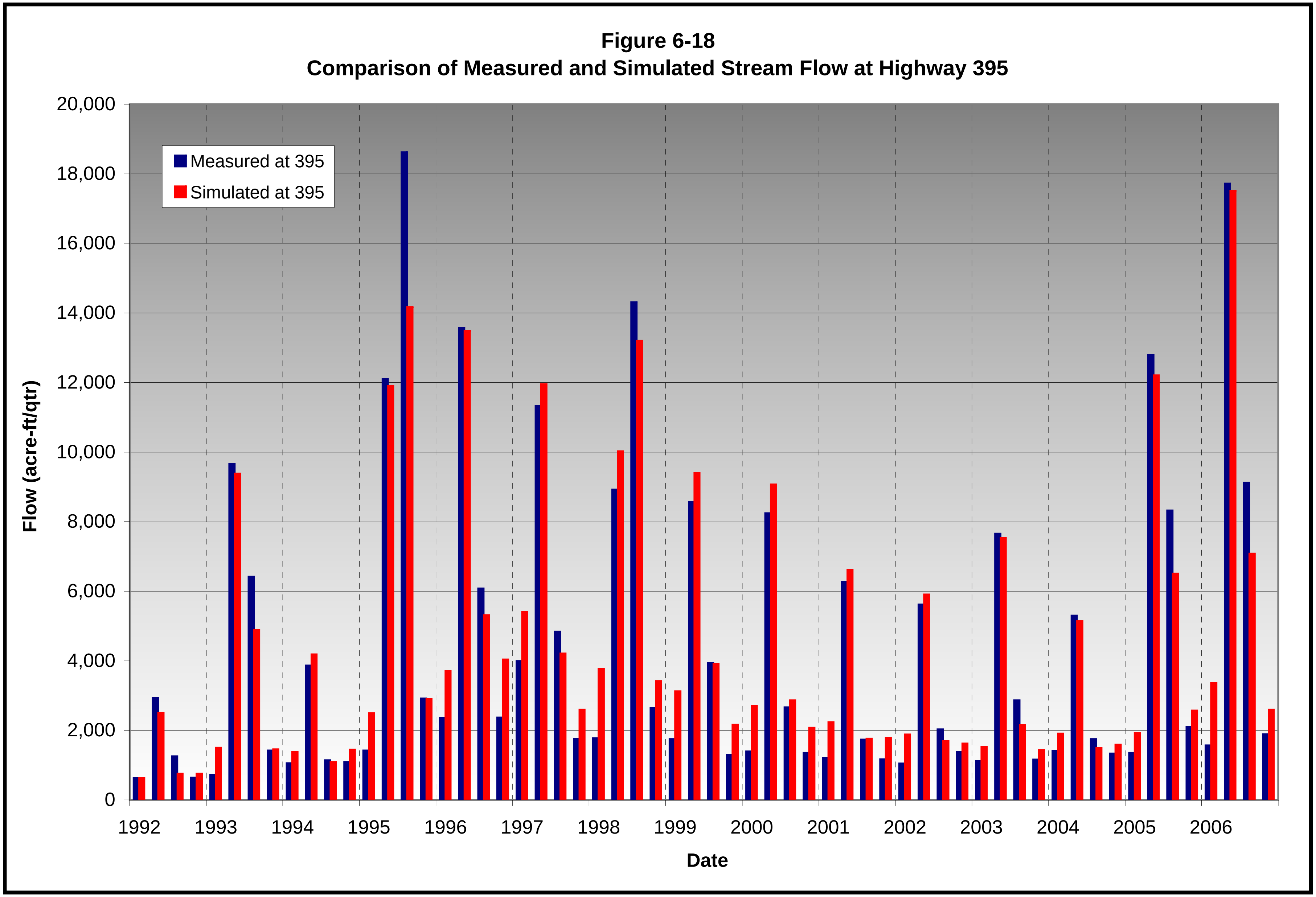

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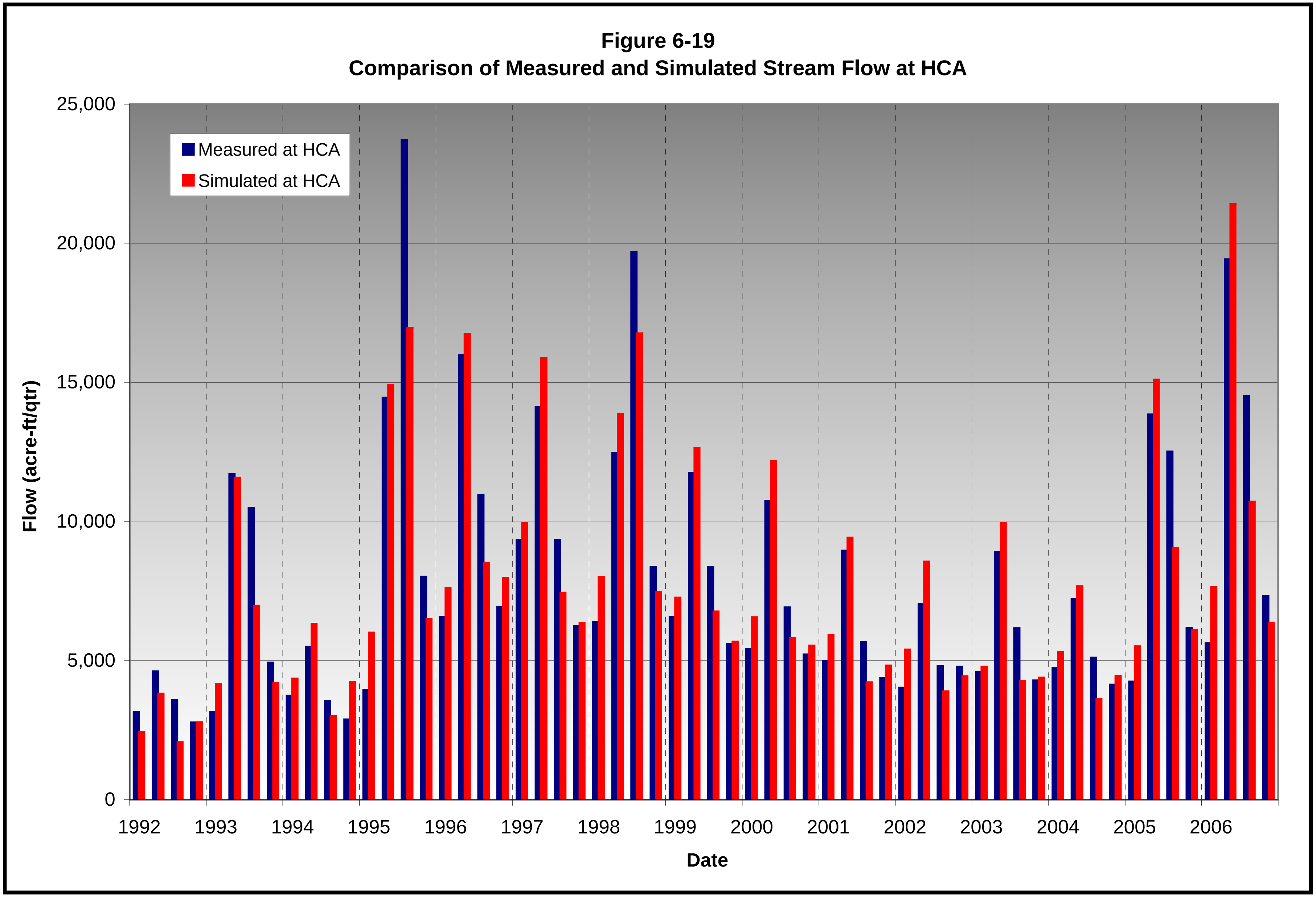

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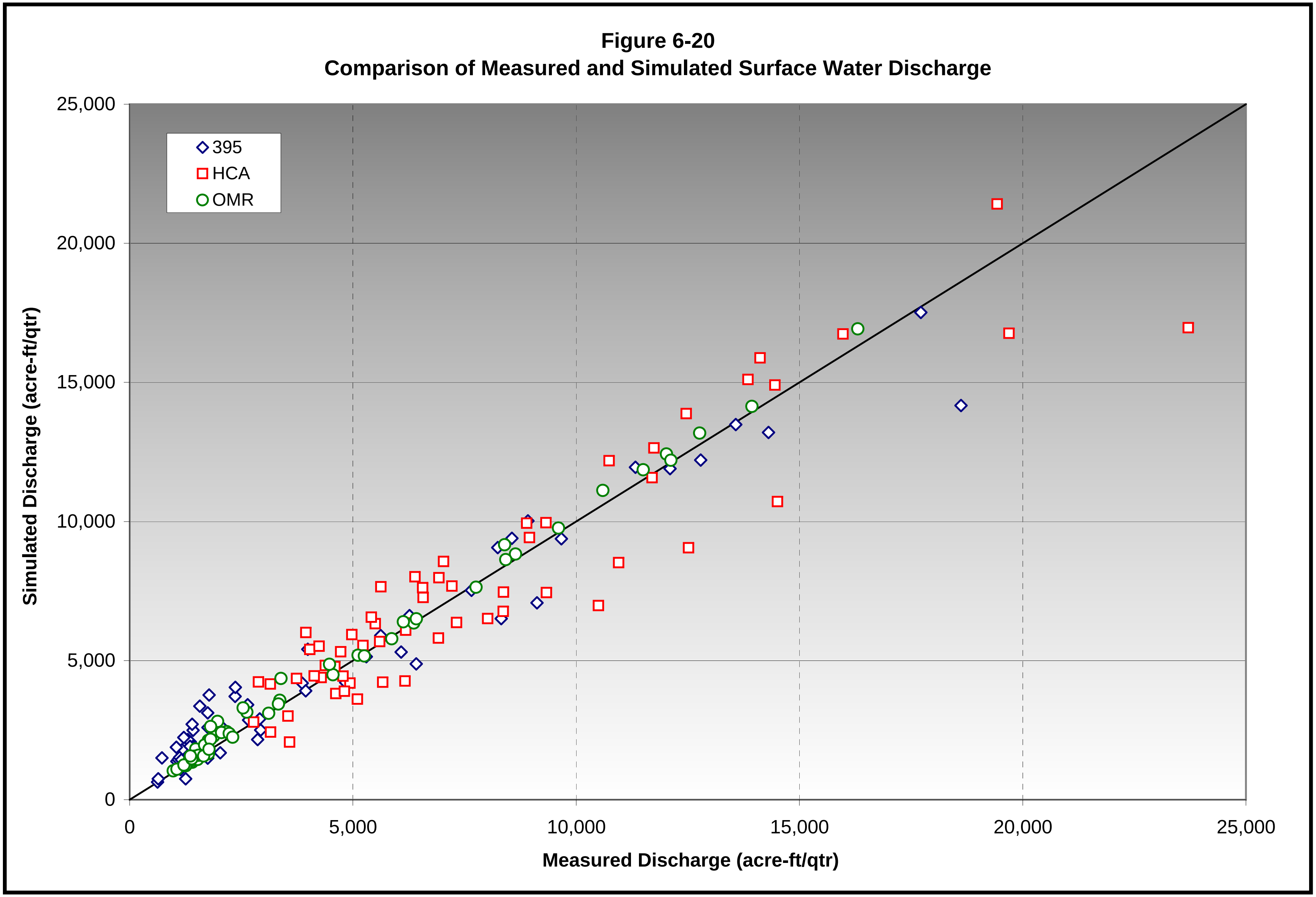

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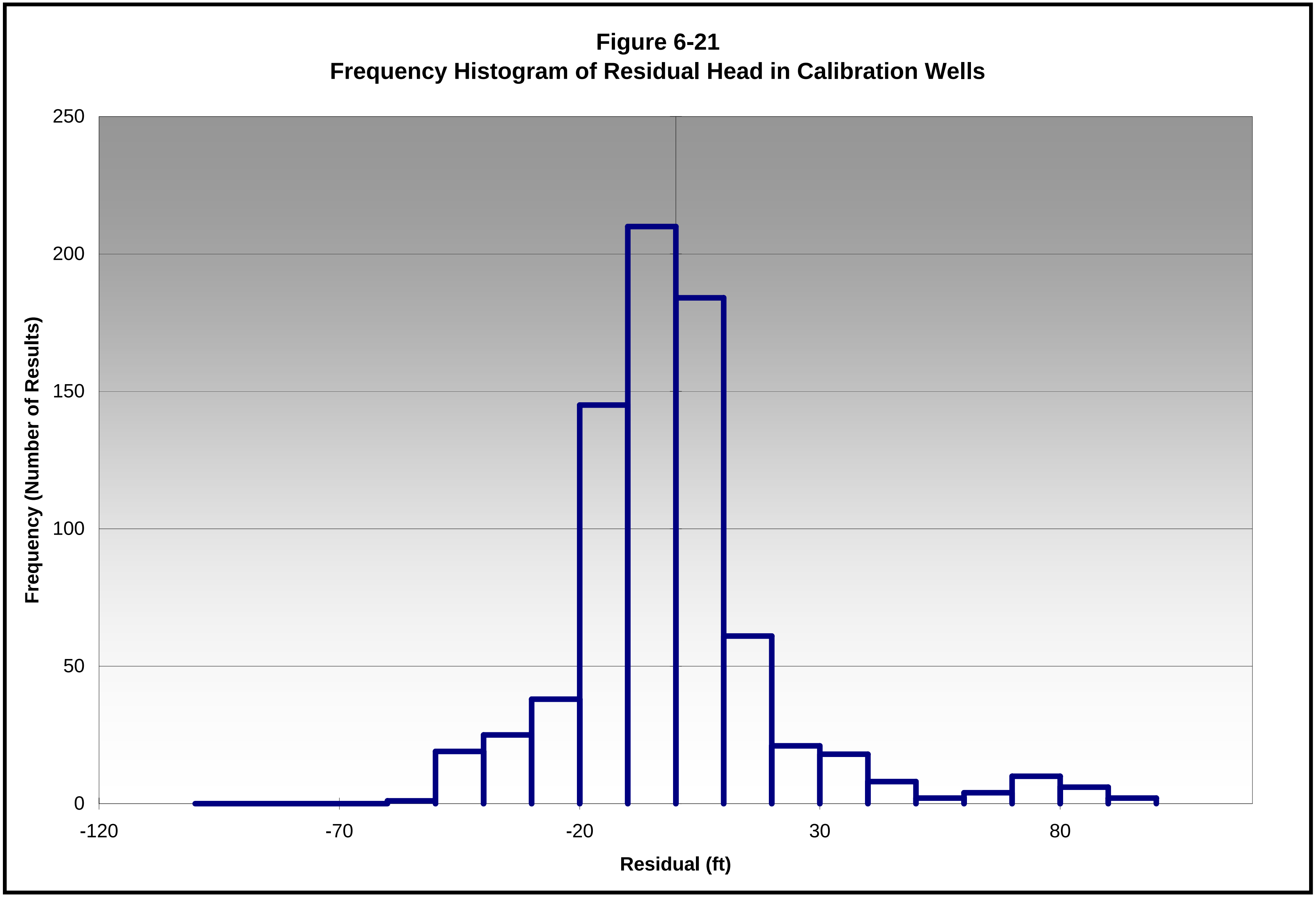

Figure6-21 and 6-22.xls

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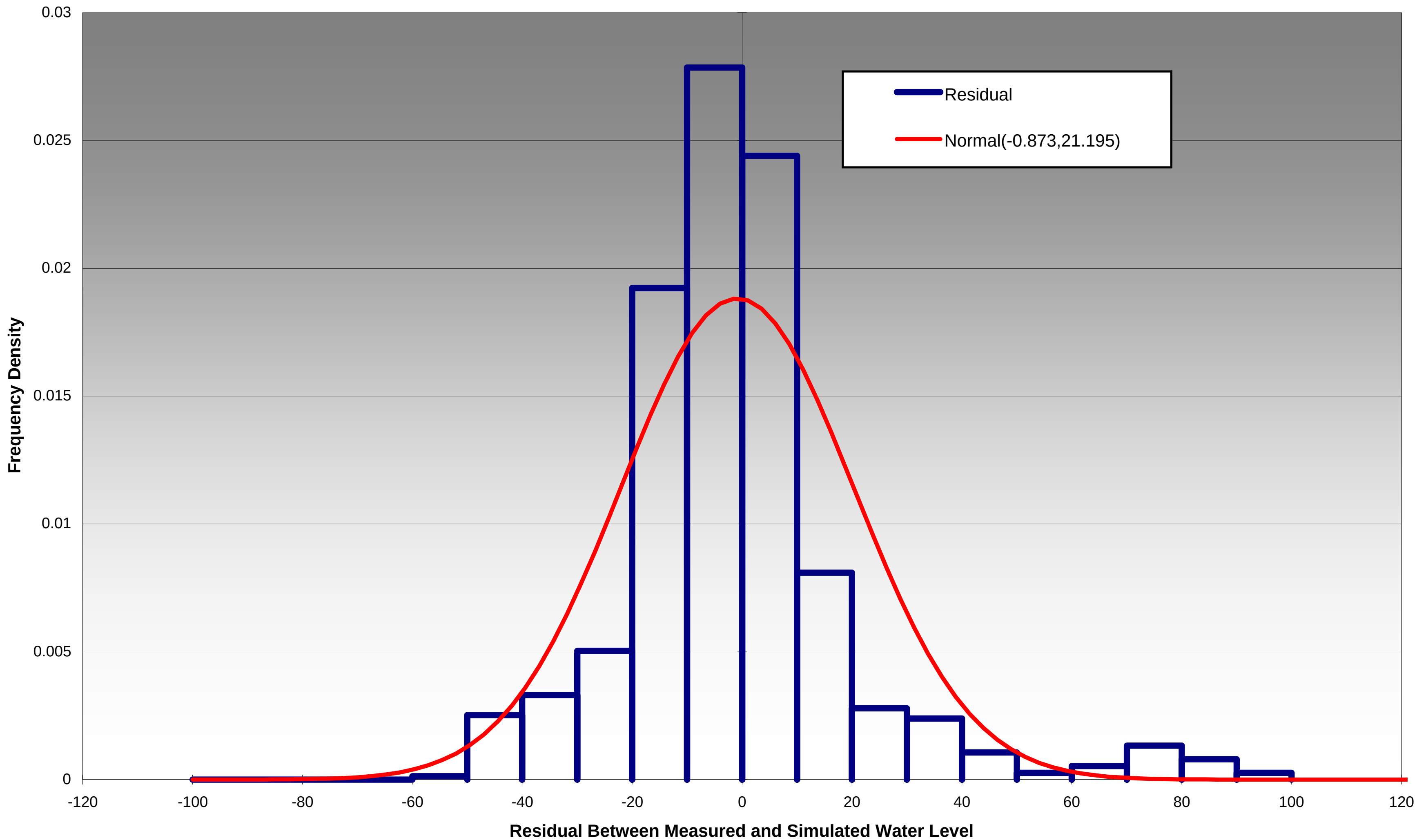
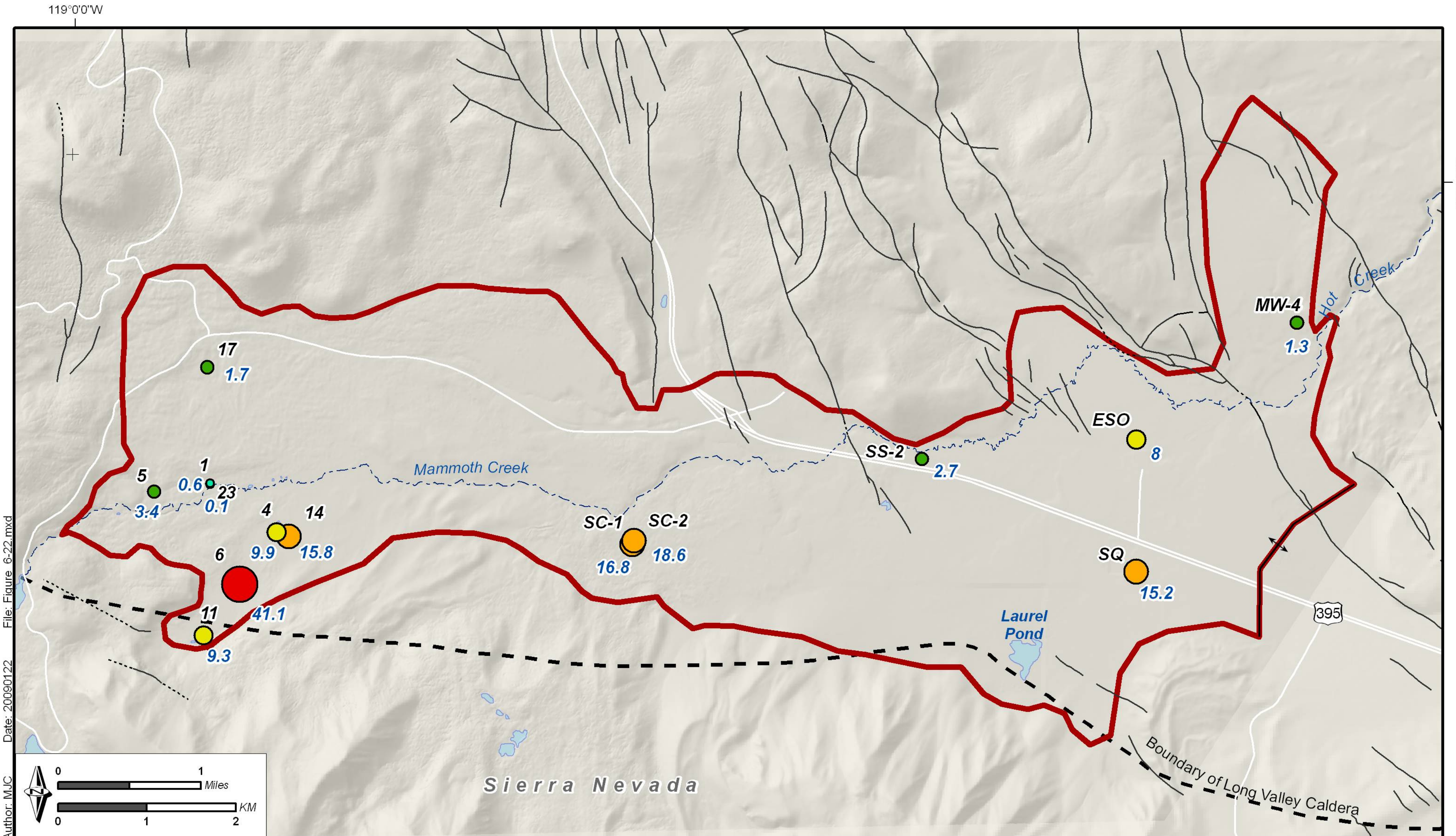
Figure 6-22
Frequency Density of Residual Distribution



Residual



File: Figure 6-22.mxd
Date: 20090122
Author: MJC

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4
9.9
(Residual = ave. difference between observed and modeled water level)

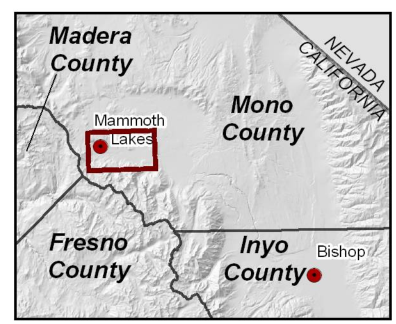
Mean Residual for Calibration Wells

0.0 - 1.0
1.01 - 5.0
5.01 - 10.0
10.01 - 20.0
20.01 - 30.0
30.01 - 41.0

MODFLOW Groundwater Flow Model Boundary

Faults

Location Certain
Location Approximate
Location Uncertain
Location Concealed



Mean Residuals for Calibration Wells

Figure 6-23

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Mammoth Basin Groundwater Model Report

This section describes the scenarios that were simulated with the calibrated model and provides the simulation results.

7.1 Current and Build-out Conditional Pumping and Diversion

Two conditional pumping and diversion simulations were conducted to determine the impacts of operating at a yield that supports groundwater and surface water demands at build-out. The first scenario mimics estimated diversions and pumping for a 50-year period. The second scenario assumes estimated diversions and planned build-out groundwater pumping over a 50-year period.

Groundwater pumping and surface water diversions are based the runoff year type. Runoff year types are defined as dry, normal, or wet, based on April 1st snowpack water content data from the Mammoth Pass precipitation station, as measured by the Los Angeles Department of Water and Power and reported by the DWR California Data Exchange Center (CDEC). The runoff year type definitions were based on a 20-80 exceedance frequency demarcation to be consistent with California Department of Fish and Game's (CDFG) recommendation and the State Water Resources Control Board's (SWRCB) Mono Basin Decision D-1631 (SWRI, 2008). The CDFG definitions (CDFG 170A, p. 1) for each runoff year type are listed below:

- Dry years are classified as years where runoff is exceeded in 80 percent of all runoff years.
- Wet years are classified as years where runoff is exceeded in only 20 percent of all runoff years.
- Normal years are years that fall within the 20 to 80 percent range.

Figure 7-1 shows the probability of exceedance for Mammoth Pass precipitation. Based on the 50-year hydrologic record from 1955 through 2005, a dry year is a year with 25.7 inches of precipitation or less (snow water content), a wet year is a year with 60.2 inches of precipitation or more, and a normal year is any year that has between 25.7 inches and 60.2 inches of precipitation. Table 7-1 summarizes each year from 1956 to 2005, including precipitation at Mammoth Pass, the percent of normal (annual precipitation divided by the 50-year average), the probability of exceedance, and the year type.

The first scenario (Current) quarterly groundwater pumping rates are conditional, based on runoff year type. The dry, normal, and wet runoff year total annual pumping amounts are based on the average pumping rates for each year type in the calibration period (1992 through 2006), as listed at the bottom of Table 7-2. Each calendar year in the calibration period was categorized by previous year runoff type per the 20-80 exceedance frequency demarcation discussed above. Table 7-2 lists each year, groundwater pumping, and previous year runoff type. Quarterly pumping rates were varied based on the historical quarterly percentage of total production. Conditional surface water diversions and groundwater pumping are listed in Table 7-3. Surface water diversions were assumed to be maximized under both scenarios and are therefore the same.

The second scenario (Build-out) quarterly groundwater pumping rates are also conditional, based on runoff year type. Similar to the Current scenario, the Build-out scenario used conditional dry, normal, and wet runoff year pumping rates, but these were based on planning-level estimates provided by MCWD staff (G. Sisson, personal communication, August 5, 2008). Table 7-3 summarizes groundwater pumping and Mammoth Creek diversions for this scenario. Quarterly pumping rates were varied based on the historical quarterly percentage of total production. The surface water diversion and groundwater pumping amounts listed in Table 7-3 assume a total build-out total water demand of 4,600 acre-ft/yr. This is an updated total water demand for 2025; it was previously listed as 4,898 acre-ft/yr in the 2005 MCWD Urban Water Management Plan (UWMP) (MCWD, 2005). This updated total demand reflects the use of recycled water at the Sierra Star Golf Course. The surface water diversion for a normal year is the same as the value listed in the 2005 UWMP. The dry year diversion was increased from 1,677 acre-ft in the 2005 UWMP to 1,780 acre-ft—an increase of six percent. There is no prior published wet year diversion. Projected Build-out groundwater production was determined by subtracting the assumed available surface water from the total water demand (MCWD, 2008).

7.2 Planning Period Hydrology

All scenarios were conducted over a 50-year time period. The assumptions and calculations made in estimating this 50-year planning period hydrology are discussed below.

7.2.1 Recharge

For the 2007 to 2056 period, the future areal recharge from precipitation was estimated based on daily measured precipitation in the Mammoth Basin from 1957 to 2006. Total quarterly precipitation and its distribution within the Mammoth Basin was estimated using the same three step-wise linear regression functions that were used in the calibration period, described in Section 3. The established precipitation-elevation relation was used to generate a 10-meter by 10-meter precipitation grid over the watershed. The generated precipitation for the Mammoth Basin was then used to calculate areal recharge and boundary inflows.

The uniform contribution coefficient obtained from the calibration period was used to obtain total quarterly subsurface inflows from each sub-watershed that contributes to the Mammoth Groundwater Basin. The same delay time used in the calibration period was assumed for each of the sub-watersheds.

A statistical hydrology model was developed to simulate quarterly aggregate stream flow at the outlet of Twin Lakes. This model is similar to the Muskingum method that is applied in hydrologic river routing. There is a seasonal pattern due to the dominant hydrologic processes of the Mammoth Basin, namely rain-induced and snow-melt-based stream flow. The modeled stream flow ($Q^i(t+1)$) at the time $t+1$ at the Twin Lakes outlet is related to current and last season precipitation conditions ($P^i(t+1)$ and $P^i(t)$) and to the known stream flow of the last season. This model is mathematically represented as follows:

$$Q^i(t+1) = \alpha_1^i Q(t) + \alpha_2^i P(t) + \alpha_3^i P(t+1) \qquad i = 1:4$$

Where $Q(t+1)$ and $Q(t)$ are modeled stream flow at time $t+1$ and t, respectively; $P(t+1)$ and

$P(t)$ are precipitation estimates at time t+1 and t, respectively; and α_j^i (j=1,2,3) are model coefficient parameters for each quarter where i denotes the quarter of interest. The best-estimated model coefficient parameters were determined by minimizing the objective function.

7.2.2 Discharge

Stream outflow from the Mammoth Basin was estimated using the calibrated groundwater flow model. For Mammoth Groundwater Basin ET, the same assumptions used in the calibration period were applied. Similar to surface water discharge, ET is dependent upon groundwater elevations. ET was estimated for each scenario.

7.3 Current and Build-out Conditional Pumping and Diversion Simulation Results

The Current and Build-out scenarios were evaluated with the model to determine if groundwater pumping at MCWD wells will be sustainable in the future.

Figures 7-2 through 7-10 show simulated groundwater levels for the Current and Build-out scenarios in all MCWD production wells. These plots also show the current top of the well screen or the top of the open-hole section of the well. Table 7-4 lists well construction information for each production well.

Some wells are projected to operate below the published screen interval under the Current Scenario. These wells include Well 1, Well 10, Well 16, Well 17, Well 18, and Well 20. No wells are projected to operate below the top of the screen interval in the Build-out scenario that would not otherwise under the Current scenario. In addition to well construction data, Table 7-4 lists the lowest water level associated with the Build-out scenario and the additional drawdown (difference between Current and Build-out) associated with Build-out conditions. The greatest effects from increased pumping are observed at Wells 15 and 16: each has a lowest water level that is about 40 feet greater under the Build-out scenario, compared to the Current scenario. The smallest impact is observed at Well 6; the greatest drawdown difference between the two scenarios at Well 6 is 6 feet.

Can the Mammoth Groundwater Basin support projected long-term MCWD groundwater pumping demands?

The model results suggest that groundwater pumping is sustainable for both scenarios.

Will changes in water levels require changes to existing wells and/or require new wells to sustain projected groundwater demand?

The MCWD may need to make mechanical and/or operational changes as a result of implementing the Current scenario and, to a greater extent, implementing the Build-out scenario. Mechanical changes may include the lowering of pumps, the deepening of wells, and/or the construction of new wells. Operational changes may include seasonal or rotational operation to manage drawdown and sustain pumping.

Table 7-1
Mammoth Pass Precipitation and Runoff Year Classification

Runoff Year	Mammoth Pass Precipitation -Snow Water Equivalent (in)	Percent of Normal	Exceedance	Year Type
1956	58.40	133%	25%	Normal
1957	34.20	78%	61%	Normal
1958	59.50	136%	22%	Normal
1959	30.80	70%	69%	Normal
1960	24.30	55%	88%	Dry
1961	25.60	58%	82%	Dry
1962	55.40	126%	29%	Normal
1963	31.40	72%	67%	Normal
1964	24.20	55%	90%	Dry
1965	48.00	109%	41%	Normal
1966	38.50	88%	49%	Normal
1967	58.50	133%	24%	Normal
1968	26.50	60%	78%	Normal
1969	86.50	197%	2%	Wet
1970	34.10	78%	65%	Normal
1971	42.00	96%	45%	Normal
1972	26.90	61%	76%	Normal
1973	60.20	137%	20%	Wet
1974	57.40	131%	27%	Normal
1975	48.50	111%	39%	Normal
1976	24.60	56%	86%	Dry
1977	12.30	28%	98%	Dry
1978	70.60	161%	10%	Wet
1979	37.30	85%	51%	Normal
1980	65.70	150%	14%	Wet
1981	36.10	82%	55%	Normal
1982	61.00	139%	18%	Wet
1983	83.70	191%	4%	Wet
1984	44.50	101%	43%	Normal
1985	49.40	113%	37%	Normal
1986	79.60	181%	6%	Wet
1987	22.80	52%	92%	Dry
1988	30.70	70%	71%	Normal
1989	35.40	81%	57%	Normal
1990	29.80	68%	73%	Normal
1991	27.70	63%	75%	Normal
1992	25.70	59%	80%	Dry
1993	55.30	126%	31%	Normal
1994	21.30	49%	94%	Dry
1995	68.10	155%	12%	Wet
1996	41.80	95%	47%	Normal
1997	54.50	124%	35%	Normal
1998	54.90	125%	33%	Normal
1999	34.10	78%	63%	Normal
2000	36.50	83%	53%	Normal
2001	25.40	58%	84%	Dry
2002	34.90	80%	59%	Normal
2003	75.19	171%	8%	Wet
2004	21.26	48%	96%	Dry
2005	62.99	144%	16%	Wet
Minimum	12.30	28%	2%	-
Maximum	86.50	197%	98%	-
Average	43.88	100%	50%	-

Table 7-2
Calibration Period Dry, Normal and Wet Year Pumping Summary

Calendar Year	Calendar Year Pumping (Acre-ft/yr)	Previous Runoff Year Type
1992	2,304	Normal
1993	1,707	Dry
1994	1,417	Normal
1995	1,166	Dry
1996	1,018	Wet
1997	987	Normal
1998	876	Normal
1999	1,061	Normal
2000	1,265	Normal
2001	2,333	Normal
2002	2,717	Dry
2003	2,518	Normal
2004	1,910	Wet
2005	2,177	Dry
2006	1,066	Wet
Average Dry	1,942	-
Average Normal	1,595	-
Average Wet	1,331	-

Table 7-3
Groundwater Pumping and Surface Water Diversion for Current and Build-out Simulations[1]

Supply Source	Normal Year	Wet Year	Dry Year
Current			
Surface Water Diversion	2,425	2,760	1,677
Groundwater Pumping	1,595	1,331	1,942
Total	4,020	4,091	3,619
Build-out			
Surface Water Diversion	2,425	2,760	1,677
Groundwater Pumping	2,175	1,840	2,923
Total	4,600	4,600	4,600

1. G. Sisson, personal communication, August 5, 2008.

Table 7-4
MCWD Production Well Construction Data and Build-out Pumping Effects

(feet)

Well	Drilled Depth[1]	Casing Depth[1]	Screen or Open Hole Interval[1]	Ground Surface Elevation[2]	Top of Screen of Open Hole Elevation[2]	Screen/Open Hole Bottom Elevation[2]	Build-out Lowest Water Level	Build-out Pumping Additional Drawdown
1	382	370	200-370	7,939	7,739	7,569	7,675	28
6	670	670	146-670	7,906	7,760	7,236	7,858	6
10	700	700	136-700	7,943	7,807	7,243	7,733	26
15	720	407	407-720	7,933	7,526	7,213	7,581	41
16	710	710	420-470 500-680	8,080	7,660	7,400	7,547	41
17	710	513	400-710	7,991	7,591	7,281	7,542	36
18	710	480	90-150 240-470	8,009	7,919	7,539	7,881	18
20	710	420	420-710	8,040	7,620	7,330	7,536	20
25	700	530	340-700	8,016.50	7,677	7,317	7,531	39

1. Schmidt (2008)

2. Elevation based on digital elevation model.

Figure 7-1
Percent Probability of Exceedance for Mammoth Pass Precipitation, 1955-2005

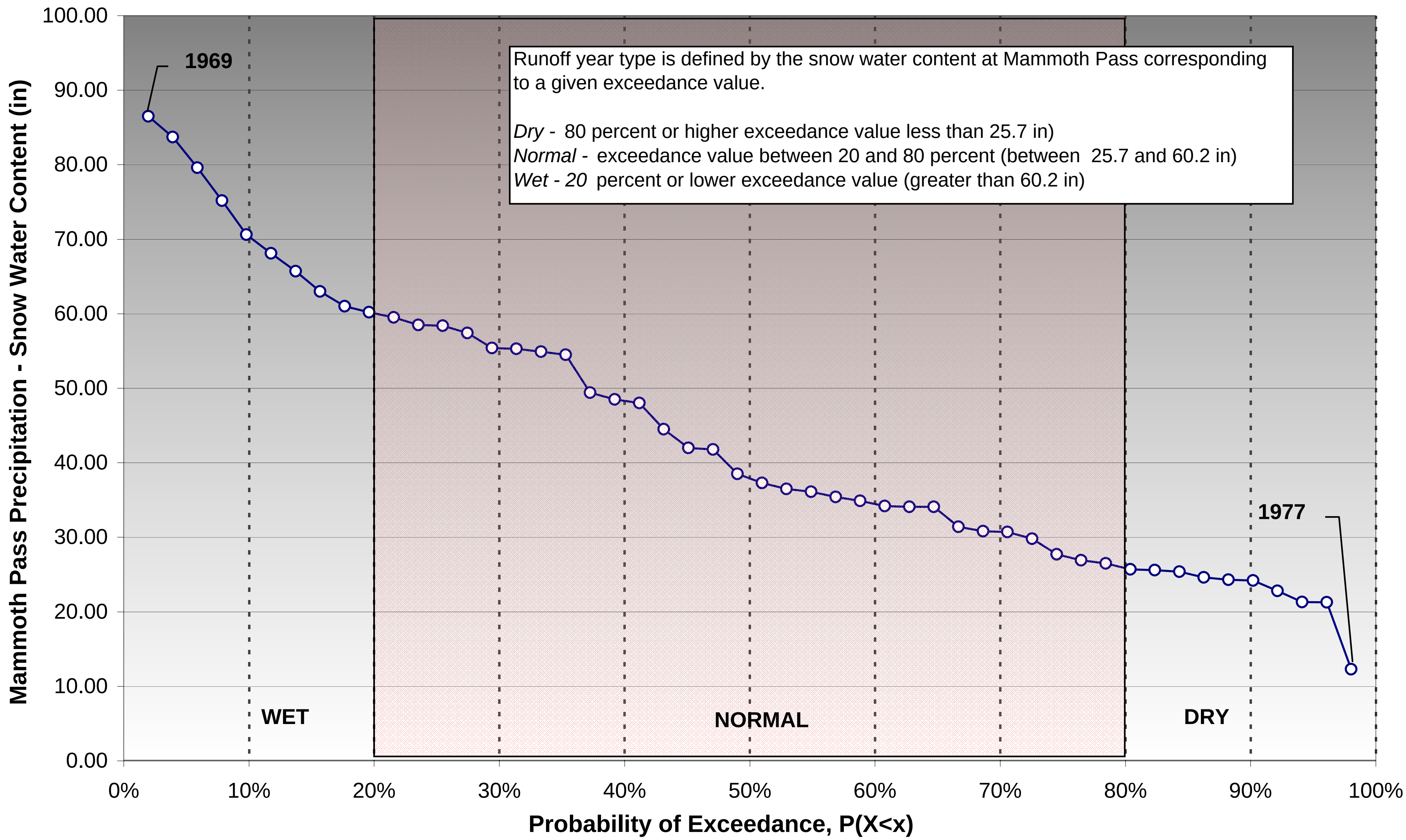
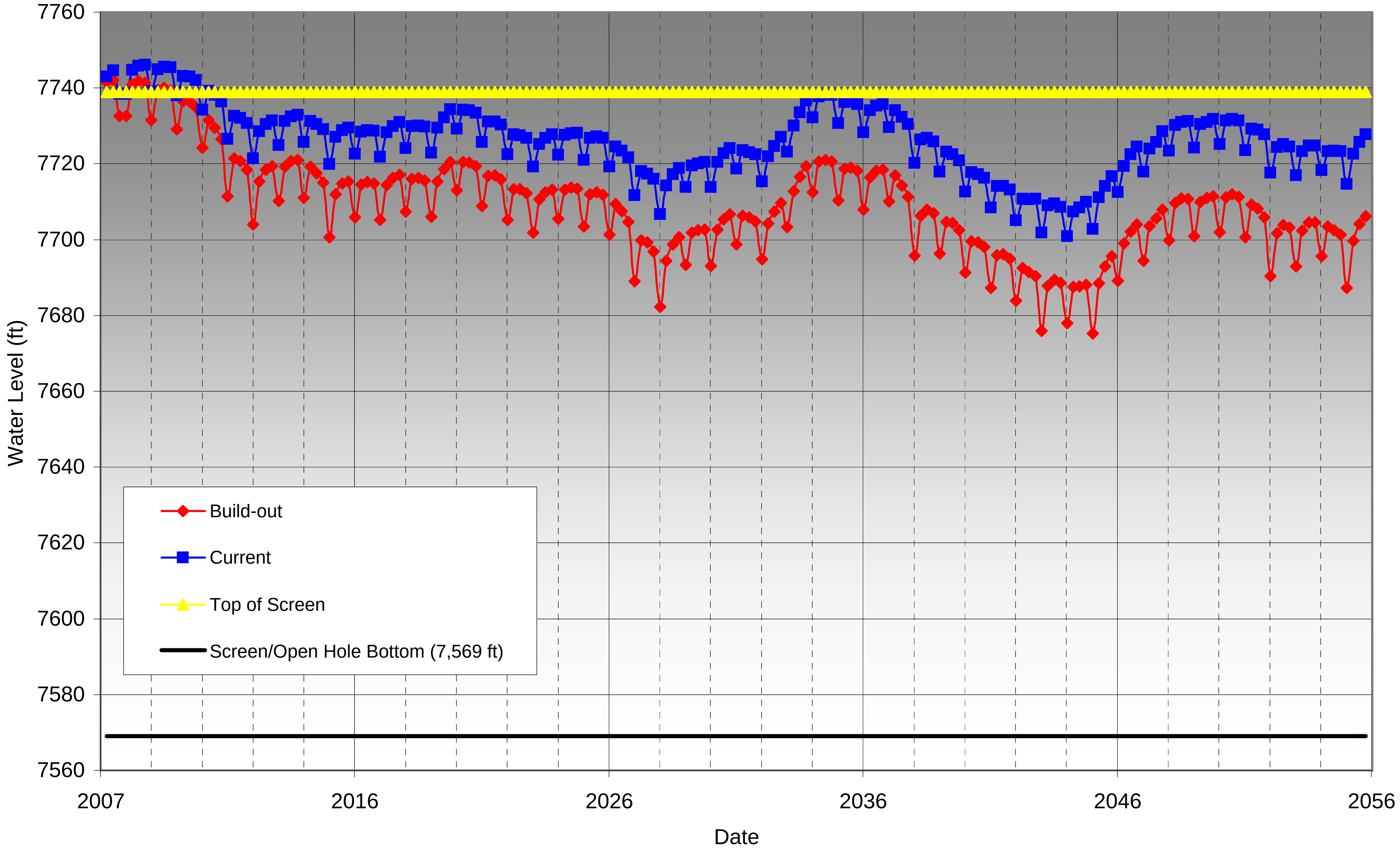


Figure 7-2
Comparison of Simulated Groundwater Water Levels for Well 1



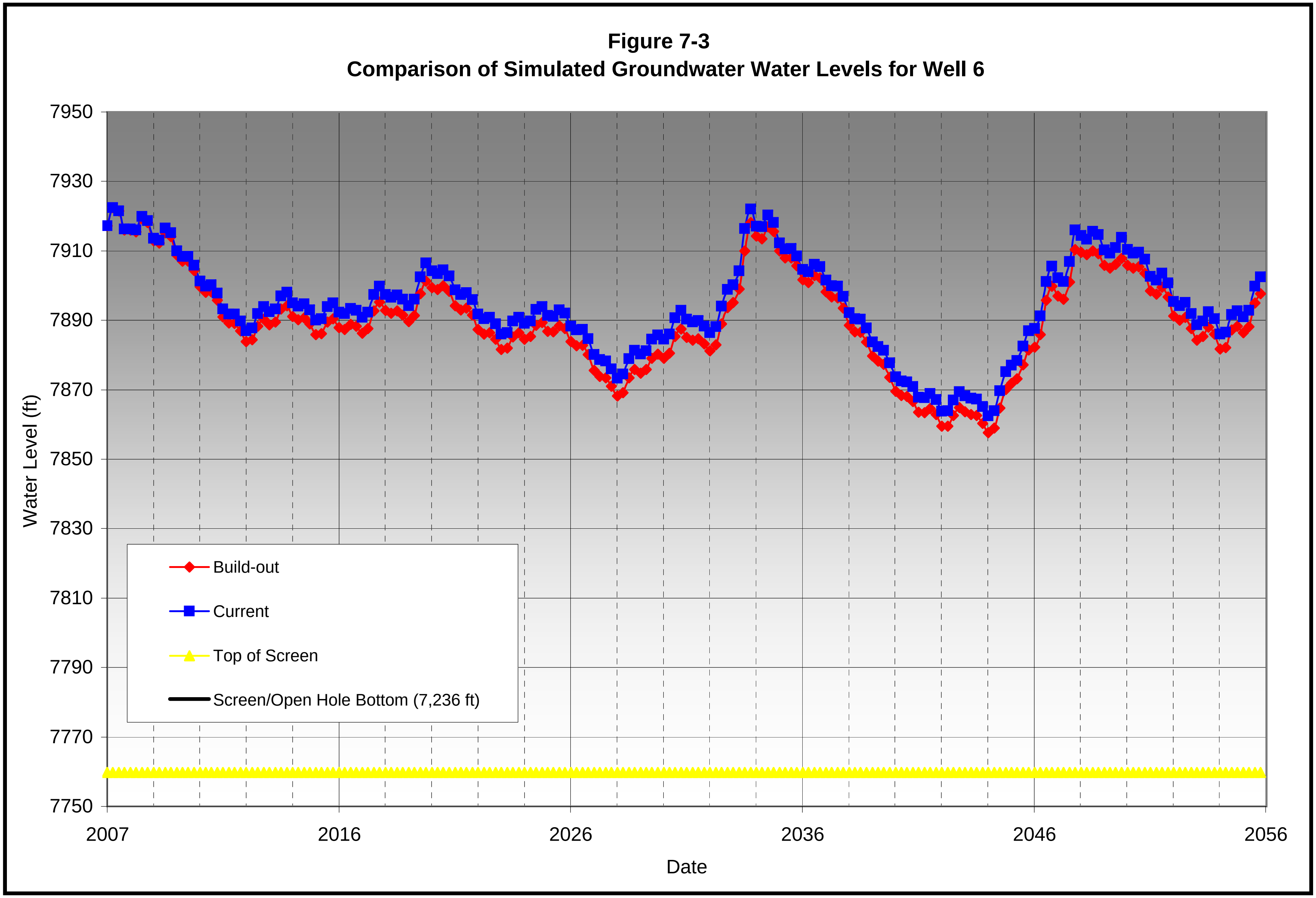


Figure7-2 through 7-10.xls

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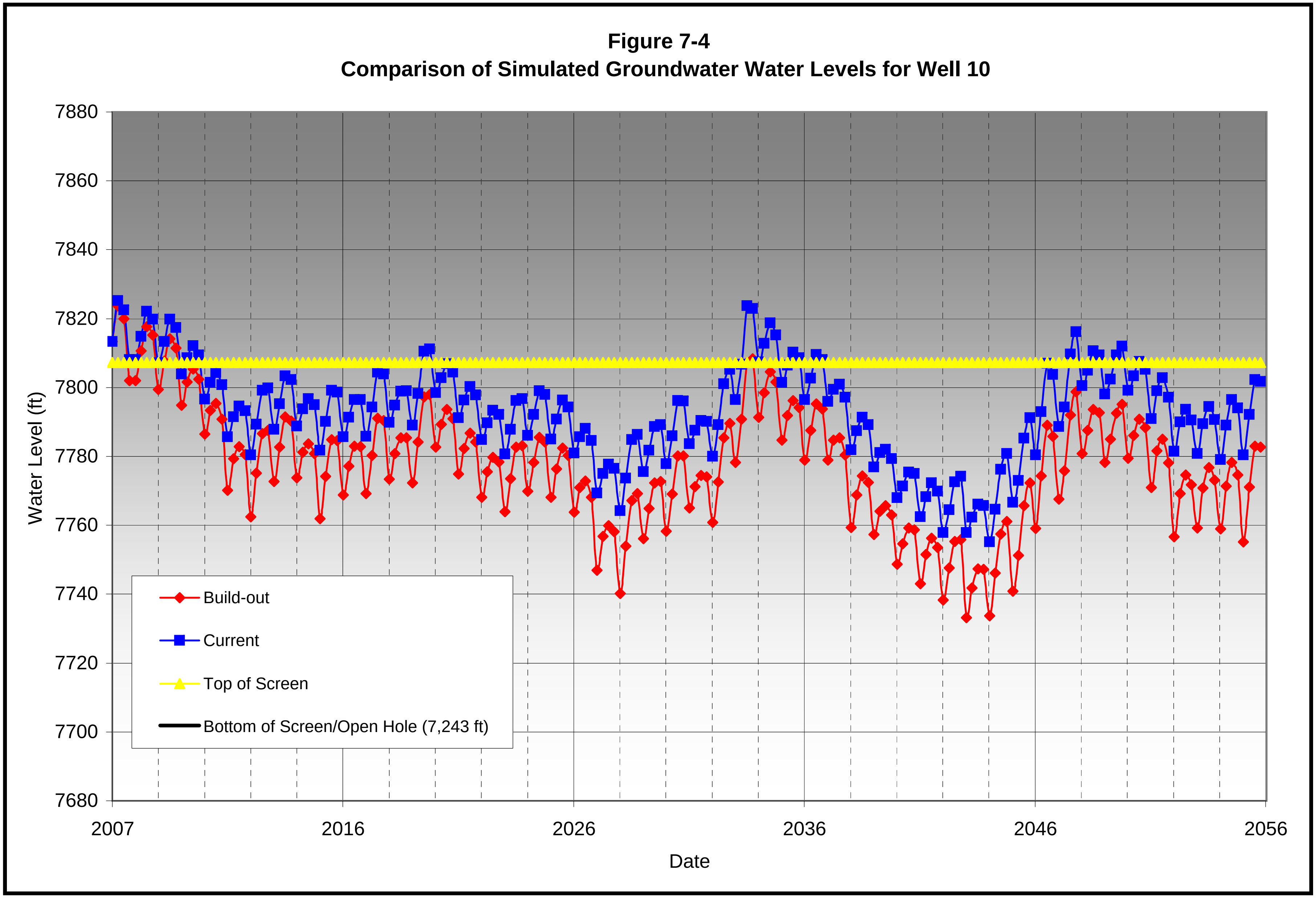

Figure7-2 through 7-10.xls

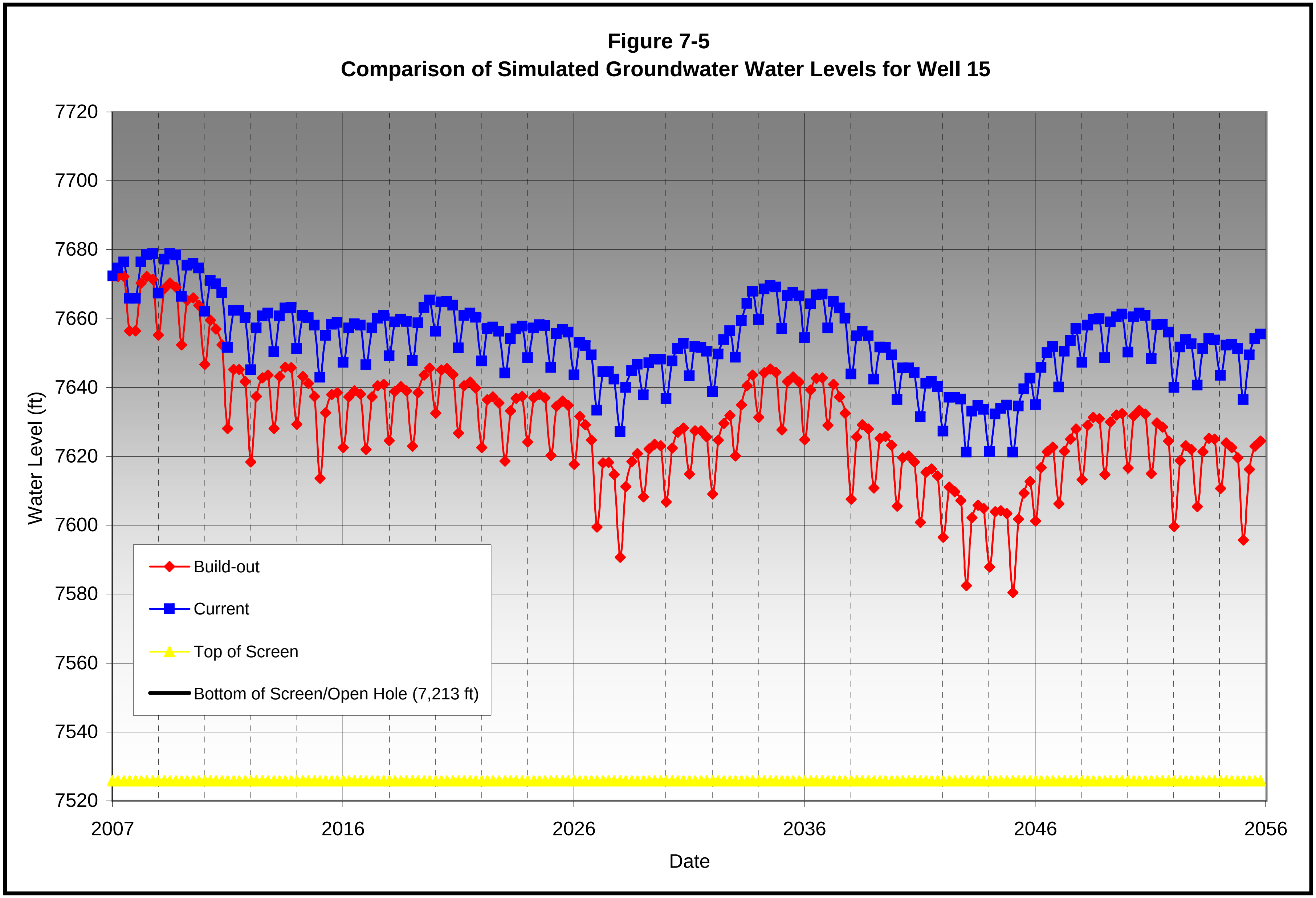

Figure7-2 through 7-10.xls

Figure 7-6
Comparison of Simulated Groundwater Water Levels for Well 16

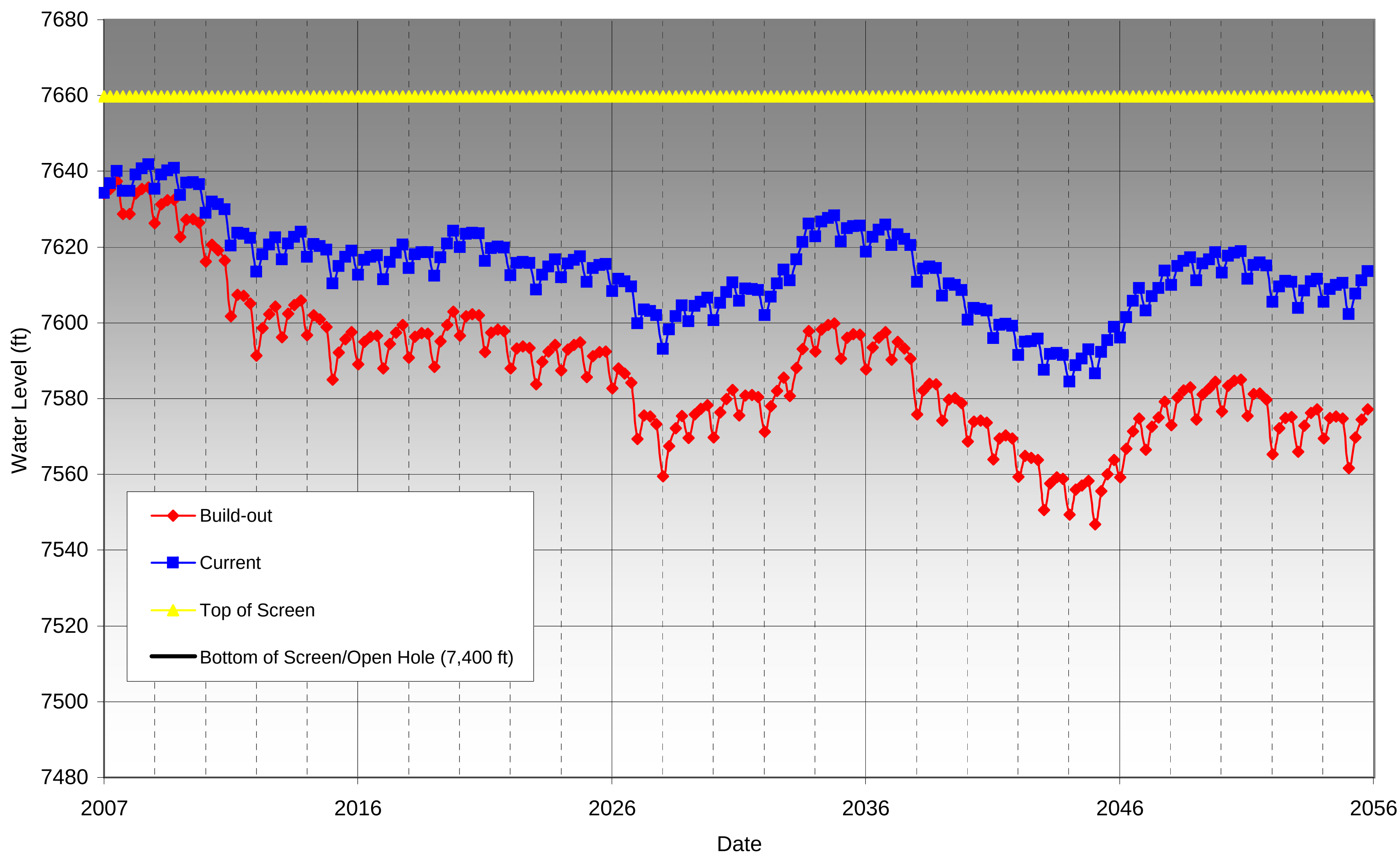

Figure7-2 through 7-10.xls

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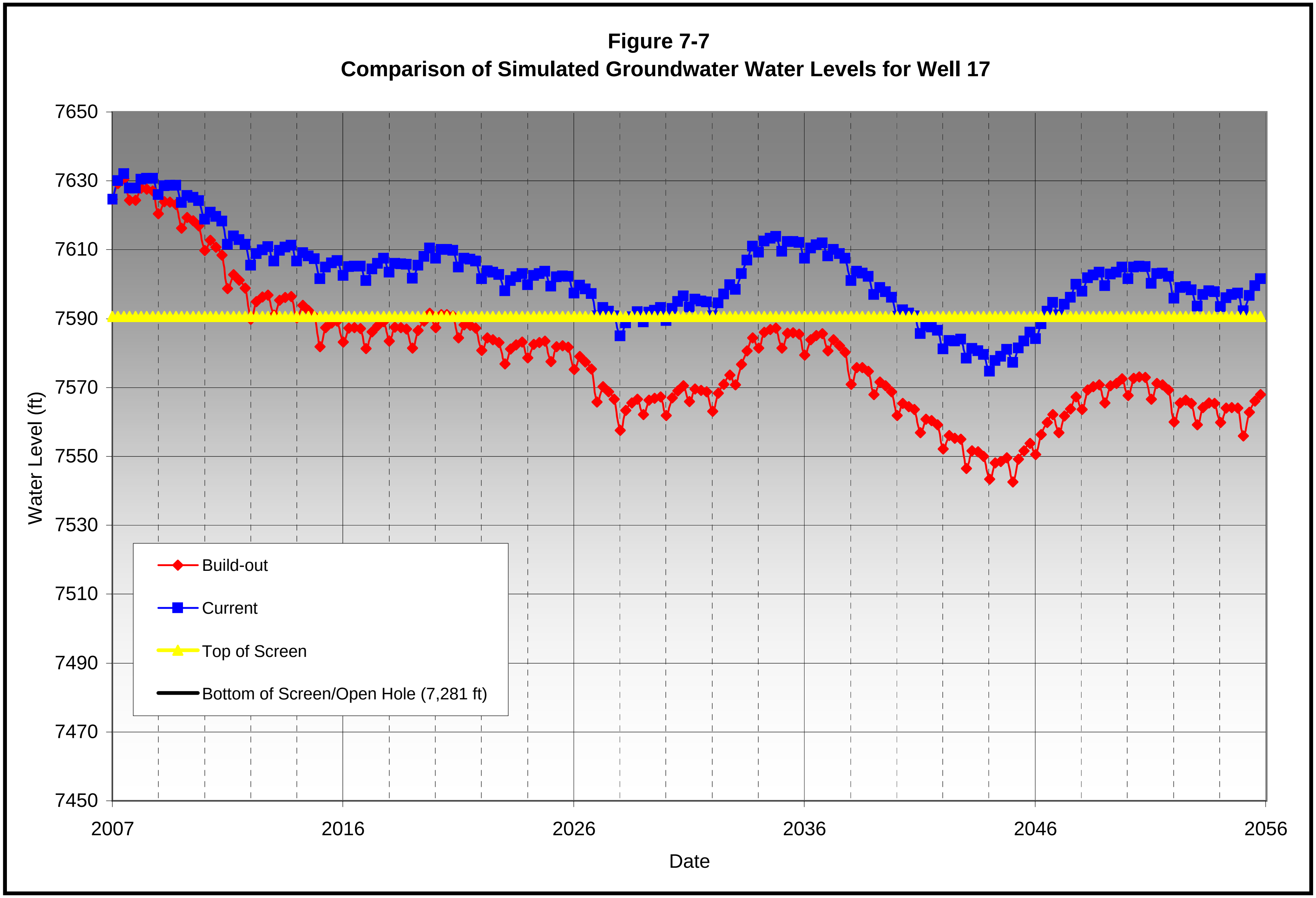

Figure 7-7
Comparison of Simulated Groundwater Water Levels for Well 17
7650
7630
7610
7590
7570
7550
7530
7510
7490
7470
7450
Water Level (ft)
2007
2016
2026
2036
2046
2056
Date
Build-out
Current
Top of Screen
Bottom of Screen/Open Hole (7,281 ft)

Figure 7-8
Comparison of Simulated Groundwater Water Levels for Well 18

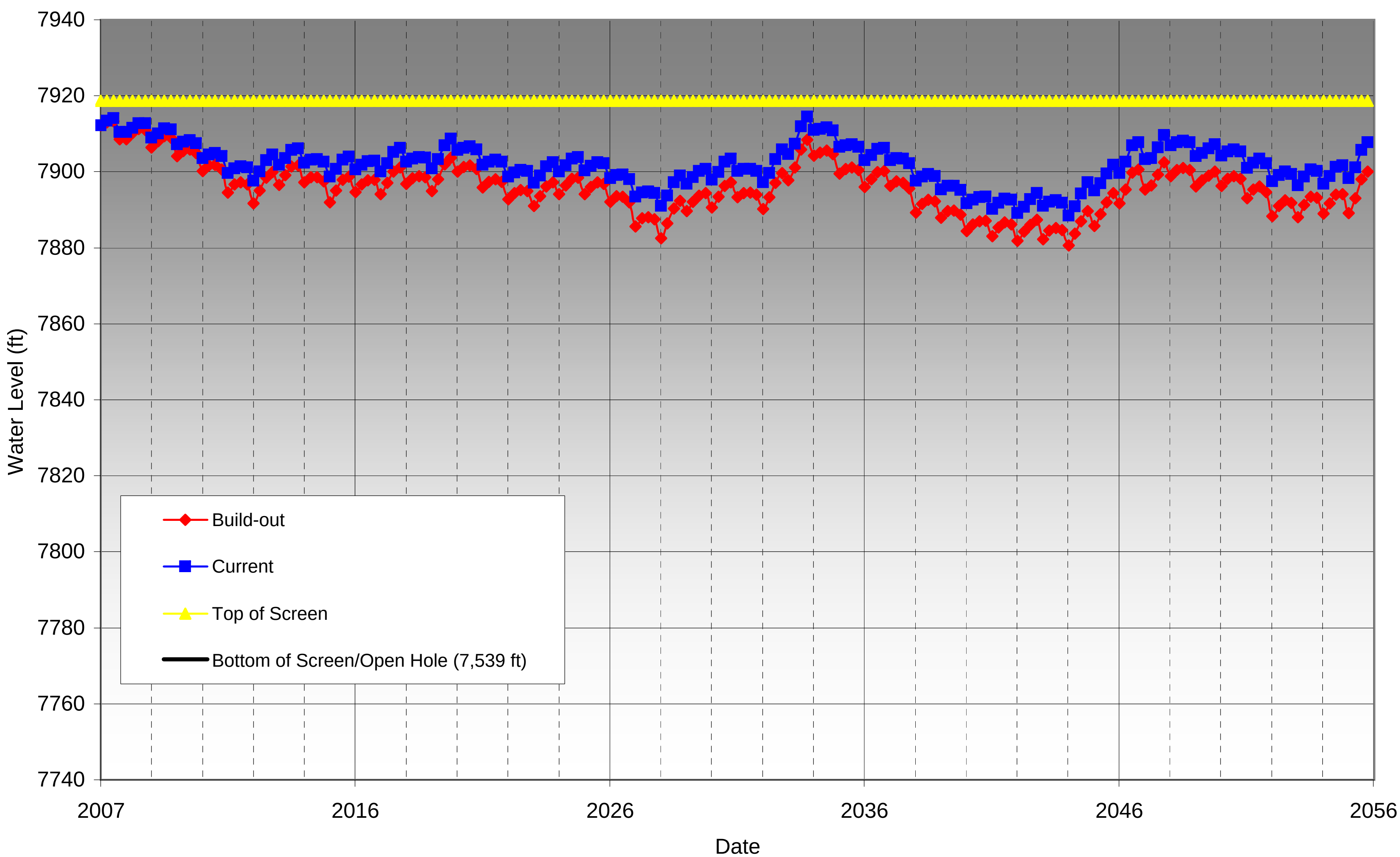

Figure7-2 through 7-10.xls

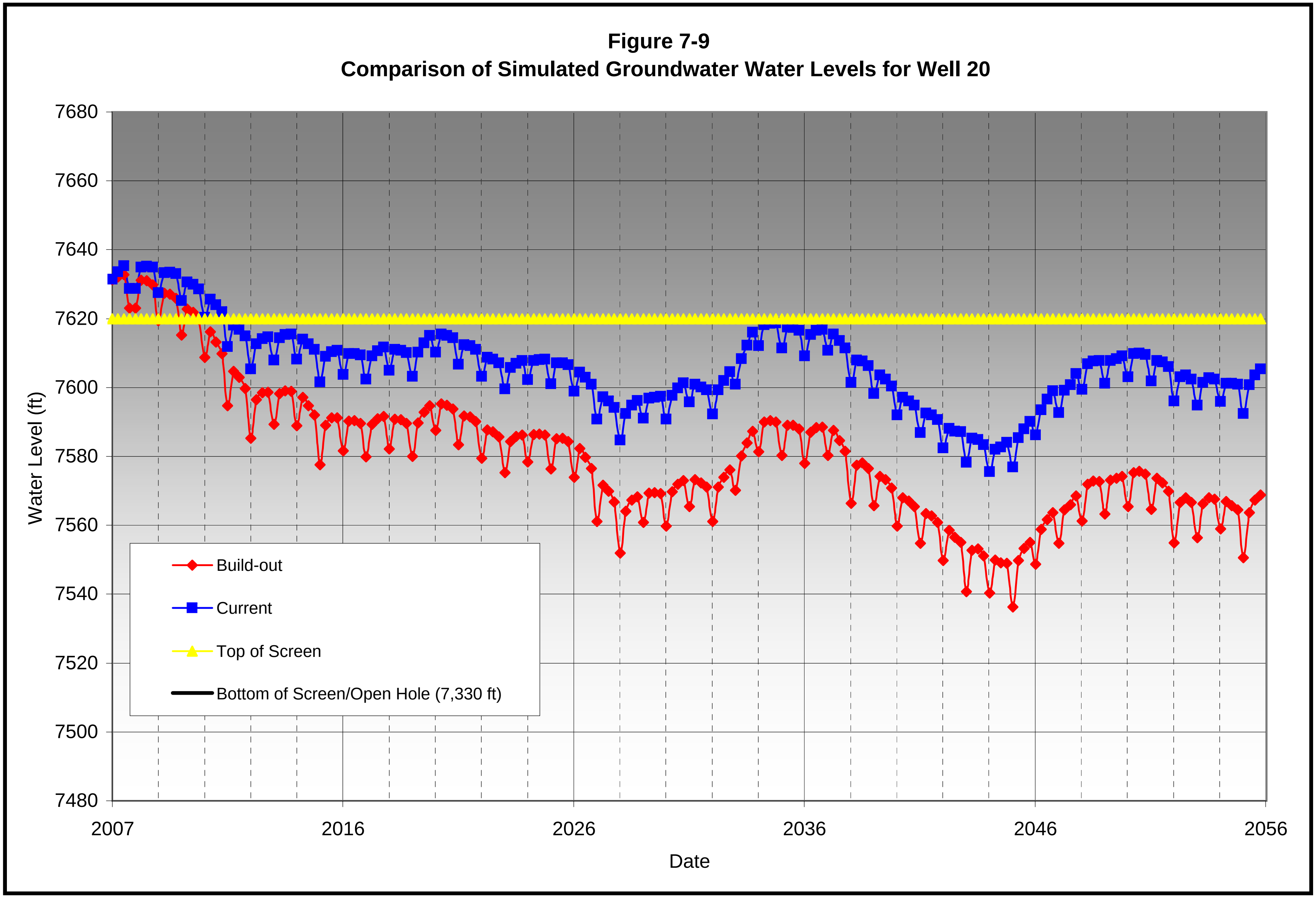
Figure 7-9
Comparison of Simulated Groundwater Water Levels for Well 20
Water Level (ft)
7680
7660
7640
7620
7600
7580
7560
7540
7520
7500
7480
2007
2016
2026
2036
2046
2056
Date
Build-out
Current
Top of Screen
Bottom of Screen/Open Hole (7,330 ft)

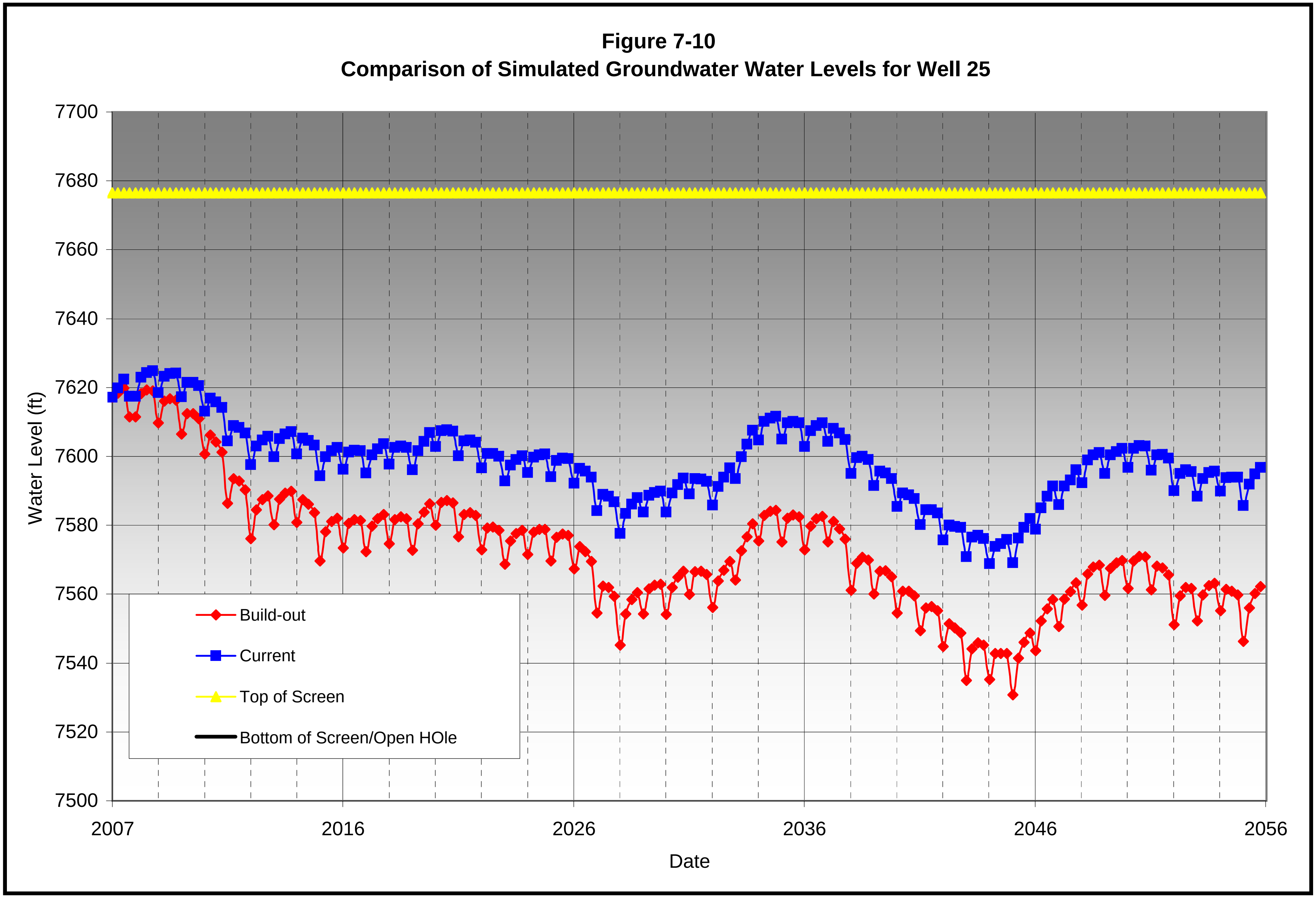

Figure7-2 through 7-10.xls

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Appendix A

Groundwater Level Time Series Charts at Wells

Groundwater-Level Time Series

Well Name: **Well #1**

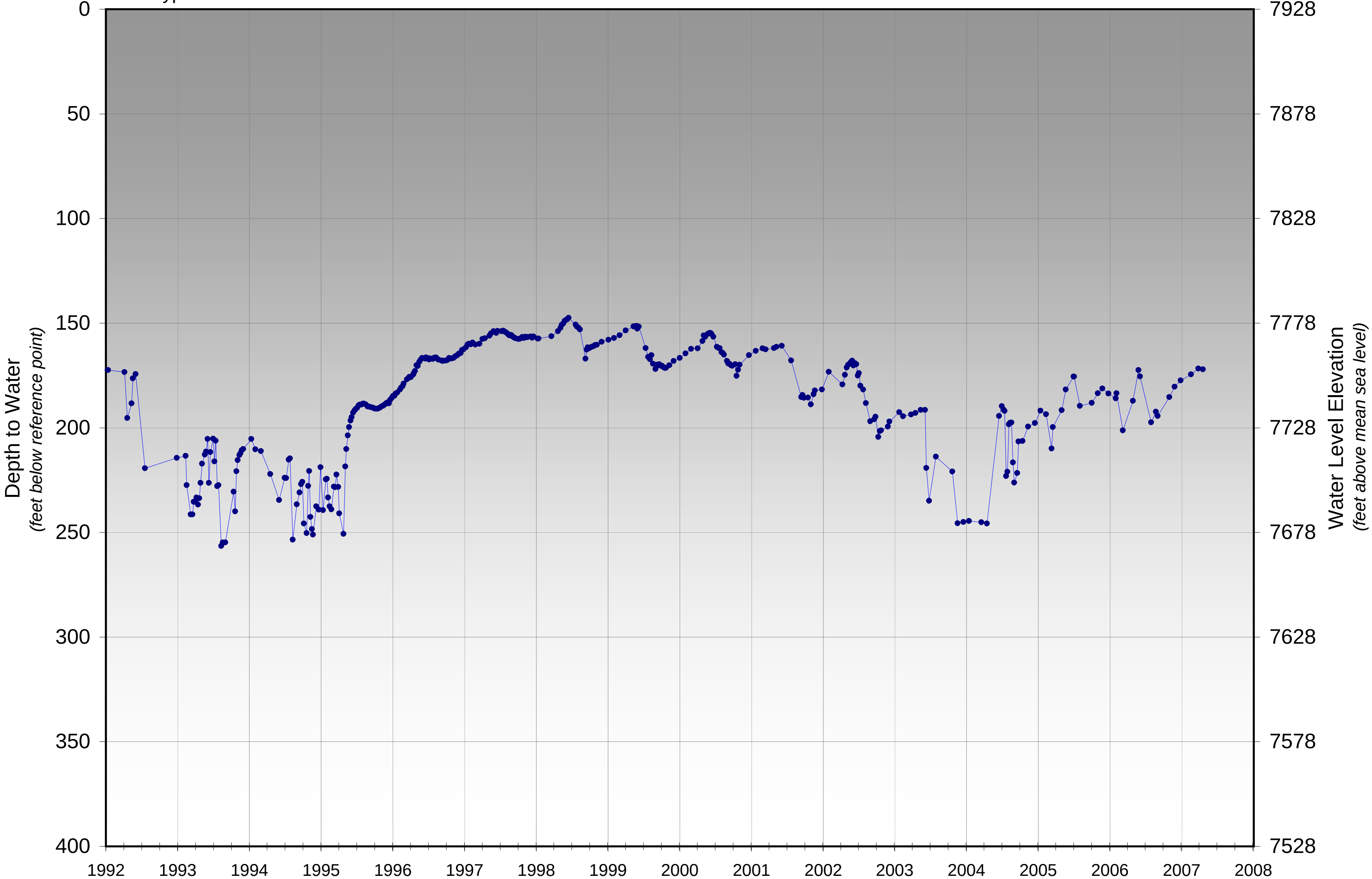
Owner Name: Mammoth Community Water District

Well Type: Production

Aquifer = Deep

Reference Point Elevation = 7928' above mean sea level

Ground Surface Elevation = 7927' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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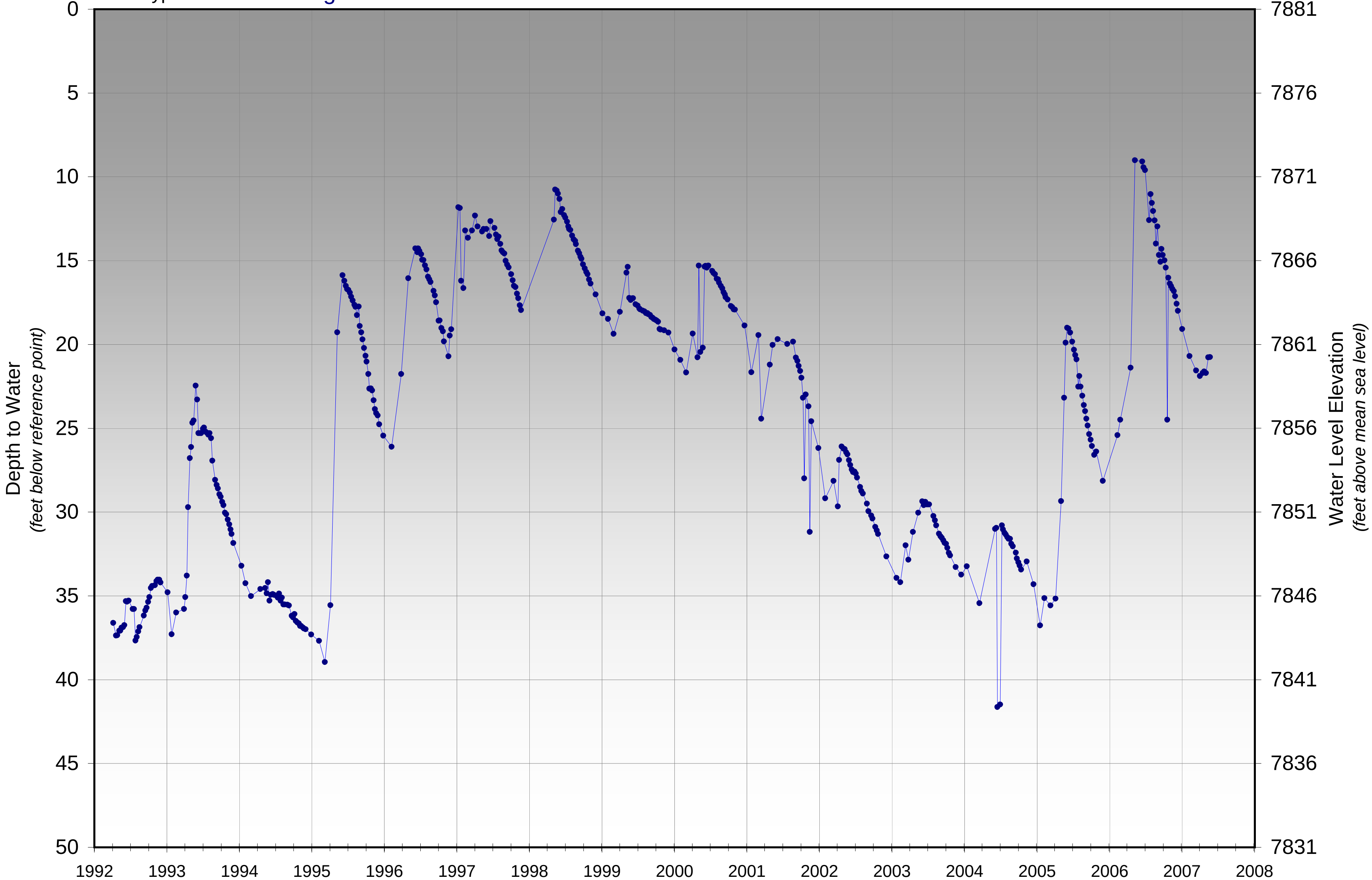
Groundwater-Level Time Series

Well Name: **Well #4M**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7881.0' above mean sea level
Ground Surface Elevation = 7883.4' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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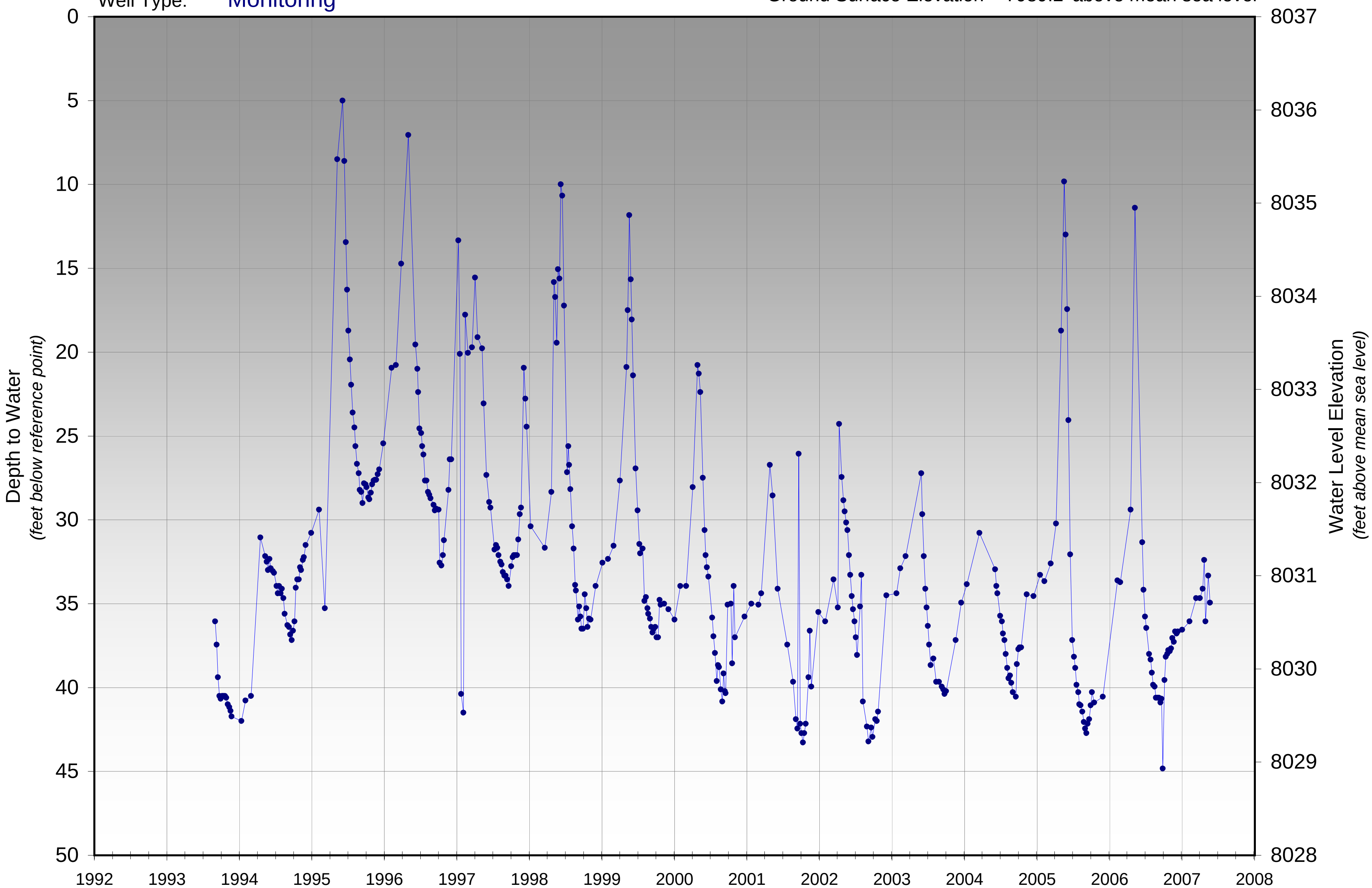
Groundwater-Level Time Series

Well Name: **Well #5M**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7989.2' above mean sea level
Ground Surface Elevation = 7989.2' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #5A**

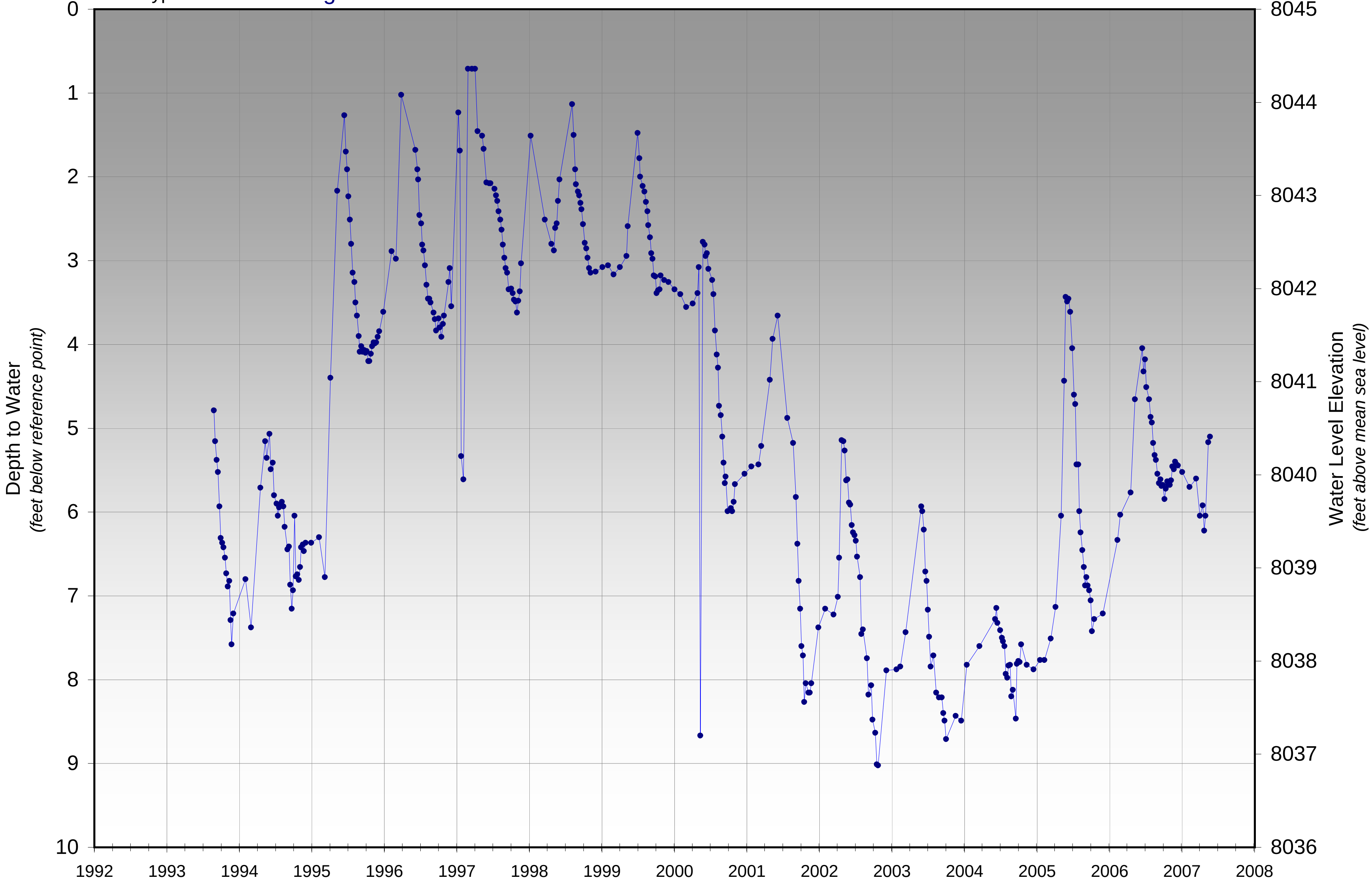
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7987.6' above mean sea level

Ground Surface Elevation = 7985.6' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #6**

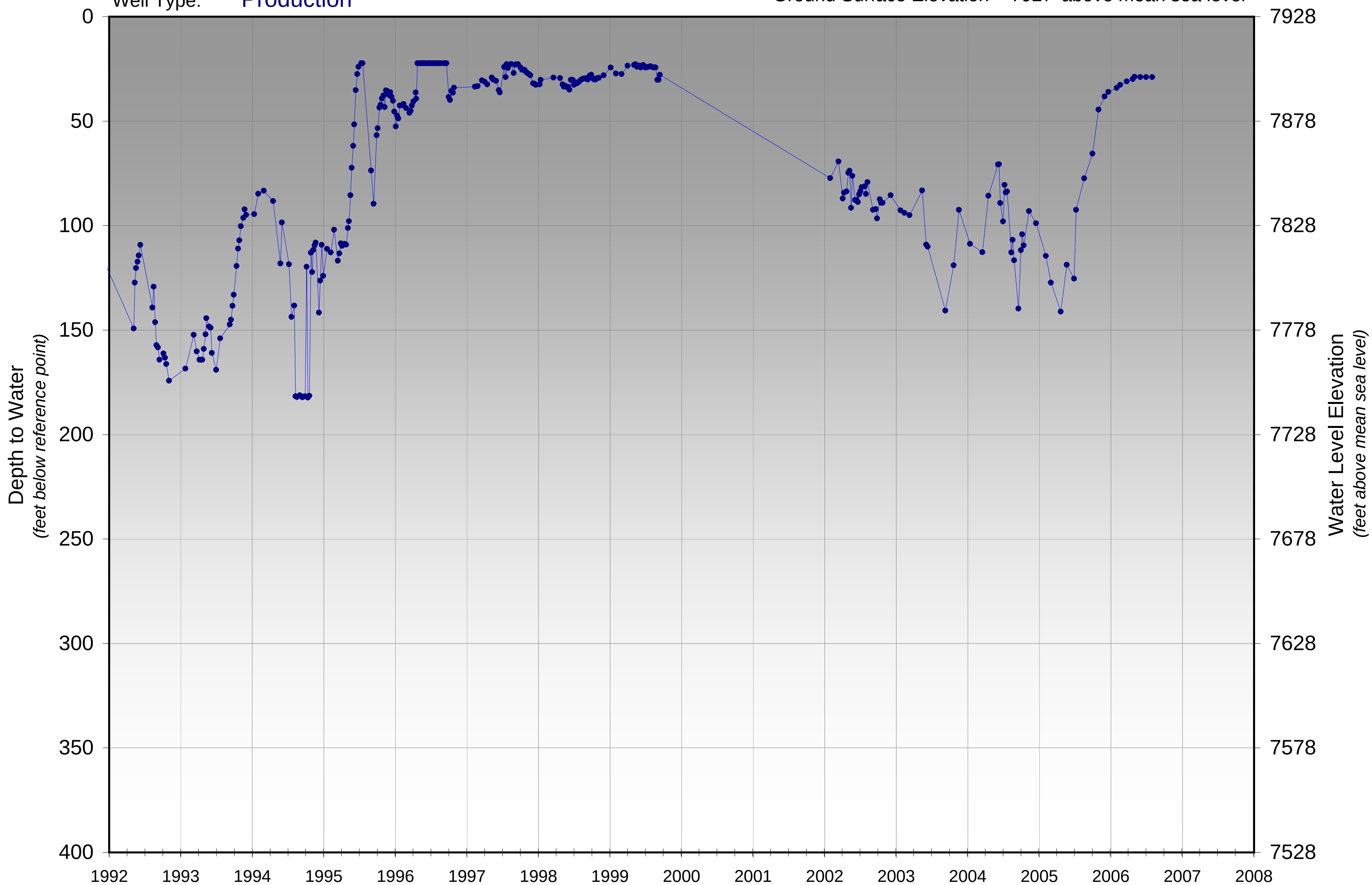
Owner Name: Mammoth Community Water District

Well Type: Production

Aquifer = Deep

Reference Point Elevation = 7928' above mean sea level

Ground Surface Elevation = 7927' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #7M**

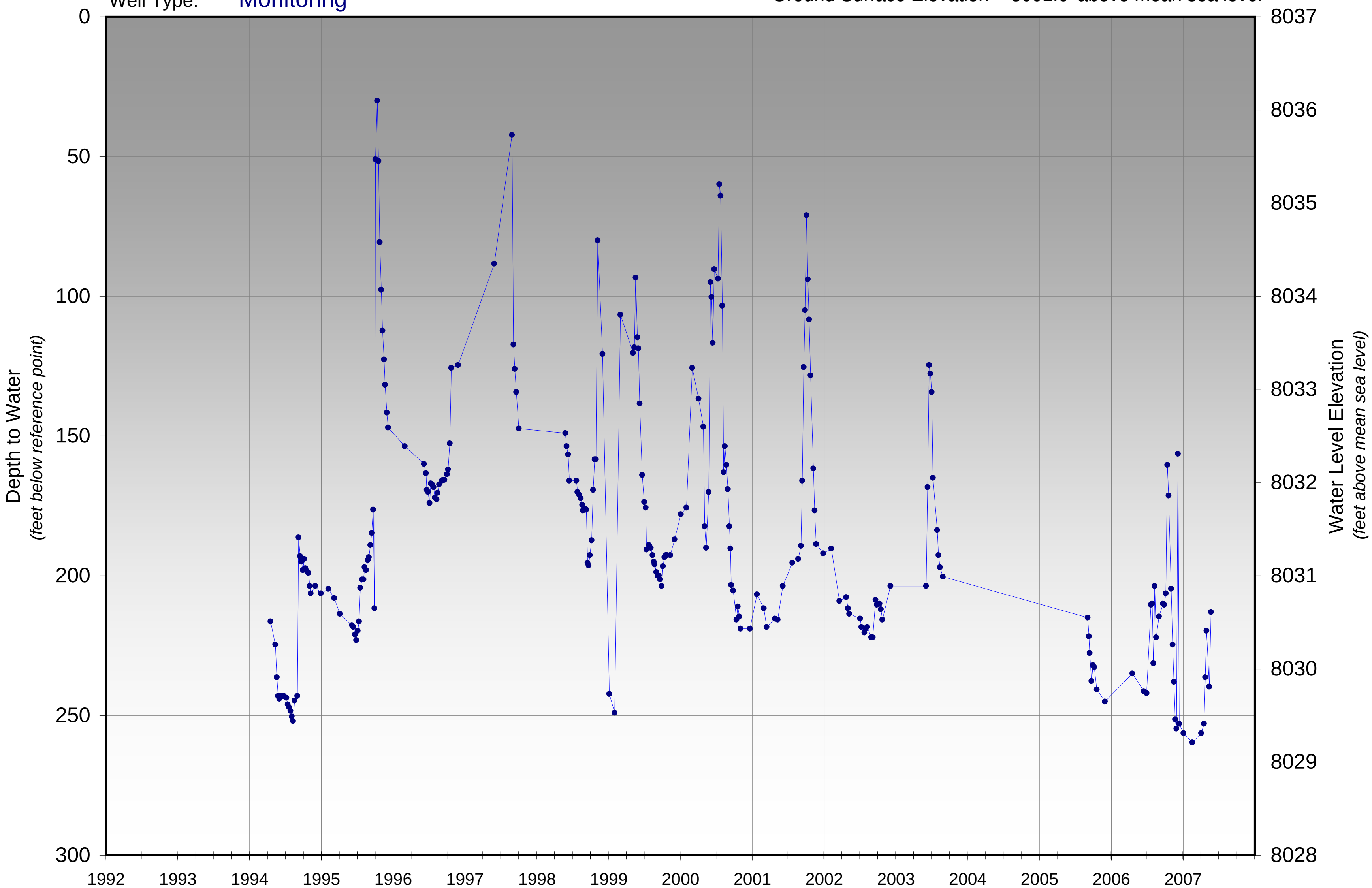
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Shallow

Reference Point Elevation = 8001.0' above mean sea level

Ground Surface Elevation = 8001.0' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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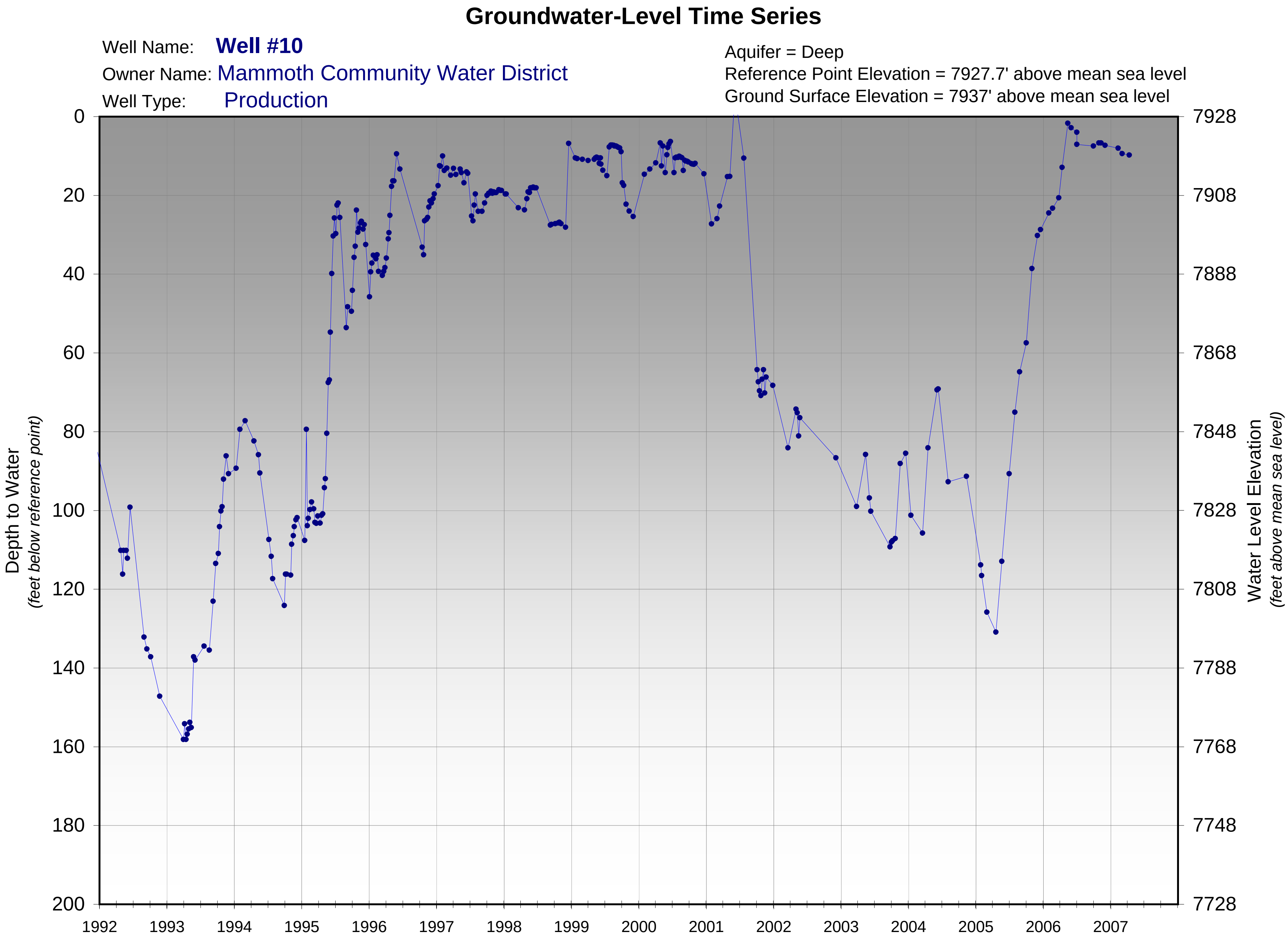

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #10M**

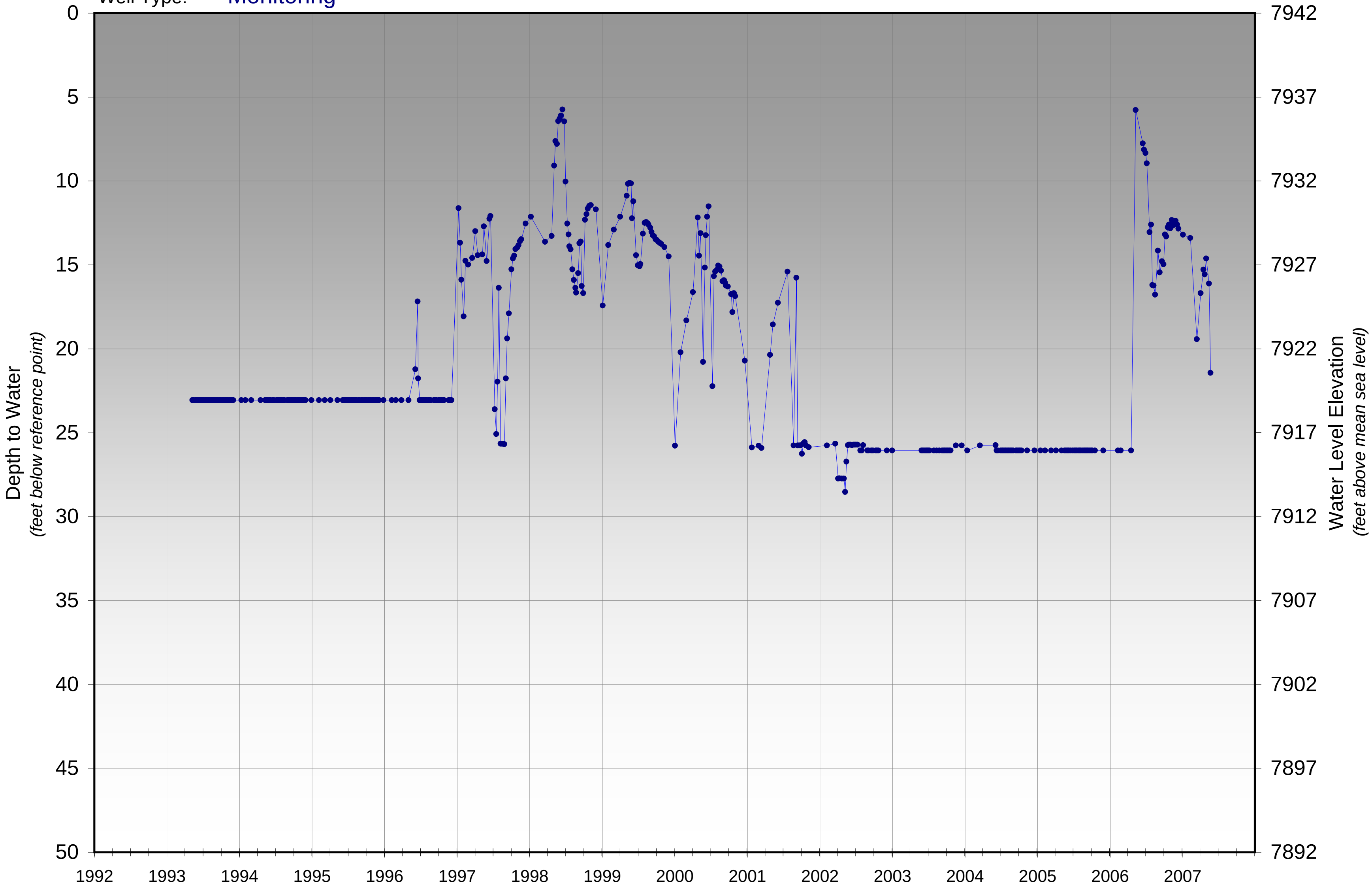
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Shallow

Reference Point Elevation = 7942' above mean sea level

Ground Surface Elevation = 7939.9' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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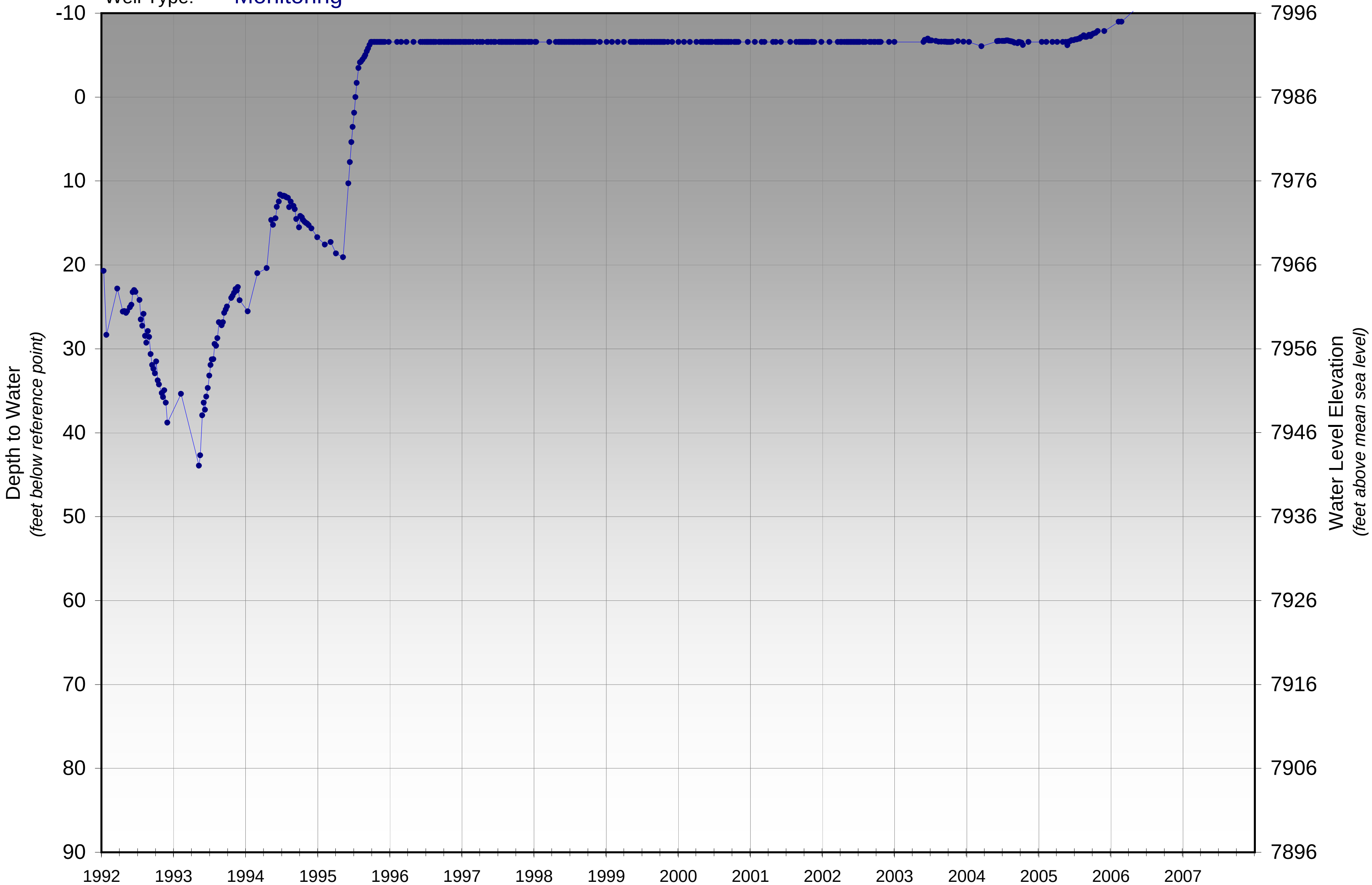
Groundwater-Level Time Series

Well Name: **Well #11**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7986.3' above mean sea level
Ground Surface Elevation = 7979.9' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #11**

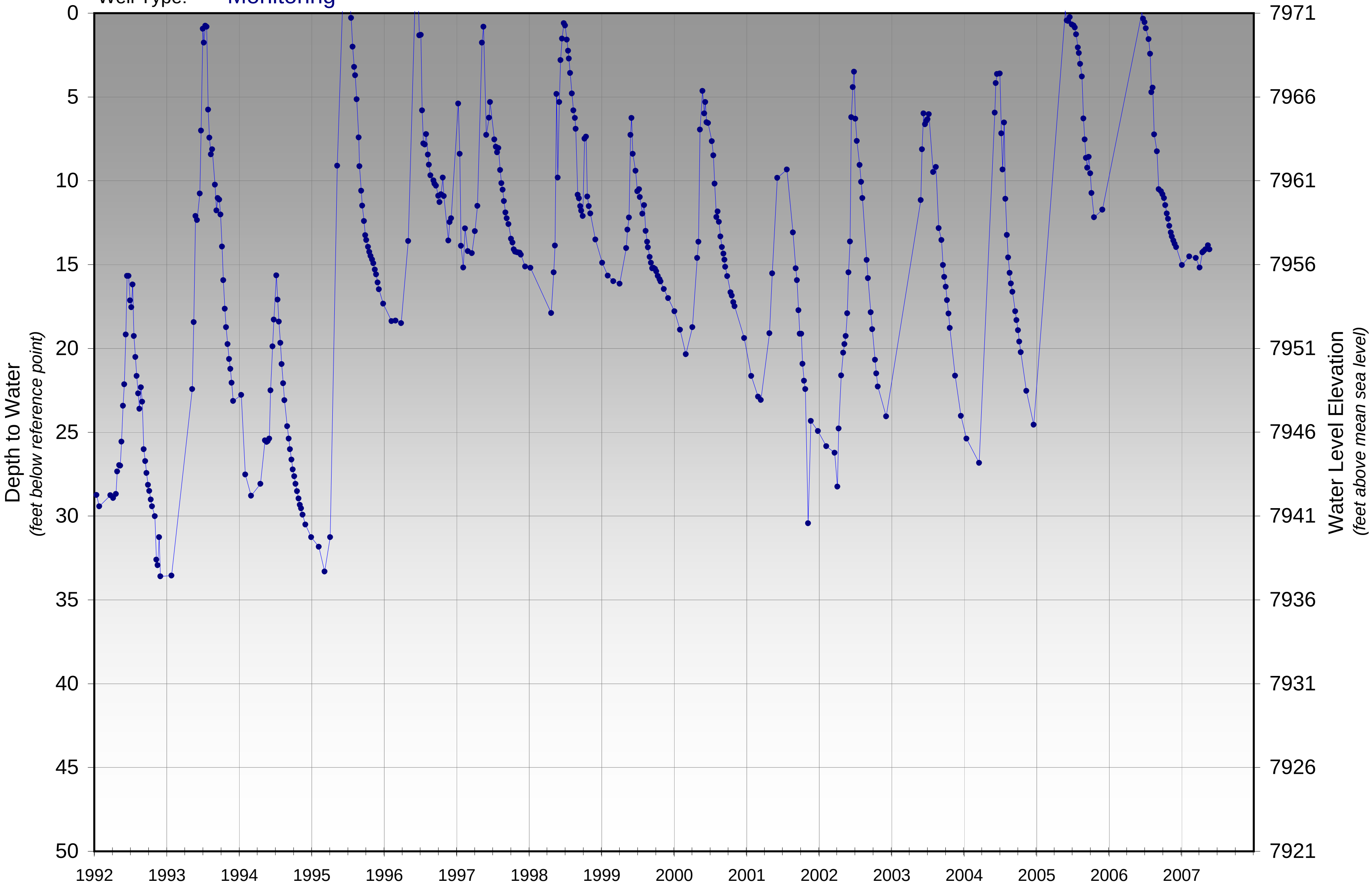
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Shallow

Reference Point Elevation = 7971' above mean sea level

Ground Surface Elevation = 7968.7' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #12M**

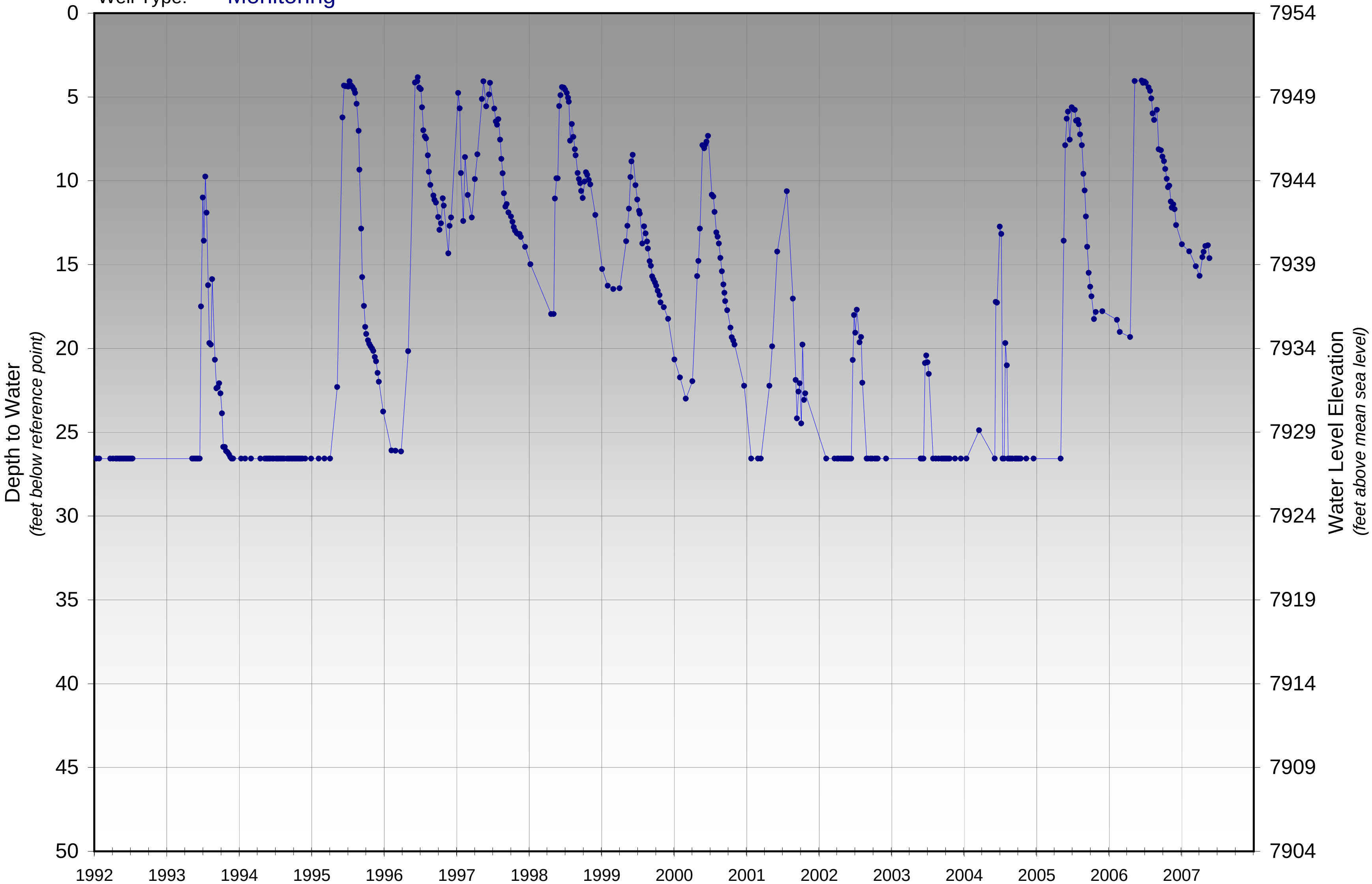
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Shallow

Reference Point Elevation = 7954.4' above mean sea level

Ground Surface Elevation = 7954.4' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #14M**

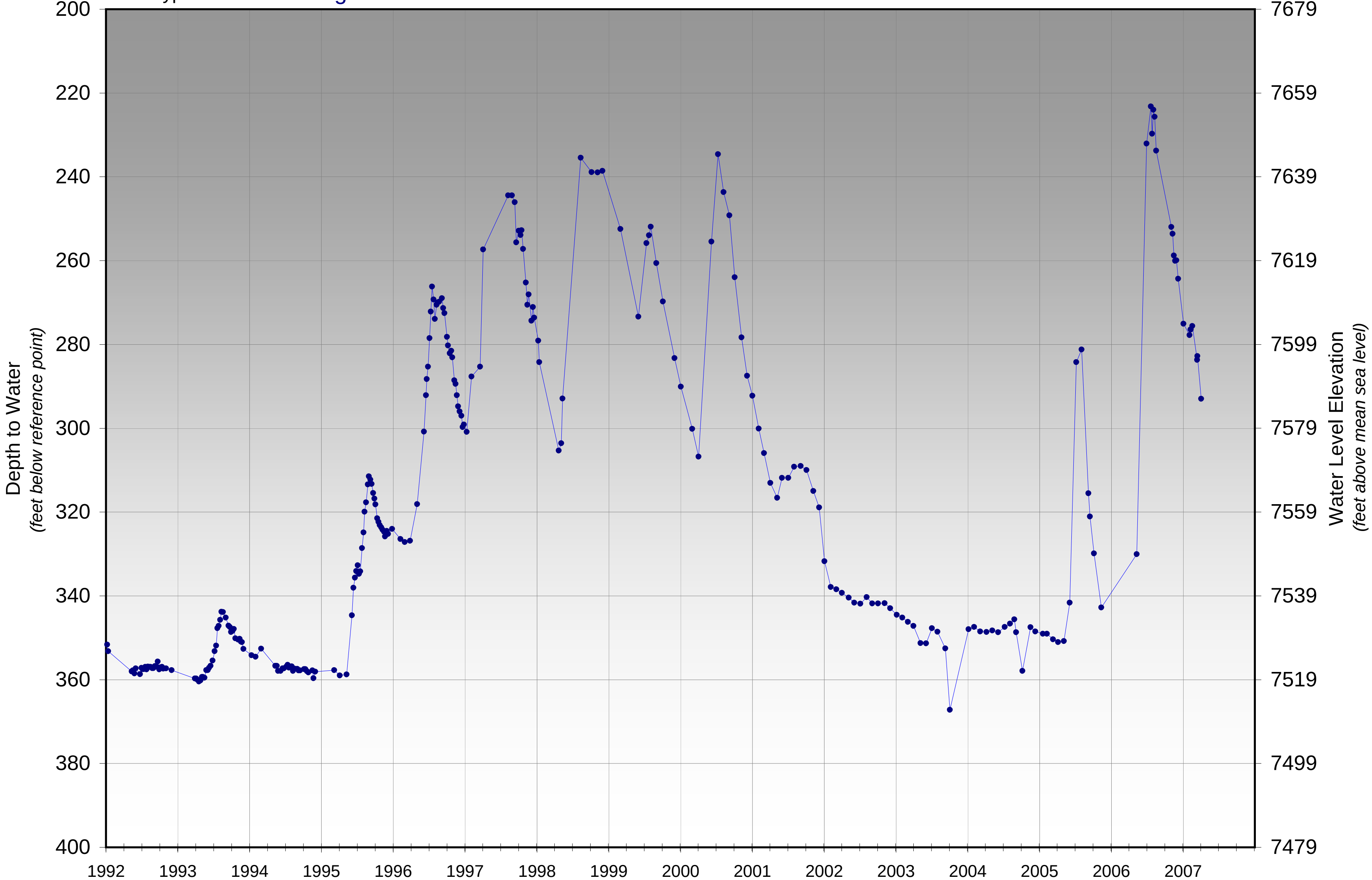
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7879.3' above mean sea level

Ground Surface Elevation = 7877.8' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #15**

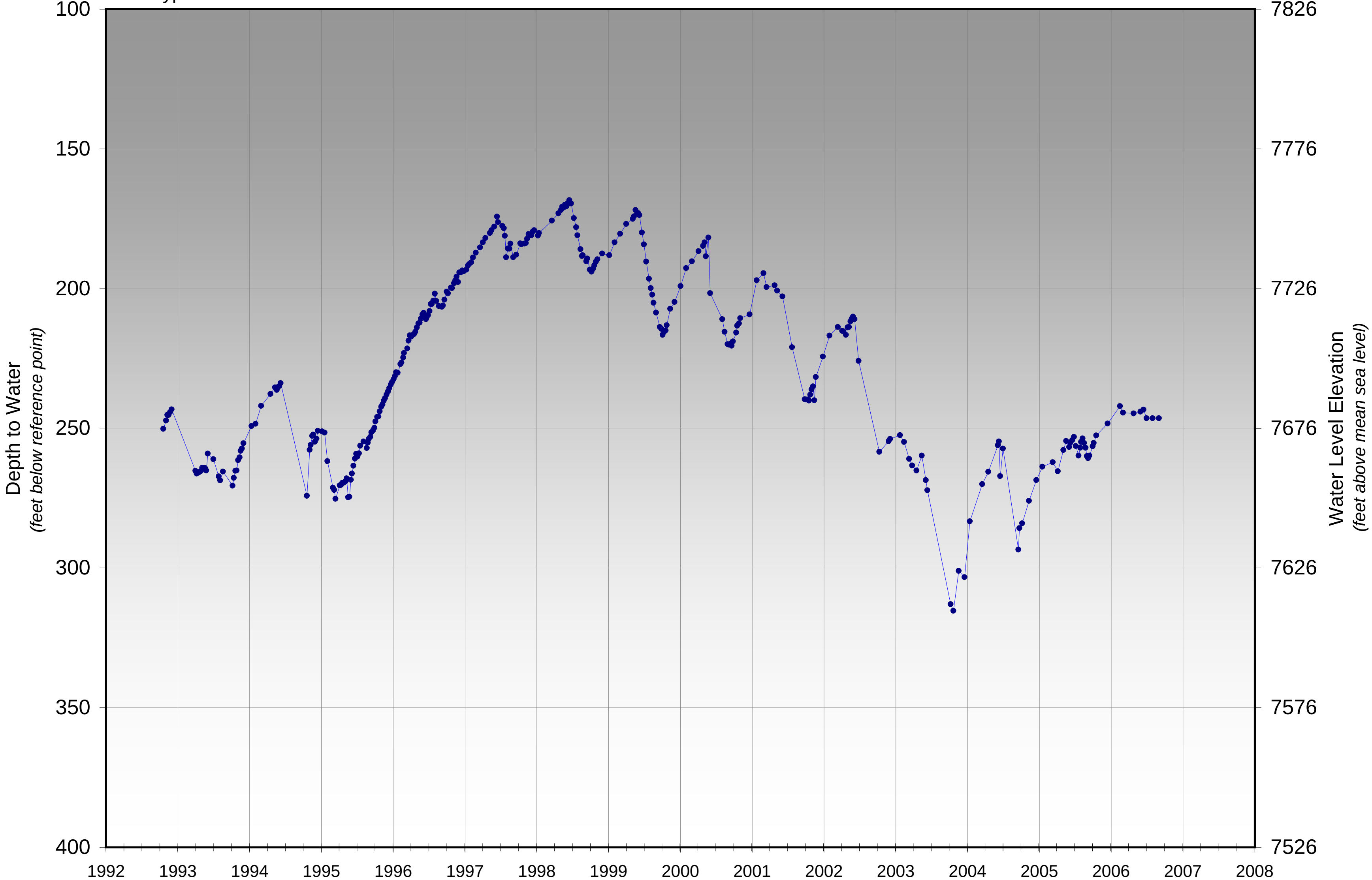
Owner Name: Mammoth Community Water District

Well Type: Production

Aquifer = Deep

Reference Point Elevation = 7925.8' above mean sea level

Ground Surface Elevation = 7925.8' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #16**

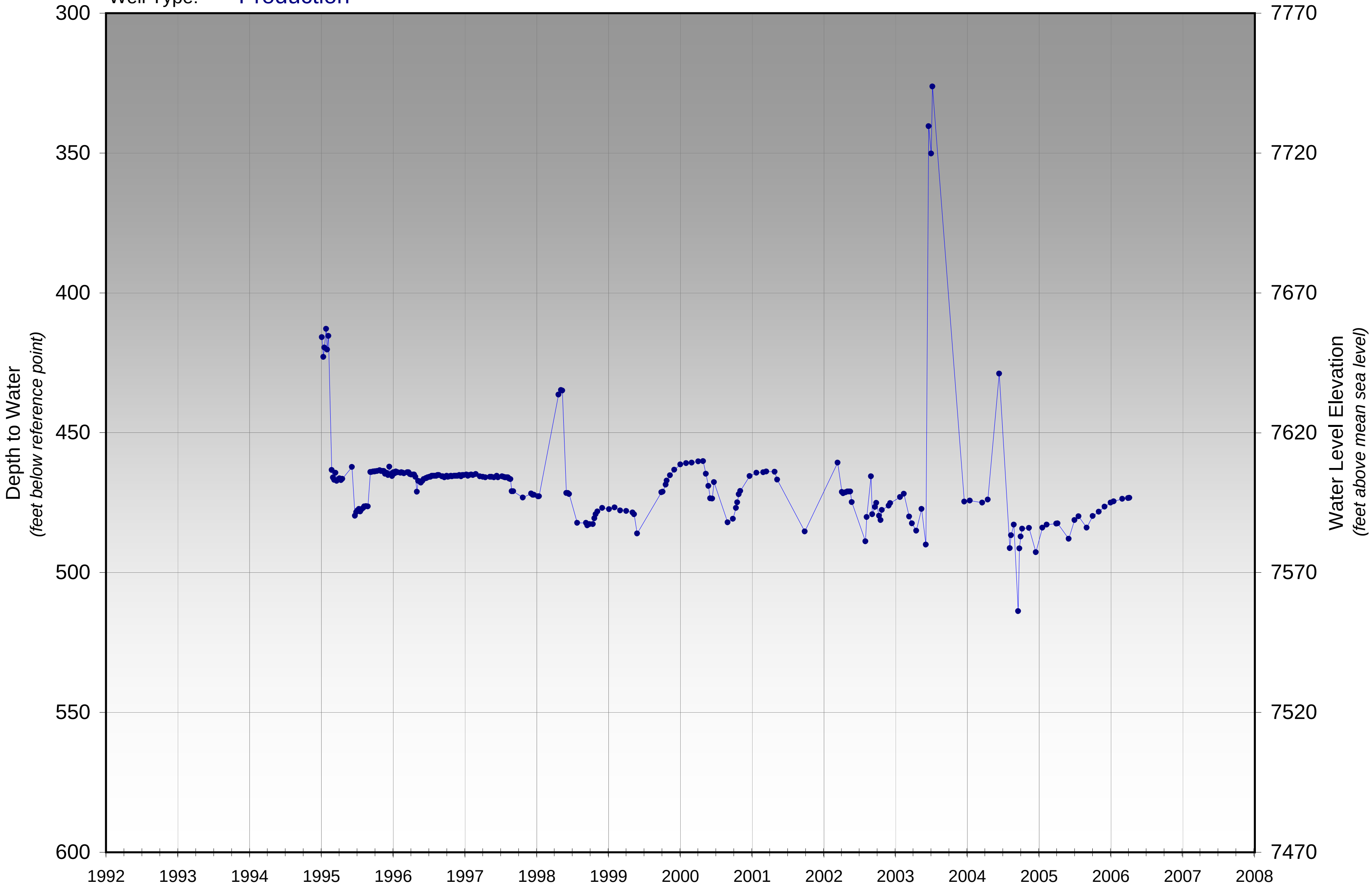
Owner Name: Mammoth Community Water District

Well Type: Production

Aquifer = Deep

Reference Point Elevation = 8070.8' above mean sea level

Ground Surface Elevation = 8070.8' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #17**

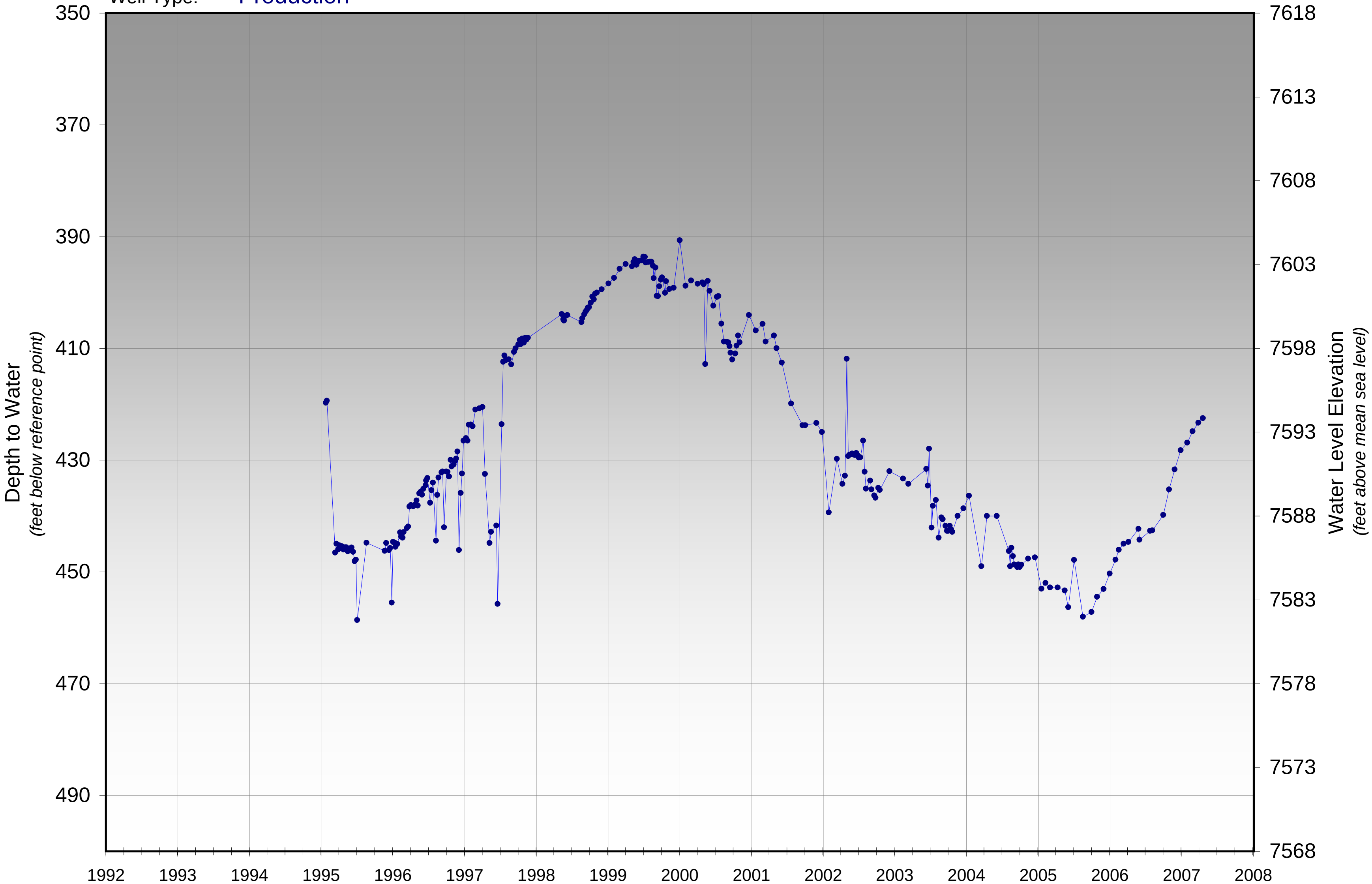
Owner Name: Mammoth Community Water District

Well Type: Production

Aquifer = Deep

Reference Point Elevation = 7968.5' above mean sea level

Ground Surface Elevation = 7968.5' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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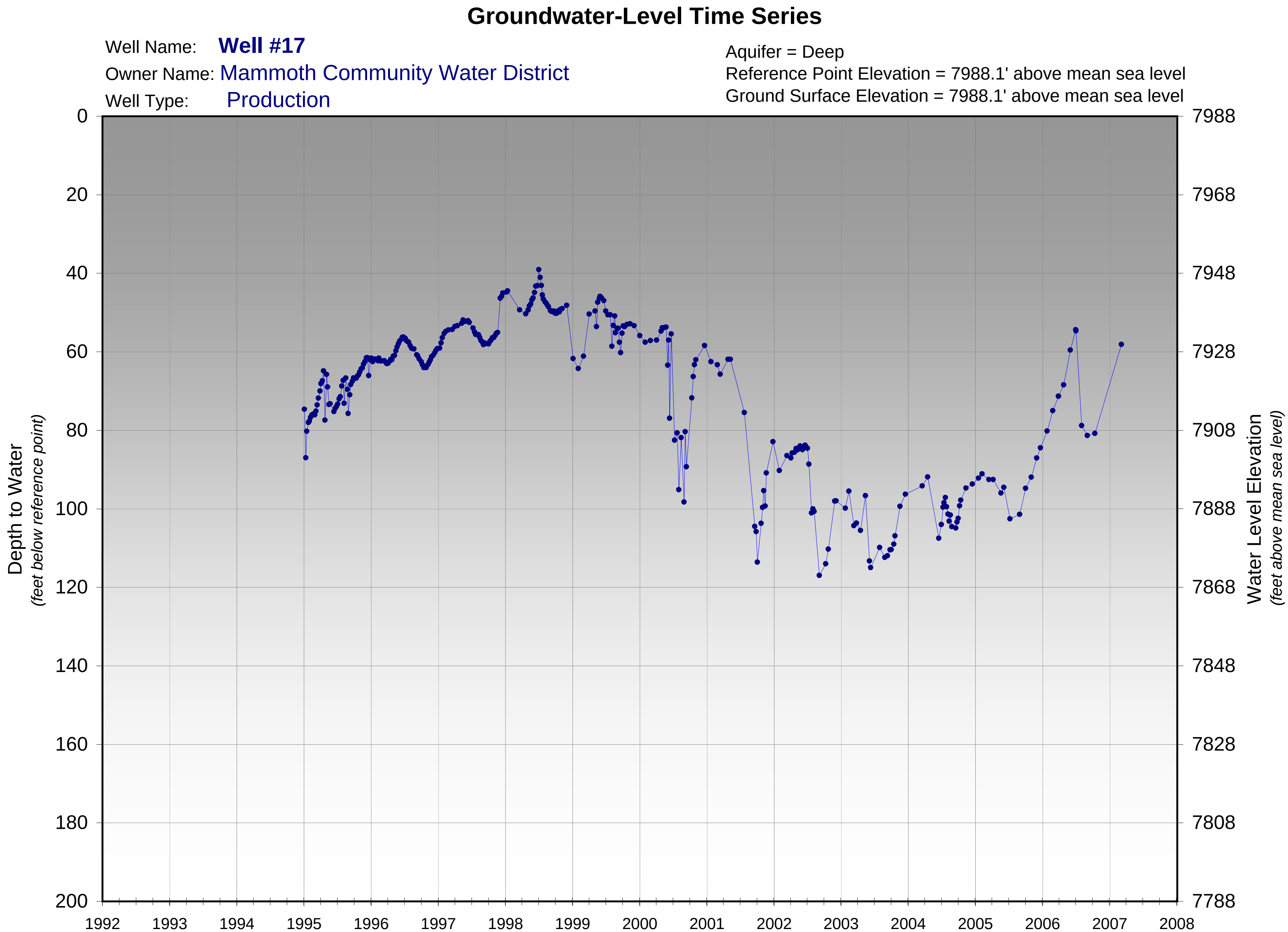

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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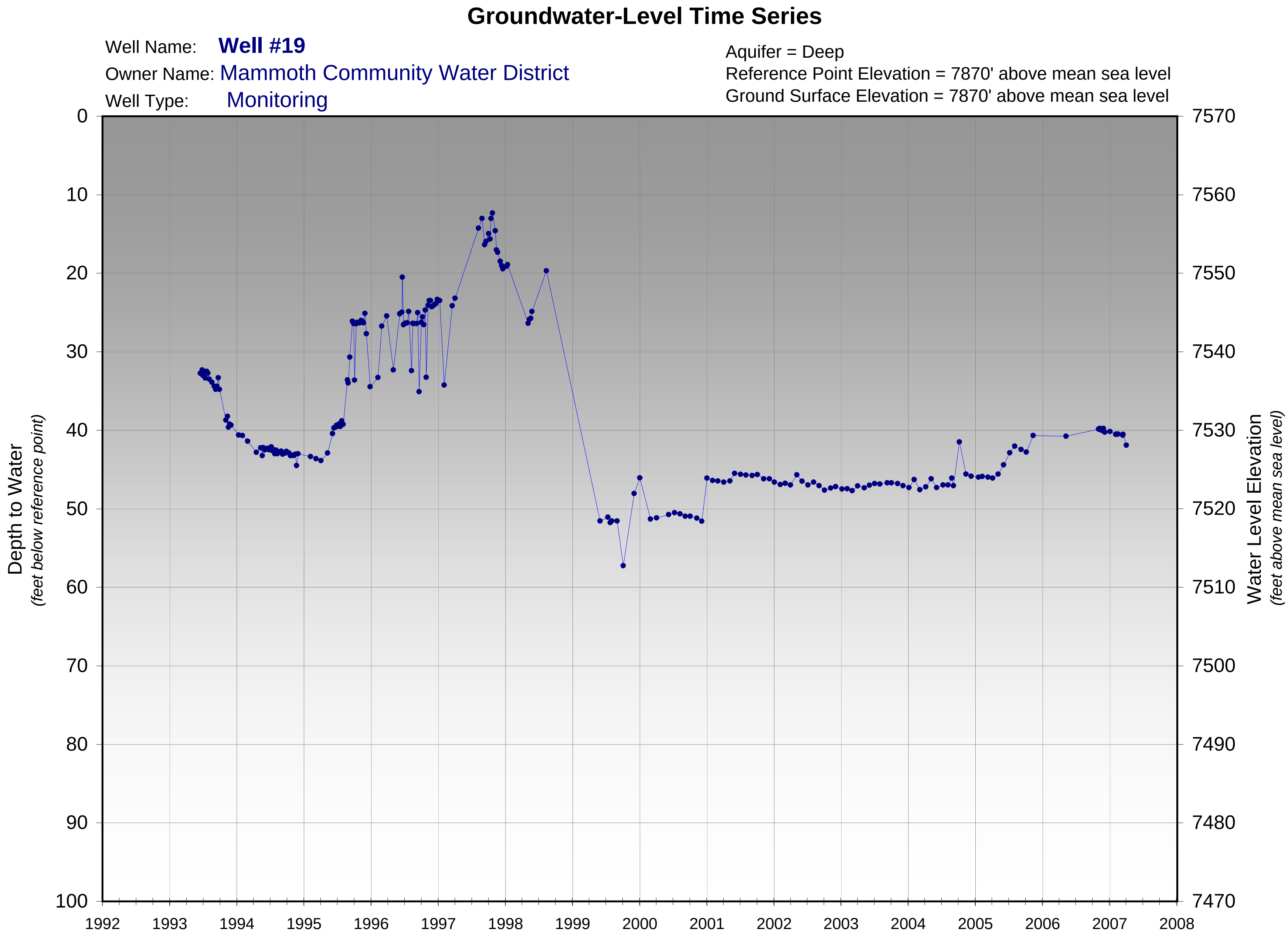

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #20**

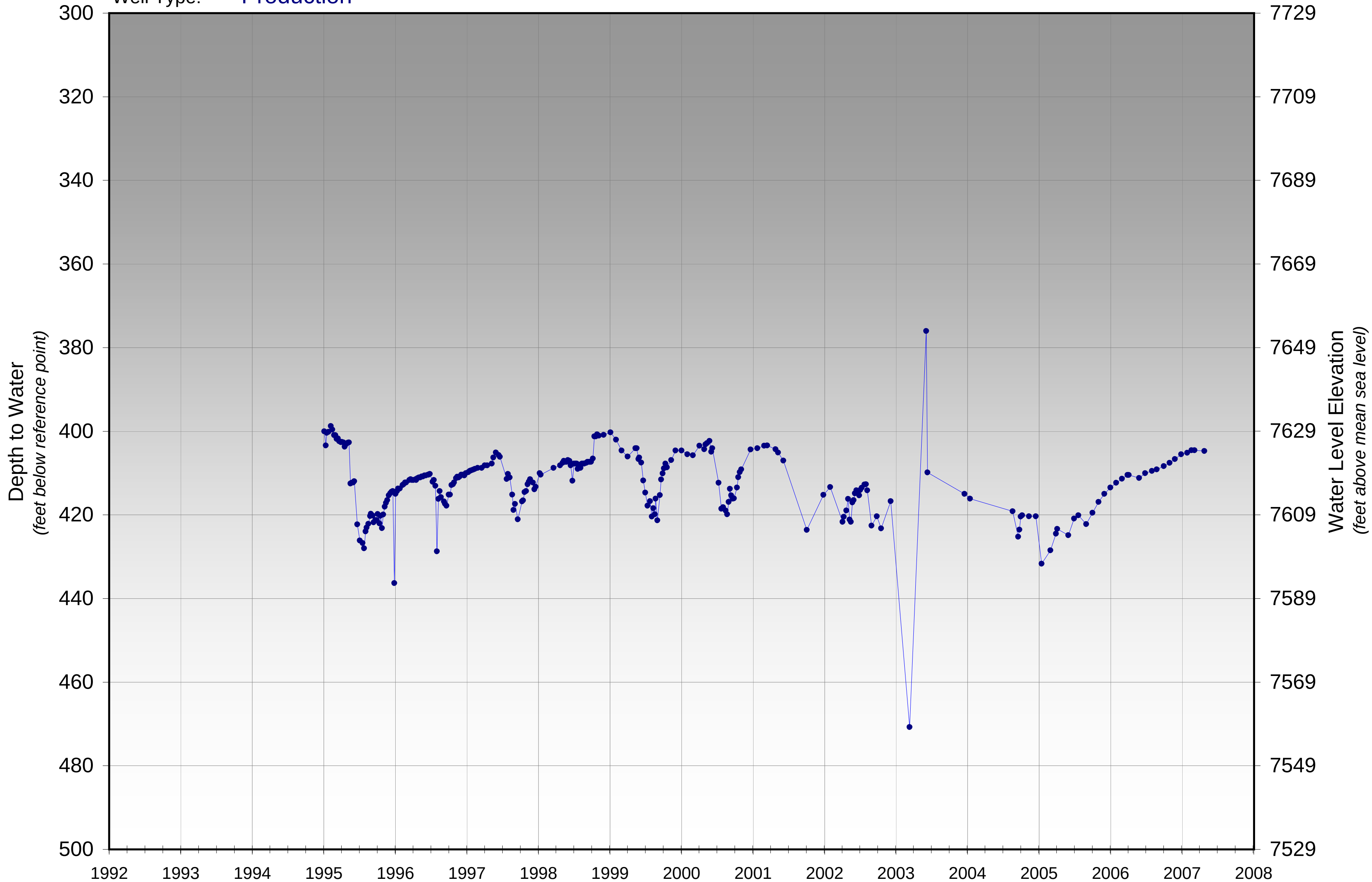
Owner Name: Mammoth Community Water District

Well Type: Production

Aquifer = Deep

Reference Point Elevation = 8029.2' above mean sea level

Ground Surface Elevation = 8029.2' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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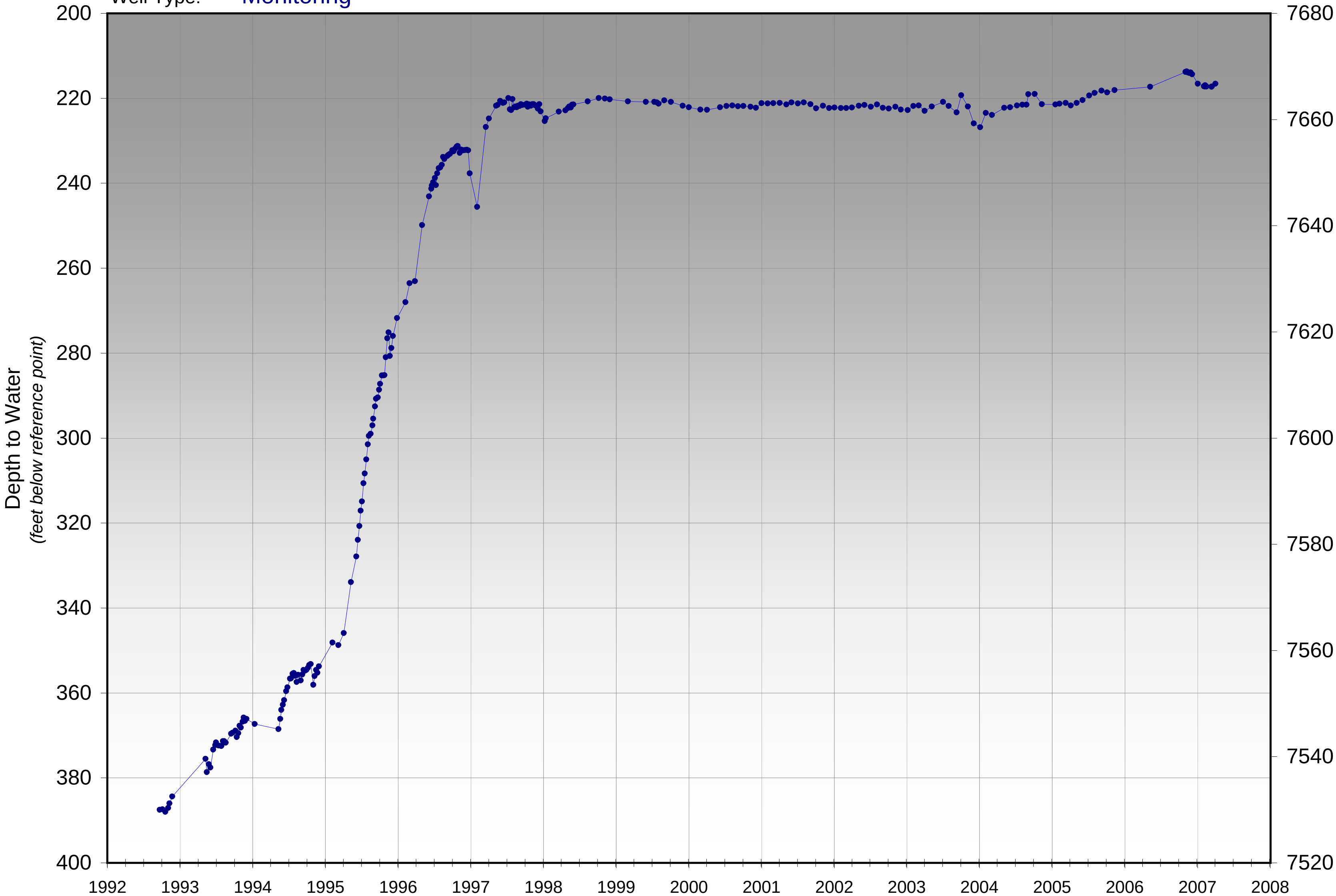
Groundwater-Level Time Series

Well Name: **Well #21**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7895' above mean sea level
Ground Surface Elevation = 7895' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **Well #22**

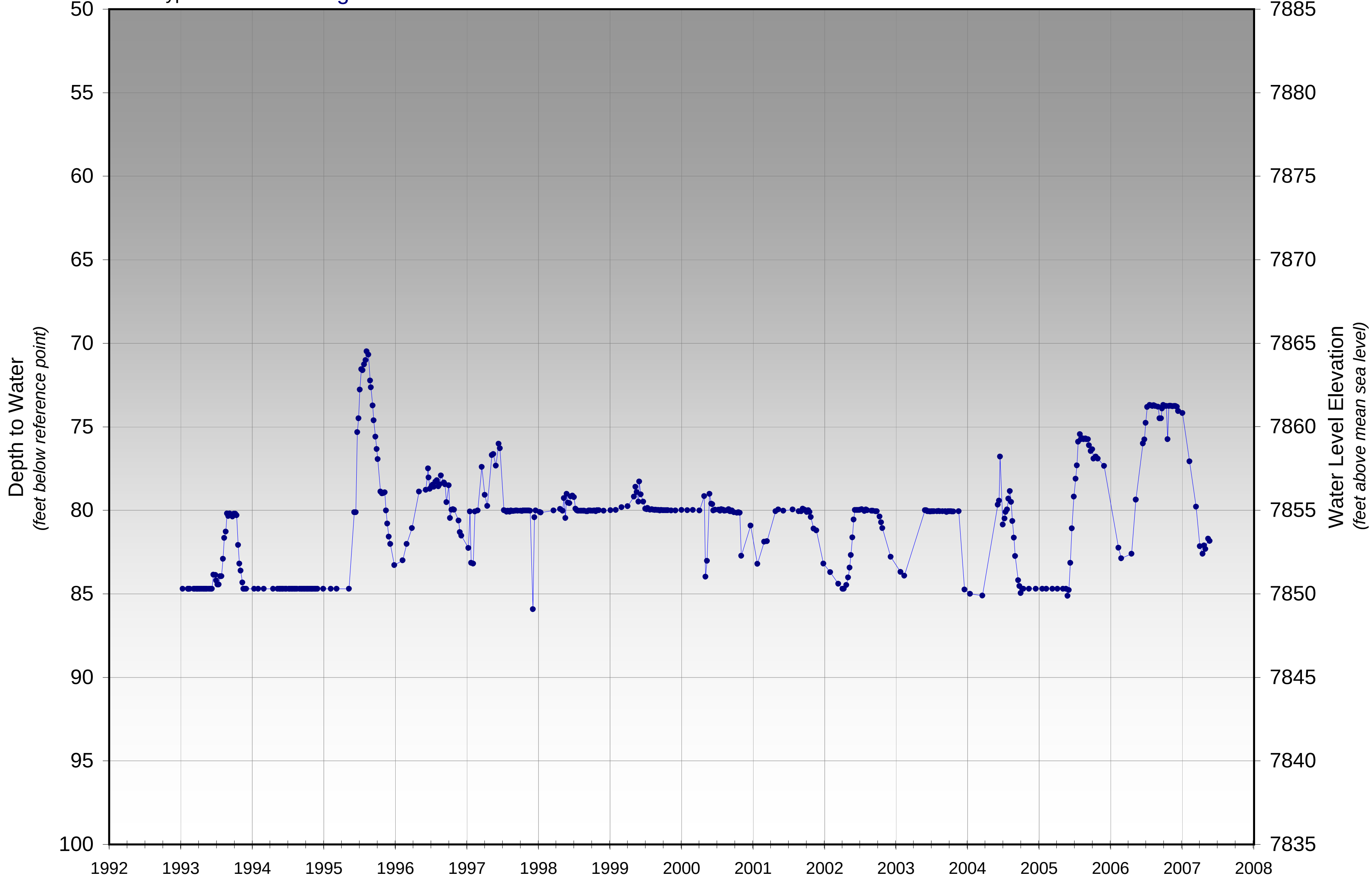
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Shallow

Reference Point Elevation = 7935.3' above mean sea level

Ground Surface Elevation = 7935.3' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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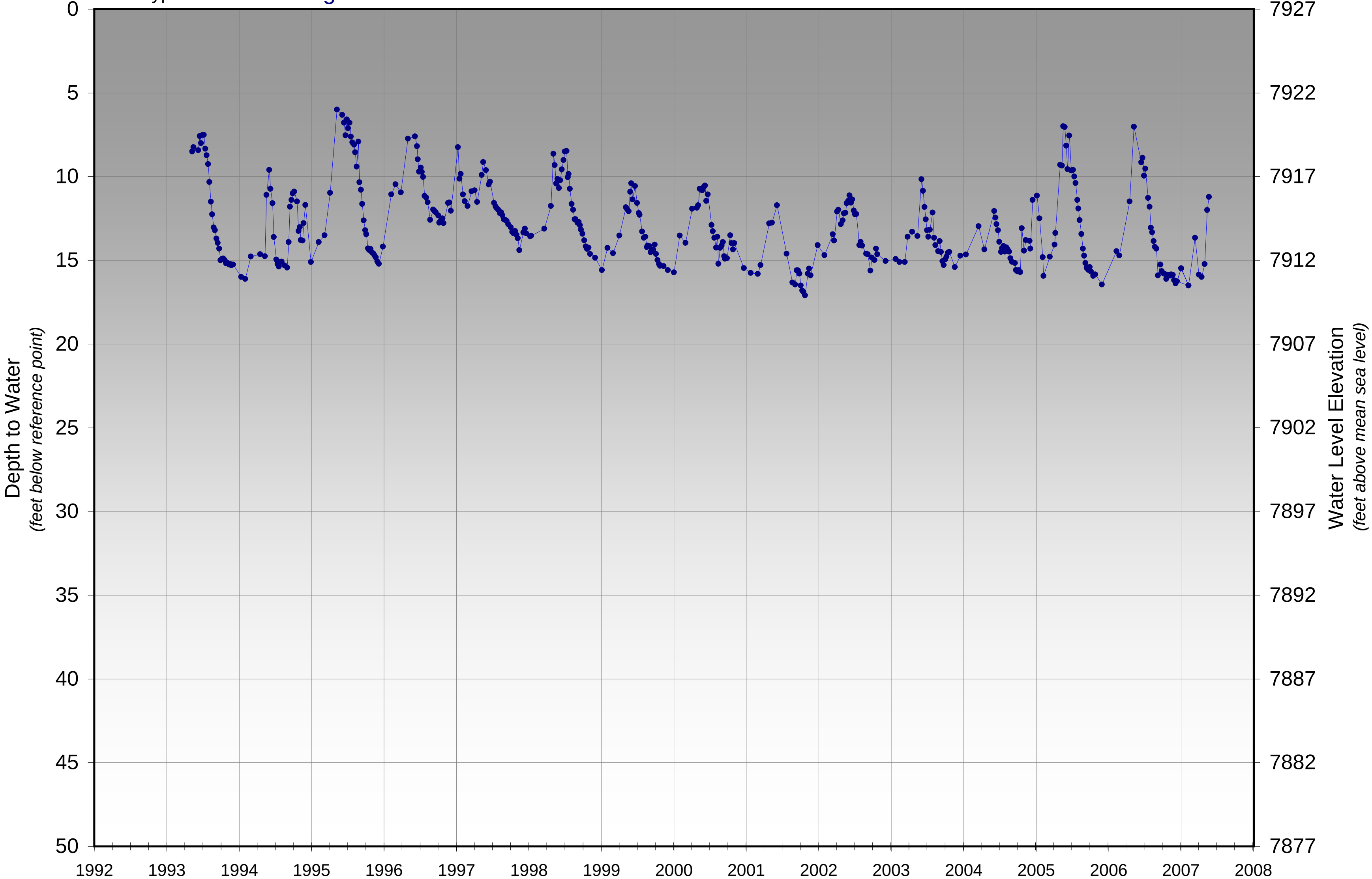
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **Well #23**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7927.0' above mean sea level
Ground Surface Elevation = 7927.0' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #24**

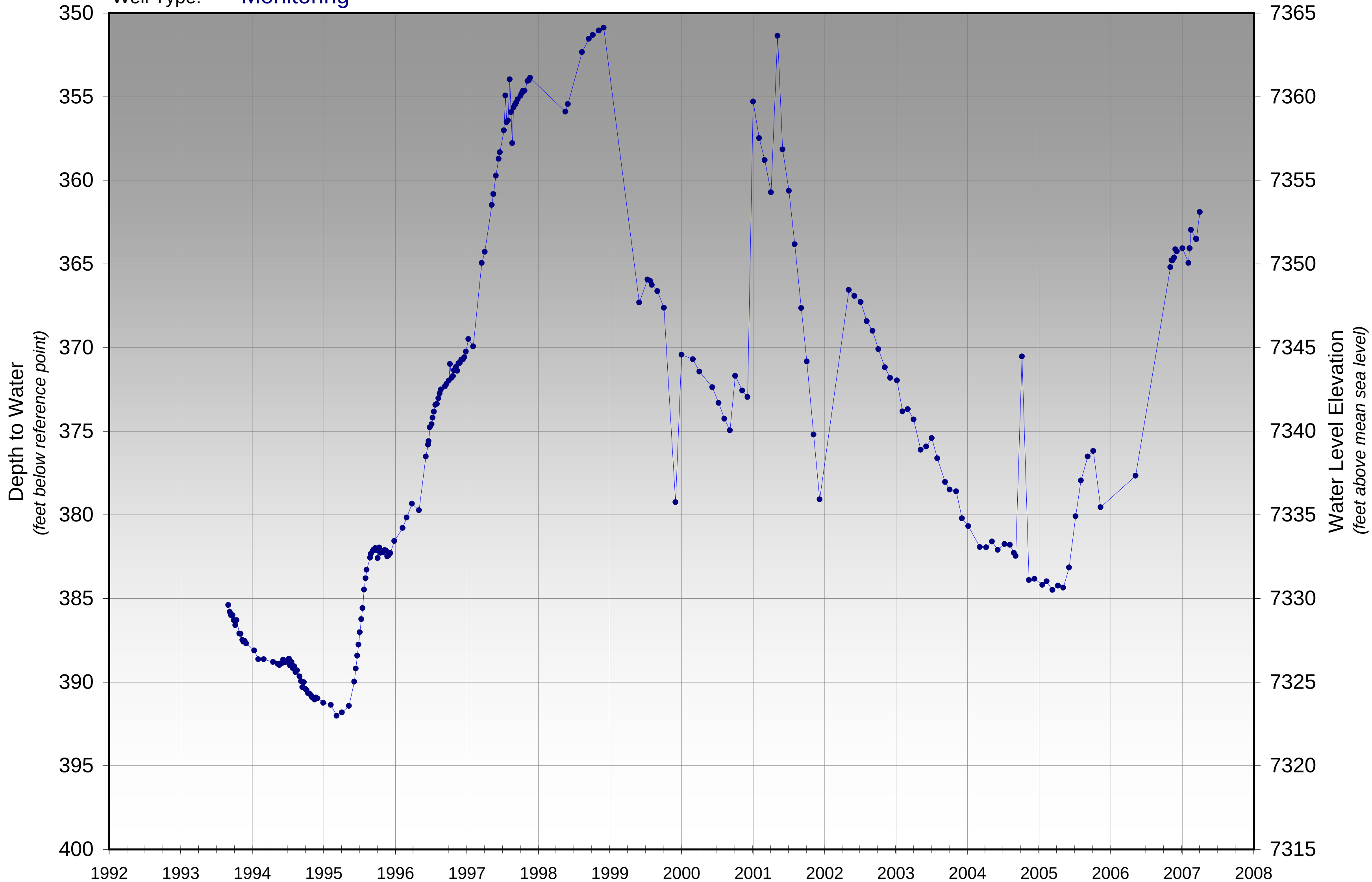
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7715' above mean sea level

Ground Surface Elevation = 7715' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #25**

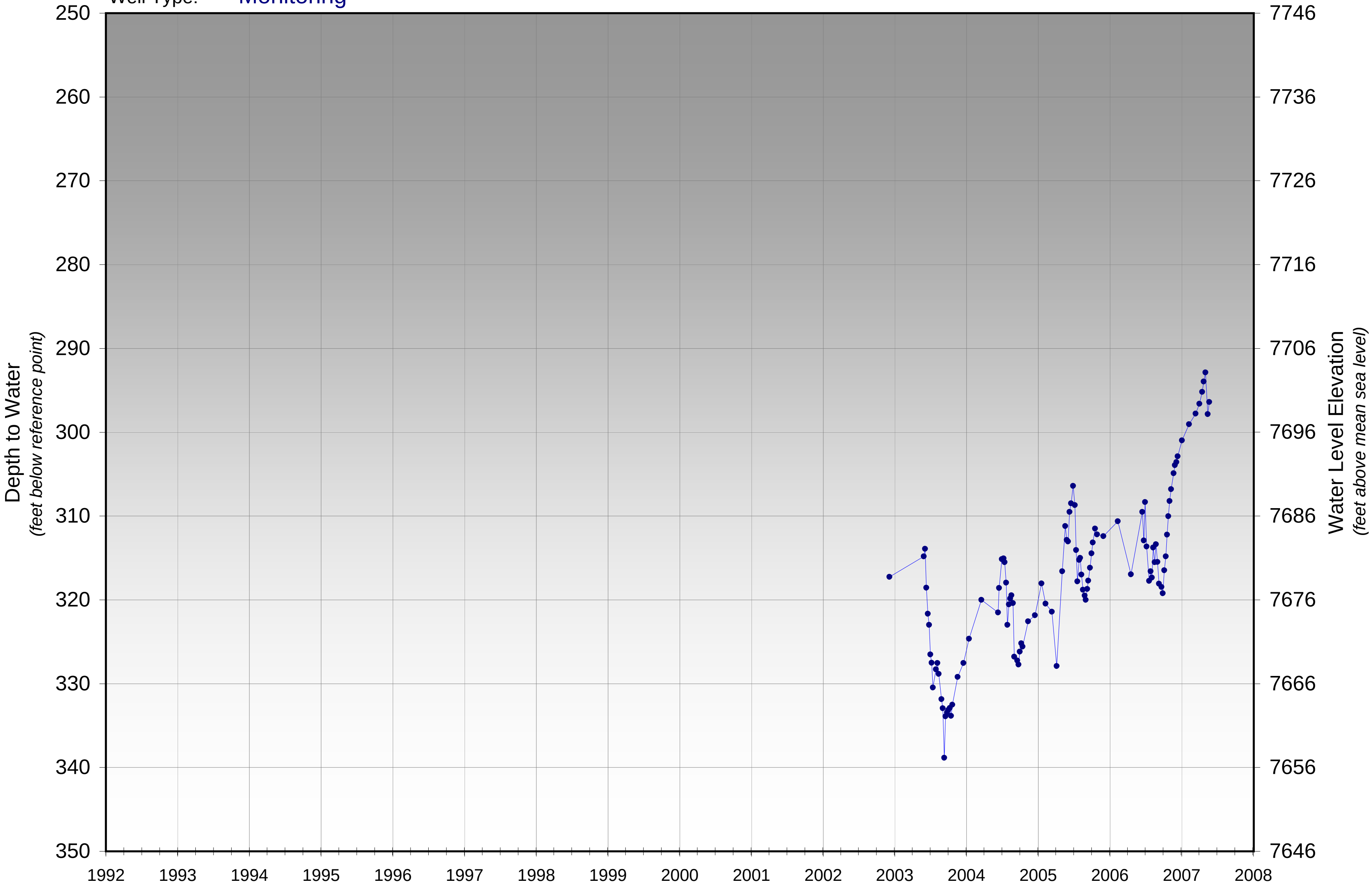
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7996.3' above mean sea level

Ground Surface Elevation = 7994.2' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **Well #26**

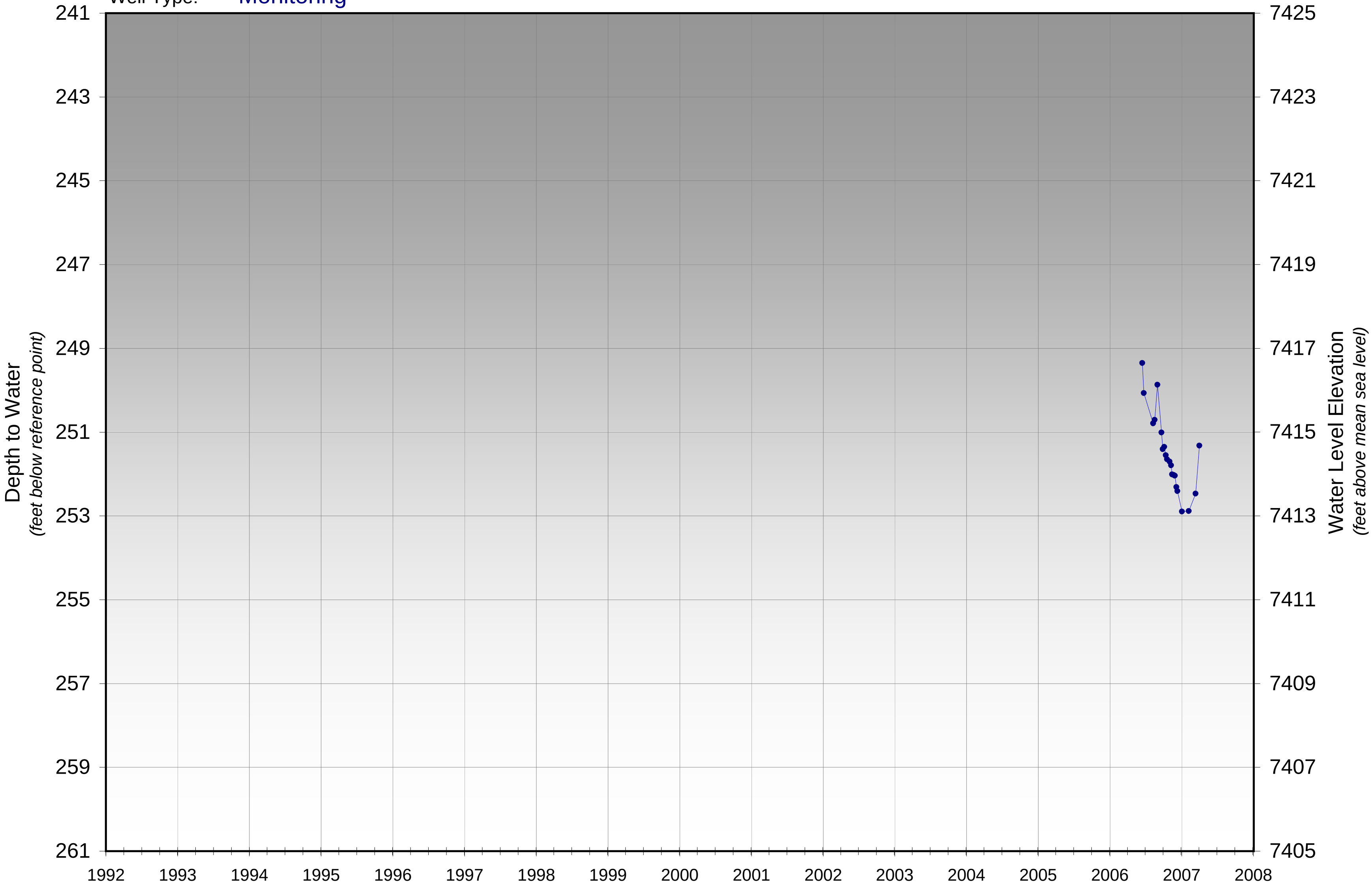
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7665.5' above mean sea level

Ground Surface Elevation = 7665.5' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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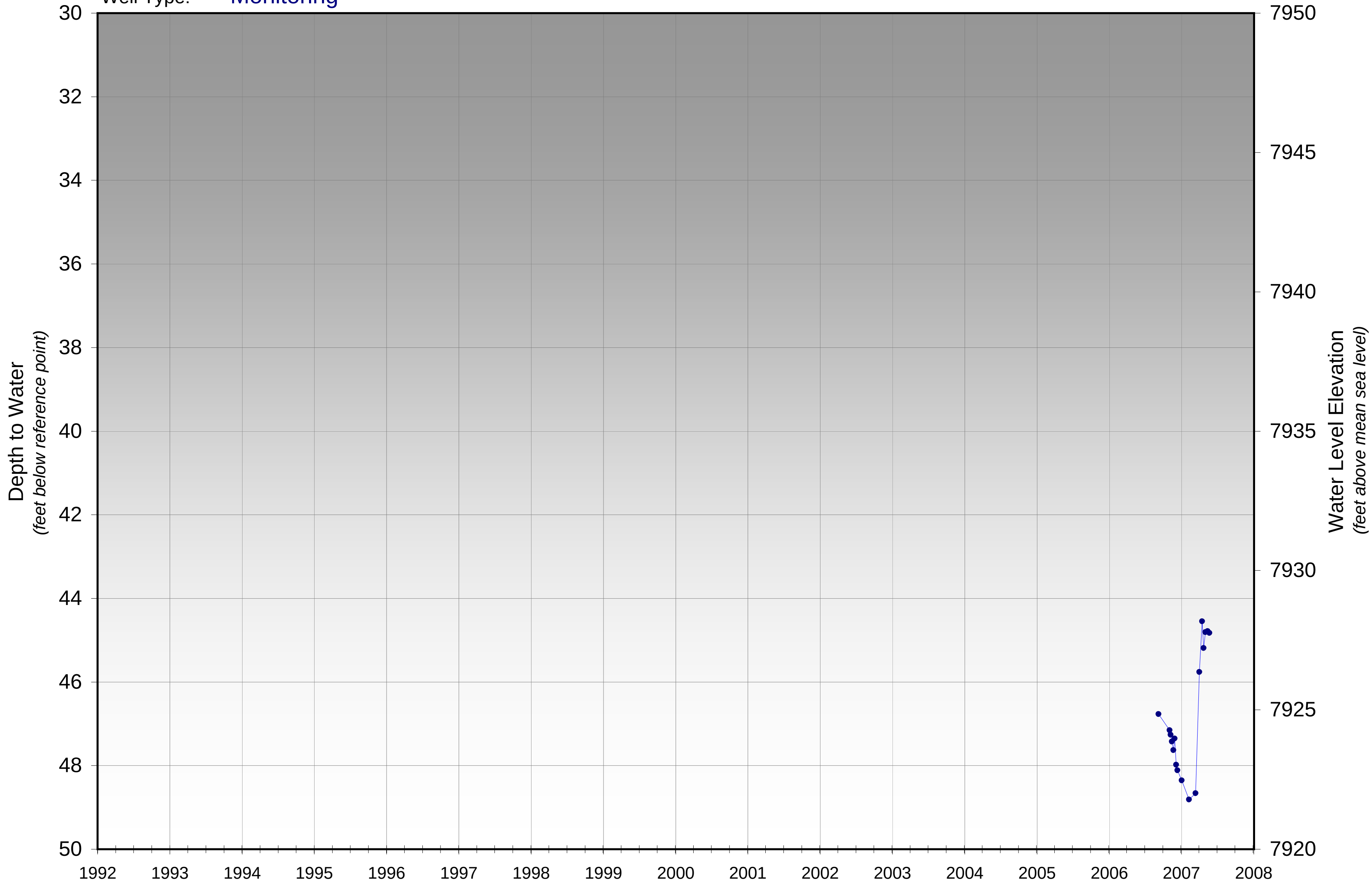
Groundwater-Level Time Series

Well Name: **Well #27**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7969.9' above mean sea level
Ground Surface Elevation = 7969.9' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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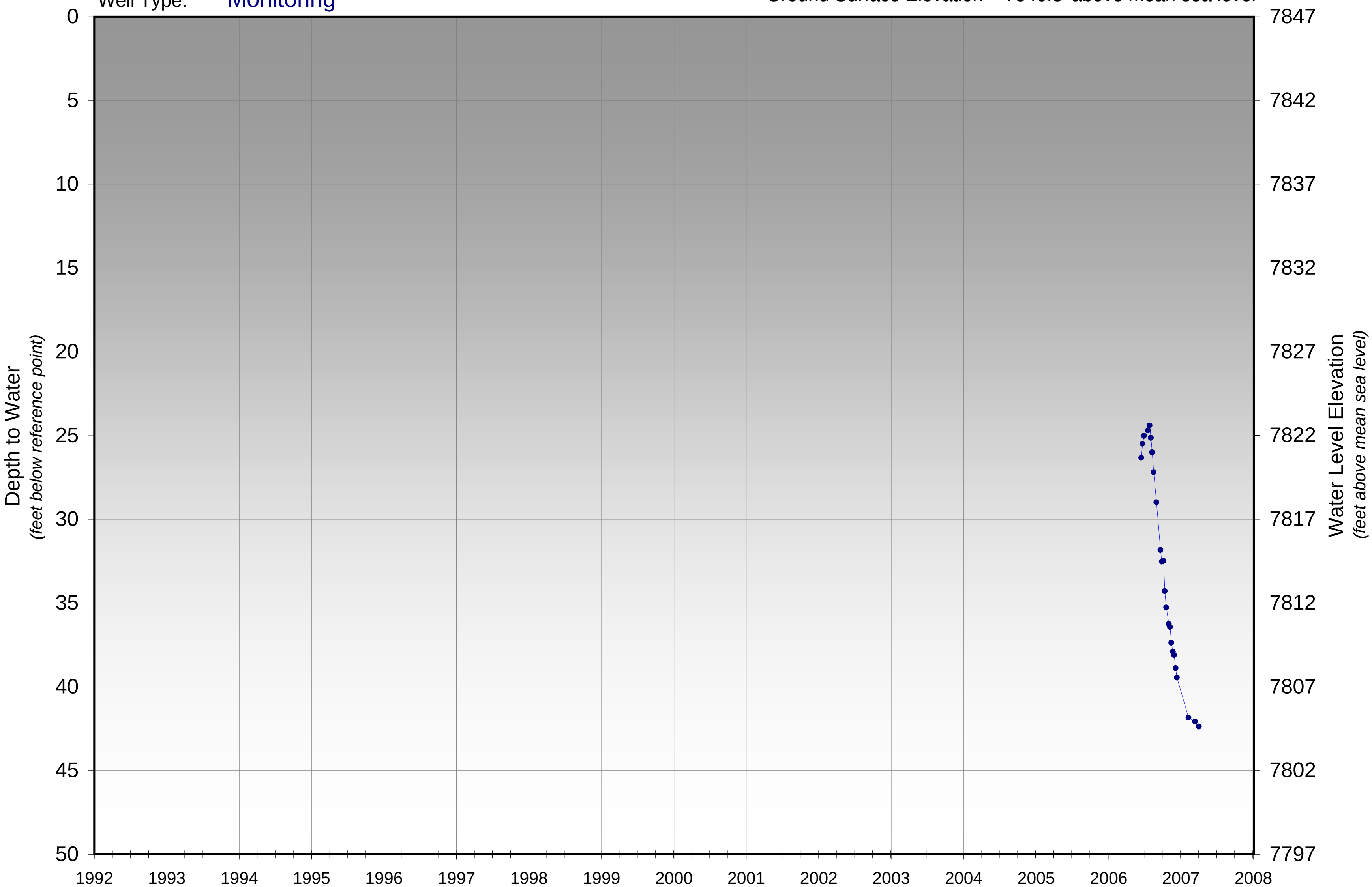
Groundwater-Level Time Series

Well Name: **Well #28**
Owner Name: Mammoth Community Water District
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7846.8' above mean sea level
Ground Surface Elevation = 7846.8' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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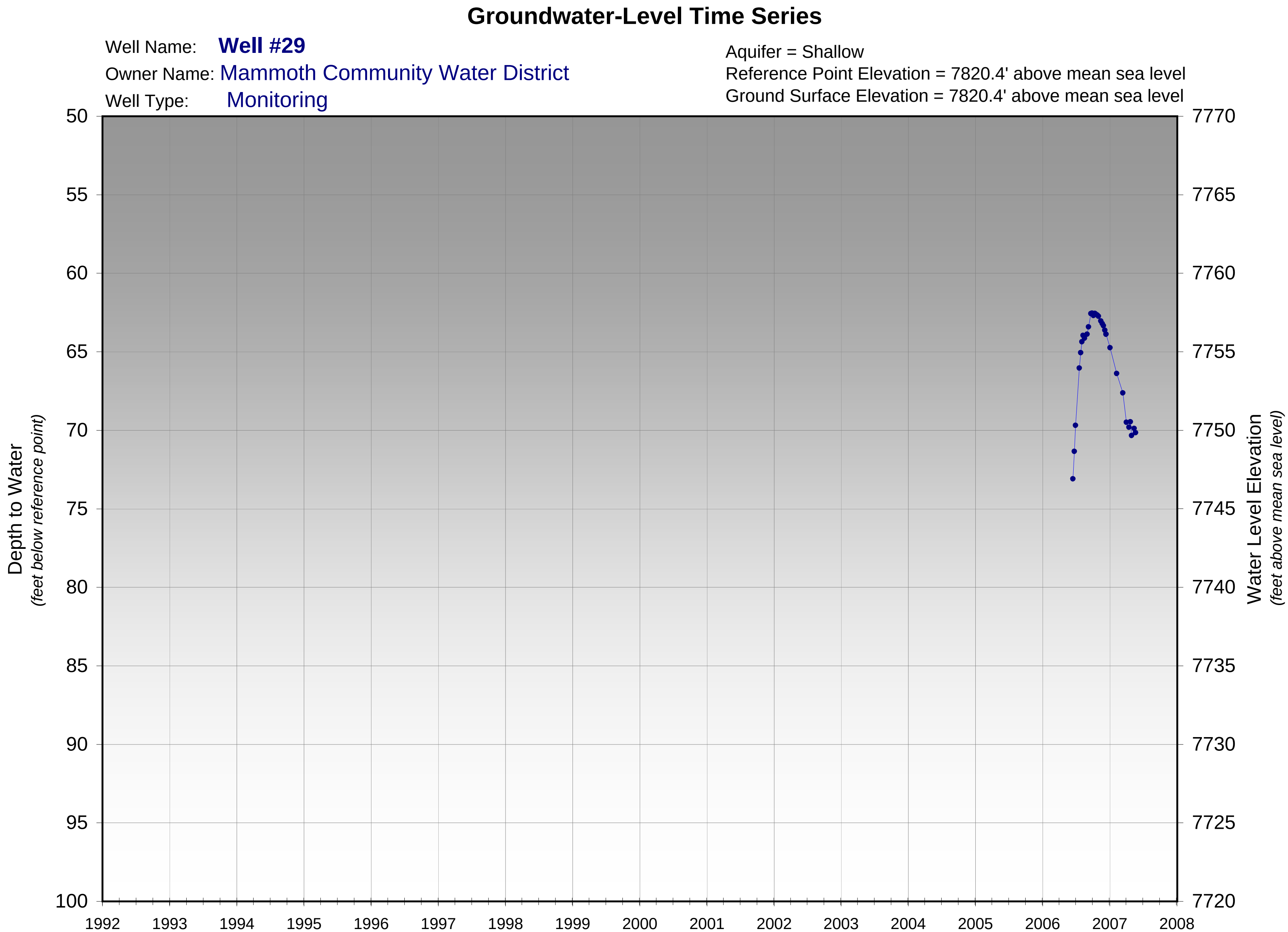

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **Well #30**

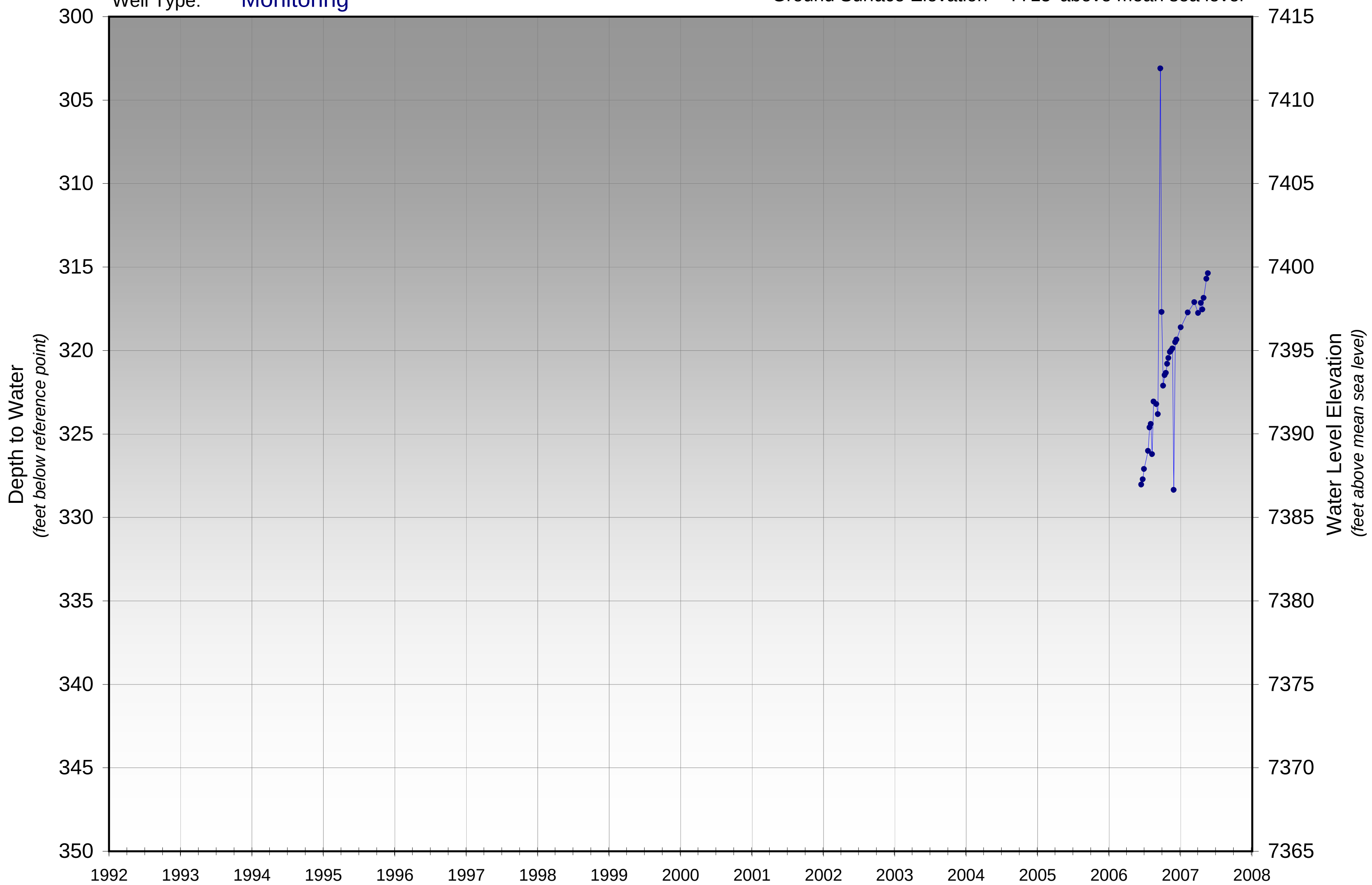
Owner Name: Mammoth Community Water District

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7715' above mean sea level

Ground Surface Elevation = 7715' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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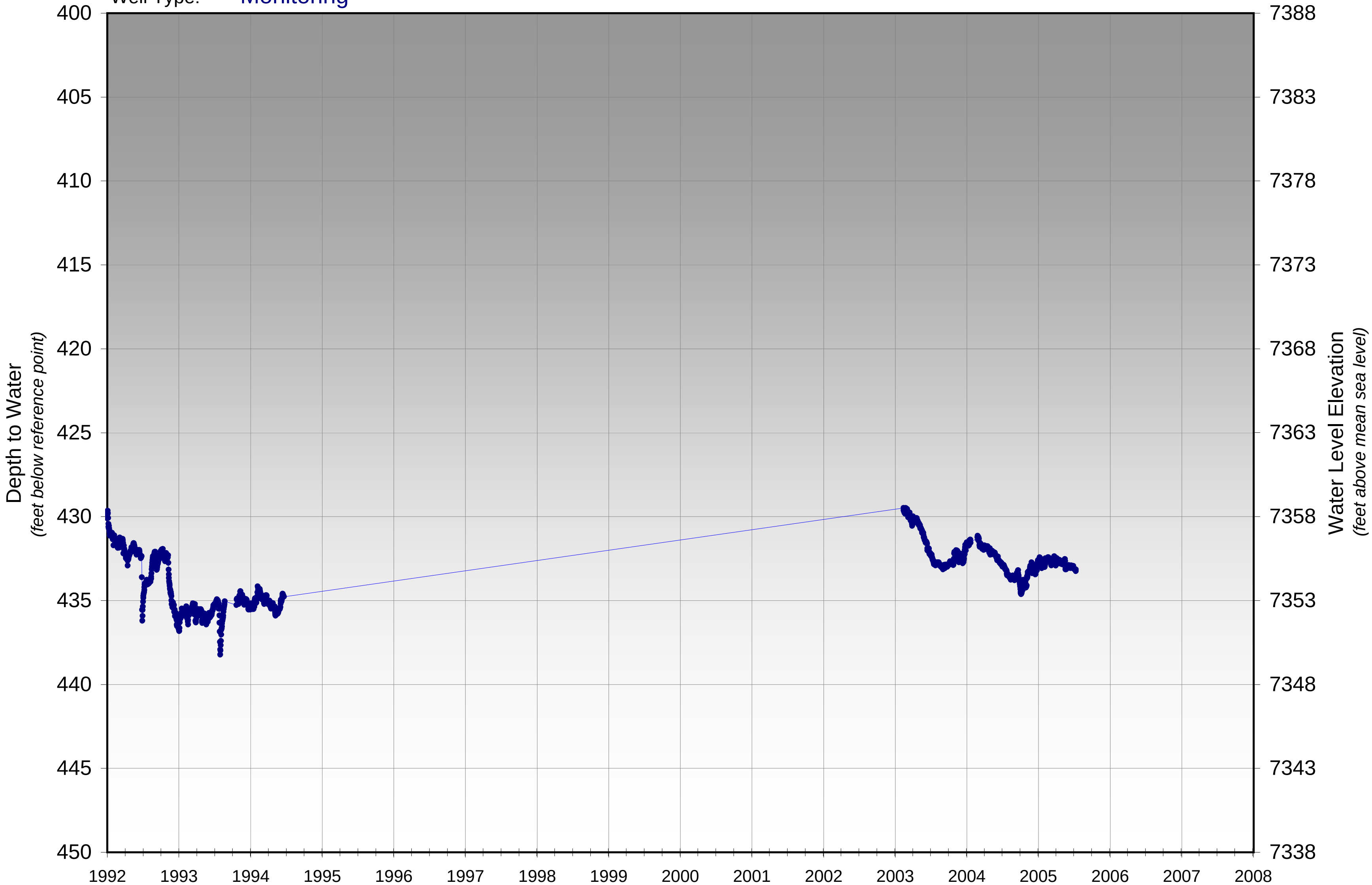
Groundwater-Level Time Series

Well Name: **RDO8**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7788.4' above mean sea level
Ground Surface Elevation = 7788.4' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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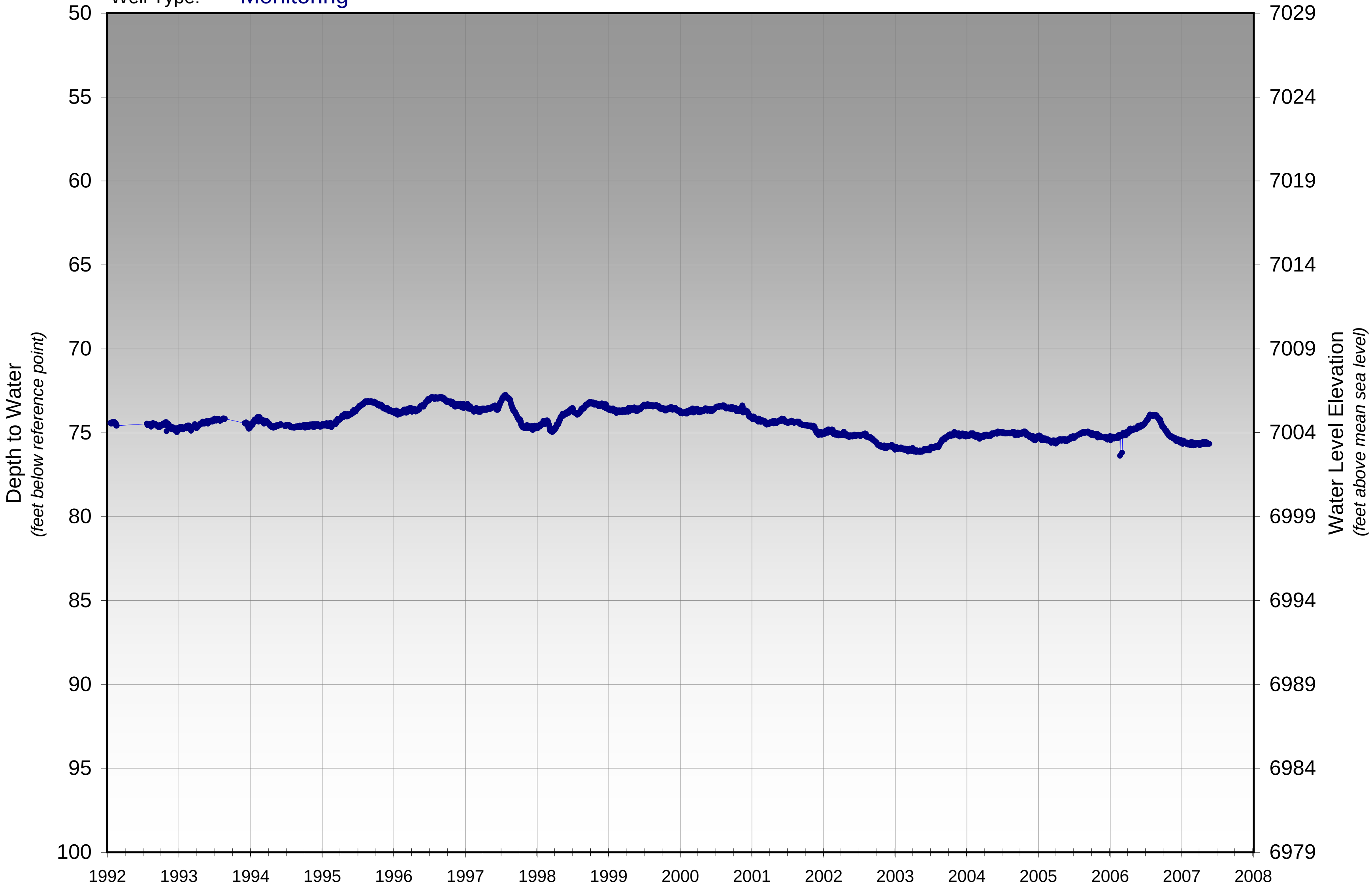
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **CH-10B**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7079' above mean sea level
Ground Surface Elevation = 7079' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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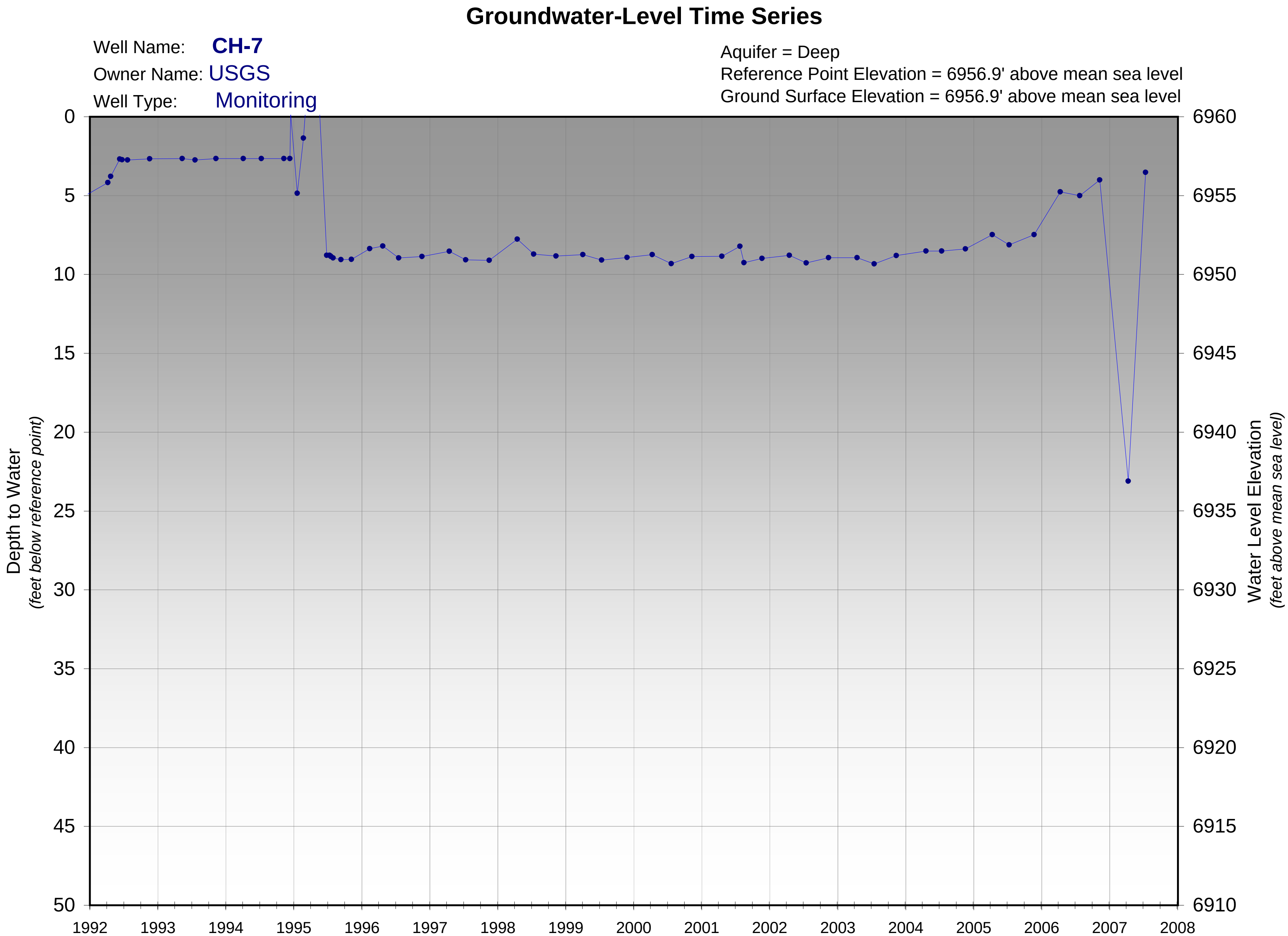

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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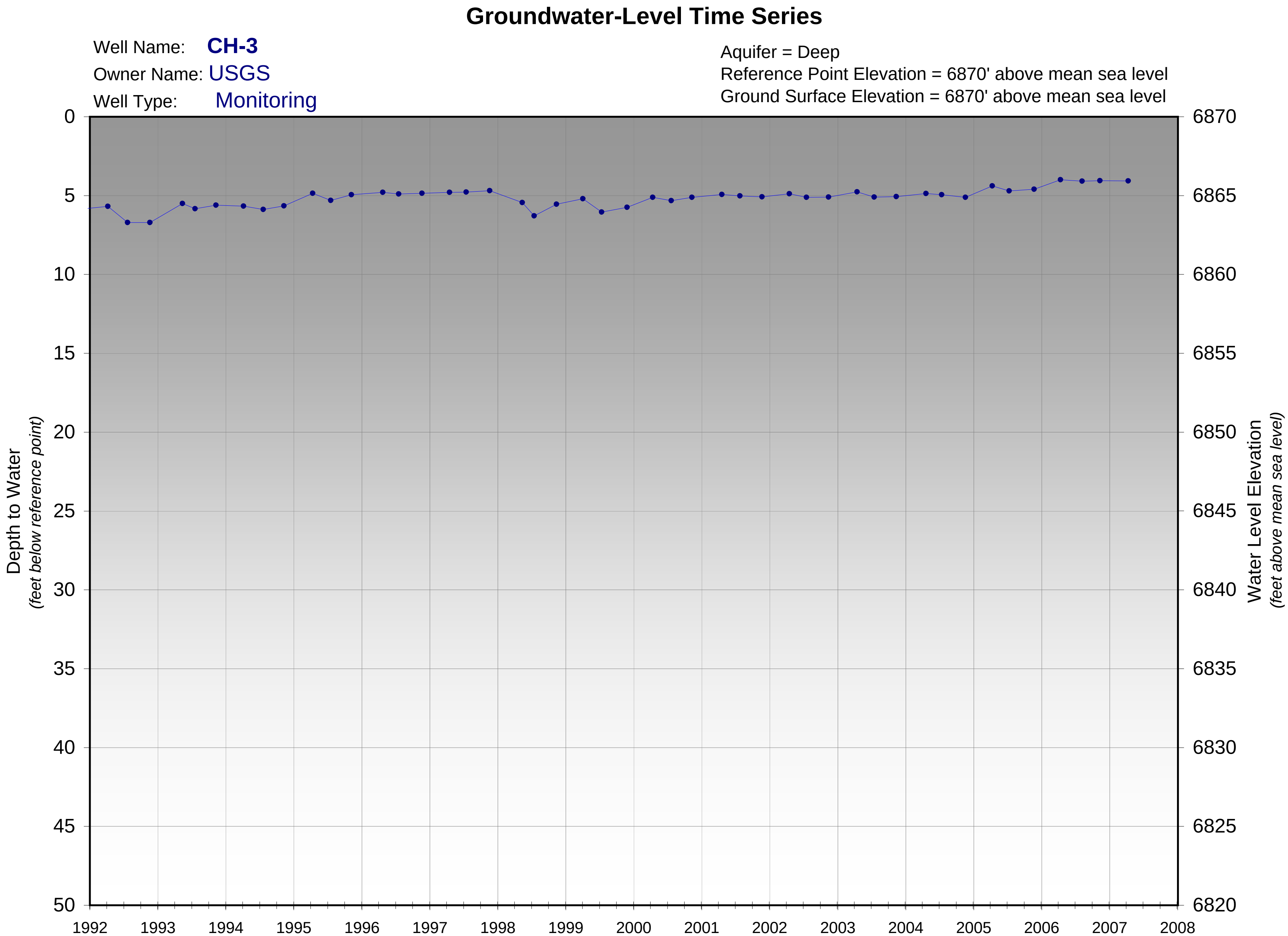

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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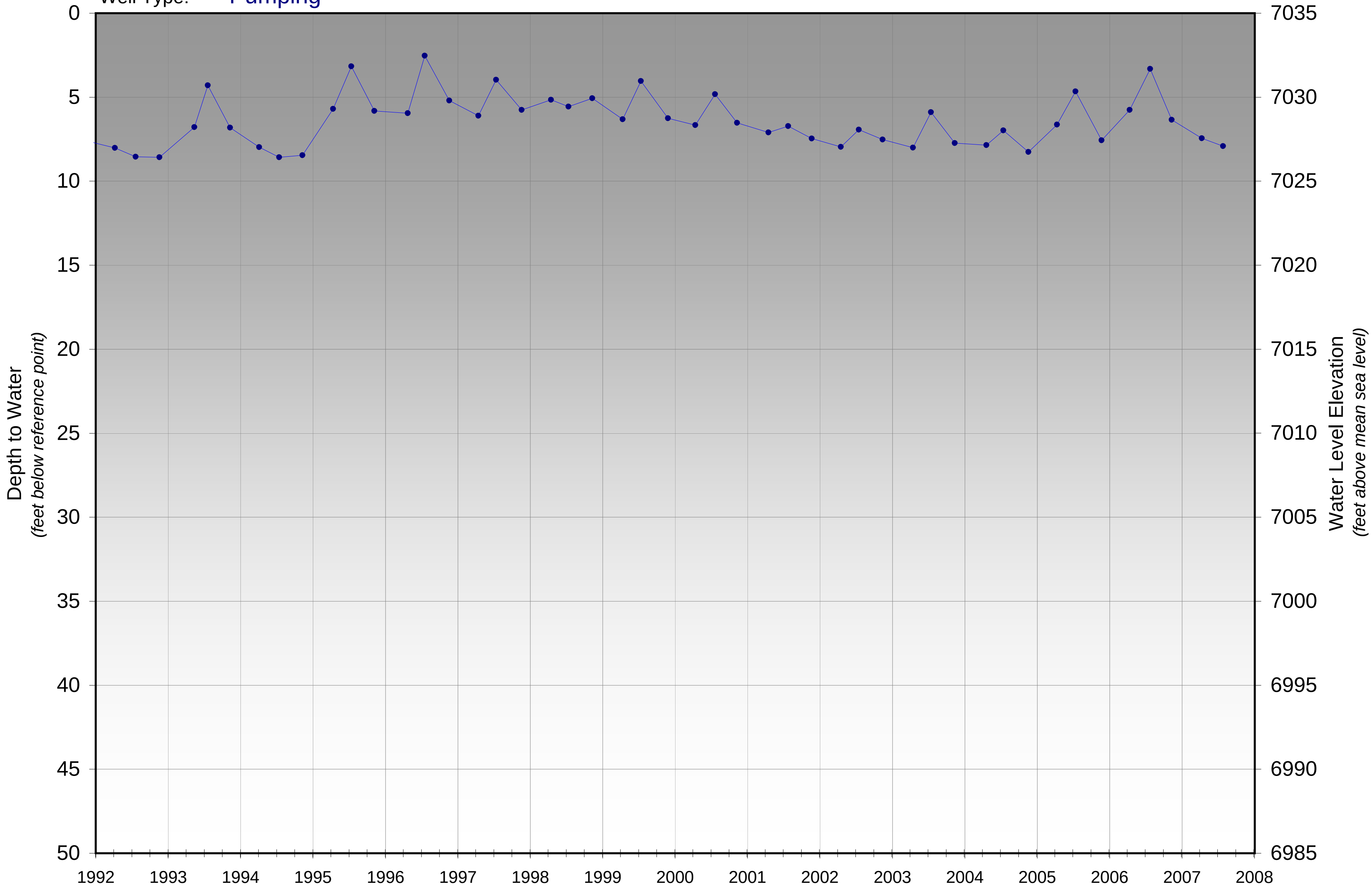
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **CHURCH**
Owner Name: USGS
Well Type: Pumping

Aquifer = Shallow
Reference Point Elevation = 7035' above mean sea level
Ground Surface Elevation = 7035' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **LV-18**

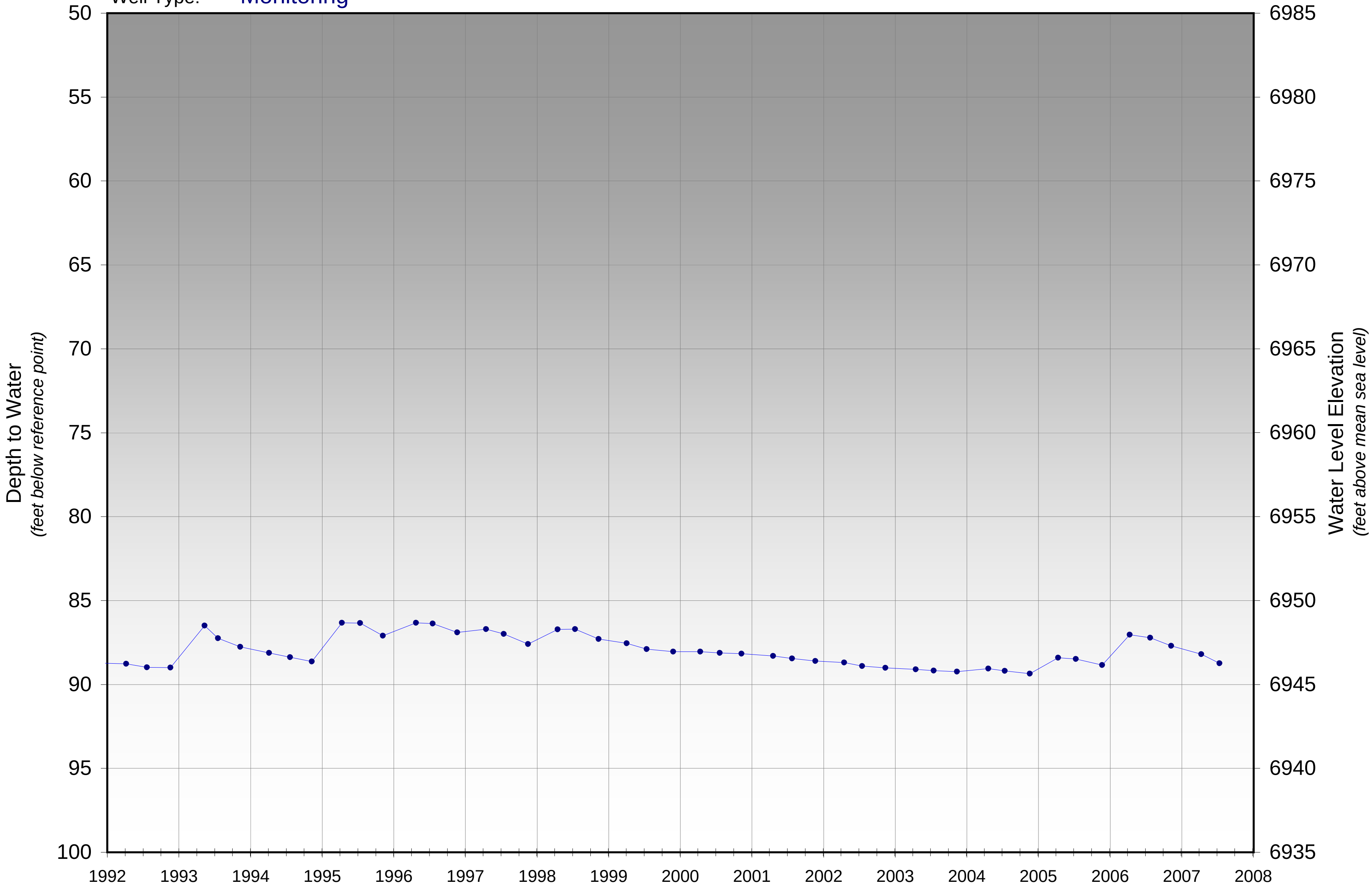
Owner Name: USGS

Well Type: Monitoring

Aquifer = Shallow

Reference Point Elevation = 7035' above mean sea level

Ground Surface Elevation = 7035' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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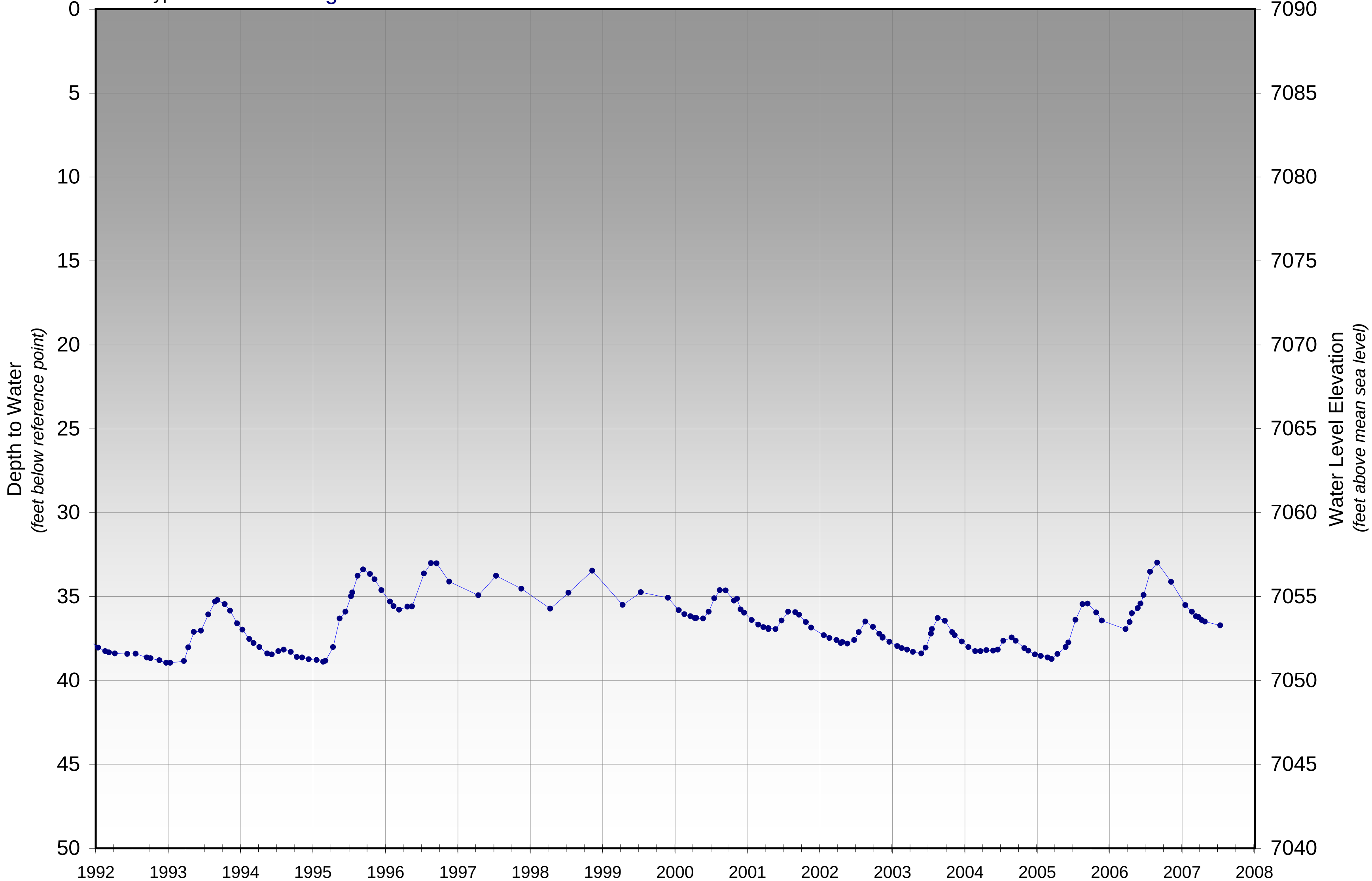
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **LV-19**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7090.4' above mean sea level
Ground Surface Elevation = 7090.4' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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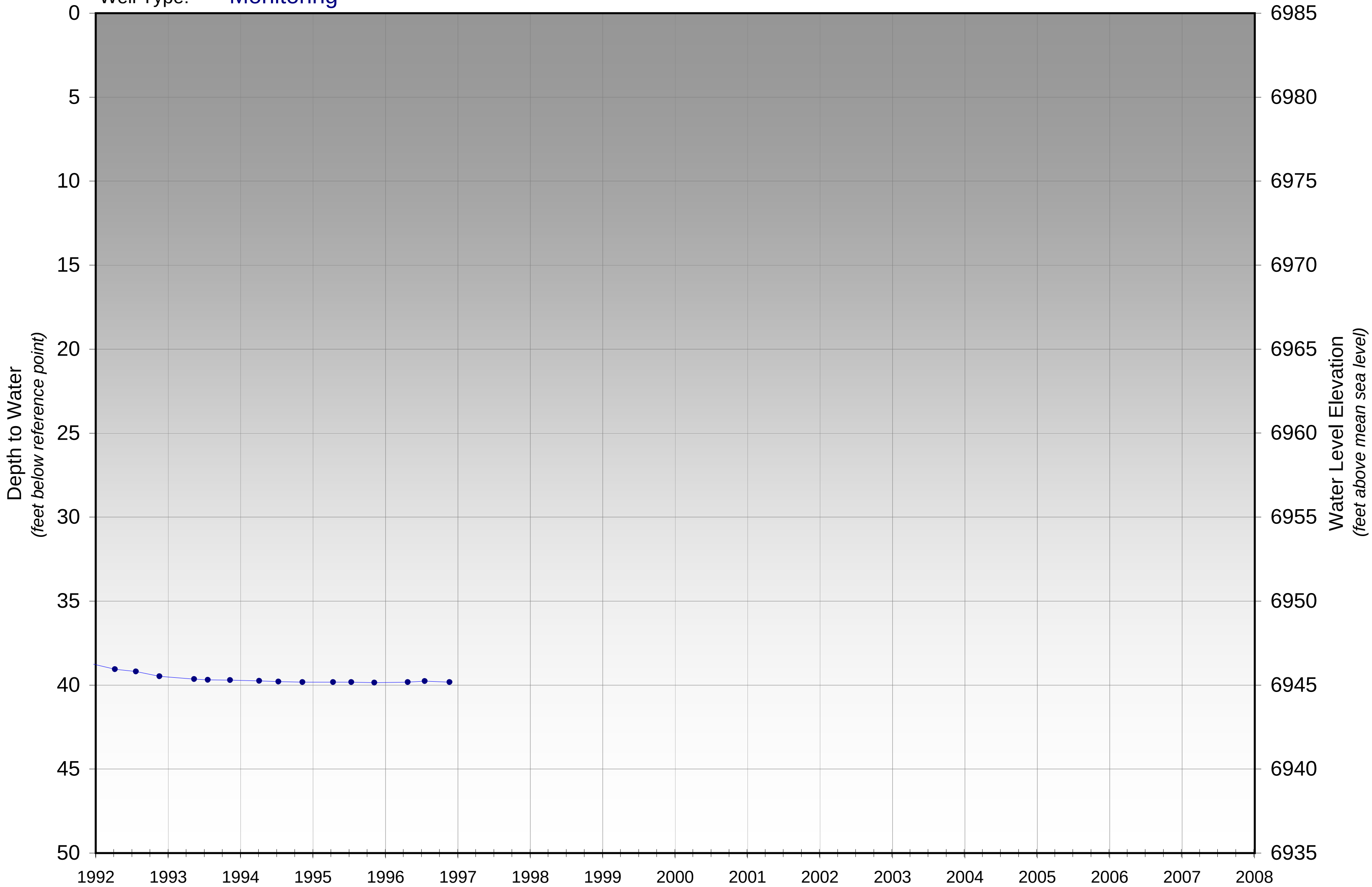
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **LV-45**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 6985.4' above mean sea level
Ground Surface Elevation = 6985.4' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **PD**

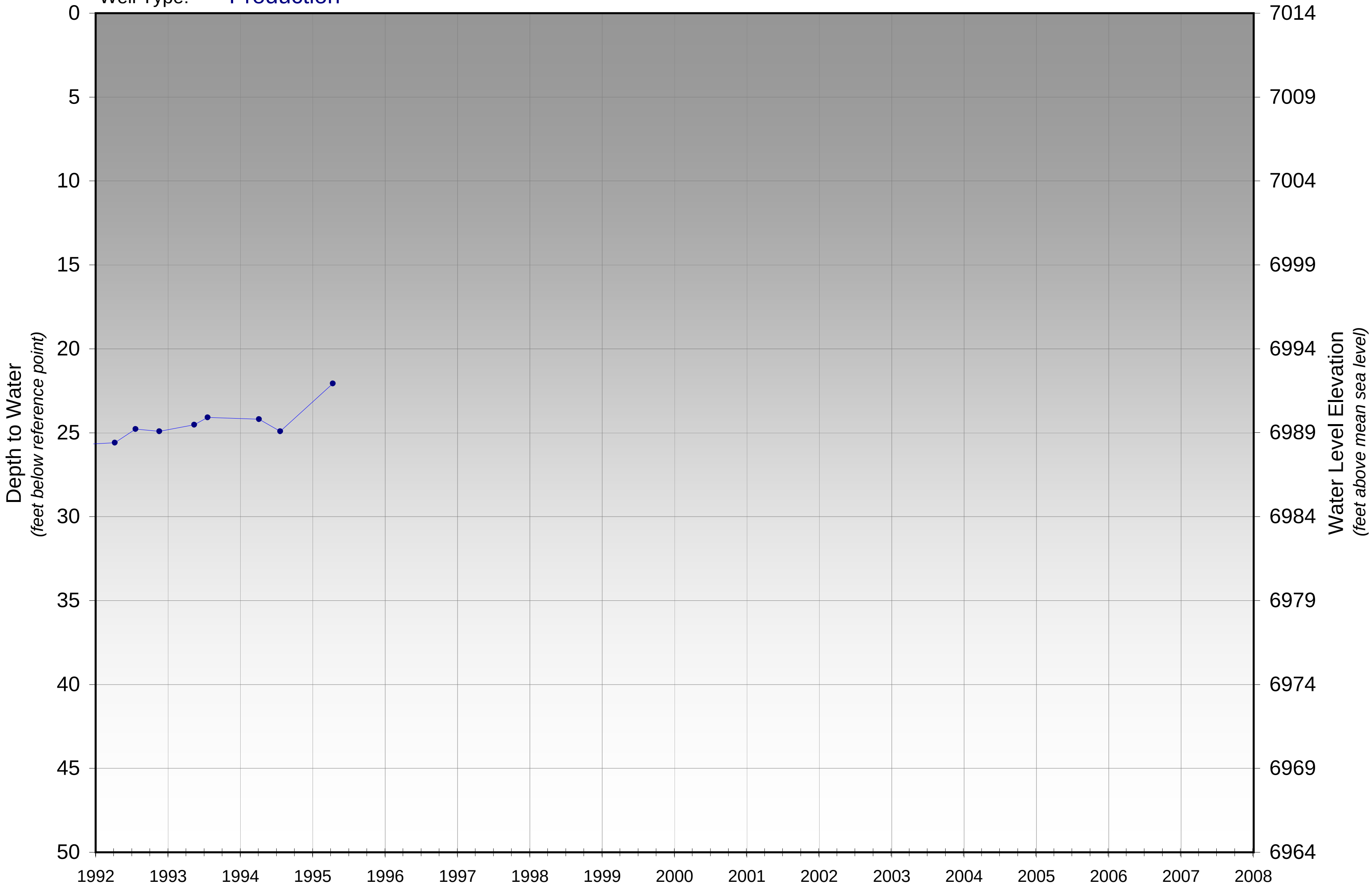
Owner Name: Mono County Probation Department

Well Type: Production

Aquifer = Shallow

Reference Point Elevation = 7014' above mean sea level

Ground Surface Elevation = 7014' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **AP**

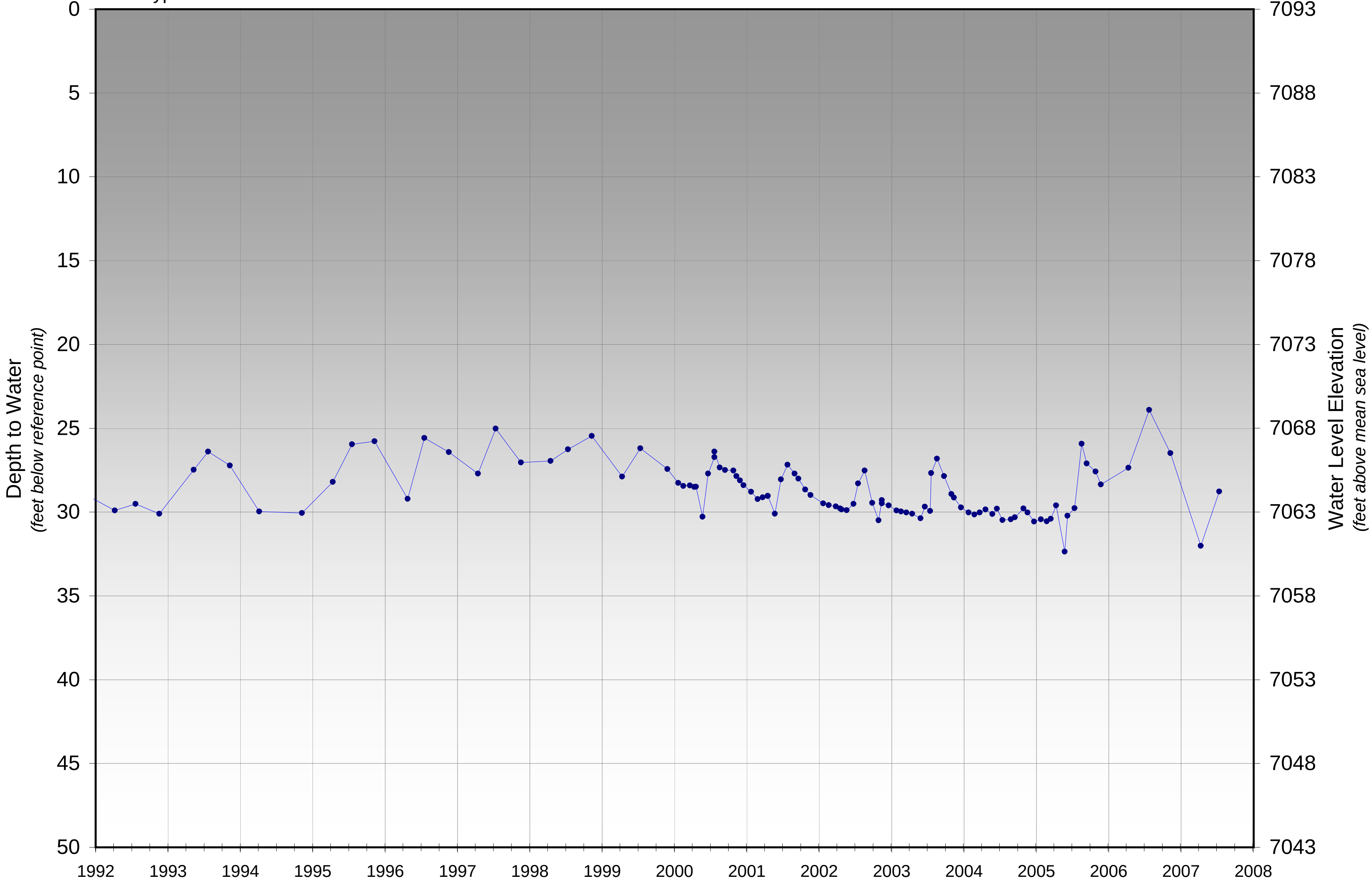
Owner Name: Airport

Well Type: Production

Aquifer = Shallow

Reference Point Elevation = 7093' above mean sea level

Ground Surface Elevation = 7093' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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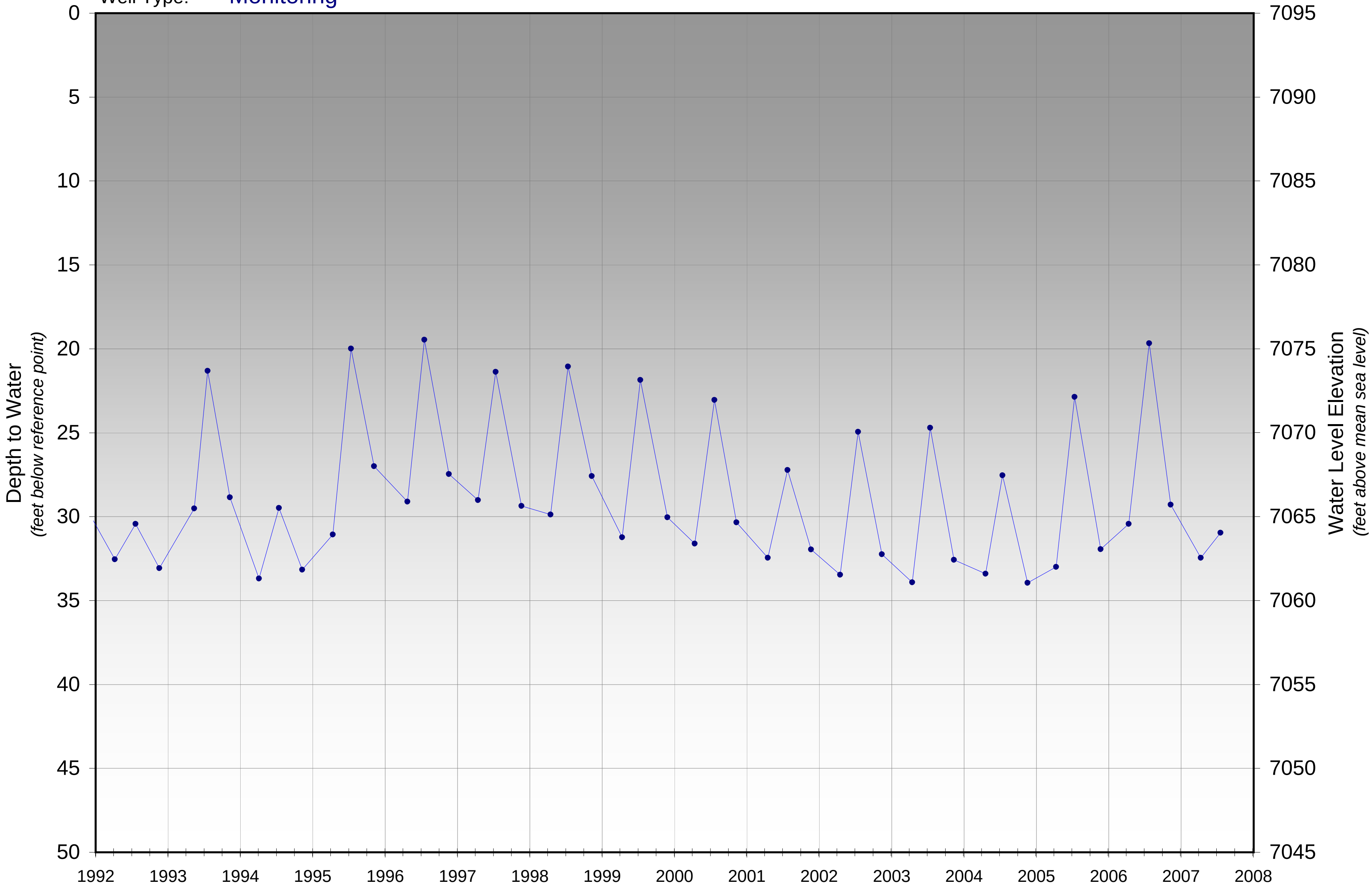
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **SNARL**
Owner Name: Sierra Nevada Aquatic Research Laboratory
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7095' above mean sea level
Ground Surface Elevation = 7095' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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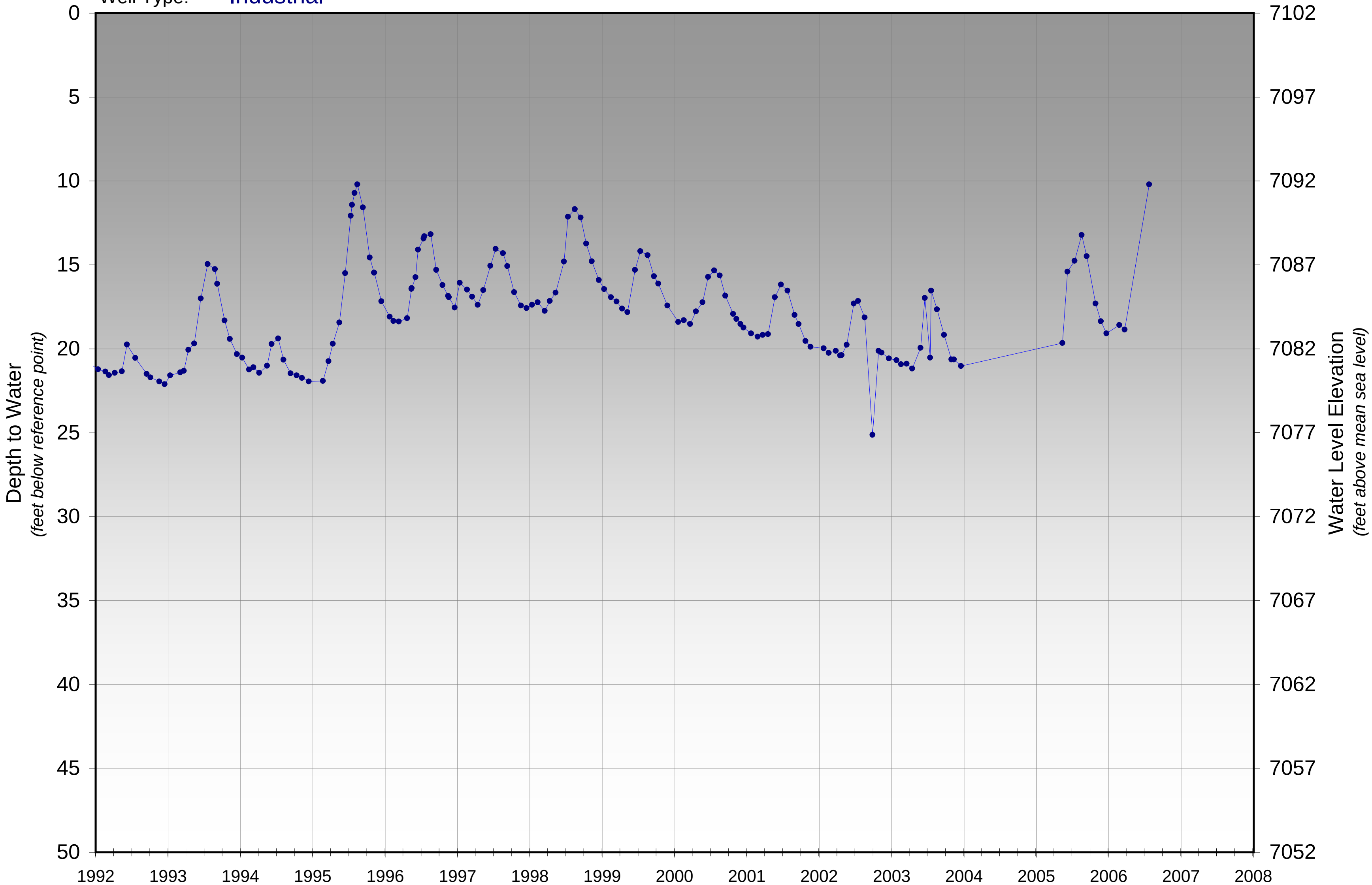
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **SQ**
Owner Name: SQ
Well Type: Industrial

Aquifer = Shallow
Reference Point Elevation = 7102' above mean sea level
Ground Surface Elevation = 7102' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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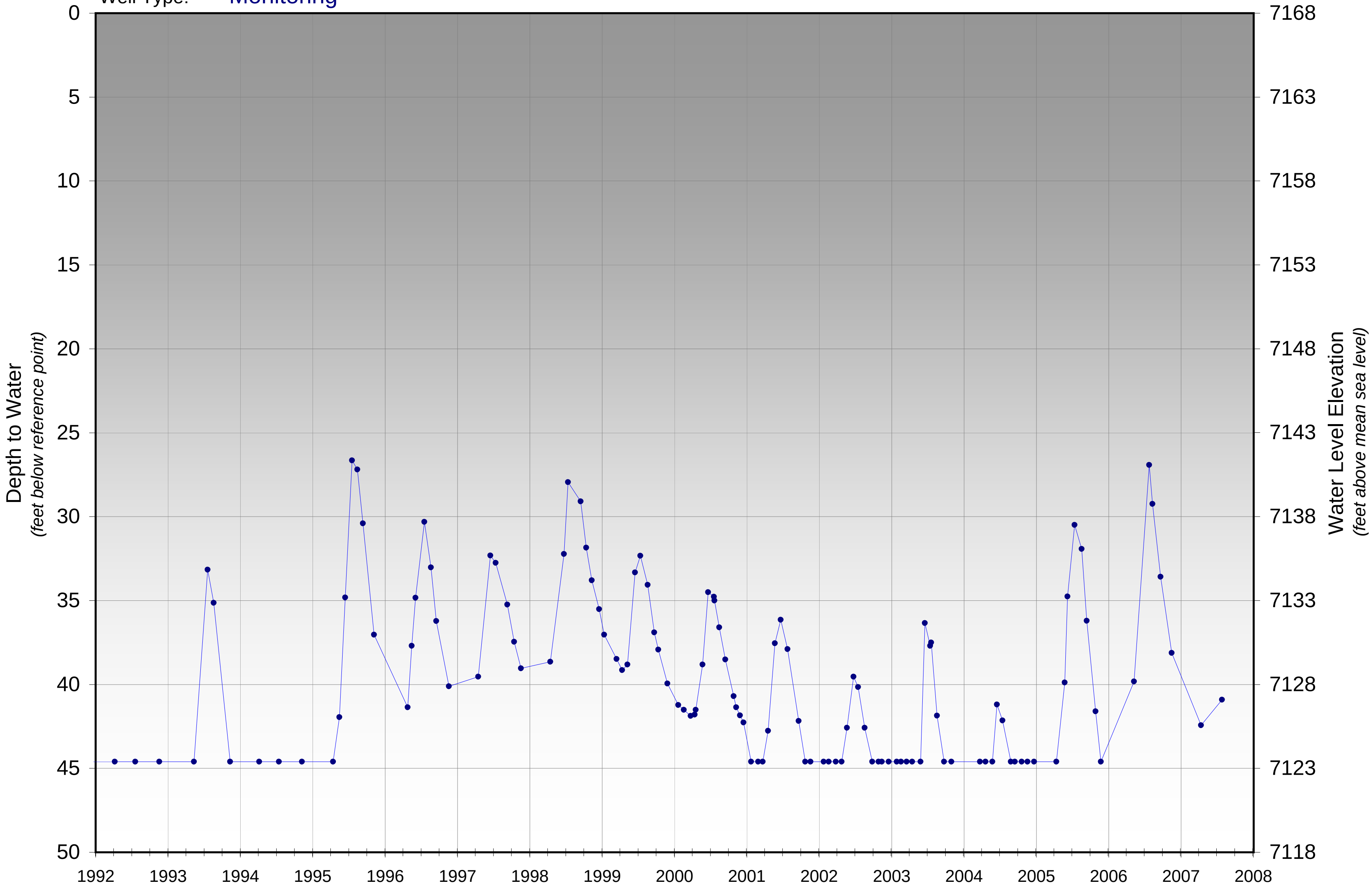
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **LV-2**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7167.4' above mean sea level
Ground Surface Elevation = 7167.4' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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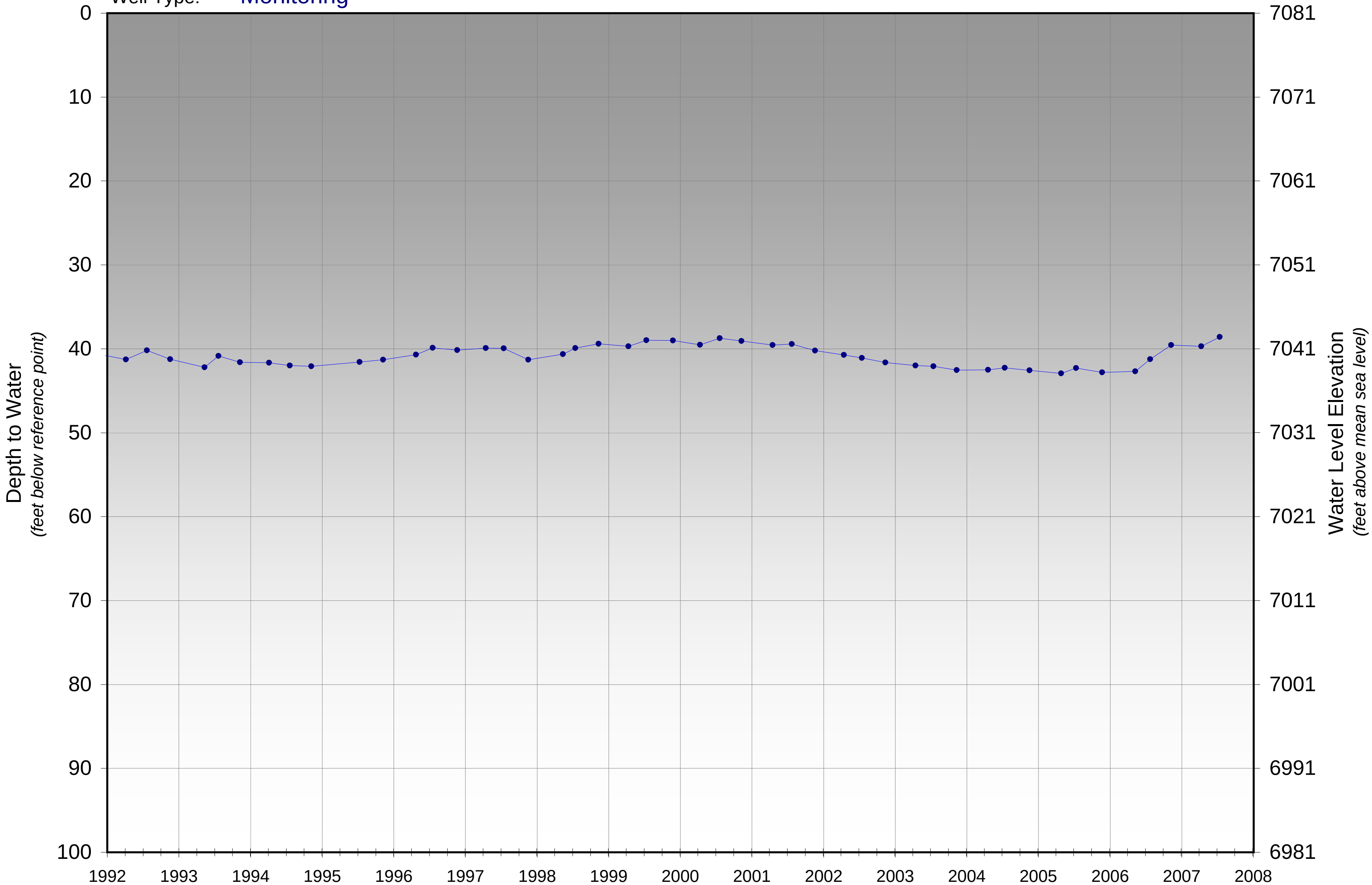
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **MW-4**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7081.3' above mean sea level
Ground Surface Elevation = 7081.3' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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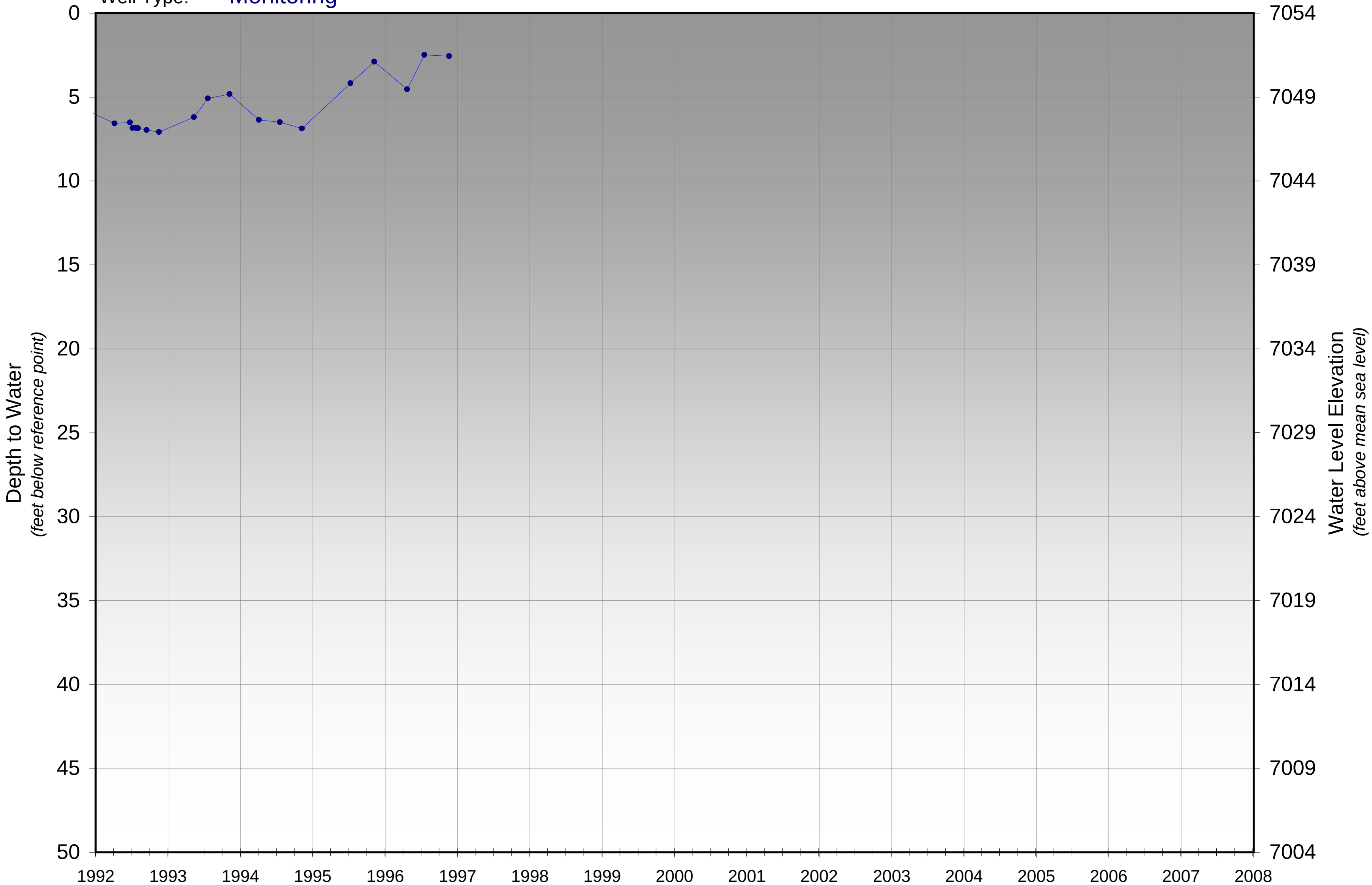
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **MW-5**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7054.1' above mean sea level
Ground Surface Elevation = 7054.1' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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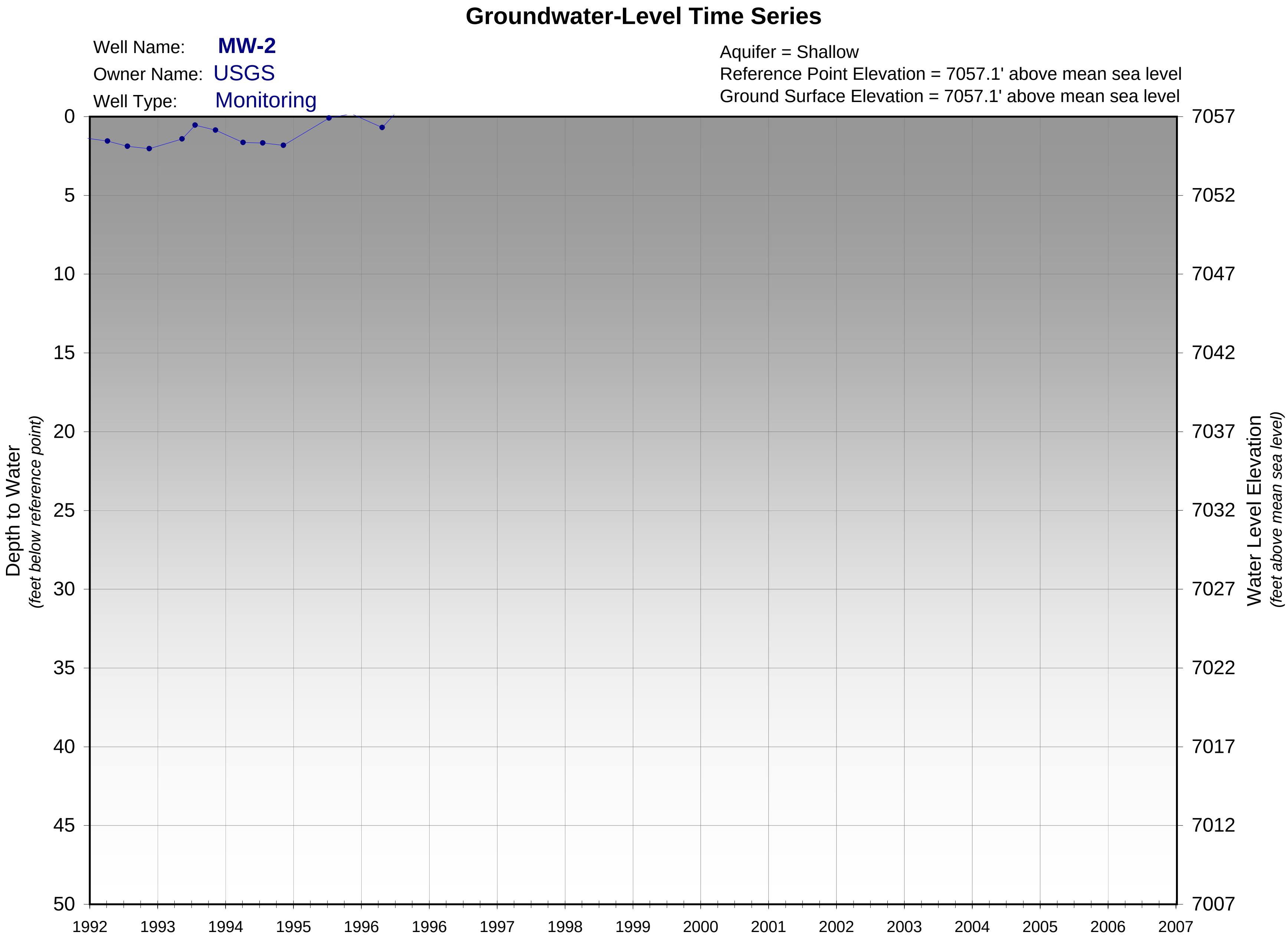
WILDERMUTH™ ENVIRONMENTAL INC.



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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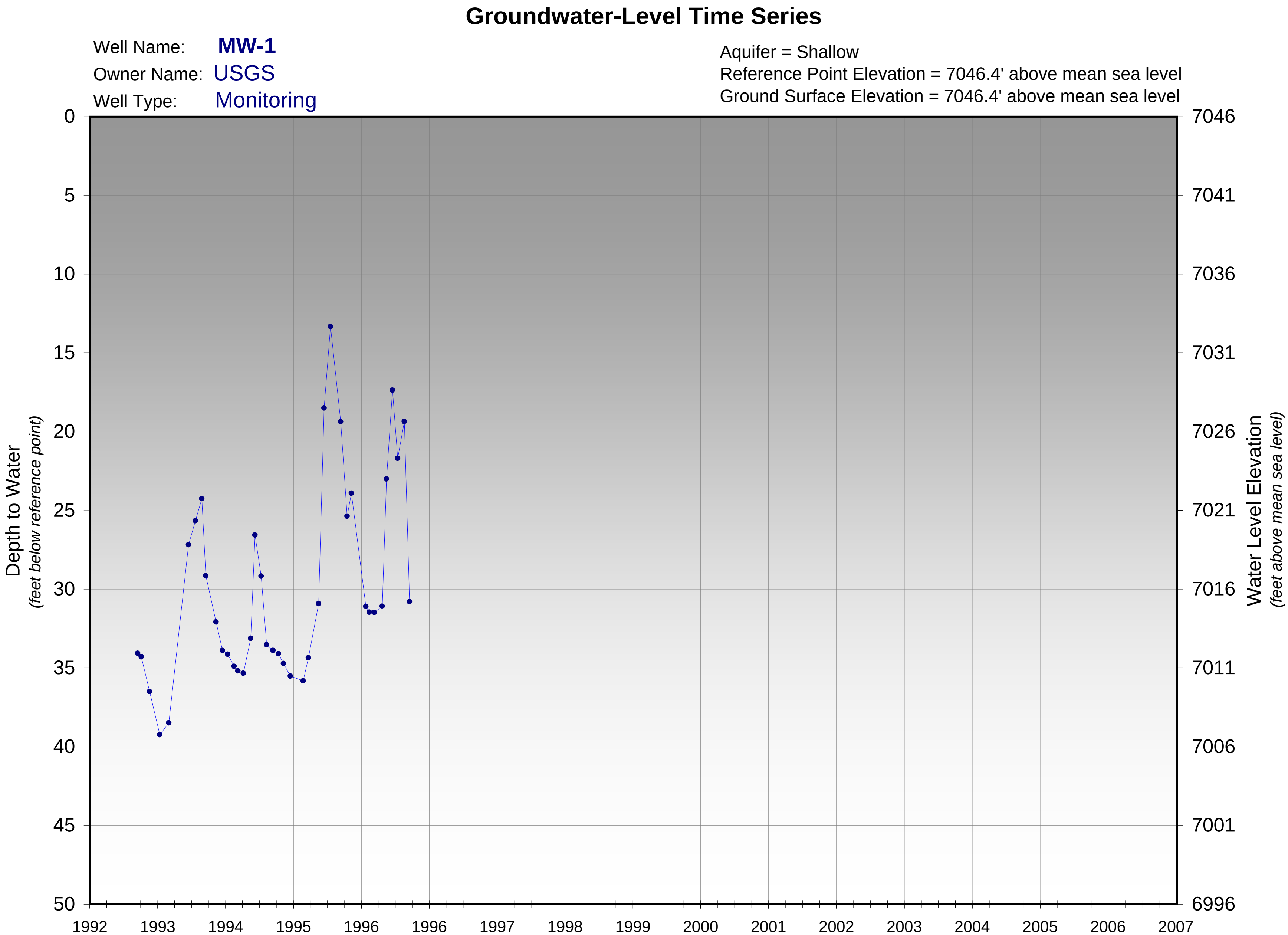

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **CW-1**

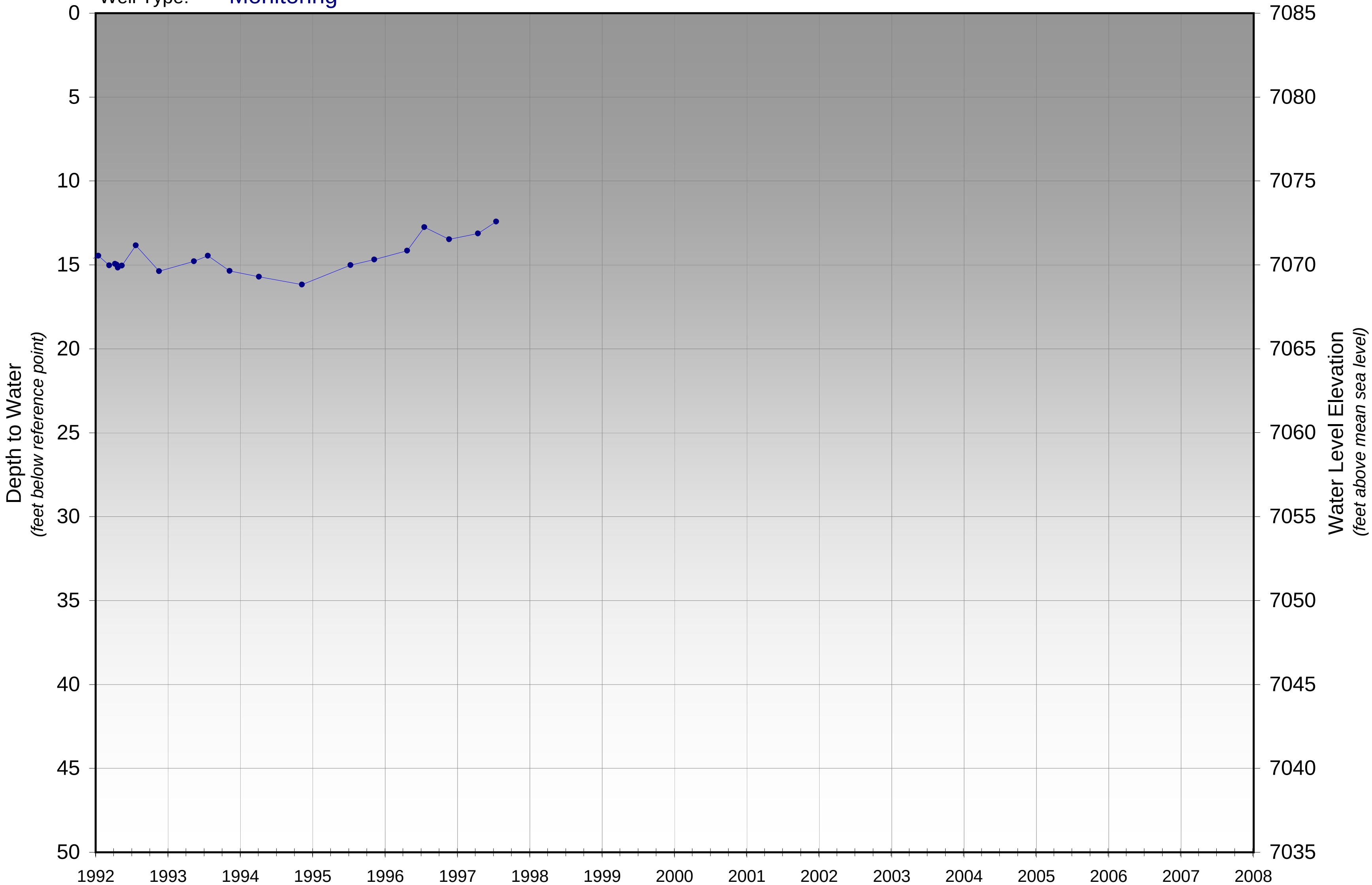
Owner Name: USGS

Well Type: Monitoring

Aquifer = Deep

Reference Point Elevation = 7085' above mean sea level

Ground Surface Elevation = 7085' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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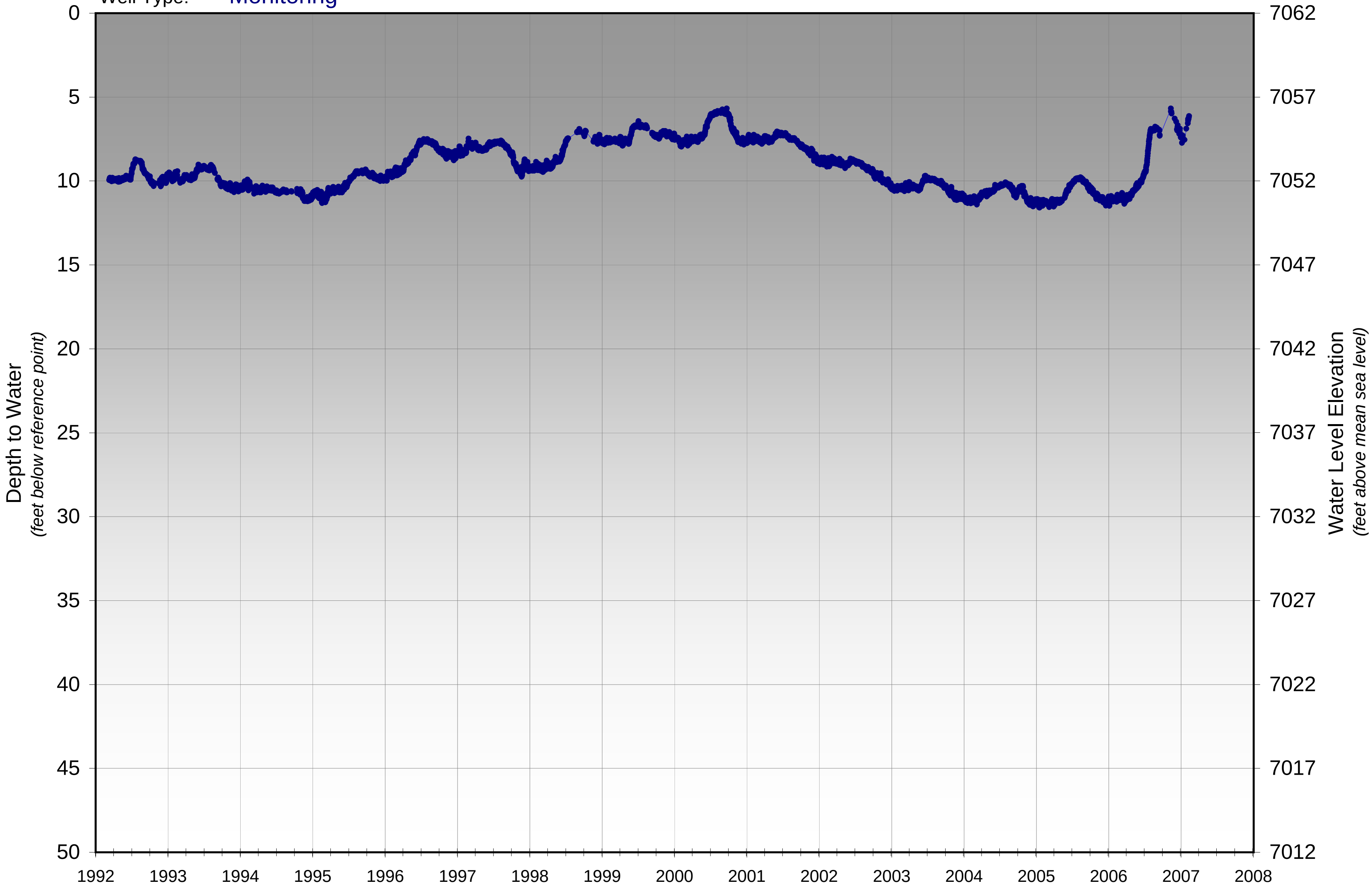
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **CW-3**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7062.2' above mean sea level
Ground Surface Elevation = 7062.2' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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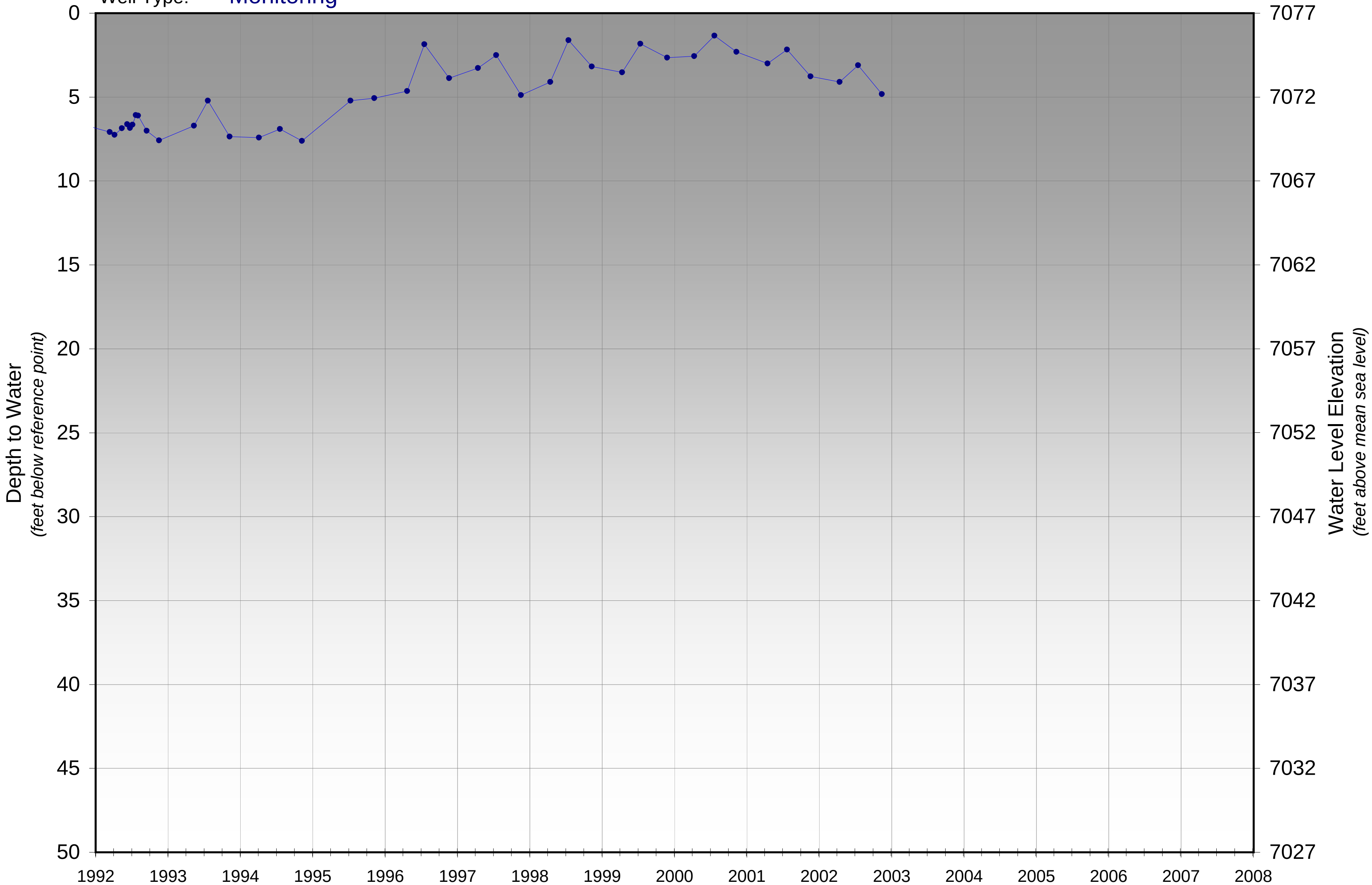
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **CM-2**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7077' above mean sea level
Ground Surface Elevation = 7077' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **SS-2**

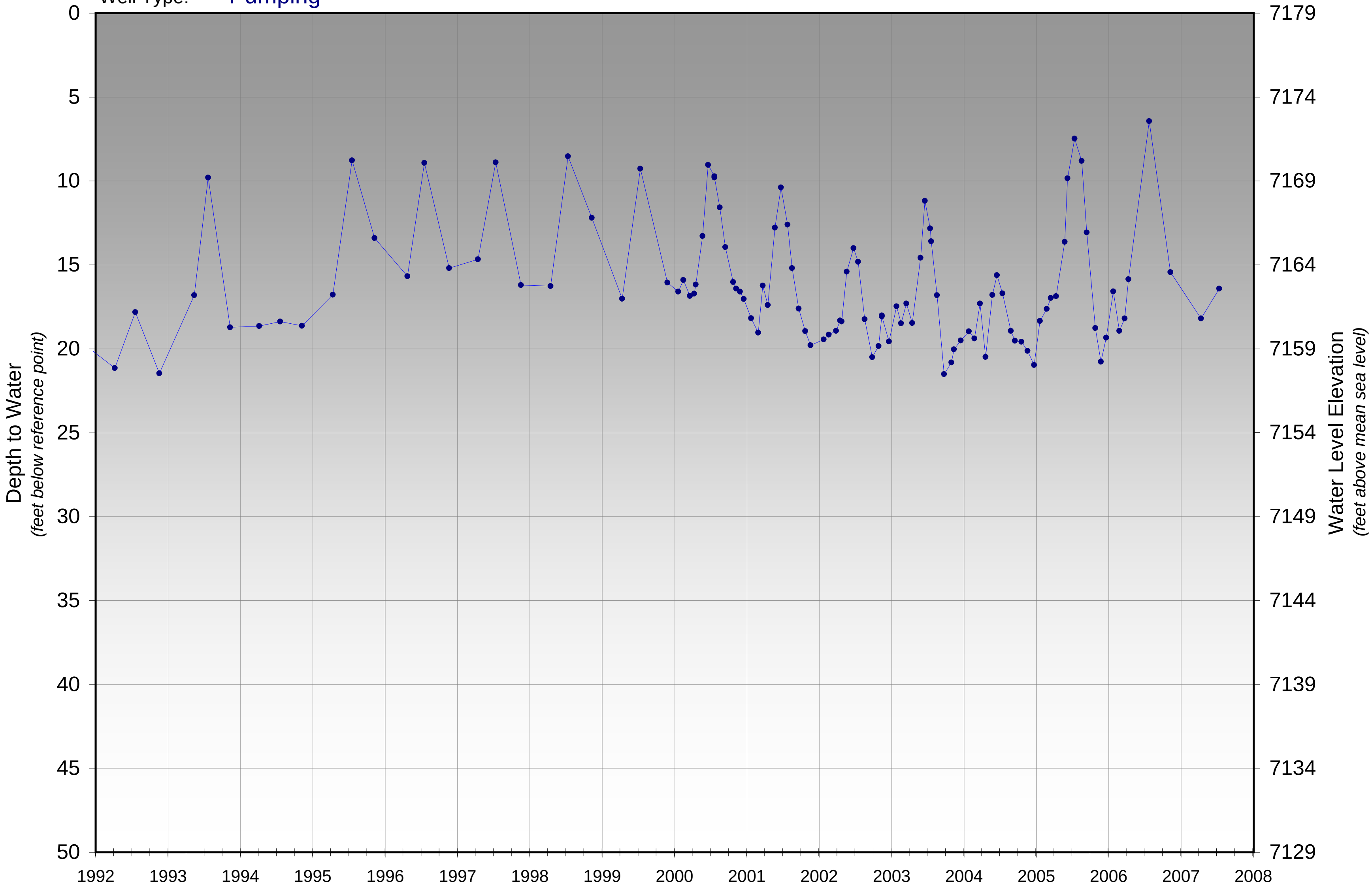
Owner Name: Mono County Sheriff Department

Well Type: Pumping

Aquifer = Deep

Reference Point Elevation = 7179' above mean sea level

Ground Surface Elevation = 7179' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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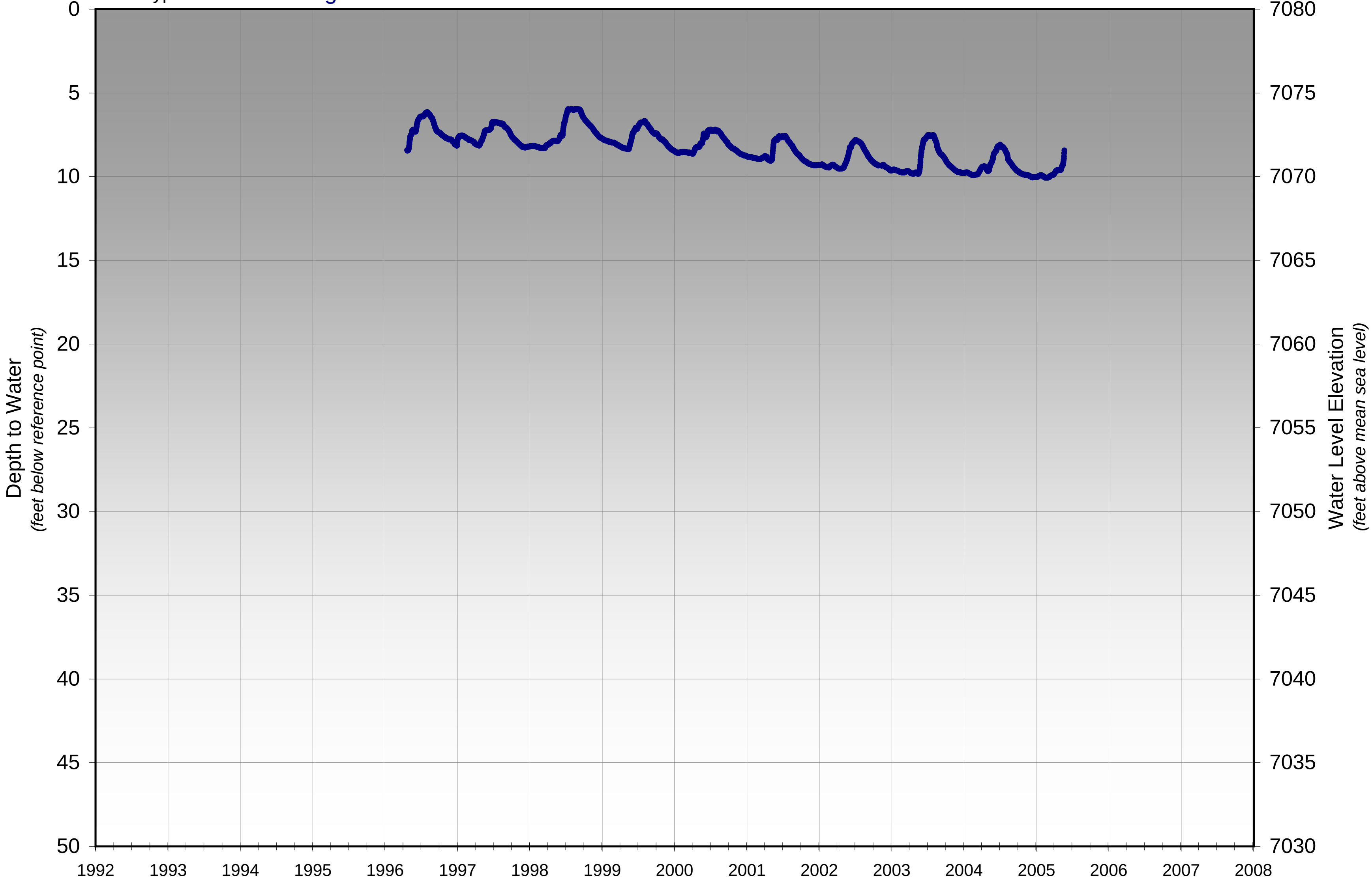
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **ESN**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7080' above mean sea level
Ground Surface Elevation = 7080' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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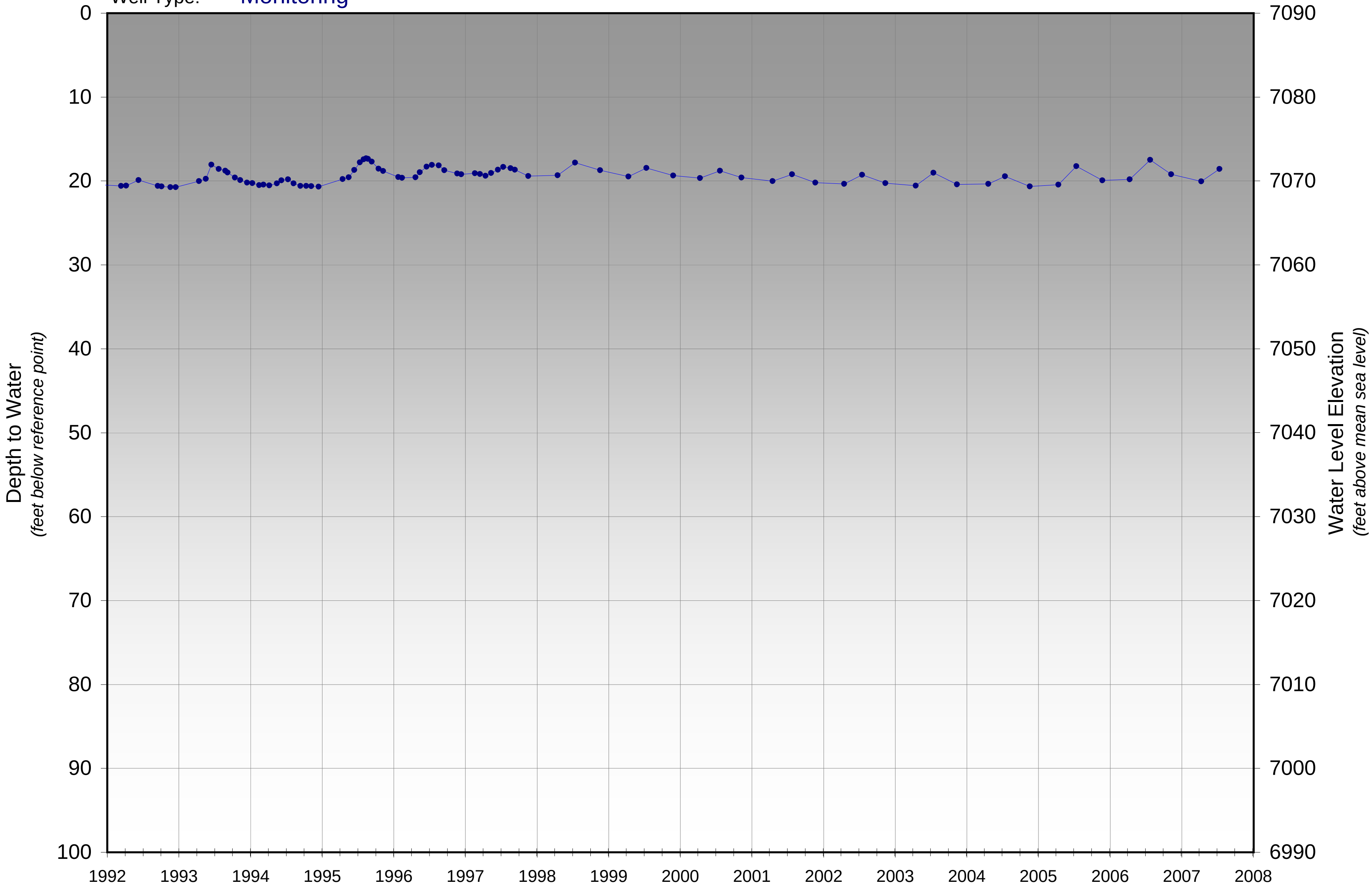
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **ESO**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7090' above mean sea level
Ground Surface Elevation = 7090' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **CR**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7161.8' above mean sea level
Ground Surface Elevation = 7161.8' above mean sea level

Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Groundwater-Level Time Series

Well Name: **CD-2**

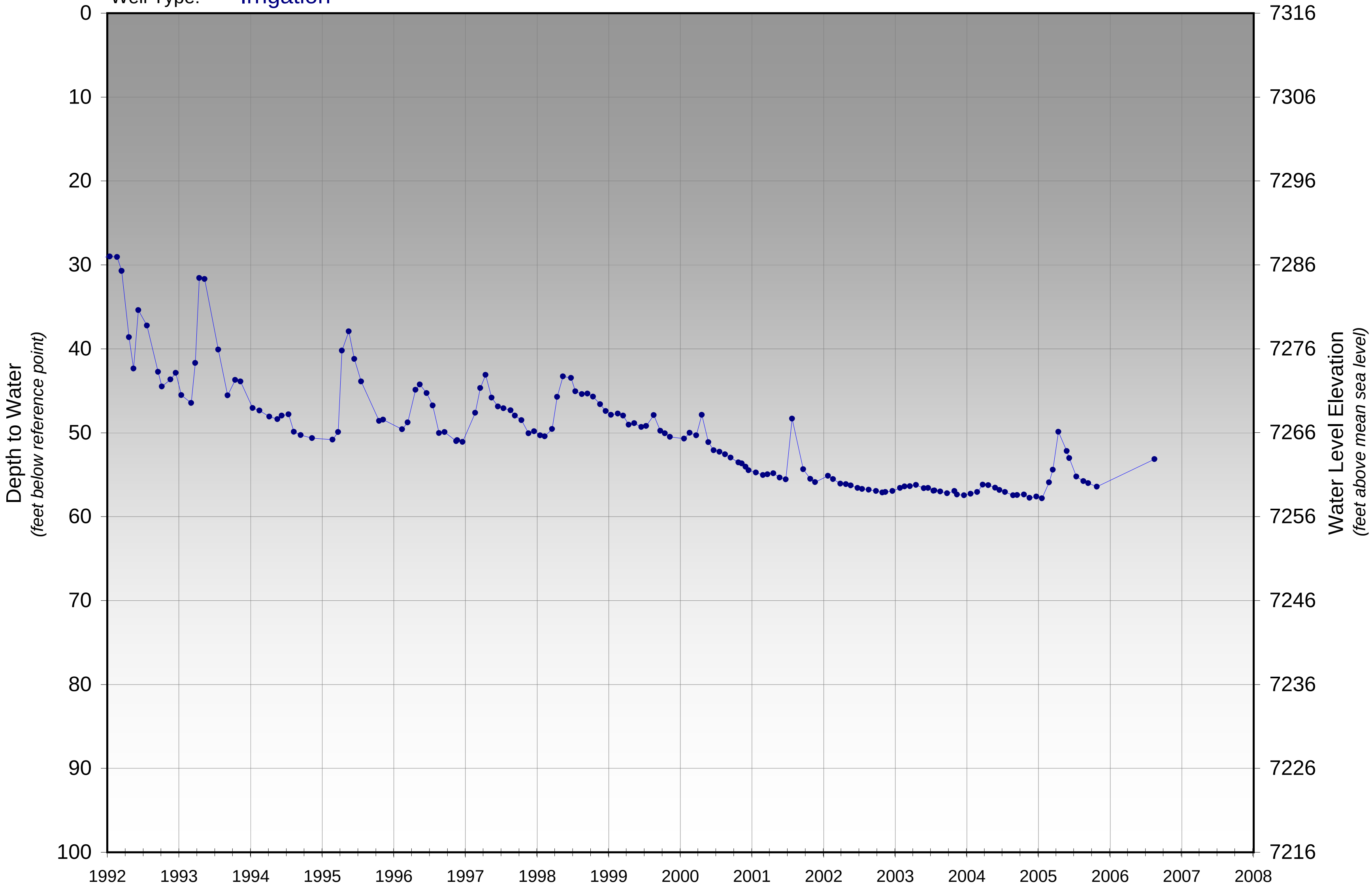
Owner Name: USGS

Well Type: Irrigation

Aquifer = Shallow

Reference Point Elevation = 7316' above mean sea level

Ground Surface Elevation = 7316' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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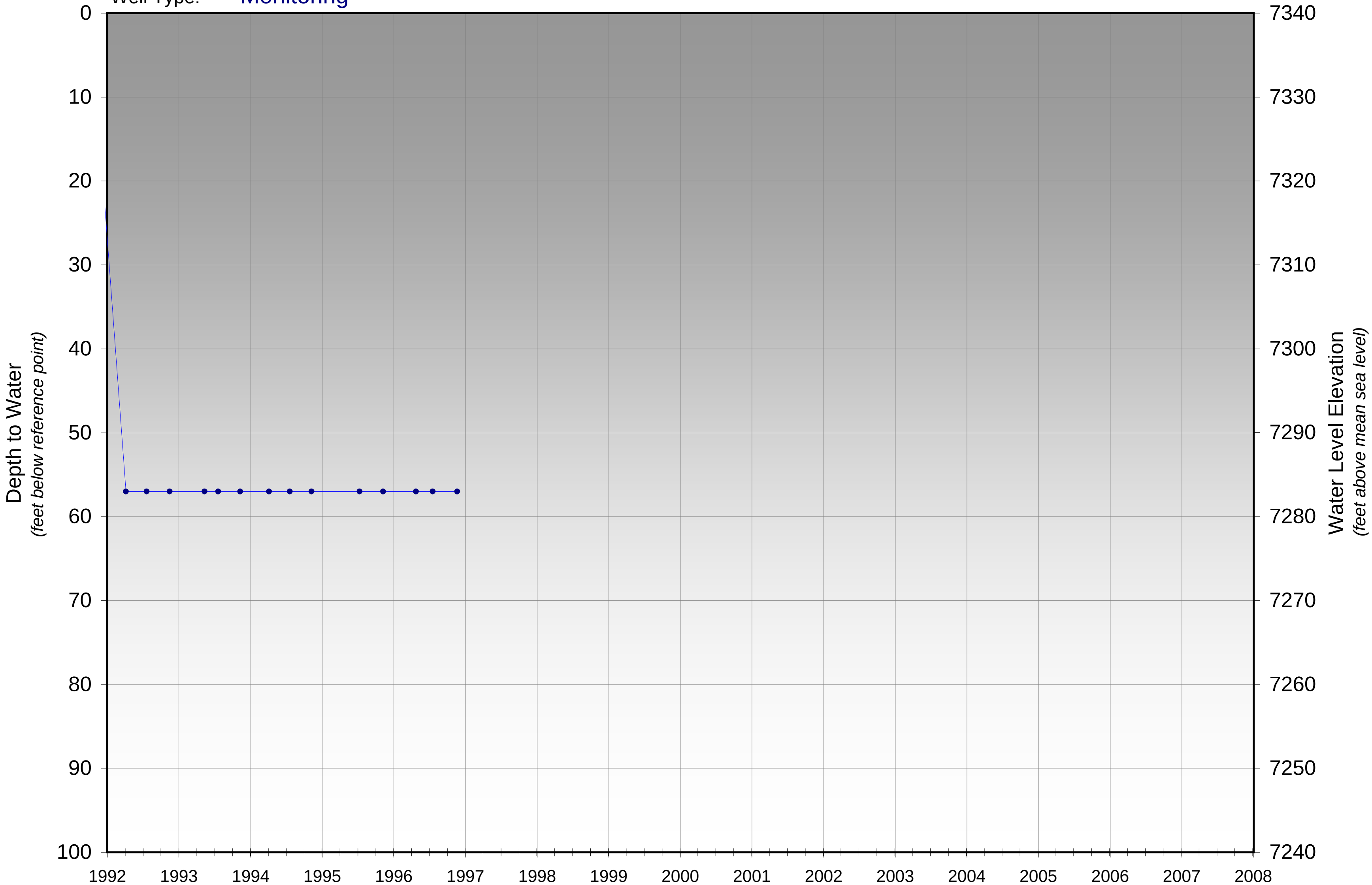
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **LV-15**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7340. above mean sea level
Ground Surface Elevation = 7340' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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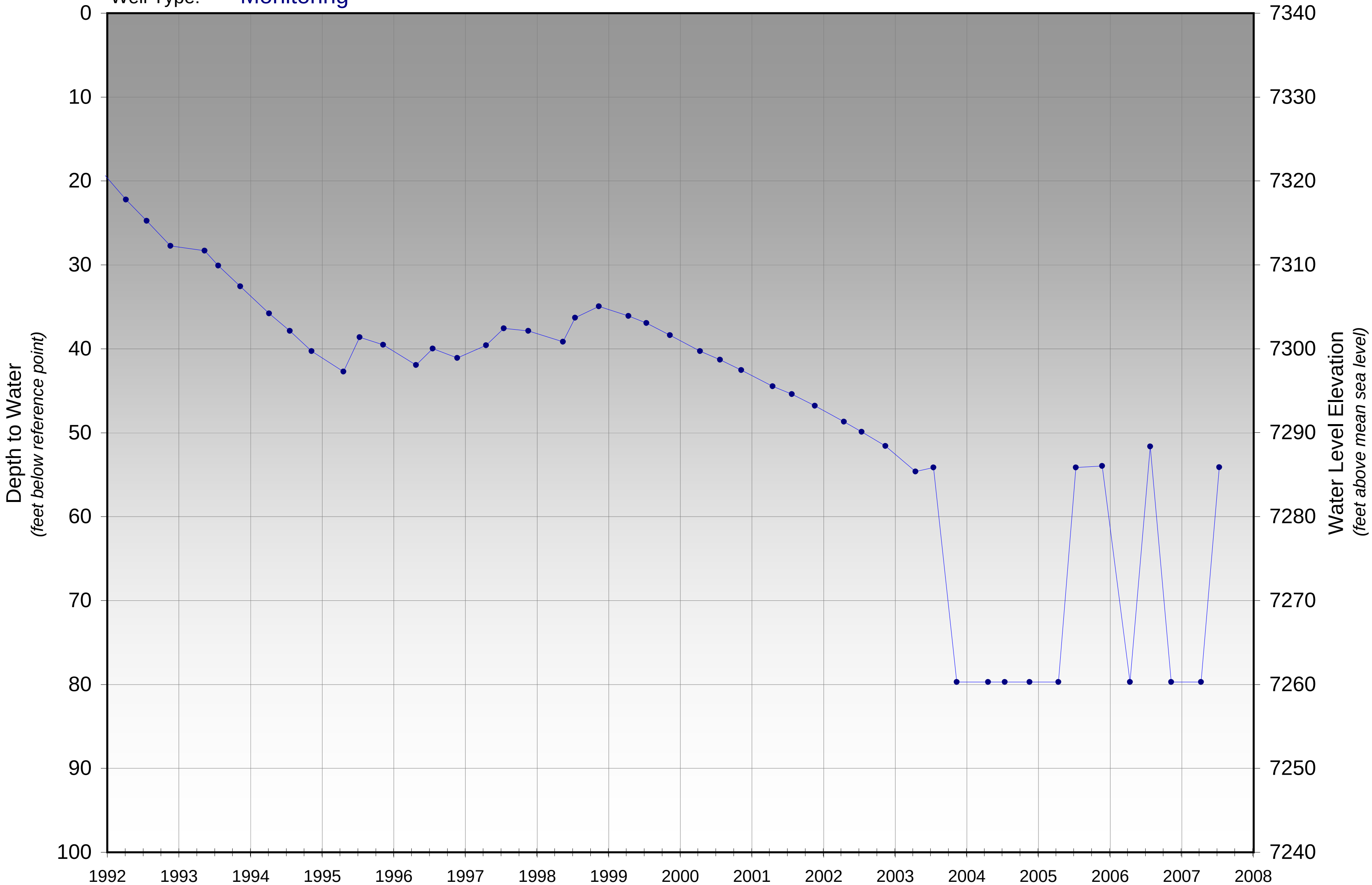
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **LV-44**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7340. above mean sea level
Ground Surface Elevation = 7340' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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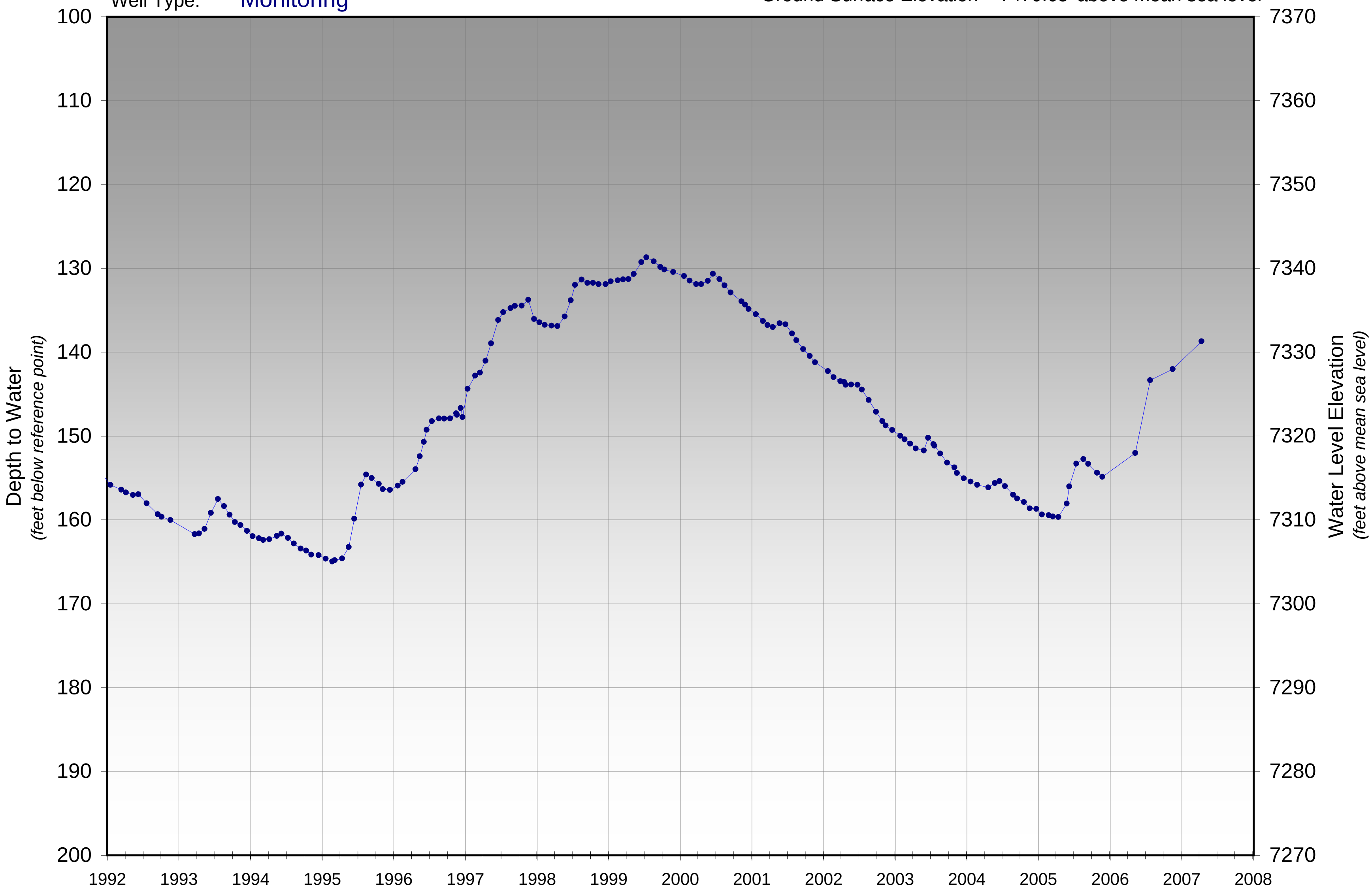
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **SC-2**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Deep
Reference Point Elevation = 7470.65. above mean sea level
Ground Surface Elevation = 7470.65' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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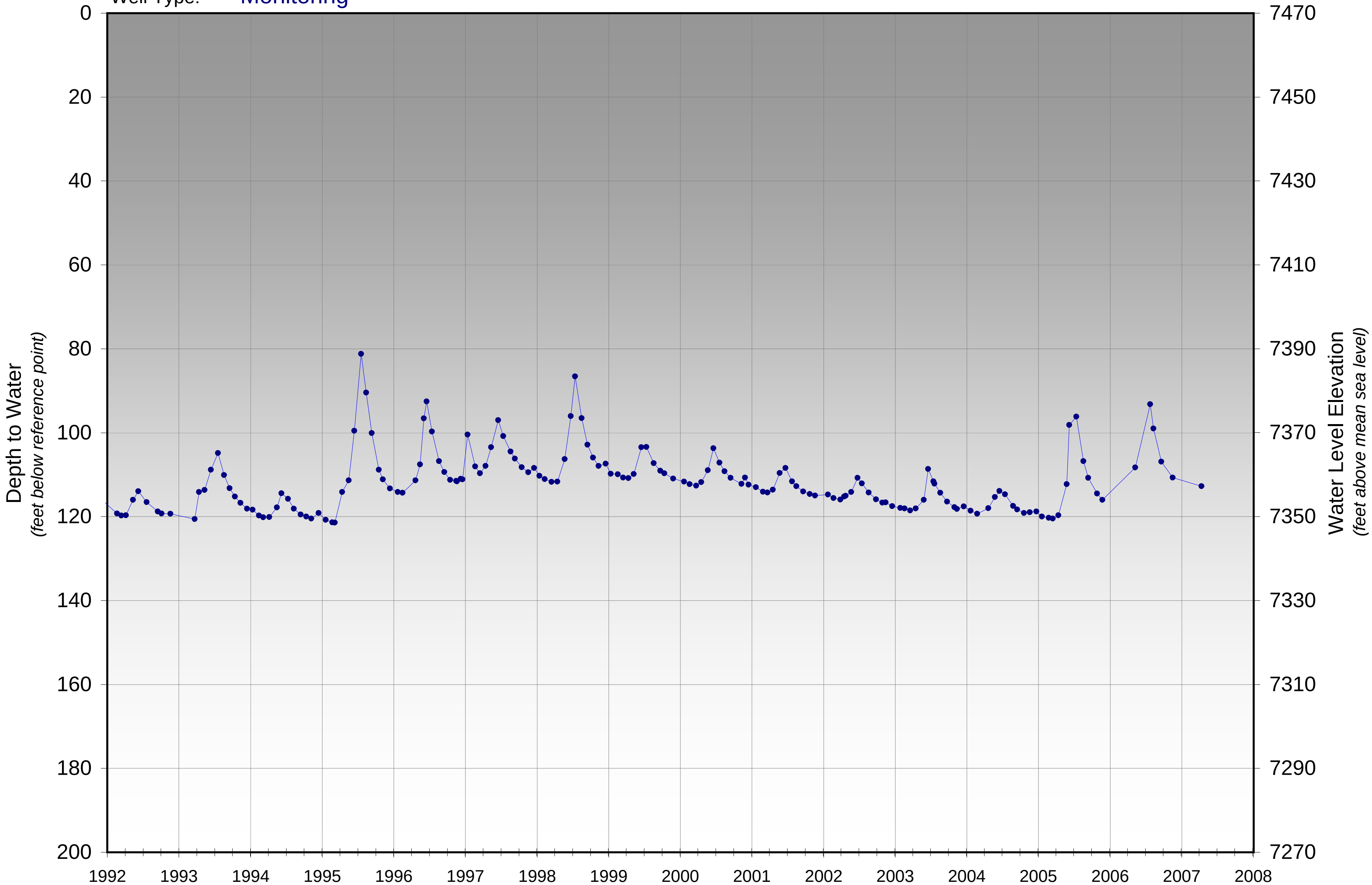
WILDERMUTH™ ENVIRONMENTAL INC.

Groundwater-Level Time Series

Well Name: **SC-1**
Owner Name: USGS
Well Type: Monitoring

Aquifer = Shallow
Reference Point Elevation = 7469.84 above mean sea level
Ground Surface Elevation = 7469.84' above mean sea level



Note: Water levels based upon well reference point elevation, not the digital elevation model.

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Appendix B

Seep and Spring Discharge Time Series Charts

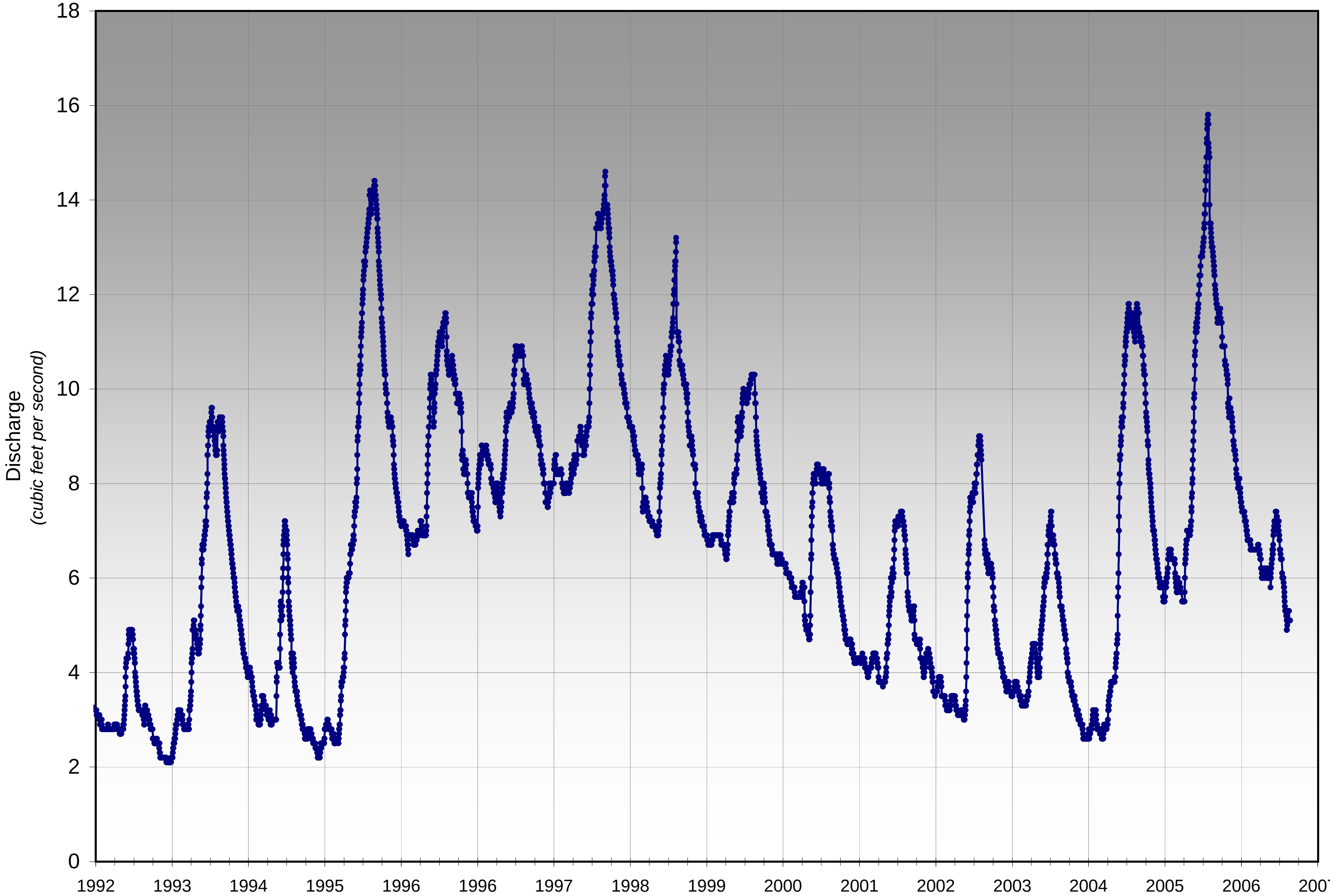
Spring Discharge Time Series

Spring Name: **Fish Hatchery Spring AB**

Owner Name: USGS

Aquifer = NA

Reference Point Elevation = 7050' above mean sea level



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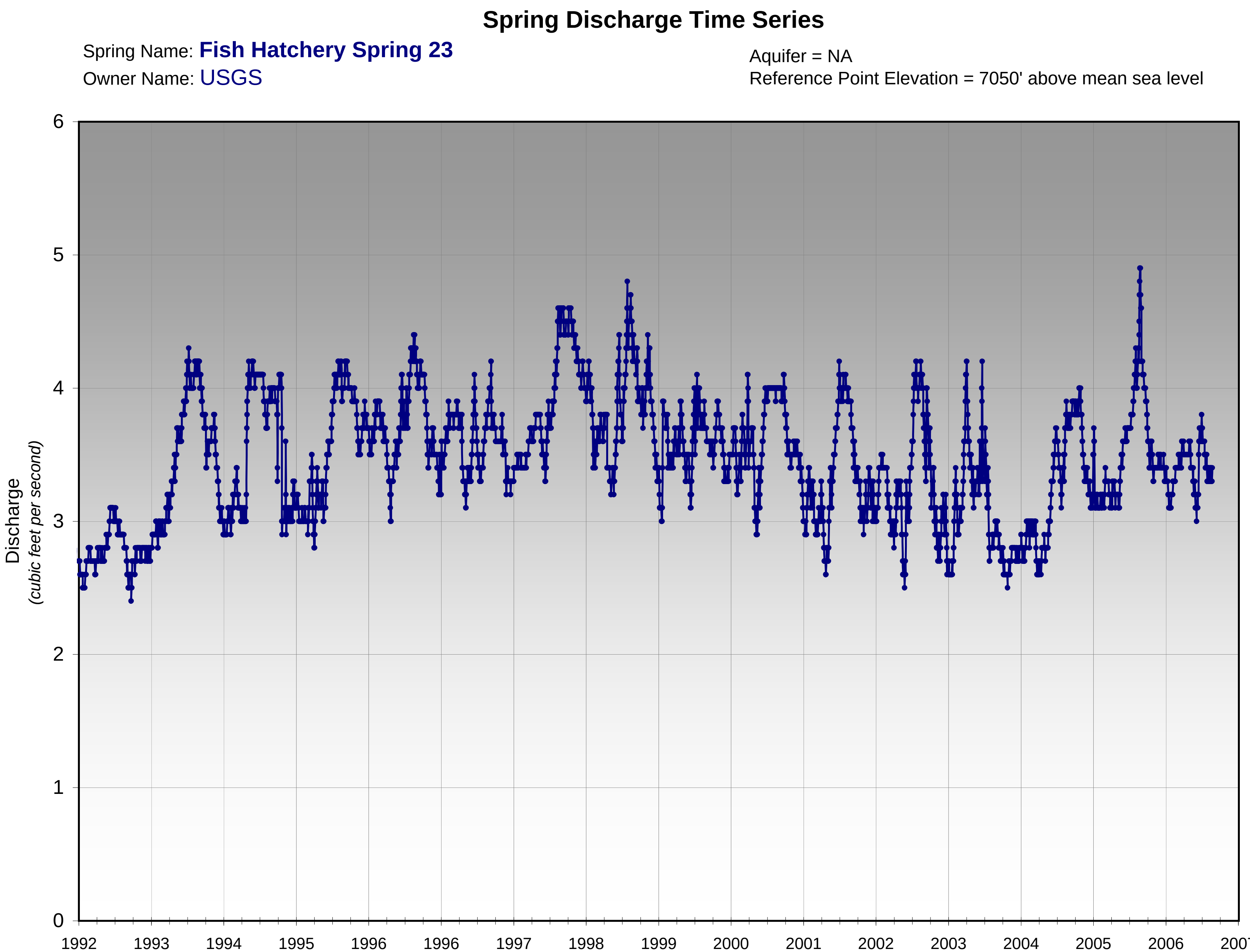

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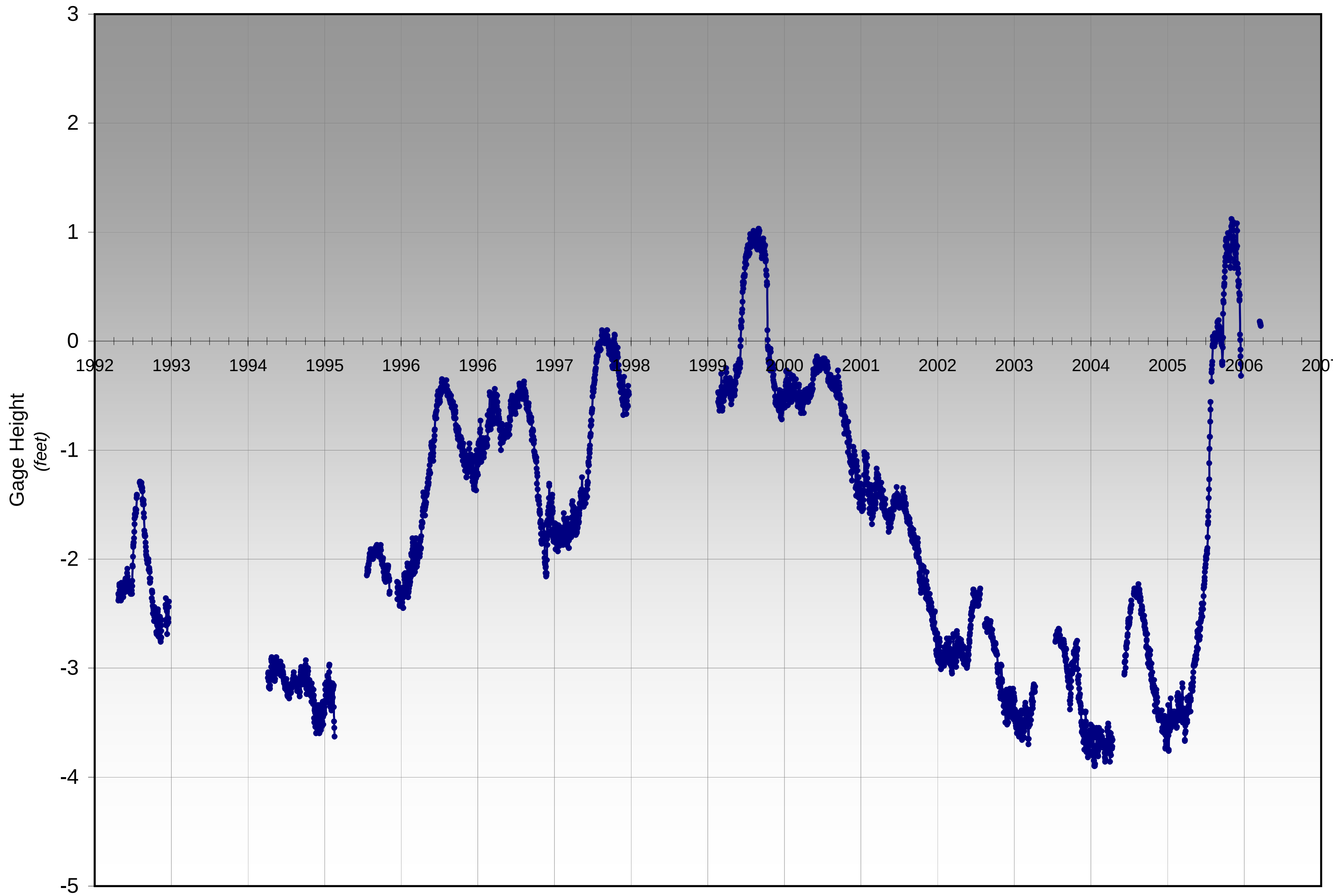
Spring Gage Height Time Series

Spring Name: **Hot Bubbling Pool**
Owner Name: USGS

Aquifer = NA
Reference Point Elevation = 7070' above mean sea level



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