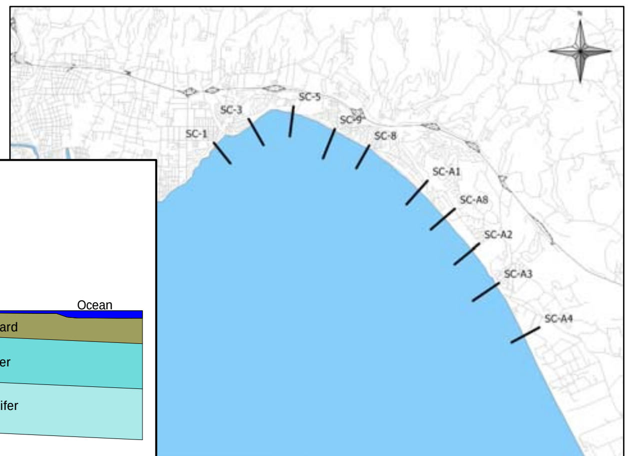
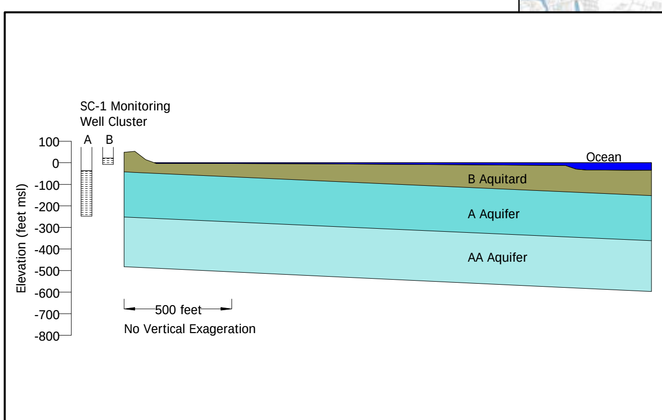
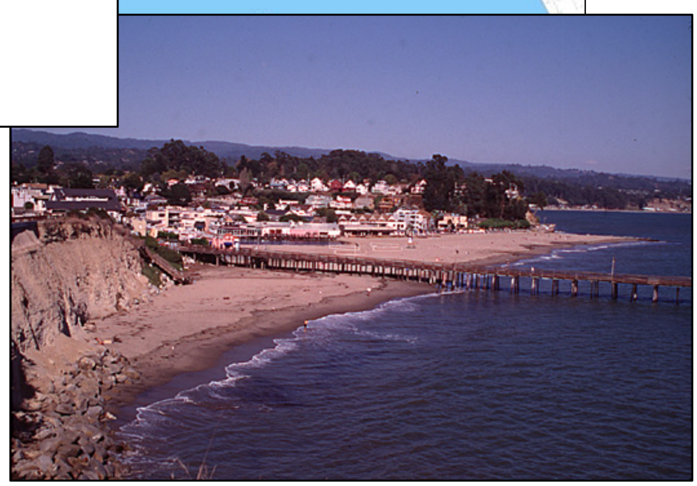
HydroMetrics LLC

Groundwater Levels to Protect against Seawater Intrusion and Store Freshwater Offshore







Prepared for:
Soquel Creek Water District

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EXECUTIVE SUMMARY

Maintaining groundwater levels to prevent seawater intrusion is identified as a Basin Management Objective in the 2007 Soquel Aptos Area Groundwater Management Plan update. Soquel Creek Water District (SqCWD) commissioned this study to develop a tool for developing groundwater levels that prevent seawater intrusion in its portion of the Soquel-Aptos groundwater basin. Two sets of groundwater levels were developed in this study: protective groundwater levels and target groundwater levels. Protective groundwater levels prevent seawater intrusion at the coastline. Target groundwater levels prevent seawater intrusion and maintain a volume of freshwater offshore which can be extracted when additional groundwater supply is needed. These protective and target groundwater levels serve as management objectives for the Soquel Creek Water District.

The freshwater/seawater interface in the Purisima Formation is currently offshore, and the location is unknown. The equilibrium position of the interface, however, does not depend on the current interface position. This equilibrium position only moves in response to changes in onshore groundwater levels relative to sea level. Simulating the equilibrium interface position allows us to estimate the onshore groundwater level that moves the interface to a specified position.

The equilibrium position of the seawater interface was estimated with a series of cross-sectional models. One cross-sectional model was created at each coastal monitoring well cluster. Protective and target groundwater levels were determined for one hydrostratigraphic unit at each monitoring well cluster. In the Purisima Formation the protected hydrostratigraphic unit is the lowest unit in which nearby municipal wells pump. In the Aromas Formation the protected aquifer zone is the depth at which there was no observed seawater intrusion when the coastal monitoring wells were first installed: generally the depth of the B-level monitoring wells. Seawater intrusion is allowed in the model below these depths.

The model code SEAWAT 2000 was selected for the groundwater flow and transport model. SEAWAT 2000 simulates variable density flow which is necessary to simulate seawater intrusion. The model code is well documented and benchmarked and is a public domain code developed by the U.S. Geological Survey.

The cross-sectional models were used to develop both protective and target groundwater levels at each coastal monitoring well cluster. Using a Monte Carlo type uncertainty analysis, a range of protective groundwater levels were developed for each coastal monitoring well cluster. This range represents the uncertainty in the aquifer characteristics. Table ES - 1 shows the range of protective groundwater levels for each monitoring well cluster and the protective water levels suggested for basin management.

Table ES - 1: Calculated and Suggested Protective Groundwater Levels

Monitoring Well Cluster	Protective Groundwater Level Range (ft msl)	Suggested Protective Groundwater Level (ft msl)
SC-1	1 to 5	4
SC-3	8 to11	10
SC-5	11 to 15	13
SC-8	8 to 11	10
SC-9	3 to 11	10
SC-A1	8 to 12	10
SC-A2	6 to 8	8
SC-A3	1 to 4	4
SC-A4	9 to 11	11
SC-A8	9 to 12	11

Target groundwater levels were developed for two distributions of stored water offshore. The standard distribution stored the target volume of water offshore of the entire SqCWD service area, including the Aromas Formation. The alternative distribution was designed to store the same amount of water offshore in a smaller area, based on two possible operational constraints:

1. Changes in SqCWD pumping may not affect Aromas area groundwater levels enough to store the target volumes offshore.

2. A cooperative groundwater management agreement with the City of Santa Cruz may set the goal for pumping near monitoring well SC-1A to capture offshore flows. This goal recognizes that SC-1A is close to the offshore outcrop and is in an area with limited offshore storage. Therefore, there may be little benefit to raising water levels at SC-1A in an attempt to store water offshore.

Constraint 1 implies that the alternative distribution of stored water only stores water in the Purisima Formation. Constraint 2 implies that no water is stored offshore of the SC-1 monitoring well cluster.

Table ES - 2 shows the range of target groundwater levels for each monitoring well cluster under the standard storage distribution and the target water levels suggested for basin management. Table ES - 3 shows the range of target groundwater levels for each monitoring well cluster under the alternative storage distribution and the target water levels suggested for basin management under this distribution.

Table ES - 2: Calculated Suggested Target Groundwater Levels – Standard Storage Distribution

Monitoring Well Cluster	Target Groundwater Level Range (ft msl)	Suggested Target Groundwater Level (ft msl)
SC-1	3 to 8	6
SC-3	9 to 12	11
SC-5	12 to 16	14
SC-8	9 to 12	11
SC-9	4 to 12	11
SC-A1	10 to 14	12
SC-A2	8 to 10	10
SC-A3	2 to 5	5
SC-A4	N/A[1]	N/A
SC-A8	12 to 16	15

[1] Well SC-A4 has no nearby District pumping, and therefore no target storage volume or target water level

Table ES - 3: Calculated Suggested Target Groundwater Levels – Alternative Storage Distribution

Monitoring Well Cluster	Target Groundwater Level Range (ft msl)	Suggested Target Groundwater Level (ft msl)
SC-1	N/A[1]	N/A
SC-3	10 to 14	13
SC-5	12 to 17	14
SC-8	10 to 14	13
SC-9	5 to 13	12
SC-A1	N/A	N/A
SC-A2	N/A	N/A
SC-A3	N/A	N/A
SC-A4	N/A	N/A
SC-A8	N/A	N/A

[1] Wells with N/A results have no offshore storage in the alternative storage distribution

Average current groundwater levels are below the protective and target groundwater level in all wells. Maintaining the current groundwater levels leads to increased risk of seawater intrusion of the protected aquifers. Groundwater levels will likely not increase at all monitoring wells without a decrease in the total pumping of the Soquel-Aptos Basin. This necessary decrease in long-term pumping will likely only be realized if a supplemental supply can be obtained.

SECTION 1
PURPOSE AND APPROACH

1.1 PROJECT PURPOSE

The freshwater/seawater interfaces in the Purisima Formation aquifers pumped by SqCWD are currently offshore and the locations are unknown. Knowing the location of the interface is necessary to develop a groundwater model that can predict intrusion rates and time-dependent seawater concentrations in aquifers. The equilibrium position of the interface, however, does not depend on the current interface position. This equilibrium position will move only in response to changes in onshore groundwater levels relative to sea level. Simulating the equilibrium interface position allows us to estimate the onshore groundwater level that moves the interface to a specified position.

The purpose of this project is to determine two different groundwater levels at each of the existing coastal monitoring wells. Protective groundwater levels protect against seawater intrusion at the coastline. Target groundwater levels protect against seawater intrusion and store a target volume of freshwater offshore. This volume of stored freshwater can be extracted by pumping above the sustainable yield when additional groundwater supply is needed. These protective and target groundwater levels were determined with density dependent vertical cross-sectional models.

1.2 SIMULATED CROSS SECTIONS

One cross-sectional model was created at each coastal monitoring well cluster. The locations of the monitoring well clusters and associated cross-sections are shown in Figure 1. The lines originating from each coastal monitoring well cluster on Figure 1 represent the horizontal extent of the cross-section that was modeled.

A schematic drawing of an example cross section is presented in Figure 2. The onshore edge of each cross-section occurs at a coastal monitoring well. The offshore edge represents a hydrostatic ocean boundary condition.

1.3 PROTECTIVE AND TARGET GROUNDWATER LEVELS

Protective and target groundwater levels were determined for one hydrostratigraphic unit at each monitoring well cluster. The protected hydrostratigraphic unit for Purisima Formation monitoring wells is the deepest unit in which nearby SqCWD pumping occurs. Seawater intrusion was allowed in units below the protected unit. The protected hydrostratigraphic depth for

Aromas Formation monitoring wells corresponds to the depth of the second deepest monitoring well at each well cluster; a well that has been historically unintruded. Seawater intrusion was allowed in sediments below the protected elevation.

Figure 2 shows how the protective and target groundwater levels result in two seawater interface locations. The area between the two interface locations determines the volume of freshwater stored offshore The seawater interface position associated with protective groundwater levels allow the toe of the intruding seawater wedge to just reach the coastline. The interface position associated with the target groundwater level increases offshore storage by a specified volume. This volume of offshore stored water is represented by the crosshatched region between the two interface positions shown in Figure 2.

The target storage volume is based on an estimated of the increase in groundwater pumping over a three year period when SqCWD would need to meet all of its projected demand with groundwater. This will occur if a supplemental supply is not available. This estimated increase in demand is calculated as follows:

2050 Projected Demand	6080 acre-feet/year
- 15% Reduction from rationing	910 acre-feet/year
- Sustainable yield pumping	4800 acre-feet/year
Estimated demand increase	370 acre-feet/year
	x 3 years
Target storage volume	1110 acre-feet

The projected demand is based on the 2050 demand estimate in the Integrated Resources Plan (Environmental Science Associates, 2006). The 15% reduction is the estimated reduction in demand that will occur under a mandatory rationing program (SqCWD, 2005). The sustainable yield pumping is the maximum annual production planned by SqCWD when supplemental supply is available. This is the pumping stated in Basin Management Objective 1-1 of the Groundwater Management Plan update (SqCWD and Central Water District, 2007). The actual annual pumping that will protect the groundwater basin may be less. Likewise, future demand and feasible reduction from rationing may be different than estimated. If any of these numbers need to be revised, SqCWD can calculate the number of years of storage the target volume of 1,110 acre-feet provides. SqCWD can then determine whether the number of years of additional storage is acceptable.

The protective and target groundwater levels guide SqCWD by showing where groundwater levels should be in the coastal monitoring wells to prevent seawater intrusion, and to maintain a buffer of freshwater stored offshore. The amount of pumping and distribution of pumping required to meet protective and target groundwater levels are yet to be evaluated.

Figure 1: Coastal Monitoring Well and Cross-Section Locations

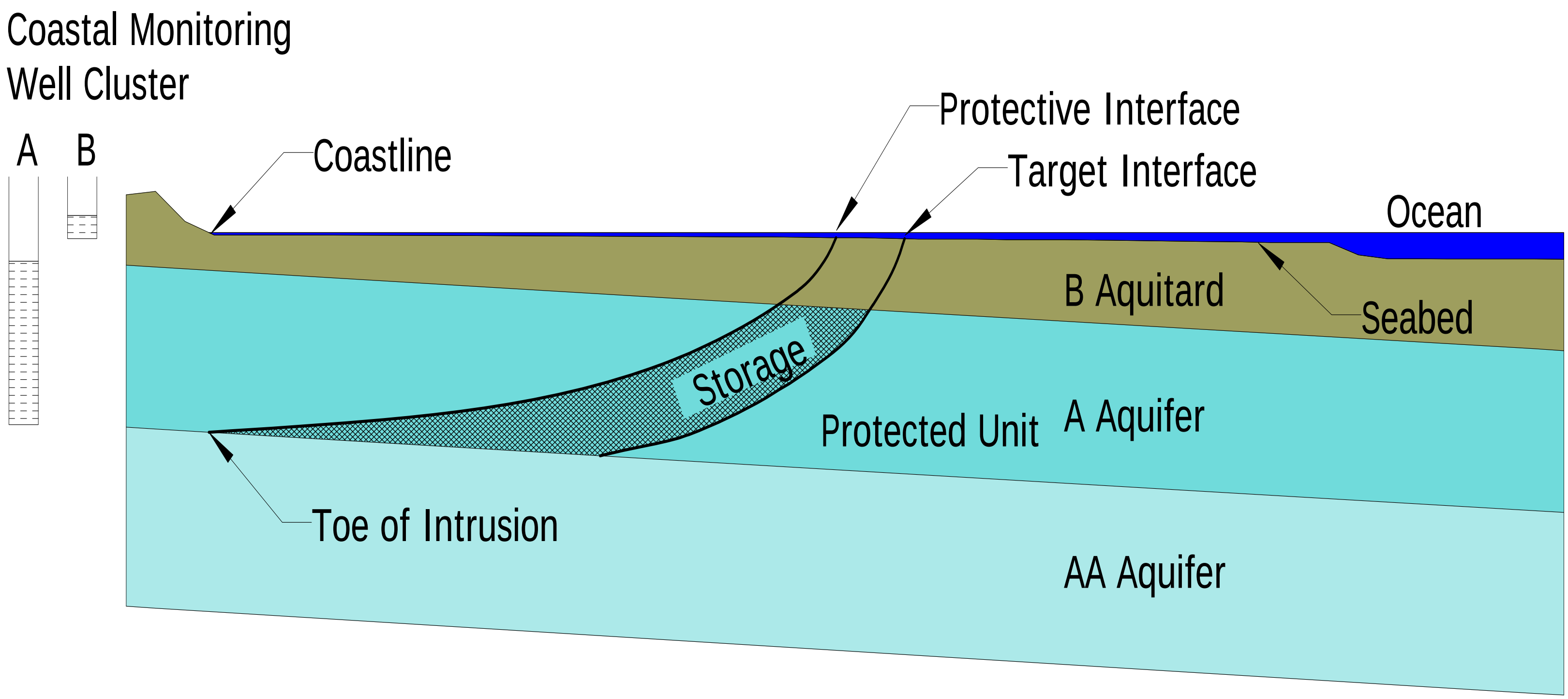

Figure 2: Schematic Showing Protective Interface Position and Target Interface Position

SECTION 2
CONCEPTUAL MODEL

2.1 GEOLOGY

The cross-sectional models are all located within the Soquel-Aptos groundwater management area (SqCWD and Central Water District, 2007). Within this area, SqCWD extracts groundwater primarily from two formations: the Purisima Formation and the Aromas Red Sands. In addition, the lowest screened interval of the Main Street well extracts groundwater from a sandstone underlying the Purisima Formation.

2.1.1 STRATIGRAPHIC UNITS

The stratigraphic framework used to define hydrogeologic units in the cross-sectional models is the revised hydrogeologic framework presented in Johnson et al (2004). This framework is reviewed below.

PURISIMA FORMATION STRATIGRAPHIC UNITS (AND UNDERLYING TU UNIT)

The late Miocene to Pliocene age Purisima Formation is a sequence of grey, sometimes described as blue, moderately consolidated, silty to clean, fine to medium sandstones containing siltstone and claystone interbeds. It underlies the entire Soquel-Aptos area; however it is blanketed by the Aromas Red Sands in the eastern third of the Soquel-Aptos area, and by relatively shallow alluvial and terrace deposits elsewhere.

Johnson et al. (2004) developed the current hydrostratigraphic model of the Purisima Formation by dividing it into hydrostratigraphic units that define regional aquifers and aquitards. This hydrostratigraphic model was derived from the stratigraphic model of Luhdorff & Scalmanini Consulting Engineers (LSCE). LSCE designated five units A through E, from oldest to youngest respectively (LSCE, 1984). Later, LSCE identified additional stratigraphic units underlying (AA) and overlying (F) the A through E units.

The hydrostratigraphic units of Johnson et al. are defined from oldest to youngest as follows:

AQUIFER TU (0 TO 300 FEET THICK)

The Tu aquifer comprises the lower part of the Tertiary age sediments below the base of the Purisima Formation. This aquifer has only been observed in deep wells and is limited in extent.

AQUITARD TP (0 TO 200 FEET THICK)

This unit consists of fine-grained sediments near the base of the Purisima that act as an aquitard where present.

AQUIFER AA (150 TO 300 FEET THICK)

This unit comprises a sequence of interbedded, moderately coarse- and fine-grained zones underlying the well defined A-unit. A fine-grained zone 20 to 70 feet thick divides the AA-unit from the overlying A-unit.

AQUIFER A (~250 FEET THICK)

This distinct aquifer is the most consistently coarse-grained aquifer within the Purisima Formation. It is sometimes divided into an upper and lower zone with the lower zone being more coarse-grained.

AQUITARD B (~150 FEET THICK)

This unit is the fine-grained lower portion of the LSCE unit B. Few production wells are screened across this unit.

AQUIFER BC (~200 FEET THICK)

The LSCE unit C is grouped with the upper portion of the LSCE unit B to form Aquifer BC. This is a moderately coarse-grained unit with a distinct 15- to 20-foot thick coarse-grained unit at the top of the unit

AQUITARD D (~80 FEET THICK)

This aquitard is the fine-grained lower portion of the LSCE unit D.

AQUIFER DEF (~330 FEET THICK)

This moderately coarse aquifer includes intermittent fine-grained zones. The top of this aquifer seems poorly defined; Johnson et al. (2004) does not identify a distinct marker or aquitard separating this aquifer from the overlying Aquifer F. None of the SqCWD production wells are screened in the upper part of this unit.

Aquifer F (150 to 500+ feet thick)

This unit consists of alternating moderately coarse- and fine-grained zones. Johnson et al. (2004) identifies this aquifer as the upper portion of the Purisima F unit that is often screened in conjunction with the lower Aromas Red Sands.

Aromas Red Sands Stratigraphic Units

The poorly consolidated Aromas Red Sands consist of interbedded fluvial, marine, and eolian sands with lenses of silt and clay. As a result of this complex depositional history, the Aromas Red Sands contain significant heterogeneities and cannot be easily subdivided into meaningful hydrostratigraphic units.

Offshore Geology

Both the Purisima Formation and Aromas Red Sands extend offshore beneath Monterey Bay. The lower Purisima units (A and AA units) are assumed to be exposed in the northeastern portions of Monterey Bay, and buried deeply beneath Monterey Bay to the southeast. Sediment mapping of the Monterey Bay seafloor with acoustic imagery has identified Purisima Formation along much of the seafloor (Eittreim et al., 2000, 2002).

Geological Map and Cross-Section

A geological map showing the extent of the hydrostratigraphic units within the Soquel-Aptos Management Area is shown in Figure 3. A geologic cross-section showing these units is shown in Figure 4. The cross-section location is shown on Figure 4.

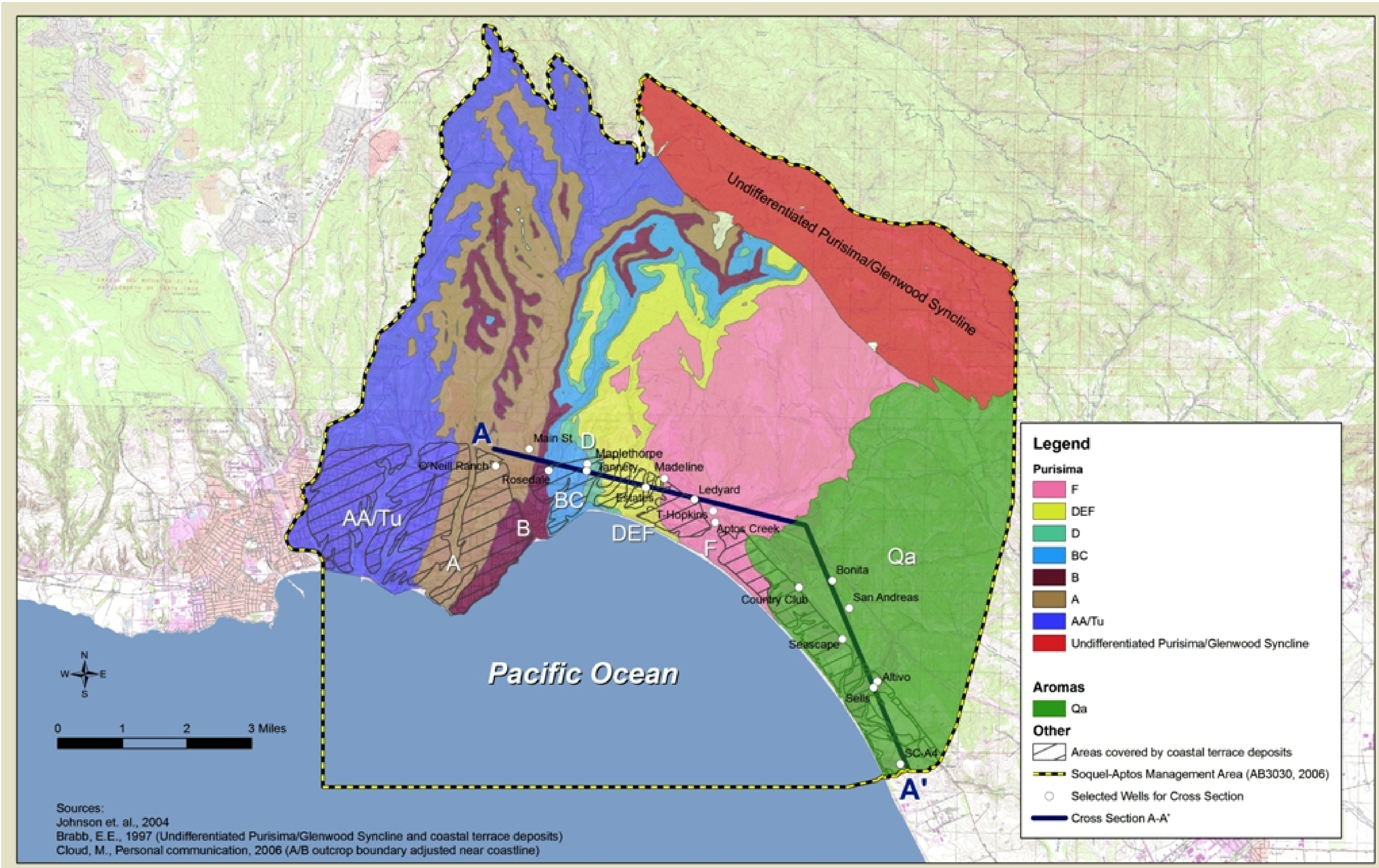

Figure 3: Estimated Surface Outcrop of Hydrostratigraphic Units

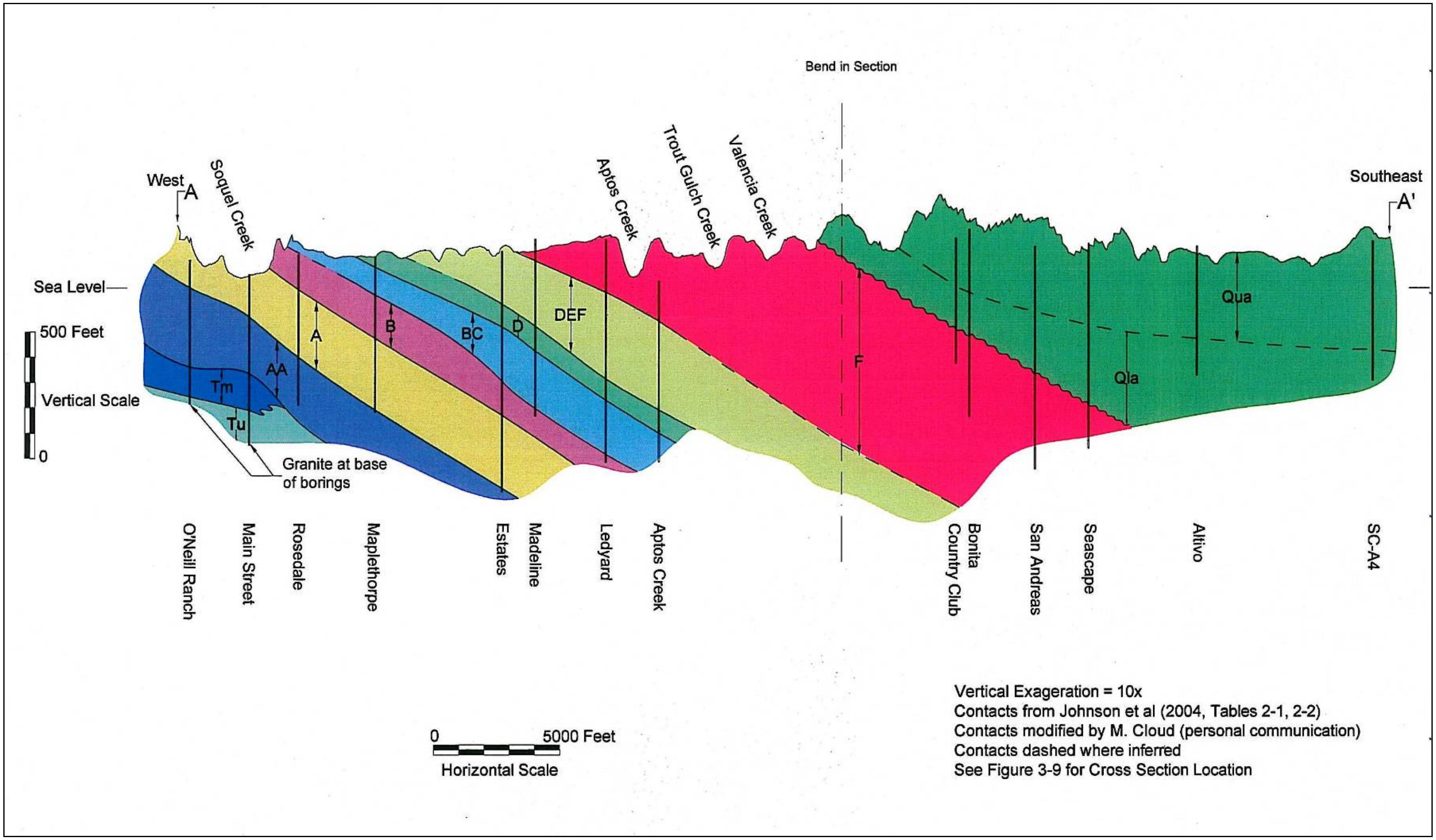

Figure 4: Cross-Section A-A′

2.1.2 GEOLOGIC STRUCTURE

In the Soquel-Aptos Basin, the Purisima Formation generally dips between 2 to 5 degrees east-southeast (Johnson et al 2004). The strike and dip were determined from correlation of marker beds between boreholes and measurement from exposed bedding.

The contact between the Purisima and the overlying Aromas is approximately parallel to the strike and dip of the Purisima Formation, as seen in Figure 4. The geologic structure within the Aromas Red Sands is uncertain; the dip of the bedding may parallel the Purisima-Aromas contact near its surface exposure as shown in the cross-section (Figure 4), but the Aromas Formation is generally considered flat lying throughout most of its extent.

2.1.3 CROSS SECTION HYDROSTRATIGRAPHY

Based on the geology described above, hydrostratigraphic cross-sections were developed for each of the cross-section locations shown on Figure 1. The cross-sections are shown in Figure 5 through Figure 14. The contacts between the hydrostratigraphic units in the cross-sections were derived from contoured stratigraphic surfaces in the *Draft Hydrogeological Conceptual Model* (Johnson et al., 2004). The elevations of the original contours were adjusted vertically to match the contact elevations at each monitoring well as listed in Table 2-2 of the *Draft Hydrogeological Conceptual Model*. The contoured surface of the top of the F unit was based on unpublished analyses by Jonathan Lear of the Pajaro Valley Water Management Agency. The ground surface elevations and ocean bottom bathymetry define the top of the cross-sections. These ground surface elevation and bathymetry data were extracted from the National Geophysical Data Center's (NGDC) *Coastal relief gridded database* (Divins and Metzger 2007).

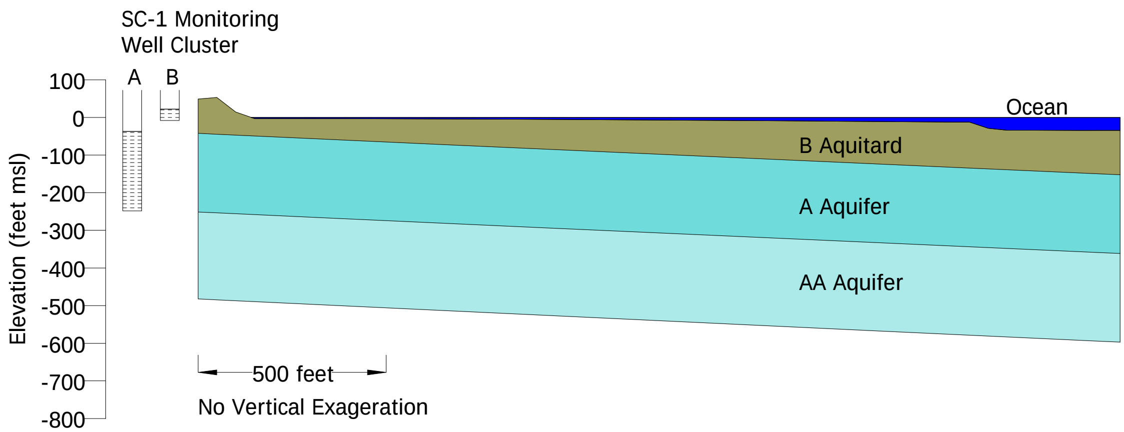

Figure 5: SC-1 Monitoring Well Cluster and Hydrostratigraphic Units

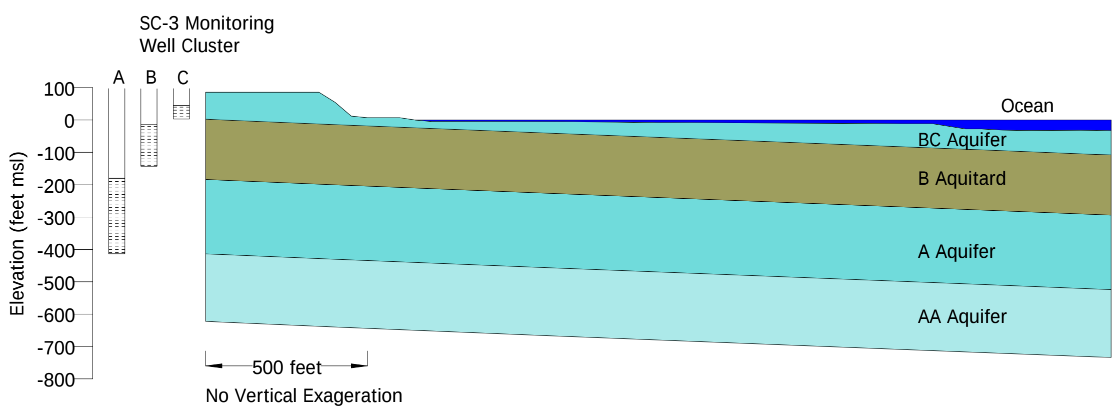

Figure 6: SC-3 Monitoring Well Cluster and Hydrostratigraphic Units

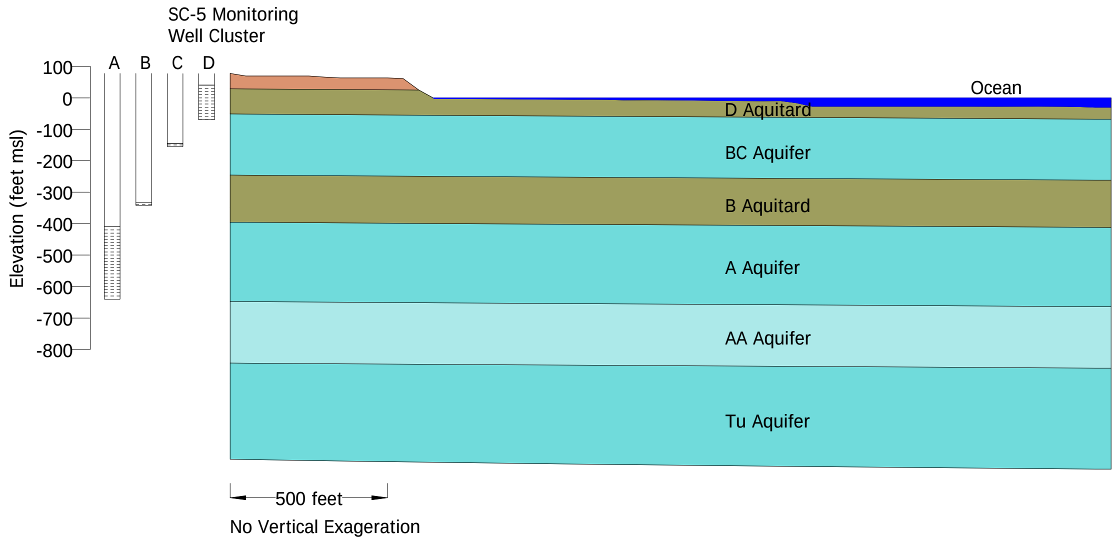

Figure 7: SC-5 Monitoring Well Cluster and Hydrostratigraphic Units

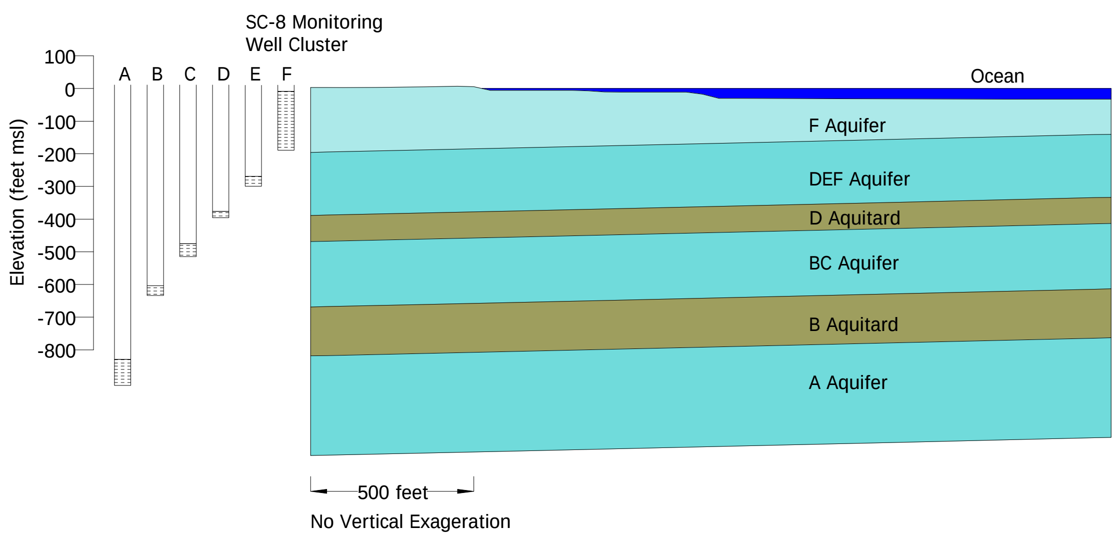

Figure 8: SC-8 Monitoring Well Cluster and Hydrostratigraphic Units

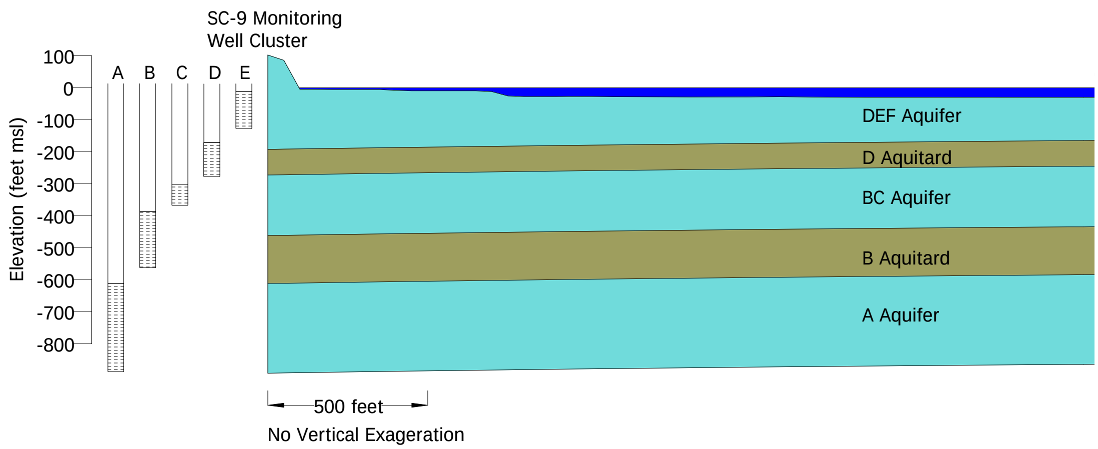

Figure 9: SC-9 Monitoring Well Cluster and Hydrostratigraphic Units

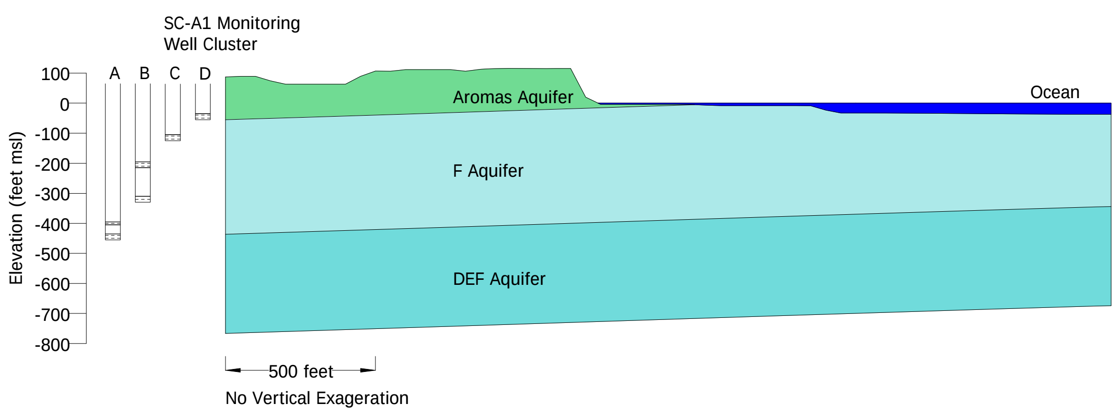

Figure 10: SC-A1 Monitoring Well Cluster and Hydrostratigraphic Units

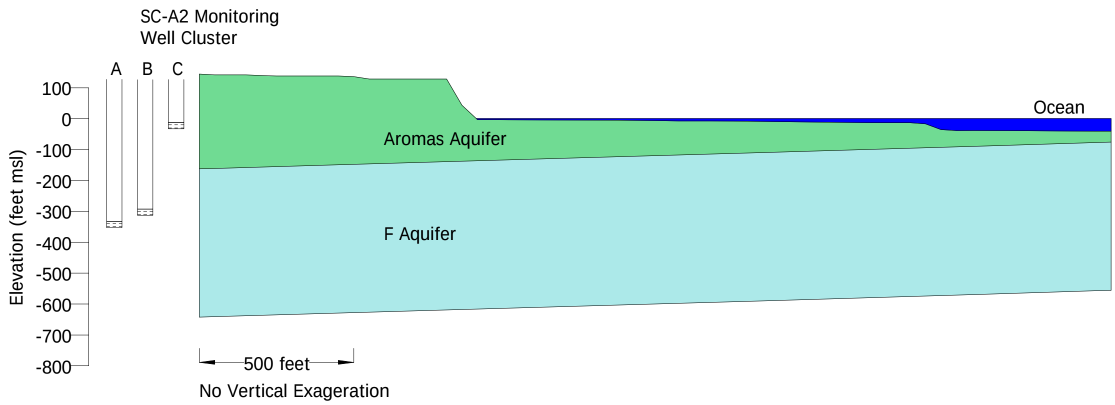

Figure 11: SC-A2 Monitoring Well Cluster and Hydrostratigraphic Units

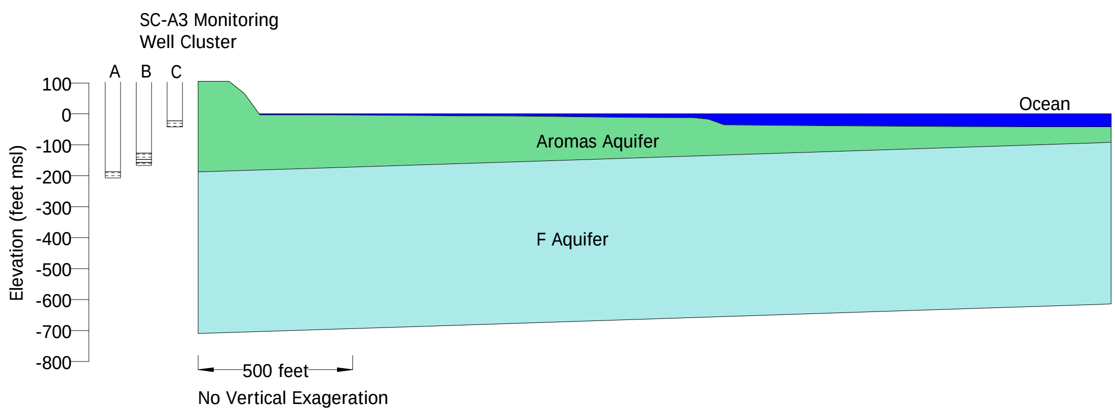

Figure 12: SC-A3 Monitoring Well Cluster and Hydrostratigraphic Units

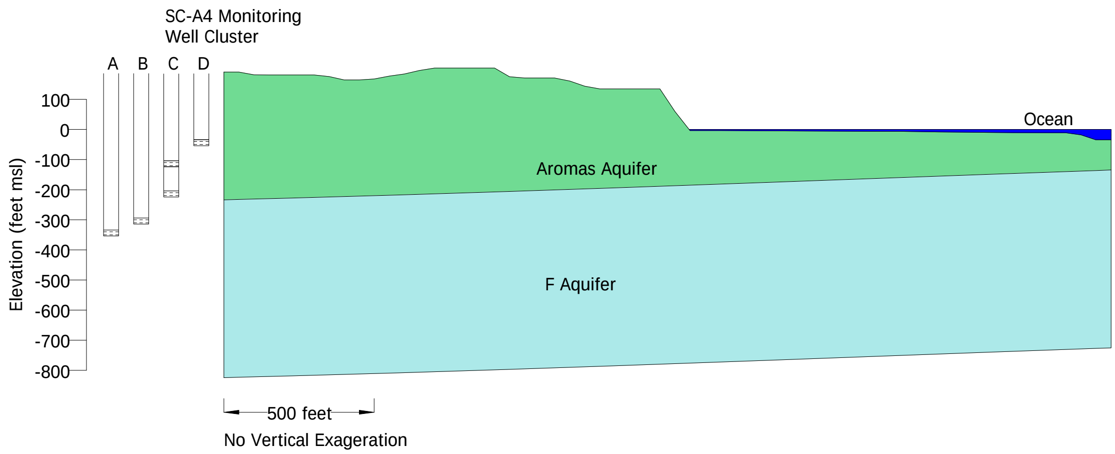

Figure 13: SC-A4 Monitoring Well Cluster and Hydrostratigraphic Units

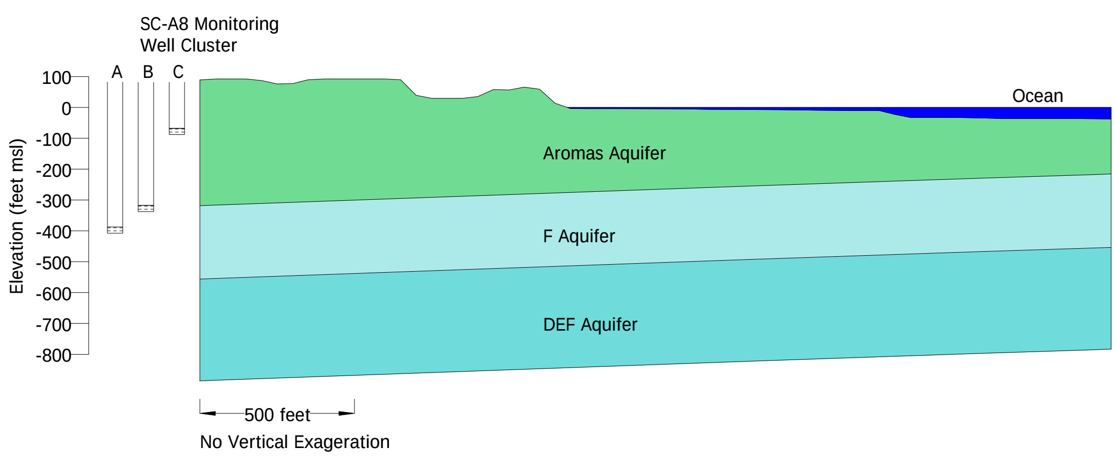

Figure 14: SC-A8 Monitoring Well Cluster and Hydrostratigraphic Units

2.2 AQUIFER PARAMETERS

Estimated aquifer parameters for the various stratigraphic units are shown in Table 1. Most of the parameter values are from Table 3-13 of the *Draft Hydrogeological Conceptual Model* (Johnson et al., 2004). The higher end of the AA unit horizontal conductivity range was taken from the hydrogeologic effects analysis for the Well Master Plan EIR (Williams et al., 2008).

Table 1: Estimates of Hydraulic Conductivities for the Soquel-Aptos Area

Aquifer/Aquitard Unit	Horizontal Hydraulic Conductivity Kh (feet/day)	Vertical Hydraulic Conductivity Kv (feet/day)
Aromas (Upper and Lower)	3 – 50	0.05 - 2
F	2 - 6	0.005 – 0.5
DEF	2 - 6	0.005 – 0.5
D aquitard	1 - 75	0.001 – 0.1
BC	1 – 3	0.005 – 0.1
B aquitard	1 - 150	0.001 – 0.1
A	7 – 18	0.05 – 2
AA	1 - 13	0.001 – 0.1
Tu	1 - 20	0.01 – 0.5

Table 3-13 in the *Draft Hydrogeological Conceptual Model* (Johnson et al., 2004) distinguished between upper and lower intervals of the Aromas Formation. The Upper and Lower Aromas Formations were lumped together in one unit for the purposes of the current cross-sectional modeling. The range of parameters for the Upper and Lower Aromas Formation were combined for this study.

SECTION 3
NUMERICAL FLOW MODEL CONSTRUCTION

This section presents basic information about how the cross sectional models were constructed. Additional details are included in Appendix A to this report.

3.1 MODEL CODE

The model code SEAWAT 2000 (Guo and Langevin, 2002) was selected for the groundwater flow and transport model. SEAWAT 2000 simulates variable density flow which is necessary to simulate seawater intrusion. The model code is well documented and benchmarked, and is a public domain code developed by the U.S. Geological Survey.

3.2 FINITE DIFFERENCE GRIDS

Figure 15 shows an example finite difference grid used by SEAWAT for a cross-sectional model. Ten of these finite difference grids were created, one specific to each of the cross-sections shown on Figure 5 through Figure 14. The grids are two dimensional and are oriented in a vertical plane. The two-dimensional vertical grid assumes that groundwater flows directly offshore, perpendicular to the shoreline. Each cross-sectional model is assumed to represent a 1,000 feet wide portion of the aquifer.

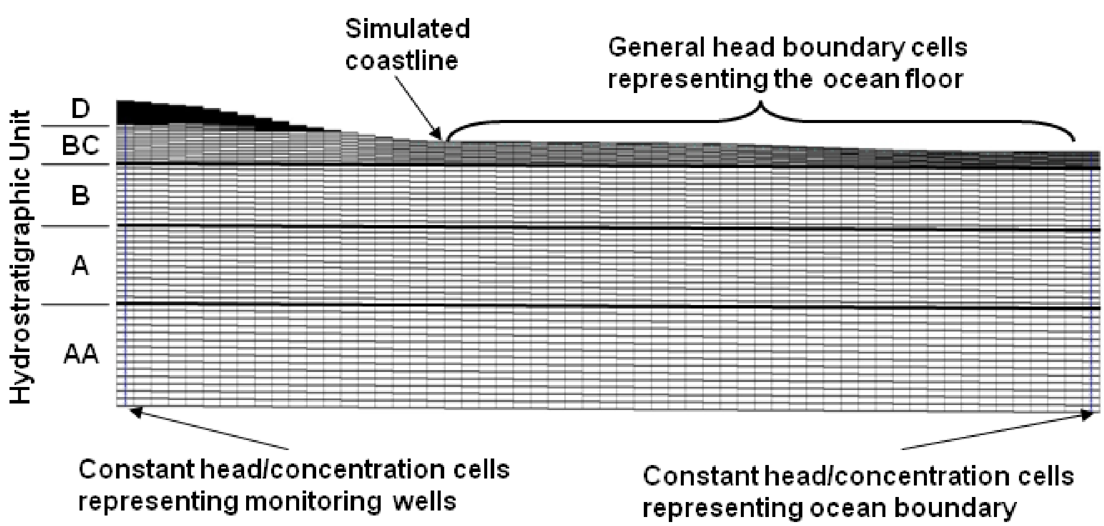

Figure 15: Example Finite Difference Grid for a Cross-Sectional Model.

The cross sectional models simulate from the ground surface down to the lowest unit screened by a nearby monitoring well. Some models required simulation of an additional unit below the lowest screened unit to allow seawater flow below the seawater interface.

3.3 Model Boundary Conditions

Numerical models require boundary conditions be defined for the sides, the top, and bottom of the model. The boundary conditions imposed on the cross sectional models are as follows.

- Inland end of model: Groundwater levels are held at a constant level, simulating the desired protective or target water level in the monitoring wells. The water in these wells is always fresh water

- Ocean end of model: Groundwater levels are held at sea level. Any water entering the model from the ocean end of the model is always full strength seawater.

- Top boundary: Onshore, the top boundary is set up so no water percolates into or out of the boundary. This implies that we do not simulate rainfall recharge with this model. Offshore, the top boundary simulates silt on the ocean floor. The water level above the silt is tied to sea level. Any water entering the model from the top boundary offshore is set to full strength seawater.

- Bottom boundary: The bottom is impermeable. No groundwater flows in or out of the model bottom.

3.4 Model Aquifer Parameters

3.4.1 Flow Parameters

Table 2 presents the base values of aquifer parameters for each hydrostratigraphic unit. Because the cross-sectional models are run to equilibrium, the aquifer storage parameters will have no effect on the final solution and are therefore not presented here.

Table 2: Base Aquifer Flow Parameter Values

Hydrostratigraphic Unit	Horizontal Hydraulic Conductivity Kh (feet/day)	Vertical Hydraulic Conductivity Kv (feet/day)
Aromas (Upper and Lower)	3	0.15
Purisima F Aquifer	3	0.15
Purisima DEF Aquifer	2.3	0.115
Purisima D Aquitard	1	0.04
Purisima BC Aquifer	2	0.1
Purisima B Aquitard	1	0.04
Purisima A Aquifer	12	0.6
Purisima AA Aquifer	10	0.5
Purisima Tu Aquifer	5	0.25

Parameters were varied about these base values to determine the sensitivity of target groundwater levels to the uncertainty of these parameter values. This is discussed further in Section 4.

3.4.2 Transport Parameters

The dispersivity and molecular diffusion parameters were set equal to zero. Setting these parameters equal to zero removes mixing of freshwater and seawater at the interface, allowing the simulation of a relatively sharp interface. Additional discussion about transport parameters are included in Appendix A to this report.

SECTION 4
IDENTIFICATION OF PROTECTIVE AND TARGET GROUNDWATER LEVELS

As introduced in Section 1, the target groundwater level for each coastal monitoring well is defined as the water level that protects the aquifer from seawater intrusion and stores a specified volume of freshwater offshore. This requires first defining an interface that protects the aquifer from being intruded. This protective interface is the condition in which there is no fresh water stored offshore because increasing pumping in the area would intrude the aquifer.

This section discusses the definition of the protective interface, defines the target storage volumes, presents the methodology and model results that identify protective and target groundwater levels, and presents an uncertainty analysis.

4.1 PROTECTIVE INTERFACE

The protective interface occurs when the toe of the intruding seawater wedge just reaches the coastline at a specified elevation (Figure 2). In this case, the aquifer inland from the coastline and above the specified elevation contains freshwater. This is consistent with SqCWD's goal to protect the aquifer and any non-SqCWD production wells that may exist between the monitoring well cluster and the coastline. Additional details on modeling the protective interface are included in Appendix A to this report.

Freshwater is defined as a chloride concentration below the secondary maximum contaminant limit (MCL) of 250 milligrams per liter (mg/L). A location is considered to have freshwater if it has a modeled chloride concentration equal to or below this limit.

The simulated coastline is defined as where the land surface drops below 0 feet mean sea level (msl). Table 3 shows the distance of the coastline from the monitoring well clusters for each of the cross section models. In general, larger distances between the monitoring well and the coastline will lead to higher water levels needed to achieve the protective interface.

Table 3: Coastline Distance from Monitoring Wells

Monitoring Well Cluster	Distance from Monitoring Well Cluster (feet)
SC-1	150
SC-3	650
SC-5	650
SC-8	550
SC-9	100
SC-A1	1250
SC-A2	900
SC-A3	200
SC-A4	1550
SC-A8	1200

The strategy for specifying the elevation at which intrusion is evaluated is different for the Purisima Formation monitoring wells and the Aromas Red Sands monitoring wells as discussed below.

4.1.1 Protected Elevation in the Purisima Formation

The protected elevation for the Purisima Formation is the bottom of the lowest producing aquifer in the area. Nearby SqCWD production wells are identified, and the lowest screen interval is used to determine the lowest producing aquifer. The entire producing aquifer is protected at the coastline. Intrusion is allowed below the lowest producing aquifer. We assumed that private production wells do not extract from below the protected aquifer.

Table 4 lists the protected aquifer for each coastal well cluster in the Purisima Formation. As mentioned earlier, the protected aquifer corresponds to the deepest producing zone, not necessarily the lowest monitoring well. Three monitoring wells exist below the protected DEF aquifer at the SC-8 well cluster and one monitoring well exists below the protected BC aquifer at the SC-9 well cluster.

Table 4: Purisima Monitoring Wells and Protected Elevations

Monitoring Well in Protected Unit	Nearby SqCWD Production Wells	Protected Aquifer Unit	Protected Elevation at Coastline (feet msl)
SC-1A	Garnet	A	-258
SC-3A	Rosedale, Tannery II	A	-440
SC-5A	Estates	A	-652
SC-8D	Aptos Creek, T-Hopkins	DEF	-377
SC-9B	Ledyard, Madeline	BC	-460

4.1.2 Protected Elevation in the Aromas Red Sands

The protected elevation for the Aromas Red Sands is the elevation immediately above the lowest monitoring well in any coastal monitoring well cluster. The lowest monitoring well in each cluster in the Aromas Red Sands was installed to be below the existing saltwater interface. Therefore, seawater intrusion in the lowest well is likely representative of long-term historical conditions. The protected elevation is chosen to ensure seawater intrusion does not occur at shallower elevations than long-term historical conditions.

Table 5 lists the protected aquifer for each coastal well cluster in the Aromas Red Sands and the protected elevation at the coast.

Table 5: Aromas Monitoring Wells and Protected Elevations

Monitoring Well Above Protected Elevation	Aquifer Unit Of Monitoring Well	Protected Elevation at Coastline (ft msl)
SC-A1B	F	-349
SC-A2B	F	-296
SC-A3B	Aromas	-181
SC-A4B	F	-296
SC-A8B	F	-412

4.2 Distribution of Offshore Storage Volume

As introduced in Section 1, the target groundwater levels are designed to store a target volume of freshwater offshore. The total target volume is 1,110 acre-feet, the estimated amount of increased pumping needed to meet three years of projected 2050 demand if no supplemental supply is available.

4.2.1 STANDARD DISTRIBUTION

The spatial distribution of stored water is based on the distribution of projected pumping at nearby SqCWD production wells: areas with higher anticipated pumping are assigned more stored water. The projected pumping is based on the most likely scenario for year 2050 drought pumping introduced in the letter discussing Hydrologic Effects of the Well Master Plan (Williams et al., 2008). This distribution includes pumping from planned municipal production wells at the O'Neill Ranch, Cunnison Lane, Austrian Way, Granite Way, and Polo Grounds sites. The plan eliminates pumping at the Monterey and Aptos Creek wells.

Table 6 shows the production wells used to distribute the volume of stored water, and the target volumes for each simulated monitoring well cluster.

Table 6: Standard Target Storage Volume Distribution

Monitoring Well in Protected Unit	SqCWD Production Wells Assigned to Distribute Storage Volumes	Percentage of 2050 Drought Pumping	Target Storage Volume (acre-feet)
SC-1A	Garnet, Main Street, O'Neill Ranch	32%	352
SC-3A	Rosedale, Tannery II, Cunnison Lane	10%	112
SC-5A	Estates	5%	56
SC-8D	T-Hopkins, Granite Way	8%	84
SC-9B	Ledyard, Madeline, Austrian Way	8%	83
SC-A1B	Aptos Jr. High, Polo Grounds	15%	160
SC-A2B	San Andreas, Seascape	9%	102
SC-A3B	Sells, Altivo	3%	36
SC-A4B	N/A	0%	0
SC-A8B	Country Club, Bonita	11%	119

4.2.2 ALTERNATIVE DISTRIBUTION

An alternative distribution of storage volumes is also considered, based on two possible operational constraints:

1. Changes in SqCWD pumping may not affect Aromas area groundwater levels enough to store the target volumes offshore.

2. A cooperative groundwater management agreement with the City of Santa Cruz may set the goal for pumping near monitoring well SC-1A to capture offshore flows. This goal recognizes that monitoring well SC-1A is close to the offshore outcrop and is in an area with limited offshore storage. Therefore, there may be little benefit to raising water levels at well SC-1A in an attempt to store water offshore.

Constraint 1 implies that the alternative distribution of storage volumes only stores water in the Purisima Formation. Constraint 2 implies that no water is stored offshore of the SC-1 monitoring well cluster. The overall target volume of 1,100 acre-feet is therefore distributed offshore of monitoring wells SC-3A, SC-5A, SC-8D, and SC-9B, based on their proportional pumping projected for a 2050 drought year. Table 7 shows the production wells used in the alternative distribution of stored water, and the target volumes for each simulated monitoring well cluster.

Table 7: Alternative Target Storage Volume Distribution

Monitoring Well in Protected Unit	SqCWD Production Wells Assigned to Distribute Storage Volumes	Percentage of 2050 Drought Pumping	Target Storage Volume (acre-feet)
SC-3A	Rosedale, Tannery II, Cunnison Lane	33%	369
SC-5A	Estates	17%	184
SC-8D	T-Hopkins, Granite Way	25%	275
SC-9B	Ledyard, Madeline, Austrian Way	25%	276

4.3 MODELING APPROACH FOR IDENTIFYING PROTECTIVE AND TARGET GROUNDWATER LEVELS

The approach for identifying protective and target groundwater levels is an incremental trial and error approach. Each cross sectional model is run with a constant head applied at the simulated monitoring wells. The simulated groundwater level in the monitoring well is then updated with an incrementally larger or smaller value based on the location of the seawater interface in previous runs. The increment used was one foot, because it will likely be impractical for SqCWD to manage to groundwater levels at a higher precision.

The groundwater levels simulated in all monitoring wells in a single cluster are assigned the same value, even though groundwater levels in shallowest units are often well above groundwater levels in pumped units. Sensitivity tests showed that a higher groundwater level in overlying units did not significantly affect results. In cases where groundwater levels in overlying units are higher than the production units, there is often vertical resistance to flow such that intrusion in each unit is relatively independent of intrusion in other units.

4.3.1 Protective Groundwater Levels

The simulated groundwater levels in the monitoring wells are updated until the protective level is identified. The protective level is the minimum level where the simulated concentration at the coastline in the protected aquifer is less than the maximum contaminant limit of 250 mg/L. This is equivalent to simulating the toe of seawater intrusion just reaching the coastline as shown on Figure 2.

4.3.2 Target Groundwater Levels

Target groundwater levels are the simulated water levels that store the target volume of water offshore. These water levels are higher than the protective groundwater levels. Target groundwater levels are estimated by first calculating how much water is stored offshore at the protective groundwater level. This is called the protective volume, and is a volume of water that cannot be extracted without causing seawater intrusion. The simulated water levels in the monitoring wells are increased in 1 foot increments above the protective groundwater level. After every increase, the volume of water stored offshore is calculated. Groundwater level increases continue until the total volume of freshwater stored in the producing unit is greater than the protective volume by at least the amount shown on Table 6 or Table 7.

4.4 Uncertainty Analysis

Specific hydrogeologic parameter sets for each cross-sectional model cannot be determined with any certainty because there are insufficient data to calibrate the models to water level or concentration data. Additionally, there are limited data for hydrogeologic parameter values offshore, adding further uncertainty. To develop reliable target groundwater levels, it is necessary to perform an uncertainty analysis that evaluates the range of reasonable outcomes given the lack of precise parameter data.

A Monte Carlo approach was used for the uncertainty analysis. This approach uses a series of randomized inputs to the model to create a range of possible model results. Ninety-nine parameter sets were created for each cross sectional model using the PEST utility RANDPAR (Doherty, 2008). The parameters varied were the horizontal hydraulic conductivities of the production unit and the underlying unit, and vertical conductivities of the aquitards above the production unit as shown in Table 8. If multiple aquitards exist above the production unit, the conductivities of the aquitards were varied together. If no aquitards exist above the production unit, the vertical conductance of the seabed was varied over two orders of magnitude. For the wells in the Aromas area, parameters for all modeled units and the seabed are varied.

Table 8: Units Varied for each Cross-Sectional Model in Uncertainty Analysis

Monitoring Well Cluster	Underlying Unit	Protected Aquifer	Overlying Unit
SC-1	AA aquifer	A aquifer	B aquitard
SC-3	AA aquifer	A aquifer	B aquitard
SC-5	AA aquifer	A aquifer	B and D aquitards
SC-8	D aquitard	DEF aquifer	Seabed
SC-9	B aquitard	BC aquifer	D aquitard
SC-A1	DEF aquifer	F aquifer	Aromas aquifer and Seabed
SC-A2		F aquifer	Aromas aquifer and Seabed
SC-A3	F aquifer	Aromas aquifer	Seabed
SC-A4		F aquifer	Aromas aquifer and Seabed
SC-A8	DEF aquifer	F aquifer	Aromas aquifer and Seabed

Parameters were varied within the ranges shown in Table 1. The range of vertical conductance for the seabed was between 1 and 1,000 feet per day. Horizontal hydraulic conductivities were selected for the 99 parameter sets using a random uniform distribution. Vertical conductivities were selected for the 99 parameter sets using a random uniform log-transformed distribution. This distribution is appropriate because hydrologic parameter values are typically distributed not by absolute value, but by order of magnitude. A uniform distribution is used because there is no information that any value within the range is more likely than any other. Anisotropy was fixed at 20:1 in all units. Parameter values for other units were fixed at values shown in Table 2.

The 99 parameter sets created for each model were added to the base parameter set shown in Table 2 to create 100 parameter sets to evaluate. This resulted in 100 protective and target groundwater levels for each cross-sectional model.

4.5 MODEL RESULTS

Model results for each of the cross-sectional models are summarized here. A complete discussion of the model results is included in Appendix A to this report.

4.5.1 PROTECTIVE GROUNDWATER LEVELS

Table 9 summarizes the protective groundwater levels estimated by the cross-sectional models. For each monitoring well cluster, a range of protective groundwater levels is presented, corresponding to the range of results from the 100 parameter sets in the uncertainty analysis. The suggested protective groundwater level on Table 9 is the groundwater level that is protective in at least 70% of the 100 simulations.

4.5.2 TARGET GROUNDWATER LEVEL RESULTS FOR THE STANDARD STORAGE DISTRIBUTION

Table 10 summarizes the target groundwater levels estimated by the cross-sectional models for the standard storage distribution described in Section 4.2.1. For each monitoring well cluster, a range of target groundwater levels is presented, corresponding to the range of results from the 100 parameter sets in the uncertainty analysis. As with the protective groundwater levels, the suggested target groundwater level on Table 10 is the groundwater level that stores sufficient water offshore in at least 70% of the 100 simulations.

Table 9: Simulated Protective Groundwater Levels

Monitoring Well Cluster	Protective Groundwater Level Range (ft msl)	Suggested Protective Groundwater Level (ft msl)
SC-1	1 to 5	4
SC-3	8 to 11	10
SC-5	11 to 15	13
SC-8	8 to 11	10
SC-9	3 to 11	10
SC-A1	8 to 12	10
SC-A2	6 to 8	8
SC-A3	1 to 4	4
SC-A4	9 to 11	11
SC-A8	9 to 12	11

Table 10: Simulated Target Groundwater Levels – Standard Storage Distribution

Monitoring Well Cluster	Target Groundwater Level Range (ft msl)	Suggested Target Groundwater Level (ft msl)
SC-1	3 to 8	6
SC-3	9 to 12	11
SC-5	12 to 16	14
SC-8	9 to 12	11
SC-9	4 to 12	11
SC-A1	10 to 14	12
SC-A2	8 to 10	10
SC-A3	2 to 5	5
SC-A4	N/A[1]	N/A
SC-A8	12 to 16	15

[1] Well SC-A4 has no nearby District pumping, and therefore no target storage volume or target water level

4.5.3 Target Groundwater Level Results for the Alternative Storage Distribution

Table 11 summarizes the target groundwater levels estimated by the cross-sectional models for the alternative storage distribution described in Section 4.2.2. For each monitoring well cluster, a range of target groundwater levels is presented, corresponding to the range of results from the 100 parameter sets in the uncertainty analysis. As with the protective groundwater levels, the suggested target groundwater level on Table 11 is the groundwater level that stores sufficient water offshore in at least 70% of the 100 simulations.

Table 11: Simulated Target Groundwater Levels – Alternative Storage Distribution

Monitoring Well Cluster	Target Groundwater Level Range (ft msl)	Suggested Target Groundwater Level (ft msl)
SC-1	N/A[1]	N/A
SC-3	10 to 14	13
SC-5	12 to 17	14
SC-8	10 to 14	13
SC-9	5 to 13	12
SC-A1	N/A	N/A
SC-A2	N/A	N/A
SC-A3	N/A	N/A
SC-A4	N/A	N/A
SC-A8	N/A	N/A

[1] Wells with N/A results have no offshore storage in the alternative storage distribution

4.5.4 Comparison of Model Results with Current Conditions

Figure 16 through Figure 25 show how the suggested protective and target groundwater levels compare to recent groundwater level data. These figures show that current groundwater levels are below both the protective and target groundwater levels at all coastal monitoring wells. Historical groundwater levels, however, have been at or above the protective groundwater levels at all Purisima and most Aromas well clusters at some point in the past. This suggests that the protective and target groundwater levels are reasonable and achievable goals.

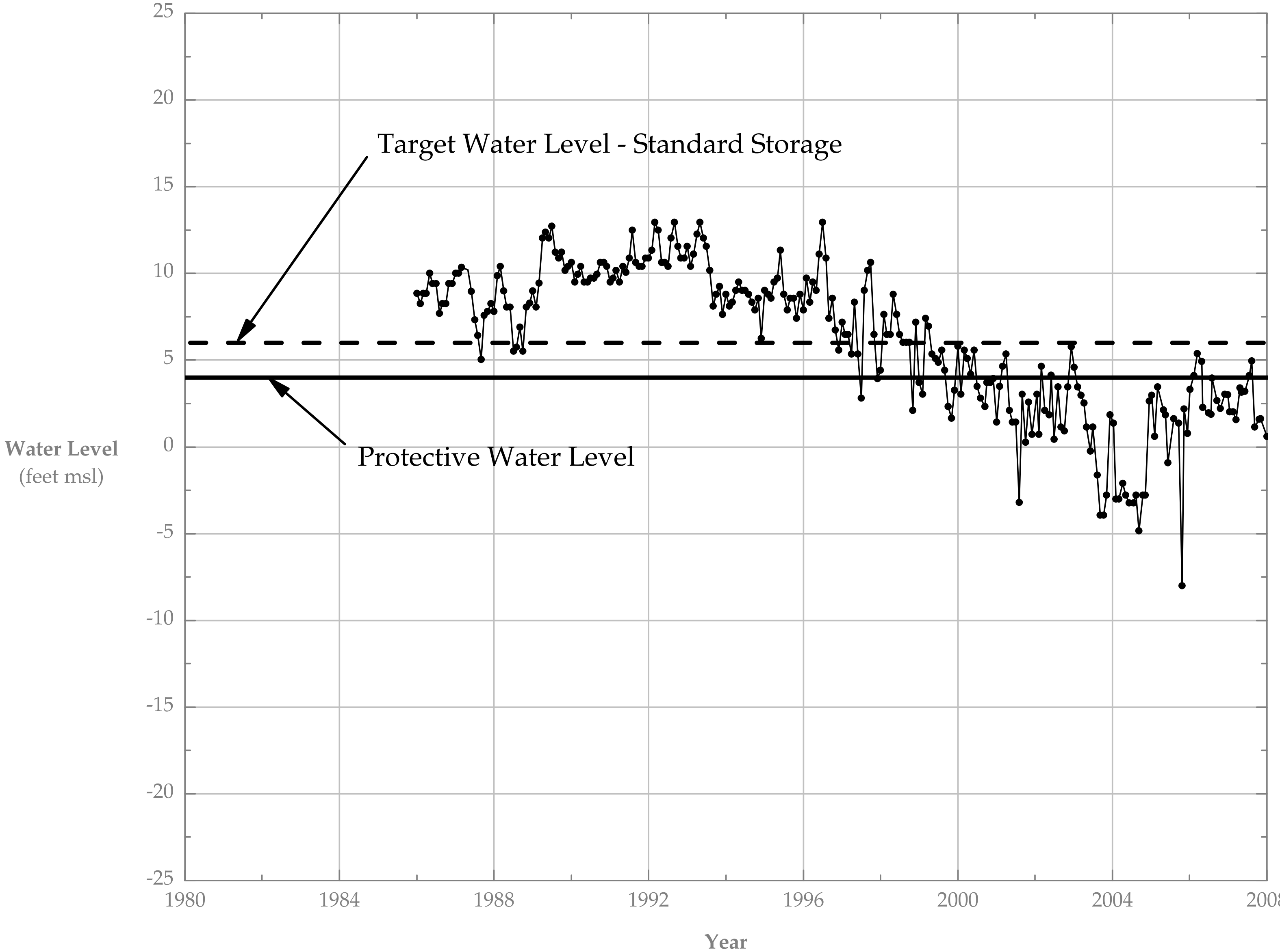

Figure 16: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-1A

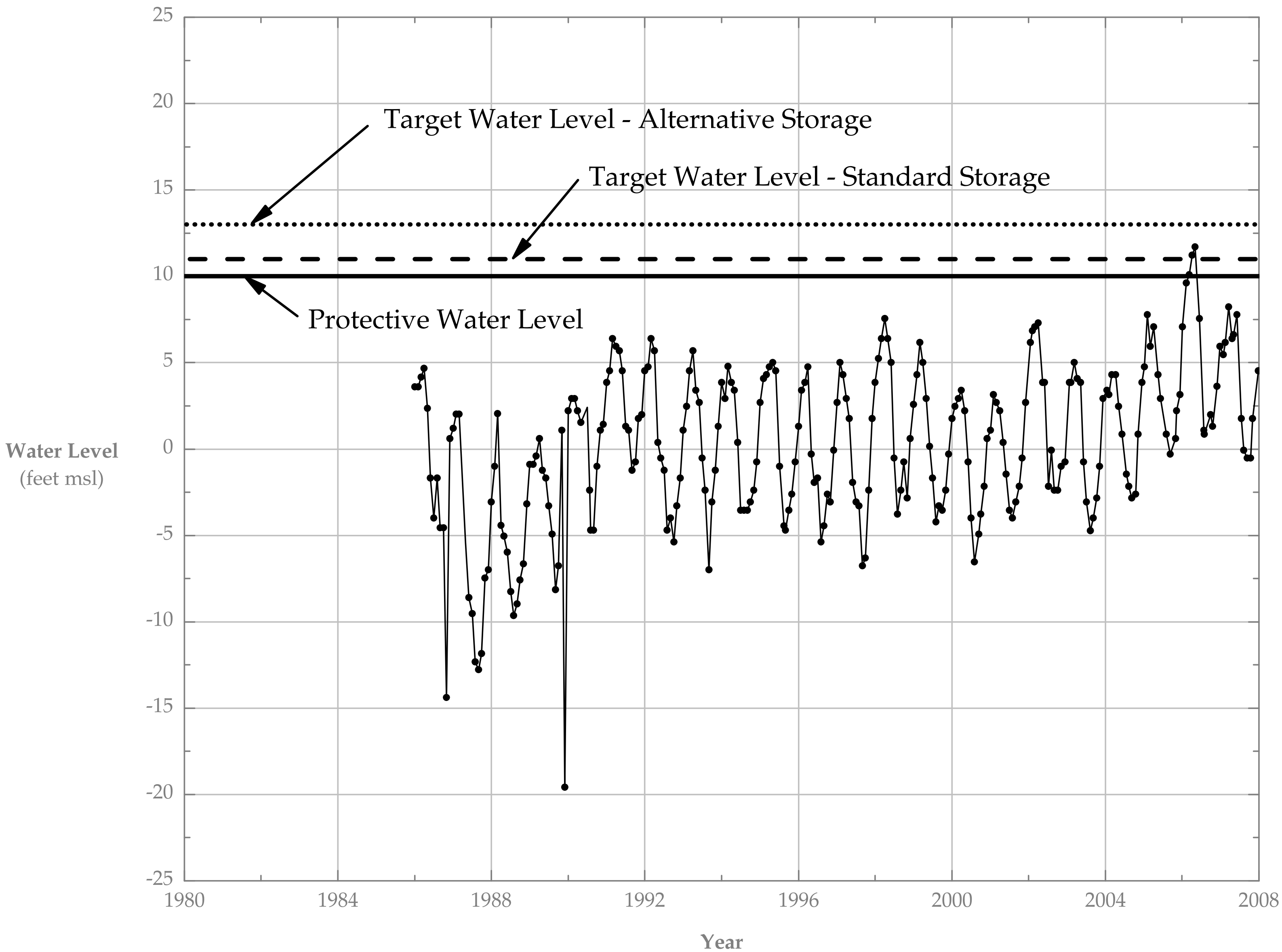

Figure 17: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-3A

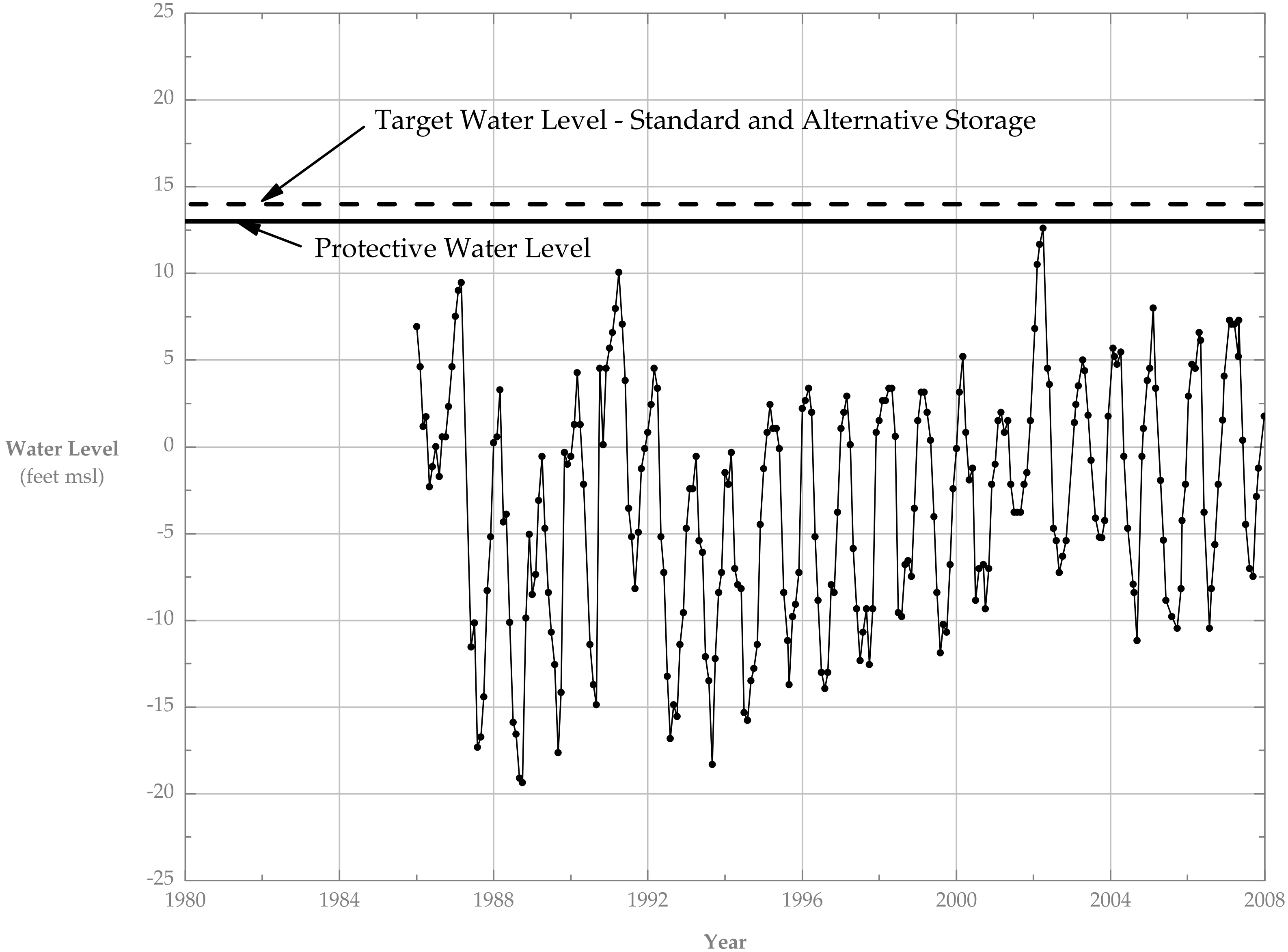

Figure 18: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-5A

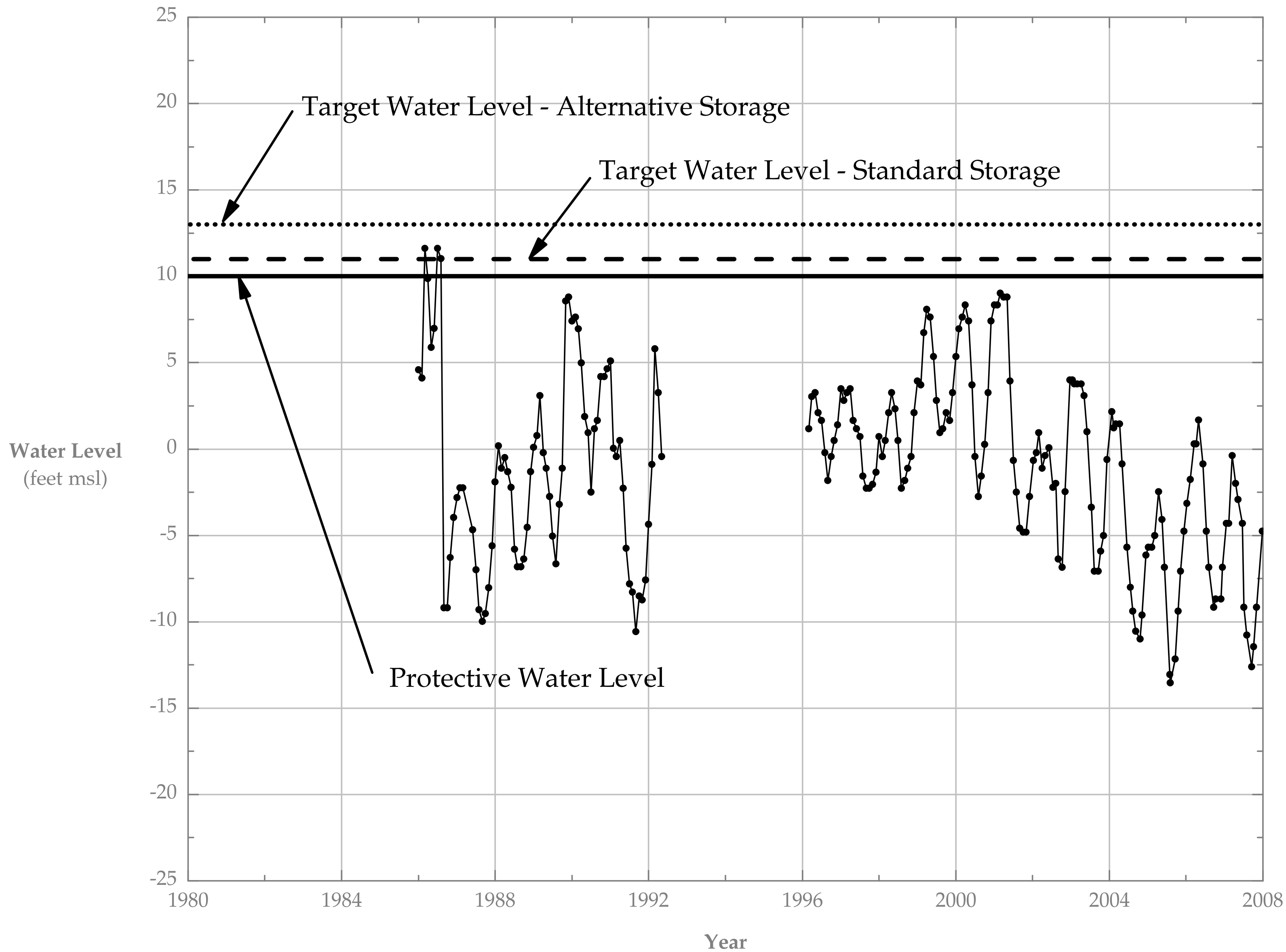

Figure 19: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-8D

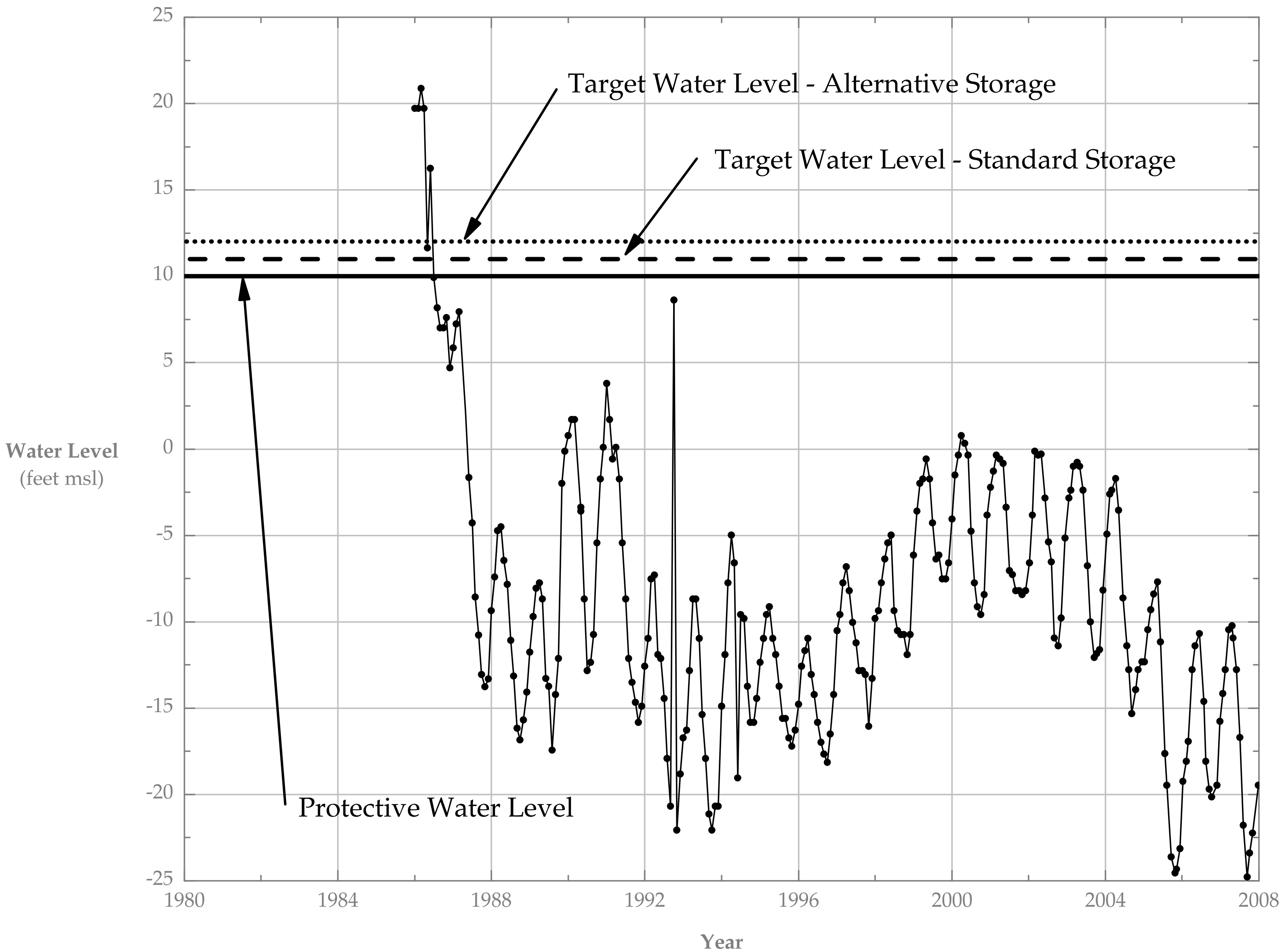

Figure 20: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-9B

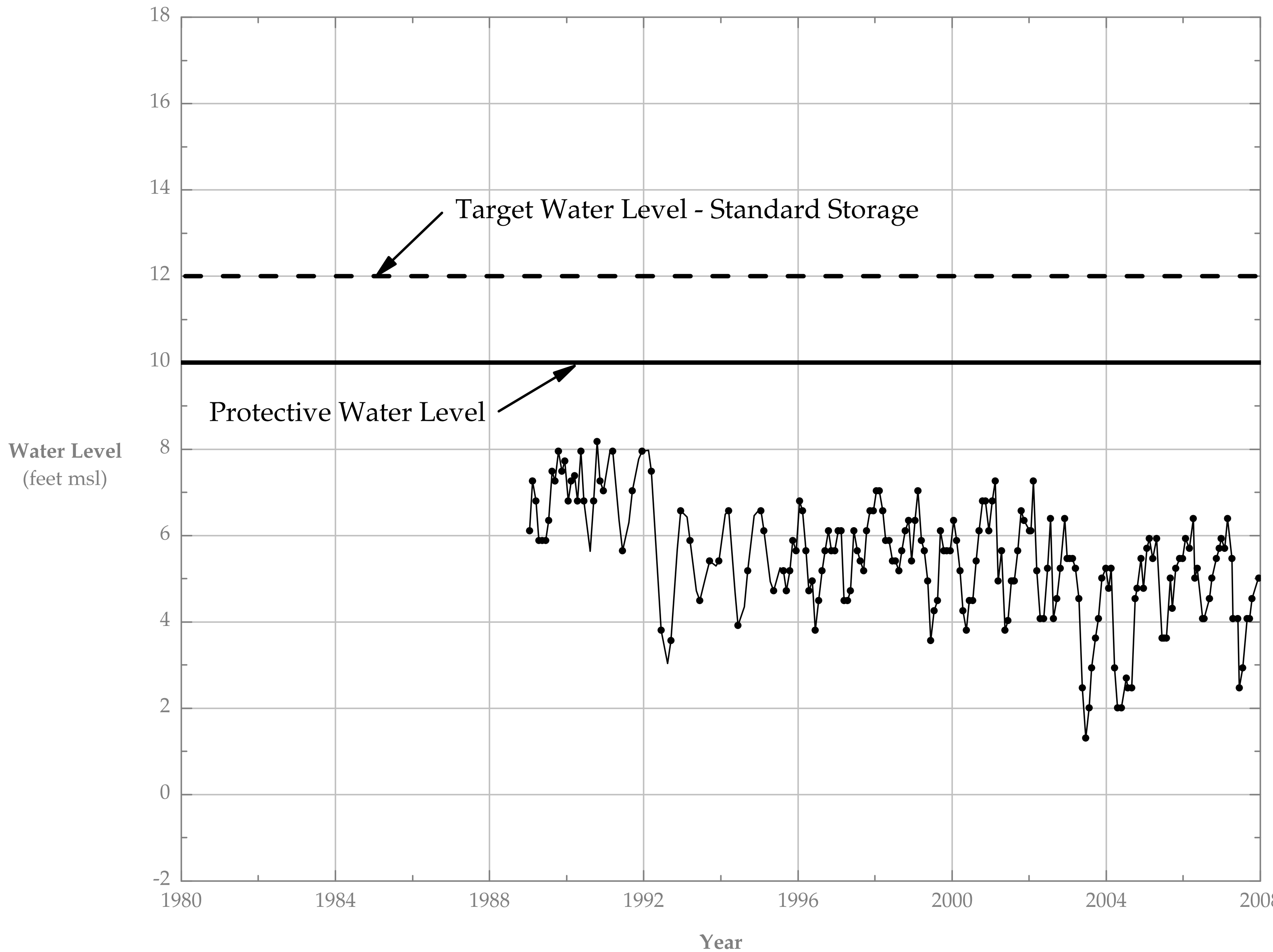

Figure 21: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-A1B

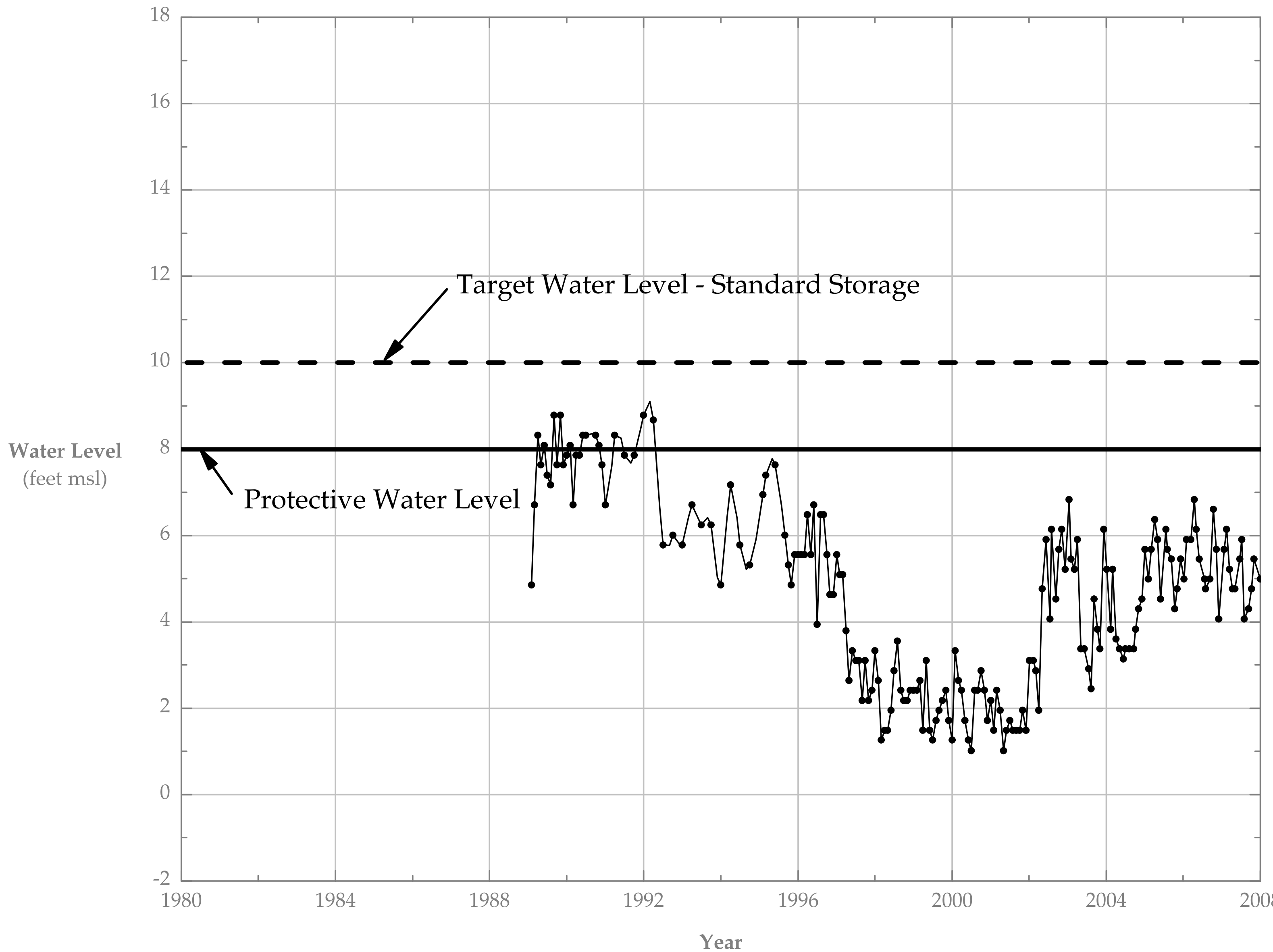

Figure 22: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-A2B

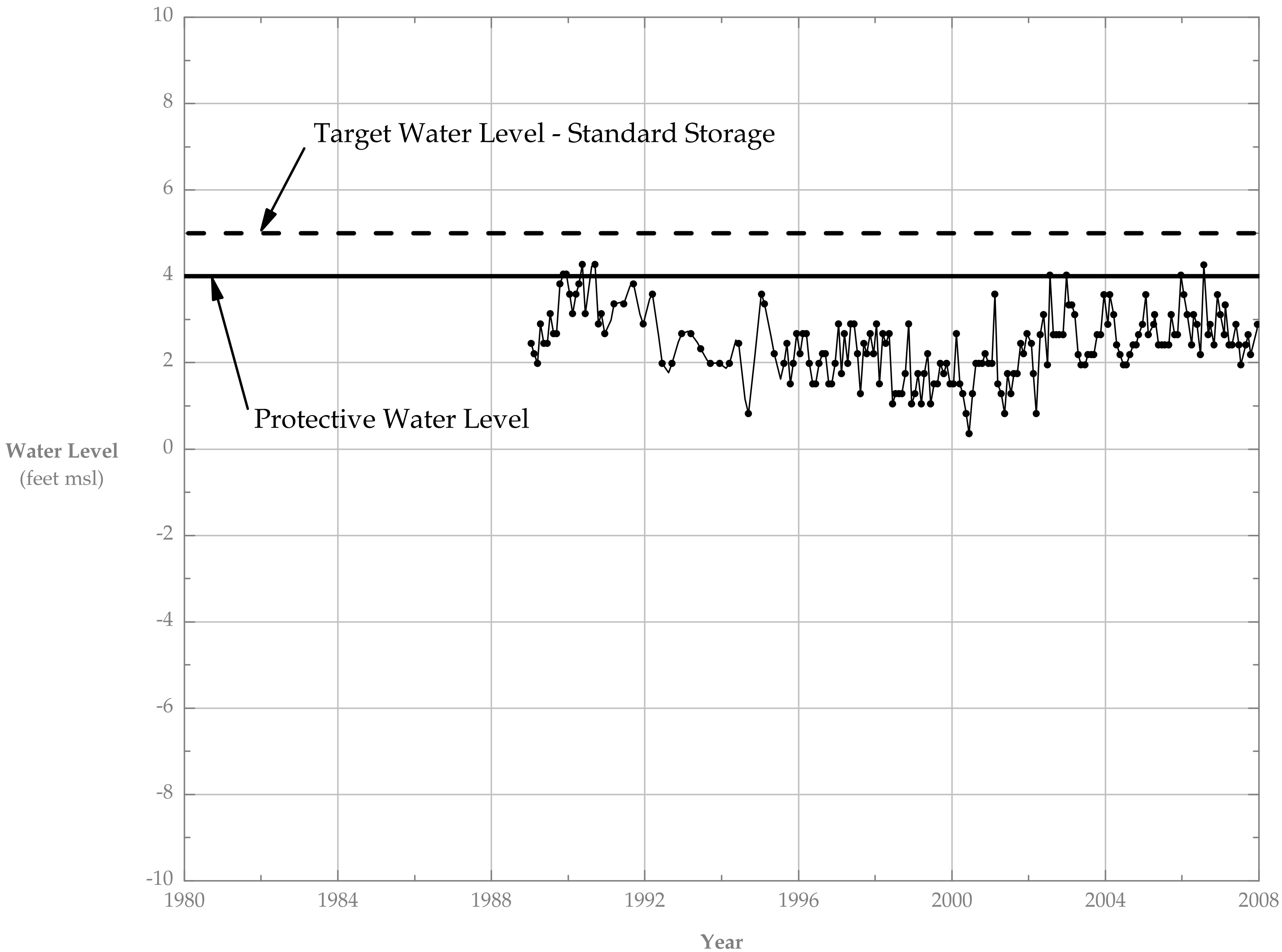

Figure 23: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-A3B

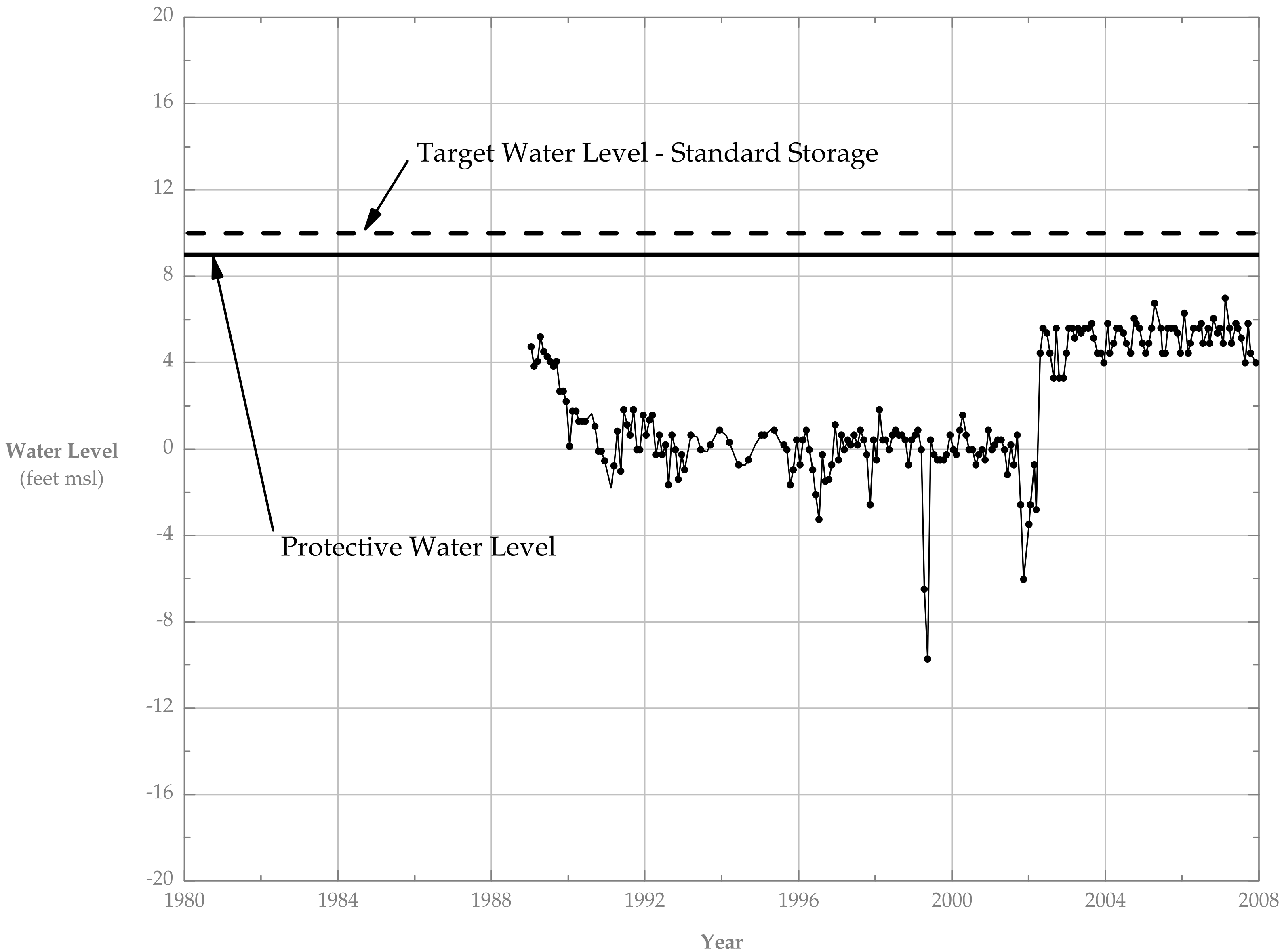

Figure 24: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-A4B

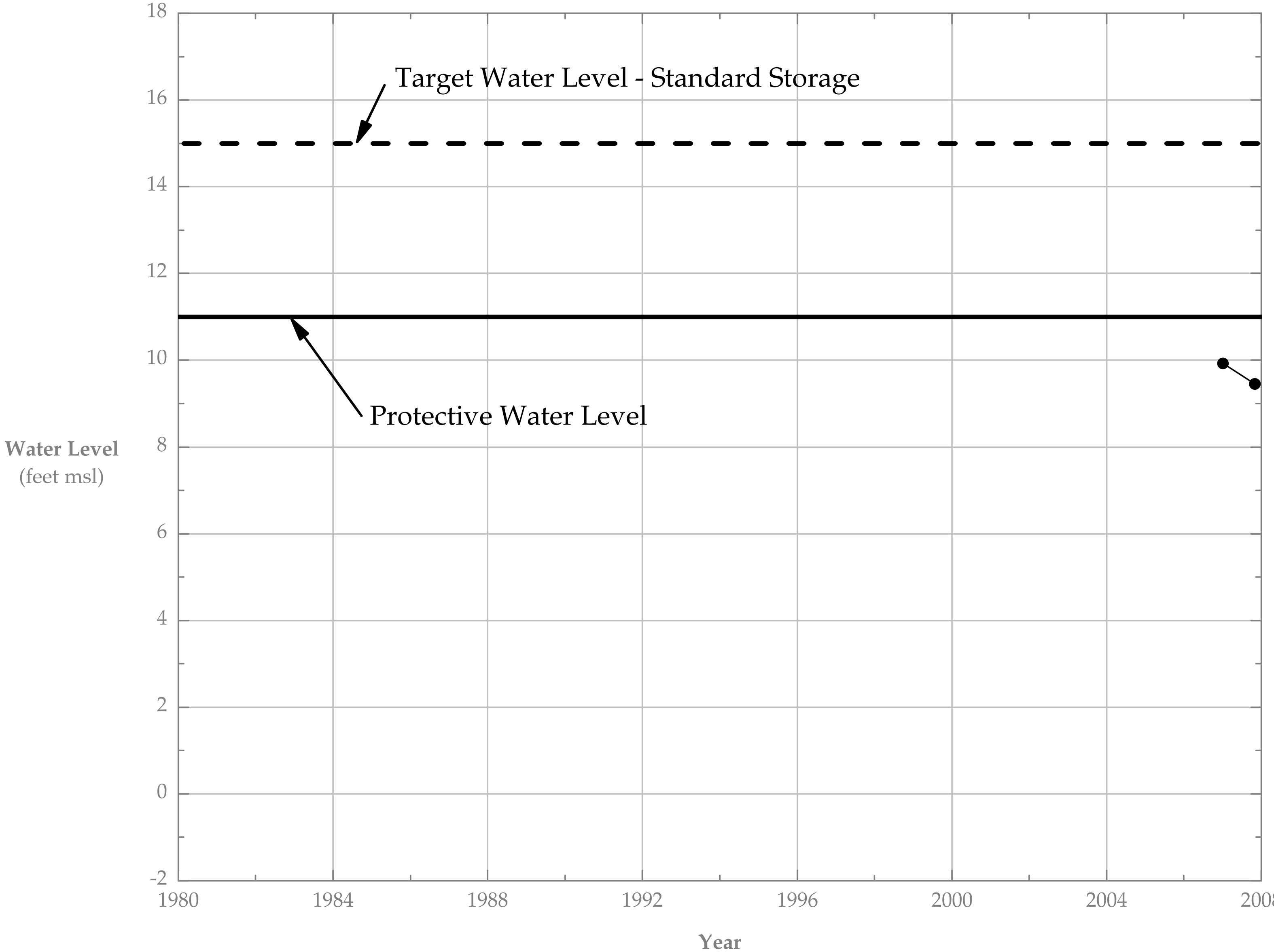

Figure 25: Comparison of Historical Groundwater Levels with Protective and Target Levels - Well SC-A8B

SECTION 5
CONCLUSIONS

Table 12 summarizes the recommended protective and target groundwater levels for the coastal monitoring wells. Table 12 also shows the groundwater level ranges for water year 2007 in the monitoring wells. Average current groundwater levels are below the protective and target groundwater level in all wells. Maintaining the current groundwater levels leads to increased risk of seawater intrusion of the protected aquifers.

Table 12: Protective and Target groundwater levels for at least 70% of Parameter Sets

Well	Water Year 2007 Water Level Range (feet msl)	Protective Water Level (feet msl)	Target Water Level for Storage (feet msl)	Alternative Water Level for Storage (feet msl)
SC-1A	1 – 5	4	6	
SC-3A	-1 – 8	10	11	13
SC-5A	-7 – 7	13	14	14
SC-8D	-13 – 0	10	11	13
SC-9B	-23 - -19	10	11	12
SC-A1B	2 – 6	10	12	
SC-A2B	4 – 6	8	10	
SC-A3B	2 – 4	4	5	
SC-A4B	4 – 7	11		
SC-A8B	10	11	15	

5.1 MANAGING TO PROTECTIVE WATER LEVELS

The protective water levels are the long-term average water levels at the monitoring wells that will protect the production aquifers from onshore seawater intrusion. Water levels in the coastal monitoring wells can have seasonal and tidal fluctuations, but long-term management should relate to long-term average water levels. The minimum length of time for calculating the average groundwater levels should be one year, and care should be taken to evaluate the bias introduced by tidal fluctuations.

Groundwater levels will likely not increase at all monitoring wells without a decrease in the overall pumping of the Soquel-Aptos Basin. This necessary decrease in long-term pumping will likely only be realized if a supplemental supply can be obtained. When a supplemental supply is obtained and pumping is decreased, SqCWD should distribute pumping where feasible to achieve protective water levels at as many coastal monitoring wells as possible. Reducing pumping may not raise water levels in all areas, such as the Aromas Red Sands.

Because the goal is to raise long-term average water levels to the protective levels, the benefit of pumping reductions should not be seasonally dependent. However, the water level response to pumping reductions in different seasons should be evaluated to add confidence that reductions in any season will increase long-term averages as planned.

SqCWD can also use the long-term nature of the protective water levels to help manage the response to a short-term increase in pumping due to a curtailment of supplemental supply. After protective water levels are met, an increase in pumping over one to several years will likely decrease annual averages below protective levels. When supplemental supply is restored and additional supply is available, SqCWD can reduce pumping beyond long-term averages so that water levels exceed protective water levels for a period of time. The period of time can be chosen so that the average water level during the entire period of increased and decreased pumping meets the protective water level. This is a reactive approach that is an alternative to using target water levels to store water in case increased pumping is necessary. This approach may be more feasible and cost-effective than decreasing pumping even further over the long-term in order to meet target water levels.

5.2 MANAGING TO TARGET WATER LEVELS

The target water levels allow SqCWD to prepare for an increase in pumping due to reduction in supplemental supply. The target water levels are the long-term average water levels at the monitoring wells that will store the target volume offshore. If long-term average water levels meet target water levels, SqCWD will be able to increase its pumping by the target volume over any period of time, such as 370 acre-feet per year for 3 years, without inducing seawater intrusion.

SqCWD should manage pumping to meet target water levels only after protective water levels are achieved at as many coastal monitoring wells as possible. If increasing Aromas Red Sands groundwater levels to protective levels is difficult even with a decrease in pumping, the alternative target groundwater levels should be used in the Purisima Formation.

An additional decrease in the overall pumping of the Soquel-Aptos Basin will likely be necessary to raise long-term water levels from protective to target levels. Therefore, additional supplemental supply will be necessary. The additional supply necessary to raise water levels will likely not be equal to the target volume.

5.3 SUMMARY

Cross-sectional models are used to calculate recommended protective and target water levels at coastal monitoring wells. A reduction in pumping will be necessary to meet the protective and target water levels. When a supplemental supply is available, SqCWD should reduce pumping to meet protective water levels. The response of water levels to the reduced pumping should be monitored to manage the pumping distribution to protect production aquifers and zones. After protective water levels are met, SqCWD may want to meet target water levels to store additional water offshore. Water quality data at the coastal monitoring wells should be regularly evaluated to make sure the raised water levels are protecting the aquifer.

SECTION 6
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