Appendix H – TM 10.3

Seawater Intrusion

Kennedy/Jenks Consultants

303 Second Street, Suite 300 South
San Francisco, California 94107
415-243-2150
FAX: 415-896-0999

Technical Memorandum 10.3

Assessment of Potential Seawater Intrusion

for the Regional Groundwater Storage and Recovery Project and San Francisco Groundwater Supply Project

24 April 2012

Prepared for

San Francisco Public Utilities Commission
525 Golden Gate Avenue, 10th Floor
San Francisco, CA 94102

K/J Project No. 0864001

Supplemental Explanation for Hydrographs - TM10.3

This supplemental explanation is prepared to address discrepancies on several graphs presented in TM 10.3.

First, the x-axis on several graphs showing model results was shifted. The x-axis is named Scenario Year which should correspond to a water year[1]. However, the graph template was plotted using a calendar year, so the intervals on the x-axis represent the period from January to December. The result is that the graph is shifted 3-months later relative to Scenario Year.

Second, the shaded area representing the Design Drought was added manually and because of this process, it was not presented consistently on the graphs. By definition per the PEIR, the 8.5-year Design Drought includes one Hold year before the 7.5-year Take period. In addition, the Design Drought needs to be shifted 3-months later for the x-axis issue to be consistent with the model output. The Design Drought should be shown as Scenario Years 35.5 to 44.0 on the shifted x-axis.

The following is a list of figures in TM 10.3 where the Design Drought shaded area is shown slightly different and does not match the correct display of the Design Drought. The figures should be viewed based on the correct representation of the Design Drought as explained above.

- Figures 10.3-4 through 10.3-17 (a total of 30 figures) have the shifted x-axis. The Design Drought should be shown as Scenario Years 35.5 to 44.0 on the shifted x-axis.

[1] A water year is October 1 of the previous year to September 30 of the current (named) year.

24 April 2012

Task 10.3 Technical Memorandum

San Francisco Public Utilities Commission

Assessment of Potential Seawater Intrusion for the Regional Groundwater Storage and Recovery Project and San Francisco Groundwater Supply Project

Prepared For: Greg Bartow and Jeff Gilman, SFPUC

Prepared by: Matthew Baillie, Michael Maley and Sevim Onsoy, Kennedy/Jenks Consultants

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1. Introduction

This Technical Memorandum (TM) was prepared to document work performed by Kennedy/Jenks Consultants (Kennedy/Jenks) for the San Francisco Public Utilities Commission (SFPUC) pursuant to the amended Task Order (TO) authorizations CUW30103-TO-1.12 of the Regional Groundwater Storage and Recovery (GSR) Project and CUW30102-TO-2.7 of the San Francisco Groundwater Supply (SFGW) Project. These projects are funded by the SFPUC's Water System Improvement Program (WSIP).

1.1. GSR and SFGW Project Description

The GSR Project is a conjunctive use project that would allow for increased groundwater supplies in the southern portion of the Westside Groundwater Basin (South Westside Basin) during periods of drought when SFPUC surface water supplies might become limited (MWH, 2008). The project would be designed to provide up to 60,500 acre-feet (af) of stored water to meet SFPUC system demands during the last 7.5 years of SFPUC's Design Drought. The SFPUC plans to install 16 new production wells for the GSR Project to recover the stored groundwater. Under the Draft GSR Operating Agreement, the SFPUC would "store" water in the South Westside Basin through the mechanism of in-lieu recharge by providing supplemental surface water as a substitute for groundwater pumping by the Partner Agencies (PAs). As a result of the in-lieu deliveries, up to 60,500 af of groundwater storage or put credits could accrue to the SFPUC Storage Account. During shortages of SFPUC Regional Water System water due to drought, emergencies, or scheduled maintenance, the PAs would return to pumping from their existing wells, and SFPUC would extract groundwater from GSR Project wells as long as a positive balance exists in the SFPUC Storage Account.

The SFGW Project would provide a reliable, local source of high-quality groundwater in the northern portion of the Westside Groundwater Basin (North Westside Basin) to supplement the

San Francisco municipal water system. The SFGW Project would construct up to four wells (and convert two existing irrigation wells in Golden Gate Park for municipal supply) and associated facilities in the western part of San Francisco and extract an annual average of up to 4.0 million gallons per day (mgd) of water from the North Westside Basin (SFPUC, 2009a). The extracted groundwater, which would be used both for regular and emergency water supply purposes, would be blended in small quantities with imported surface water before entering the municipal drinking water system for distribution. The SFGW Project includes two phases. In phase one, SFPUC would build four new groundwater wells at the Lake Merced Pump Station, West Sunset Playground, South Sunset Playground, and the Golden Gate Park Central Pump Station. In phase two, SFPUC would modify two existing irrigation wells (South Windmill Replacement and North Lake) in Golden Gate Park, converting them into municipal water supply wells.

The locations of existing and proposed GSR and SFGW wells, existing PA wells, and monitoring wells are shown on Figure 10.3-1. Additional detailed discussion of the GSR and SFGW Projects is provided in Task 10.1 Technical Memorandum - Groundwater Modeling Analysis for the Regional Groundwater Storage and Recovery Project and San Francisco Groundwater Supply Project (TM-10.1).

1.2. Objective

Implementation of the proposed GSR and SFGW Projects would influence groundwater heads in the Westside Groundwater Basin (Westside Basin, or Basin). Because the Westside Basin underlies both the Pacific Ocean west of San Francisco and San Francisco Bay near San Bruno, there is the potential for seawater intrusion to occur as a result of implementation of the GSR and SFGW Projects.

The purpose of this TM is to present the results of an evaluation of potential changes in groundwater head resulting from operation of each of the GSR and SFGW Projects, as well as the cumulative effects of both the GSR and SFGW Projects (along with other reasonably foreseeable future groundwater projects in the Basin), in order to assess the potential for seawater intrusion in areas that may be susceptible. The potential changes in groundwater head resulting from implementation of the GSR and SFGW Projects and other reasonably foreseeable future projects were evaluated based on groundwater model scenarios developed using the existing Westside Basin Groundwater-Flow Model (HydroFocus, 2007, 2009, and 2011). These model results were evaluated with respect to the potential to induce seawater intrusion. This TM presents information on the past, current, and future subsurface conditions that are relevant to the issue of seawater intrusion along with a conceptual discussion of the mechanisms that control seawater intrusion.

2. Approach and Conceptual Understanding of Seawater Intrusion

Before analyzing seawater intrusion in the context of the Westside Basin, a conceptual understanding of the process of seawater intrusion is presented. This section includes a description of the process, including the variables involved, the time-frame over which intrusion typically occurs, and hydrogeological factors that control intrusion.

2.1. General Approach

The general approach used to evaluate potential seawater intrusion for this TM is based on an analysis of the changes in groundwater conditions in the Basin, including groundwater heads[1] and flux, resulting from the operation of the GSR and SFGW Projects. This TM is part of a series of technical memoranda that address various aspects of the GSR and SFGW Projects. Two of these include significant data and analysis that are used for this TM. These include the following:

- Task 8B Technical Memorandum No.1 Hydrologic Setting of the Westside Basin (referred to in the text as TM#1; LSCE, 2010)
- Task 10.1 Groundwater Modeling Analysis for the Regional Groundwater Storage and Recovery Project and San Francisco Groundwater Supply Project (referred to in the text as TM-10.1; Kennedy/Jenks, 2012)

The primary quantitative tools for evaluating potential future conditions are model scenarios generated using the existing Westside Basin Groundwater-Flow Model developed by HydroFocus (2007, 2009, and 2011). For this analysis, the potential for seawater intrusion is evaluated using scenarios that evaluate the proposed GSR and SFGW Projects in isolation. A Cumulative Scenario is evaluated that includes both the GSR and SFGW Projects along with other reasonably foreseeable future groundwater projects in the Basin. The development of the model scenarios is documented in TM-10.1.

This TM includes a brief conceptual understanding of the hydrogeologic processes and factors that influence seawater intrusion and a hydrogeological evaluation summarizing the current conditions with respect to seawater intrusion in the Westside Basin. Much of the information used for this analysis is discussed in detail in TM#1.

[1] As used in this TM, head is the elevation at which groundwater would rest in a piezometer completed in the referenced aquifer. In an unconfined aquifer, this is equivalent to the water table elevation; in a confined aquifer, this is equivalent to the piezometric head.

2.2. Westside Groundwater Basin

This section provides a brief overview of the physical setting and Basin hydrogeology. More detailed evaluations of the hydrogeology of the Westside Basin are presented in TM#1 and TM10.1.

Figure 10.3-2 provides a representative cross-section from north to south across the Westside Basin. There are three aquifer systems that are commonly referred to within the Westside Basin. These include:

- Shallow Aquifer: this aquifer is present in the northern part of the Basin, in the vicinity of Lake Merced and the southern portion of the Sunset district of San Francisco. The base of the Shallow Aquifer is defined as the top of the "-100 foot clay."
- Primary Production Aquifer: this aquifer is present throughout the Basin, overlying the "W-clay" where present. Where the W-clay is not present in locations to the south (in the South San Francisco area), the Primary Production Aquifer is divided into shallow and deep units separated by a clay unit at an elevation of approximately -300 feet mean sea level (msl).
- Deep Aquifer: this aquifer underlies the W-clay, and thus its extent is limited to the generally-known extent of that clay unit (TM#1).

The three aquifer systems are separated by thick, extensive clay units (e.g., the -100 ft clay and W-clay). Because of the discontinuous nature of these clay layers, the basin is considered to be a semi-confined aquifer system with limited flow between the different aquifer systems where local geologic conditions permit (TM#1).

2.2.1. Areas Susceptible to Seawater Intrusion

The Westside Basin is bounded by bedrock highs in Golden Gate Park to the north and at Coyote Point to the south (Rogge, 2003; San Bruno, 2007; DWR, 2003). San Bruno Mountain and the San Francisco Bay form the eastern boundary of the Basin (Cal Water, 2006). The San Andreas Fault and Pacific Ocean form the Basin's western boundary, and its southern limit is defined by a bedrock high that separates it from the San Mateo Plain Groundwater Basin (Rogge, 2003, DWR, 2003, and San Bruno, 2007). The Westside Basin opens to the Pacific Ocean on the northwest and San Francisco Bay on the southeast. Major structural features include the San Andreas Fault system and the Serra Fault.

Areas that are considered potentially susceptible must be investigated for the occurrence of seawater intrusion. Two areas of the Basin are likely to be susceptible to seawater intrusion given certain conditions (Figure 10.3-1). The first is along the Pacific Ocean, between Lincoln Park in the north and Lake Merced in the South. The second is along San Francisco Bay, from the Basin border with the Visitacion Valley Basin in the north to the border with the San Mateo

Plain Basin to the south. The susceptibility of the Westside Basin to seawater intrusion is discussed in more detail in Section 7.

2.2.2. Current Seawater-Intrusion Monitoring System

The two areas monitored for seawater intrusion (the Pacific Coast and the Bay Coast) contain a number of monitoring wells completed in the various aquifers present in the Westside Basin. The two sets of wells are known as the coastal and Bay side monitoring networks. Groundwater head in the Westside Basin is monitored in a network of production and monitoring wells as part of the semi-annual monitoring program that was initiated throughout the Basin in 2000. Results of the most recent groundwater level monitoring were reported in the 2010 Westside Basin Annual Groundwater Monitoring Report (SFPUC, 2011), prepared by SFPUC in coordination with the City of Daly City (Daly City), the City of San Bruno (San Bruno), and the California Water Service Company (Cal Water). Annual monitoring reports have been published by the SFPUC since 2006 (LSCE, 2006 and SFPUC, 2007, 2008a, 2009b, 2010, and 2011); these reports are summarized in TM#1 and TM10.1.

The coastal monitoring network consists of a series of wells stretching along the Pacific Coast from the west end of Golden Gate Park south to Thornton Beach in Daly City (SFPUC, 2009b). The three well clusters (nested wells) along the Old Great Highway (near Kirkham, Ortega, and Taraval Streets) and the well cluster at the San Francisco Zoo were installed specifically for the purpose of monitoring seawater intrusion, and were completed by 2004. Head in some of these wells is monitored continuously using pressure transducers, while in others it is measured quarterly by hand. The results of these monitoring activities are presented as hydrographs in Appendix B of TM#1.

Nested wells or well clusters are present at the South Windmill (57 and 140 feet below land surface; ft bls), Kirkham (130, 255, 385, and 435 ft bls), Ortega (125, 265, 400, and 475 ft bls), Taraval (145, 240, 400, and 530 ft bls), Zoo (275, 450, and 565 ft bls), and Thornton Beach (225, 360, and 670 ft bls) locations. Additional monitoring wells in the coastal monitoring network are present at Lake Merced (LMMW-9SS, LMMW-1D, LMMW-1S) and Fort Funston (S and M).

The Bay side monitoring network is less extensive. Head data were provided to SFPUC for two monitoring wells by the San Francisco Airport (UAL MW13C, constructed to a depth of 146 ft bls, and MW13D, constructed to a depth of 41.5 ft bls) from late 2003 to 2006, and since then SFPUC has been collecting data. Two additional clusters of wells were installed in the Bay side area by San Bruno in 2006 (WRIME, 2007) at the San Francisco Airport (SFO-S, 74 ft bls, and SFO-D, 146 ft bls) and in Burlingame (Burlingame-S, 98 ft bls, Burlingame-M, 166 ft bls, and Burlingame-D, 280 ft bls). These wells have been monitored for groundwater elevation and various chemical constituents since November 2006.

The groundwater elevation and water quality data collected to date from these monitoring wells are provided in TM#1, and the monitoring results are discussed in Sections 7.2 and 7.3.

2.3. Conceptual Understanding of Seawater Intrusion

Seawater intrusion is the movement of saline water from an ocean or bay into freshwater aquifers. Some degree of seawater intrusion occurs in virtually all coastal aquifers, as long as they are hydraulically connected with seawater. Seawater intrusion usually occurs when coastal freshwater aquifers begin to be developed as sources of water supply. Pumping of freshwater from an aquifer reduces the groundwater head and gradient towards the seawater-freshwater interface, drawing seawater into the freshwater aquifer. The increase in chloride and other constituents that accompanies seawater intrusion can cause the freshwater aquifer to become unfit for beneficial uses such as drinking or irrigation.

The intrusion of seawater into a freshwater aquifer is an effect of the respective heads in the ocean and the freshwater aquifer and the difference in densities of the two fluids (the standard value of density for freshwater is 1.0 grams per cubic centimeter, g/cm^3, and a typical value of seawater density is 1.026 g/cm^3). Because freshwater is less dense than seawater, it actually floats on top of the saline water when both are present in an aquifer. The depth of the interface between the saline and freshwater depends on the freshwater head in the aquifer, with a higher head leading to a greater depth to the salt water. Under a simplified aquifer system with groundwater flowing toward the ocean, the freshwater head declines closer to the ocean, so the seawater-freshwater interface gets progressively closer to the ground surface moving from inland toward the ocean; this has led to the seawater intrusion into the aquifer being termed a "wedge" (Figure 10.3-3).

As discussed above, due to its high salt content seawater has a density about 2.6% higher than does freshwater. Based on this difference in densities, the Ghyben-Herzberg principle states that, for every foot of freshwater head in an unconfined aquifer above sea level, there will be 38 feet of fresh water in the aquifer below sea level at equilibrium (Badon-Ghyben, 1888; Herzberg, 1901).

When freshwater heads drop, the seawater-freshwater interface can migrate inland, and over time the interface may eventually reach coastal wells. If the groundwater head were to rise again, the seawater-freshwater interface would migrate back seaward. Movement of the seawater-freshwater interface is a slow process. Seawater intrusion may not reach a production well for a number of years, and only when the conditions leading to seawater intrusion are sustained for an extended period of time.

It is important to note that the freshwater head does not need to be lowered below sea level for seawater intrusion to occur, although a groundwater head below sea level certainly increases the potential rate and extent of seawater intrusion. Instead, the groundwater head must simply be dropped to a level lower than 1/38 the depth below sea level of the bottom of the aquifer. If this occurs, the thickness of freshwater is no longer great enough to exclude seawater from intruding along the base of the aquifer. The presence of freshwater head above this level represents what in this TM is termed a hydrologic control.

In addition, seawater intrusion does not necessarily need to follow the typical conceptual route of intruding from the location of freshwater discharge to the seawater body, as shown in Figure 10.3-3; instead, an aquifer can be intruded via another, bounding aquifer. To illustrate this, we can consider an unconfined aquifer in direct contact with the ocean overlying a semi-confined aquifer that is not in direct contact with the ocean, and is separated from the unconfined aquifer by a discontinuous low-permeability confining layer. If head in the unconfined aquifer is lowered far enough to allow it, seawater would intrude along the base of the aquifer. If the intruding wedge encounters a gap in the low-permeability base of the unconfined aquifer, its density, higher than that of freshwater, dictates that it would sink and intrude into the lower semi-confined aquifer.

The seawater-freshwater interface is not actually a sharp interface because of the action of dispersion and diffusion, instead it forms a transition zone where chloride concentrations range from values typical of freshwater to those of seawater (Bear and Cheng, 1999). The movement of the transition zone within the aquifer is due to changing of the groundwater conditions on the freshwater side of the interface. As the seaward flow of freshwater and/or the groundwater elevations near the interface decline, the interface can move landward. If freshwater flow and groundwater head later increase, the interface would move back toward the ocean; however, some of the salt can remain in the freshwater aquifer even after the interface moves away. Once salt water enters a part of the freshwater aquifer, it is very difficult to expunge, demonstrating that it is important to prevent the movement of the interface into the freshwater aquifer to the extent possible (Bear and Cheng, 1999).

Geologic features can limit communication between the freshwater aquifer and ocean water. In order for seawater to intrude into a freshwater aquifer, that aquifer must be in contact with the ocean in some way, usually by being exposed on the ocean floor. Other geologic configurations can limit or prevent seawater intrusion. These can include tilted beds, impermeable bedrock, gradational changes in aquifer permeability (i.e., the freshwater aquifer grading from sand inland into mud offshore), or fault zones. If one or more of these physical controls exists between the freshwater aquifer and the ocean, and is sufficiently low in permeability, it can serve as an effective barrier to the intrusion of seawater into the aquifer. If this is the case, less care would be required to prevent seawater intrusion, as long as the barrier (or barriers) is known to be sound and continuous. Of course, no natural barrier is truly impervious to flow, but its hydraulic conductivity may be so low that the flux of seawater through it would not have a substantial effect on the quality of water in bounding freshwater aquifers. These structural controls, referred to herein as physical controls, are, for all intents and purposes, permanent.

The two types of controls noted above (hydrologic and physical) are discussed further throughout this TM, and can be used to consider the vulnerability of a given freshwater aquifer to seawater intrusion. As is implied by the above discussion, either a hydrologic control or a physical control can prevent seawater intrusion; therefore, both must be absent for seawater intrusion to occur. In locations where physical controls on seawater intrusion (such as a low-permeability clay layer or fault zone) are absent, hydrologic controls are necessary to limit intrusion. For locations where physical controls do exist, freshwater head below the level dictated by the Ghyben-Herzberg relationship may be possible without leading to any intrusion, depending on the nature of the physical control.

3. Groundwater Model Analysis

Groundwater models are useful tools that can help quantify the changes in groundwater conditions due to future activities. This section summarizes previous modeling studies of seawater intrusion along the Pacific Coast of the Westside Basin and documents the results of the current modeling conducted for this study using the existing Westside Basin Groundwater-Flow Model (HydroFocus, 2007, 2009 and 2011).

3.1. Previous Seawater Intrusion Model

CH2M HILL (1995) performed a numerical modeling exercise to determine the effect that proposed increases in groundwater extraction would have on the intrusion of seawater into the freshwater aquifers of the North Westside Basin. Although focused in the same area, their model does not deal with the same changes in pumping as would be entailed in the SFGW Project.

There are important differences between the CH2M HILL seawater intrusion model (SIM) and the numerical model for the Westside Basin discussed here. The most important difference is that the SIM was constructed as a steady-state model, unlike the transient Westside Basin model; this means that the results of the model indicate the seawater intrusion that would eventually happen if a given pumping rate was maintained indefinitely, and cannot deal with changes in pumping rate or climatic conditions (e.g., an extended drought). The SIM does not simulate the connection between Lake Merced and the North Westside Basin, instead assuming a general head boundary to be present just north of Lake Merced that imposes head values that are constant in time and assumed to be uniform vertically throughout the aquifer. This rigid assumption does not allow head in the aquifer in the Lake Merced area to vary, meaning that the North Westside Basin cannot be dynamically linked to the South Westside Basin using this model, and therefore does not have the capacity to simulate changes to the groundwater system in the North Westside Basin due to changes in hydrologic conditions in the South Westside Basin, a key component of this analysis. In particular, the head in the Deep Aquifer along this boundary is assumed to be the same as the head in the Shallow Aquifer, which does not conform to measurements (see TM#1). Finally, the model assumes that the gradient across the entire model domain is the same as in Golden Gate Park, while the gradient across the southern Sunset District has been shown to be lower than in Golden Gate Park (see, for example, HydroFocus, 2009). Unlike the Westside Basin model, the SIM is explicitly designed to handle the problems of dual-density fluids and the movement of seawater onshore. The SIM used a combination of the finite-element code MicroFem and a seawater migration routine developed by CH2M HILL.

The SIM simulated the intrusion of seawater into the North Westside Basin under various pumping conditions (total of 9 scenarios). These scenarios dealt with the installation of three wells, and increased pumping in one previously-existing well. The new wells, located between Golden Gate Park and Lake Merced: one at the location of the currently proposed West Sunset Playground well, one at the Francis Scott Key Elementary School, and one at Noriega Early

Education School. The previously existing well was the Elk Glen well in Golden Gate Park. All other pumping in the study area was set equal to values estimated for water year 1988. The total pumping under their calibration scenario was 1.02 mgd.

Total additional pumping in the four wells mentioned varied from 0.54 to 0.94 mgd in the nine model scenarios. For all of these scenarios, the greatest pumping occurred at the Elk Glen well, due to the fact that the freshwater flux through Golden Gate Park is assumed to be greater than it is to the south of the Park. The pumping was generally assumed to be equal in the three proposed Sunset wells.

The results of this modeling exercise indicate that the North Westside Basin can handle an additional pumping load of about 0.9 mgd above the rates of water year 1988, as long as the pumping is properly configured. Rates between 0.91 and 0.94 mgd did induce seawater intrusion into the proposed Sunset wells, which are well inland (some 2,000 feet or more) from the coast. This implies that smaller amounts of pumping in the Sunset area would induce substantial seawater intrusion some way inland of the coast. The baseline scenario of the CH2M HILL model (which involved no changes from existing pumping) calculated the top of the freshwater-seawater interface (i.e., the point where the freshwater discharges from the seafloor) as being about 1,400 feet offshore. Figure 10 in CH2M HILL (1995) shows the calculated location of the interface along a cross-section perpendicular to the coast that runs through their proposed well at the Francis Scott Key School; at this location, the toe of the interface wedge stretches inland from the shore by about 2,200 feet, while the well is about 2,600 feet inland. Under one pumping scenario shown, the toe of the wedge stretches inland for more than 4,600 feet, although the interface does not actually intersect the well since it is not screened across the entire model thickness. The results of the CH2M HILL model indicate that, at least in the North Westside Basin, pumping of about 2 mgd may result in the landward shift of the seawater-freshwater interface.

As stated above, the CH2M HILL model has certain limitations that make it less than ideal for analyzing seawater intrusion into the North Westside Basin along the Pacific Coast. The first is that the model is a steady-state model, meaning that it simulates seawater intrusion at equilibrium. Thus, it does not have the capacity to model seawater intrusion in the context of changing conditions, whether these changes are in the amount and location of pumping, or in the climatic conditions that act as inputs to the model (such as wet years and droughts). Second, the SIM does not have the capacity to allow conditions from Lake Merced south to change dynamically, meaning that it cannot simulate how the North Westside Basin would respond to changes in the South Westside Basin. Therefore, the HydroFocus Westside Basin model is considered a better tool to assess the dynamic vulnerability of the North Westside Basin to seawater intrusion.

3.2. MODFLOW Model

The existing Westside Basin Groundwater-Flow Model (HydroFocus, 2007, 2009, and 2011) was used as a tool to provide the level of analysis necessary to evaluate the potential for

seawater intrusion as a result of the GSR and SFGW Projects. The setup and results of the model are documented in TM-10.1. A limitation of this model is the handling of the boundary conditions representing the Pacific Ocean and San Francisco Bay. These boundary conditions are set to a constant head of zero elevation. This usage is overly rigid, limiting the ability of the near-Ocean head in the aquifer to behave dynamically. HydroFocus (2007) states that "model results should be interpreted with caution near constant head boundaries like the Pacific Ocean or San Francisco Bay."

The model does not simulate dual-density flow. Therefore, the application of the model results to the problem of seawater intrusion is accomplished in this TM chiefly by analyzing how hydrologic controls are affected by the conditions simulated by the various scenarios, rather than by any direct simulation of seawater flow and transport. The two important hydrologic controls that will be examined here are the flux toward the Ocean or Bay and the groundwater (freshwater) head elevation. The more the oceanward flux is reduced, or the lower the groundwater head drops, the less effective would be the hydrologic controls preventing seawater intrusion (as discussed above, a lack of hydrologic control on seawater intrusion does not automatically imply actual intrusion, as physical controls may still exist that effectively prevent intrusion).

3.3. Model Scenario Summary

Five model scenarios were constructed and simulated to evaluate potential groundwater and related hydrological effects from the GSR and SFGW Projects and from the Cumulative Scenario that includes the GSR and SFGW Projects and other reasonably foreseeable future projects. The following is a summary of the five scenarios used for the groundwater model analysis:

- Scenario 1, Existing Conditions: Scenario 1 represents the continuation of the Existing Conditions into the future and does not include the SFPUC Projects (either GSR or SFGW Project). Groundwater pumping by the PAs and irrigation pumping are representative of the existing pumping conditions (as of June 2009). The PA pumping was established based on the historical pumping rates, using the median of the 1959-2009 pumping data for individual agencies.
- Scenario 2, GSR Project Only: Scenario 2 represents implementation of the GSR Project operations including put periods when groundwater pumping by SFPUC and the PAs does not occur and groundwater is placed into storage using in-lieu recharge; hold periods when the PAs are pumping and no in-lieu recharge is occurring because the SFPUC Storage Account is full, and take periods which represent periods when both SFPUC and the PAs are pumping from the South Westside Basin.

- Scenario 3a, SFGW Project Only (3 mgd): For Scenario 3a, the four new wells constructed for the SFGW Project would pump an annual average of 3.0 mgd; however, the two existing irrigation wells in Golden Gate Park would remain irrigation wells, and their pumping rates would be the same as in Scenario 1.
- Scenario 3b, SFGW Project Only (4 mgd): For Scenario 3b, the four news wells constructed for the SFGW Project and the two modified irrigation wells in Golden Gate Park would pump an annual average of 4.0 mgd. Irrigation in Golden Gate Park is assumed to be replaced by the WestsideRecycled Water Project. Total combined pumping in the Westside Basin for Scenario 3b is slightly less than Scenario 3a, because the total SFGW Project pumping in Scenario 3b would increase by 1.0 mgd, whereas the irrigation pumping that is replaced would be slightly more than 1.0 mgd.
- Scenario 4, Cumulative Scenario: Scenario 4 represents implementation of both the GSR and SFGW Projects (Scenarios 2 and 3b) along with other reasonably foreseeable future projects. The other foreseeable projects are discussed in more detail in TM-10.1 but primarily include the Daly City Vista Grande Drainage Area Improvements Project, which increases stormwater diversions into Lake Merced, and a minor increase in irrigation pumping based on the planned build-out of the Holy Cross cemetery.

As discussed in TM-10.1, the strongest predictive capability of the existing model is to forecast relative changes over time, rather than absolute predictions of head. Therefore, analyzing differences in head relative to a base case rather than the actual groundwater elevation output by the model is the more appropriate method to evaluate the results of the groundwater model. However, in the case of seawater intrusion, the important relationship is between groundwater head in the model and sea level, so absolute head must be considered in this analysis as well. Scenario 1 (the Existing Conditions scenario) forms a basis of comparison for evaluating the results of the GSR-only, SFGW-only, and Cumulative Project scenarios.

To allow for the model scenarios to be directly comparable, all five model scenarios are set up using similar sets of assumptions regarding initial conditions and background hydrology. All of the modeled scenarios have the same projected simulation period of 47.25 years and use initial groundwater conditions representing June 2009 conditions.

All five model scenarios use the same hydrologic sequence and include the 8.5-year Design Drought period included in the Water System Improvement Program Environmental Impact Report PEIR (SFPUC, 2008b and 2009c). The 8.5-year Design Drought repeats the December 1975 to March 1978 drought period following the dry hydrologic conditions of July 1987 to November 1992. To incorporate the Design Drought, the historical hydrological sequence was rearranged. A more detailed discussion of the development of the background hydrology is presented in TM-10.1.

Table 10.3-1 presents a summary of the estimated Basin-wide average pumping rates corresponding to each of the model scenarios. Note that, in addition to the anticipated GSR and

SFGW Project wells, average pumping rates are also provided for the PA wells and for irrigation wells in Golden Gate Park.

3.4. Use of Model Results

As stated above, HydroFocus (2007) suggests that the strongest predictive capability of the MODFLOW model is to forecast relative changes over time, rather than absolute predictions of head. Therefore, the model analysis for the different scenarios will consider differences in head and flux relative to the Existing Conditions Scenario (Scenario 1). However, because seawater intrusion is dependent on the relationship between elevations of the seawater and the freshwater aquifers, it is necessary to evaluate the simulated groundwater elevations as well as the relative changes, to evaluate the potential for seawater intrusion.

For the evaluation of the model scenarios, the results of the MODFLOW model are applied to seawater intrusion by considering the flux of water across the coastal boundary conditions and the head just landward of the coastal boundaries. These quantities will be analyzed for each of the five model scenarios listed at the beginning of this section.

3.4.1. Head Results

The numerical model includes the capability of monitoring head at 87 different monitoring points, included to track head in the aquifer. Of these, this section examines the results for 9 monitoring points along the Pacific Coast and 3 monitoring points along the Bay Coast. Hydrograph representations for each of the monitoring points are presented as Figures 10.3-4 through 10.3-15. In each of these figures, the upper panel includes the absolute simulated head for each of the five scenarios; the lower panel is the difference between the results of each scenario and those of Scenario 1. Each figure presents results for Model Layer 1, 4, or 5 as representative of conditions in the Shallow, Primary Production, or Deep Aquifer, respectively. The exclusion heads plotted on these figures represent a theoretical freshwater head that must be maintained at the well location to prevent seawater intrusion to reach that location; see Section 3.5. Selected statistics (average, maximum and minimum as calculated from the 47.25 years of model simulation) were compiled for the difference between the head results of the four Project scenarios and Scenario 1 (Table 10.3-2).

Along the Pacific coast, 9 monitoring locations were set in the numerical model. All of these except for North Windmill correspond to locations of an actual monitoring well or well cluster, which correspond to the seawater intrusion monitoring network already existing along the Pacific Coast (Figure 10.3-1). The North Windmill location corresponds to a historical well location, but not an active monitoring well. These locations include:

- North Windmill
- South Windmill
- Kirkham
- Ortega
- West Sunset Playground

- Taraval
- Zoo
- Fort Funston
- Thornton Beach

Along the Bay Coast, monitoring locations were set in the numerical model at the locations of actual monitoring well clusters (UAL, SFO, and Burlingame). These locations correspond to the seawater intrusion monitoring network already existing in the South Westside Basin (Figure 10.3-1). The UAL cluster consists of pre-existing monitoring wells, but the SFO and Burlingame clusters were installed as part of work conducted under Assembly Bill 303[2] specifically to track the occurrence of seawater intrusion (WRIME, 2007).

In addition to the absolute and relative heads depicted in the hydrographs (Figures 10.3-4 through 10.3-15), seasonal fluctuations in absolute head were computed for each of the model scenarios. These values were determined by calculating the average annual difference in head values under each scenario for May (generally representing the highest annual heads) and November (generally representing the lowest annual heads). These values were analyzed to determine whether the aquifer experiences annual head declines sufficient to leave it substantially more susceptible to seawater intrusion during the dry parts of the year.

3.4.2. Flux Results

The flux of groundwater out to the Ocean or Bay from the coast is a convenient variable for tracking the occurrence of seawater intrusion in the model domain because it tracks the amount of water passing through the boundary conditions placed along the coastlines. The fluxes are presented as total fluxes for the entire North Westside Basin (Pacific Coast) (Figure 10.3-16) and South Westside Basin (Bay Coast) (Figure 10.3-17). This means that these flux values indicate whether or not each of the coasts is, as a whole, experiencing seawater intrusion on average. Seawater intrusion is expected to occur locally during its initial stages, and this would not be captured in this analysis. However, in the context of the strengths and limitations of the numerical model discussed above, this approach is considered a sufficiently comprehensive, conservative, and scientifically-sound evaluation that properly addresses seawater intrusion.

A positive freshwater flux toward the Ocean or Bay does not necessarily preclude seawater intrusion, because the seawater wedge would enter into the lowest part of the freshwater aquifer. Therefore, the use of modeled freshwater flux as a proxy for seawater intrusion is a way to indicate when intrusion is predicted to be a major problem, rather than when it might begin to occur.

As with the head analysis, this analysis of the flux calculated by the numerical model is not able to give accurate quantification of the intrusion of seawater into the freshwater aquifer. This is

[2] Passed by the California Legislature in 2000, Assembly Bill 303 created the Local Groundwater Assistance Grant Program, providing funding to local public agencies for the performance of groundwater studies or to carry out groundwater monitoring and management activities.

due to several factors: the flux numbers are totals of flux along the entire coastline; the boundary condition along the coastline does not accurately reflect the dynamic conditions at the land-Ocean interface; and the real occurrence of seawater intrusion is a complex process involving aquifer heterogeneity, tidal fluctuations, diffusive transport, and dual-density fluid flow, which are not captured in the existing model.

3.4.3. Groundwater Contour Map Analysis

Under Scenario 1, the model-simulated groundwater elevations for the Shallow Aquifer (Model Layer 1) are above sea level throughout the North Westside Basin (Figure 10.3-18). The water table gradient was highest through Golden Gate Park and along the fronts of the elevated bedrock areas, and lowest just north of Lake Merced. Water table elevations were predicted to be between five and ten feet above sea level in the direct vicinity of the Coast, with higher elevations along the northern part of the Coast. This indicates that the existing conditions are not anticipated to induce seawater intrusion along the Pacific Coast.

3.5. Application of Analytical Method Along the Pacific Coast

As mentioned, the Westside Basin model does not have the capability to evaluate seawater intrusion using the density differences between freshwater and saline water. Therefore, an analytical evaluation is included with the groundwater model results to incorporate the density driven components of seawater intrusion while evaluating the MODFLOW output.

3.5.1. Methodology

The movement of the seawater-freshwater interface is a dynamic process that is dependent upon the relative difference in the freshwater and seawater groundwater head, flux and density. The analytical method discussed in Attachment A was used to evaluate the freshwater head, based on the Ghyben-Herzberg relationship, necessary to maintain hydrologic control, keeping seawater from intruding into freshwater aquifers (a function of the depth below sea level of the bottom of the aquifer). This value is termed the “exclusion head” and it represents a conservative analysis for maintaining freshwater aquifer conditions (see Section A.5).

The freshwater head results from the numerical model were compared to the exclusion head at the various monitoring points; it is assumed that groundwater head at a location equal to or greater than its exclusion head indicates that the location would not experience seawater intrusion.

For locations where the groundwater head stays above the exclusion head, the pressure of the freshwater aquifer is sufficient that seawater would not intrude to this location based on the Ghyben-Herzberg relationship for the aquifer thickness at a given location.

For locations where groundwater head falls below the exclusion head, there is the potential that seawater could intrude to this location. However, there are other factors that control seawater intrusion, so groundwater head below the exclusion head does not necessarily imply that seawater intrusion may reach this location, but rather that the hydrologic potential exists for the landward migration of the seawater-freshwater interface. Therefore, this is a conservative analysis of the potential for seawater intrusion.

If groundwater head moves back above the exclusion head, the interface could be expected to slow or reverse its movement toward land. It should be noted that sustained, repeated fluctuations in head, even when they remain above the exclusion head, would result in a widening of the transition zone between seawater and freshwater.

Movement of the seawater-freshwater interface is a slow process. Seawater intrusion may not manifest in a production well for a number of years, and only when the conditions leading to seawater intrusion are continuously sustained for an extended period of time, depending on aquifer conditions. Additionally, physical controls, where present, can prevent seawater intrusion even if head conditions are maintained below the exclusion head long-term.

Uncertainty in these results is due mostly to uncertainties in the prediction of the input parameter, *b* (aquifer thickness below sea level). However, uncertainties in the estimate of *b* must be very large to create substantial errors in the estimate of the exclusion head, due to the fact that the exclusion head is only a fraction of the aquifer thickness. Additionally, the analytical method assumes that the individual aquifers are single bodies; if aquifers are divided up into several discrete sections separated by continuous low-permeability layers, seawater intrusion would be less extensive than indicated by this method because the exclusion head is higher in the thicker, composite aquifer than in the thinner, separate aquifers.

It is important to note that the analytical analysis presented here assumes that the aquifer is near horizontal. As the analytical method shows (Attachment A), this has some effect on the length of intrusion. The aquifers present in the North Westside Basin are actually sloped toward the Ocean, and so the intrusion length could be expected to be somewhat smaller than shown by the analytical method, thus making the analysis more conservative with relation to the potential for seawater intrusion.

3.5.2. Definition of Parameters

For this analysis, the elevation of the base of the aquifer is the only variable that must be known. Because the offshore structure of the coastal aquifers (e.g., the continuity of low-permeability layers between aquifers, which is key to the movement of intruding seawater) is not precisely known, two approaches were taken to compute the exclusion head. The thicknesses were then input into the Ghyben-Herzberg equation to determine the exclusion head. These levels are indicated on Figures10.3-4 through 10.3-15, and given in Table 10.3-3.

Along the Pacific Coast, the sediment thickness is considered to include several aquifers (multiple-aquifer case). The thicknesses of the individual aquifers were determined using the cross-sections of LSCE (2010) by estimating (to the nearest 10 feet) the elevations of the bottom of each aquifer below sea level. It should be noted that extensive clay layers present within an aquifer (e.g., the Y clay within the Primary Production Aquifer at the Taraval and Zoo clusters) are not removed from the aquifer thickness, so that these clay layers are counted as part of the aquifer. This is a conservative assumption, as excluding them would reduce the thickness of the aquifer, thereby reducing the exclusion head. Because the Primary Production Aquifer is thicker than the other two aquifers, the values of exclusion head in this aquifer are higher than in the others.

3.5.3. Use of the Analytical Evaluation

As discussed, the results are a conservative estimate of the potential for seawater intrusion along the Coast, but do provide a point of reference for evaluating the MODFLOW results with respect to the density aspects of seawater intrusion. The analysis can identify areas where seawater intrusion would not occur, or where there is the potential that seawater intrusion may occur. Other factors have to be considered. A major limitation to evaluation of seawater intrusion is that the seawater-freshwater interface has not been located along the Pacific Coast.

The results of this analysis for the Pacific Coast are discussed for the SFGW-Only and Cumulative Scenarios. The GSR-Only Scenarios are not presented, because the MODFLOW model analysis showed little variation from Scenario 1.

4. GSR Only Scenario Analysis

The GSR-Only Scenario analysis evaluates the potential for seawater intrusion from the operation of the GSR Project. The GSR Project is a conjunctive use project that would allow for increased groundwater supplies in the Westside Basin during periods of drought (MWH, 2008). The GSR Project is sponsored by the SFPUC in coordination with its PAs: Cal Water, Daly City, and San Bruno. The GSR Project is located within San Mateo County in the South Westside Basin. This Project is discussed in more detail in Section 1.1 of this TM, and in TM-10.1. In summary, the PAs would reduce pumping during normal and wetter than normal times (put periods) to naturally replenish groundwater in the South Westside Basin, and both SFPUC and the PAs would extract groundwater during drier than normal times (take periods). The total pumping capacity to be developed by the Project would be about 7.2 mgd, and the maximum amount of groundwater that would be placed in a storage account via this in-lieu recharge would be 60,500 af (MWH, 2008). If surface water is available, but the storage account is full (hold periods), the PAs would pump as during a take period, but SFPUC would not extract groundwater, aside from a small amount to exercise the Project wells[3].

4.1. Conceptual Analysis

The GSR Project consists primarily of using excess surface water instead (or “in-lieu”) of pumping groundwater from the Westside Basin. The Project is planned to have up to 60,500 af of in-lieu recharge capacity. During the take cycle, both SFPUC and the PAs would be pumping groundwater; however, SFPUC would not take more than the amount of in-lieu recharge available in the SFPUC Storage Account.

In addition, the GSR Project would be operated in the South Westside Basin, where groundwater head has been substantially below sea level for decades. This portion of the Basin appears to be isolated from sources of saline water from the Pacific Ocean and San Francisco Bay.

Because of this mode of operation, the GSR Project would typically produce groundwater head similar to or higher than Scenario 1 in the South Westside Basin. Higher groundwater head would typically have the effect of reducing the potential for seawater intrusion due to the higher freshwater head and flux towards the Ocean and the Bay. Therefore, in general, the likelihood of seawater intrusion resulting from the GSR Project is considered to be low.

4.2. Model Results along the Pacific Coast

The GSR-only Scenario (2) does not include any additional pumping in the North Westside Basin, so large changes in head are not anticipated in this area. Hydrographs (Figures 10.3-4 through 10.3-12) present the model-derived head for this scenario, as well as the differences in

[3] Exercising the production wells would entail pumping for a few hours approximately monthly, with an anticipated average monthly total production rate for all of the wells of 0.04 mgd.

head between this scenario and Scenario 1. Table 10.3-2 presents the maximum, average, and minimum differences between the results for this scenario and those of Scenario 1.

4.2.1. Head

In Model Layer 1, head at the various monitoring locations is generally slightly higher than under Scenario 1 throughout most of the simulation duration, dropping slightly below Scenario 1 levels at the end of the simulation. The maximum increase over Scenario 1 (Table 10.3-2a) is less than a foot at all of the monitoring locations except the West Sunset Playground well (1.3 ft; Figure 10.3-8) and the Zoo cluster (2.7 ft; Figure 10.3-10). The maximum decrease compared to Scenario 1 at the end of the simulation reaches a maximum of 0.4 ft at the Zoo cluster, and is 0.2 ft or less at all other locations.

In Model Layer 4, the difference in head from Scenario 1 follows a similar pattern to that of Model Layer 1, but the changes tend to be more pronounced, especially in the southern part of the North Westside Basin. The maximum increase over Scenario 1 (Table 10.3-2b) varies from 0.1 ft at the South Windmill cluster (Figure 10.3-5) to 6.1 ft at the Zoo cluster. In almost all monitoring locations, the head results from Scenario 2 are above those of Scenario 1 except during and after the Design Drought, except at the Thornton Beach cluster (Figure 10.3-12), where head drops below the Scenario 1 results around Scenario Year 28. The maximum decrease compared to Scenario 1 near the end of the simulation varies from 0.1 ft at the South Windmill cluster to 4.3 ft at the Zoo cluster. This Model Layer is not present at the North Windmill location.

In Model Layer 5, the difference in head from Scenario 1 follows a similar pattern to that of the other Model Layers, with still more pronounced changes. The Scenario 2 heads are below those of Scenario 1 during the take periods (as shown by large downward deflections in relative head difference) at many locations. The maximum increase over Scenario 1 (Table 10.3-2c) varies from 0.3 ft at the Kirkham cluster (Figure 10.3-6) to 12.2 ft at the Zoo cluster. The greatest relative decrease at all locations occurs just after the Design Drought, and varies from 0.2 ft at the Kirkham cluster to 14.4 ft at the Zoo cluster. Head values recover to levels similar to or above those of Scenario 1 throughout the North Westside Basin by the end of the simulation period. This Model Layer is not present at the North Windmill location or the South Windmill cluster.

The average differences presented here indicate that the GSR Project would not have a substantial effect on the occurrence of seawater intrusion in the North Westside Basin within the Shallow Aquifer. There would also not be much of an effect north of the Zoo cluster in the Primary Production Aquifer. In the southern part of the North Westside Basin, head dips during take periods, particularly the Design Drought. The effect is smallest in Model Layer 1, greater in Model Layer 4, and largest in Model Layer 5 (Figures 10.3-4 through 10.3-12). The magnitude of the dips in head is indicated by the maximum relative decrease compared to the results of Scenario 1 (“minimum difference” in Table 10.3-2). Although the declines in head during the take periods are locally substantial (greatest during the Design Drought in the southern part of the North Westside Basin in the Deep Aquifer; see results for the Zoo cluster above), the aquifer returns to conditions similar to Scenario 1 by the end of the simulation period, indicating that the situation of lowered head is fairly short-lived.

Simulated seasonal fluctuations in head (defined in Section 3.5.1; Table 10.3-4) varied in Model Layer 1 from 0.5 ft at the Taraval cluster to 1.7 ft at the North Windmill location, from -0.7 ft (South Windmill cluster) to 0.3 ft (Kirkham, Ortega, and Taraval clusters and West Sunset Playground well) in Model Layer 4, and from -0.5 ft (Zoo cluster) to 0.3 ft (Kirkham and Ortega clusters) in Model Layer 5; it should be noted that negative values of seasonal fluctuation indicate that head is generally higher in the summer than in the winter. The greatest fluctuations are in Model Layer 1 at every location, as the Shallow Aquifer (represented by Model Layer 1) directly receives recharge from precipitation, the root cause of the seasonal fluctuations. These results indicate that seasonal changes in head are not very large, and would not substantially affect the occurrence of seawater intrusion in the North Westside Basin.

4.2.2. Groundwater Flux

Freshwater flux leaving the model domain through the Pacific Coast is the result of recharge in the upper reaches of the North Westside Basin that flows through the aquifers in this Basin toward the Ocean. A reduction in this freshwater flux indicates an increasing chance of seawater intrusion occurring along this coast. Figure 10.3-16 shows the fluxes predicted for the North Westside Basin by the numerical model, as well as the difference between the results of each scenario and Scenario 1. Table 10.3-5 gives the maximum, minimum, and average monthly freshwater fluxes and fluxes relative to Scenario 1 for each scenario.

As discussed above, the GSR Project pumping conditions included in Scenario 2 are not expected to have a large effect on head in the North Westside Basin. Therefore, the freshwater flux into the Pacific Ocean is not expected to change very much. Indeed, Figure 10.3-16 indicates very minor differences between Scenario 1 and this scenario. For most of the duration of the model simulation, the freshwater flux out of the Pacific Coast remains above the Scenario 1 conditions, up to 30 acre-feet per month (afm). Toward the end of the simulation, during the Design Drought, the freshwater flux dips slightly below the Scenario 1 conditions, by up to about 10 afm. The minimum freshwater flux for this scenario was about 150 afm, the same as for Scenario 1. Compared to the absolute flux values (an average of about 270 afm for Scenario 2 versus an average of about 260 afm for Scenario 1), the differences in flux values indicate, as do the head results, that the GSR Project pumping conditions are not expected to have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

4.2.3. Groundwater Contour Map Analysis

Under Scenario 2, the model-simulated groundwater elevation map for the Shallow Aquifer at the end of the simulation period (Figure 10.3-19) is almost identical to that simulated under Scenario 1 (Figure 10.3-18), with slightly lower groundwater elevations (by approximately 5 feet or less) in the southern part of the North Westside Basin; almost no difference is visible north of

Lake Merced. This confirms that the operation of the GSR Project by itself would have little effect on the water table in the North Westside Basin. This indicates that the GSR Project is not anticipated to induce seawater intrusion along the Pacific Coast.

4.2.4. Evaluation

Pumping in the South Westside Basin for the GSR-only Scenario (2) would have only a minor effect on groundwater head in the North Westside Basin. These conditions are anticipated to lead to minimal landward movement of the seawater-freshwater interface due to operation of the GSR Project.

None of the monitoring points in Model Layer 1 show head falling below sea level, although some of the heads do approach sea level. In Model Layer 4, the head drops below sea level at the Zoo and Taraval clusters and the West Sunset Playground well. In Model Layer 5, the head drops below sea level at the Ortega, Taraval, Zoo, and Fort Funston clusters and the West Sunset Playground well. In fact, head is largely below sea level throughout the simulation period in the southern half of the North Westside Basin in Model Layers 4 and 5, indicating that the hydrologic conditions would be conducive to seawater intrusion; however, as noted above, these layers are likely to have physical controls that would prevent intrusion from happening. In addition, at no location does head drop below sea level in the Scenario 2 results without also dropping below sea level in the Scenario 1 results. The differences between this scenario and Scenario 1 are not great, with generally higher head through most of the simulation except the take periods (Section 4.2.1), indicating that the changes in the pumping regime included in the GSR Project would not substantially alter the likelihood of seawater intrusion along the Coast. The drops in head seen during the take periods may lead to conditions more favorable for seawater intrusion along the Pacific Coast, but the drops do not persist for more than a few years after the end of each take period, indicating that any such increase in the possibility of seawater intrusion due to the operation of the GSR Project would be temporary. Similarly, seasonal declines in freshwater head throughout the North Westside Basin are unlikely to substantially alter the likelihood of seawater intrusion along the Pacific Coast, as the declines are temporary and compensated for by seasonal increases. In much of the North Westside Basin, the differences between Scenarios 2 and 1 are not great, indicating that the GSR Project is not responsible for any substantial decreases in head.

4.3. Model Results along the San Francisco Bay Coast

The GSR-only scenario (Scenario 2) focuses on changes in the pumping regime in the South Westside Basin, so substantial changes in head may occur in this area. Figures 10.3-13 through 10.3-15 show heads for this scenario, as well as the differences in head versus Scenario 1 (note that the results for this Scenario are nearly identical to those of Scenario 4, so their lines overlap on the hydrograph figures). Table 10.3-2 presents the maximum, average, and minimum differences between the results for this scenario and those of Scenario 1.

4.3.1. Head

Under GSR-only conditions, the heads in the Bay monitoring system react similarly to the Scenario 1 conditions. Compared to Scenario 1, the head results of Scenario 2 at the Burlingame cluster are mostly higher than under Scenario 1 (up to maximums of 1.3 ft in Model Layer 1 and 2.3 ft in Model Layer 4), although at the end of the simulation period the head in Model Layer 4 is lower, by up to 0.6 ft (Figure 10.3-13, Table 10.3-2b). At both the SFO (Figure 10.3-14) and UAL (Figure 10.3-15) clusters, the Scenario 2 results are higher (up to 3.1 ft at the SFO cluster and 2.4 ft at the UAL cluster) in Model Layer 1 than in Scenario 1. Model Layer 4 is not present at the SFO and UAL clusters, and Model Layer 5 is not present at any of the three well clusters along the Bay coast.

To understand the implications of the Scenario 2 results, it is helpful to note how groundwater head behaves in this area under Scenario 1. The Burlingame cluster is projected to see a substantial decline in head during Scenario 1, approaching sea level in Model Layer 1 (Figure 10.3-13), while in Model Layer 4, head at the Burlingame cluster begins just above sea level, and declines throughout the scenario. These results indicate that, if there is a route for seawater intrusion, intrusion would become more rapid over the simulation period in both Model Layers. Because Scenario 2 head results are mostly higher than under Scenario 1 throughout the simulation, the potential rate of seawater intrusion over time would actually be lower than in Scenario 1. At the SFO (Figure 10.3-14) and UAL (Figure 10.3-15) clusters, head under Scenario 2 rises throughout most of the simulation period, indicating that, if seawater intrusion were occurring in this area, its pace may decline or even reverse.

Whether heads are higher or lower under Scenario 2, the results are not very different from those of Scenario 1. This indicates that the GSR Project pumping rates would not have a substantial effect on the occurrence of seawater intrusion in this part of the Basin because groundwater head is mostly higher than under Scenario 1.

Seasonal fluctuations along the Bay Coast are very small, and all between +0.1 ft and -0.1 ft for this scenario (Table 10.3-4). These results indicate that seasonal fluctuations in head would not have a substantial effect on seawater intrusion in this area.

4.3.2. Groundwater Flux

Freshwater flux into the San Francisco Bay is expected to be substantially lower than flux into the Pacific Ocean. The exposed coastline is somewhat shorter, the Bay Mud presents a low-permeability barrier between the freshwater aquifer and the saline water, the aquifer is thinner, and heads on land are lower. As discussed in Section 7.3, this area may or may not be physically susceptible to seawater intrusion. Table 10.3-5 gives the maximum, minimum, and average monthly freshwater fluxes and fluxes relative to Scenario 1 for these scenarios.

Scenario 2 adds the pumping entailed in the GSR Project. The maximum freshwater flux is about 110 afm, while the minimum is about 70 afm (Figure 10.3-17); these maximum and minimum numbers are similar to those of Scenario 1. The freshwater flux is slightly higher than in Scenario 1 through most of the simulation before dropping below Scenario 1 conditions around Scenario Year 40, during the Design Drought. Because the freshwater flux is generally higher than under Scenario 1 conditions, GSR Project pumping is not anticipated to have a substantial effect on seawater intrusion along the Bay Coast.

4.3.3. Evaluation

In general, the changes to groundwater pumping for the GSR-only Scenario (2) would not have a substantial effect on the potential for seawater intrusion compared to Scenario 1 conditions. The freshwater flux out of the aquifer into the San Francisco Bay is quite low, and is not modified to any great degree by the pumping configurations simulated in the numerical model.

The modeling results suggest that the Bay Coast is not especially vulnerable to seawater intrusion, at least under the conditions simulated by the model (Figure 10.3-17). The presence of the Bay Mud is considered to represent a physical barrier that limits the potential for seawater intrusion along the San Francisco Bay Coast, even when groundwater head is lowered.

5. SFGW Only Scenario Analysis

The SFGW Project would provide a local source of high-quality groundwater within the North Westside Basin. The SFGW Project is discussed further in Section 1.1 and TM-10.1.

The SFGW Project Scenarios (3a and 3b) simulate increased pumping in the North Westside Basin, and so the model predicts a much greater change in head in this area under these scenarios than under the GSR Project Scenario (2). Scenario 3a assumes that irrigation in Golden Gate Park would continue as in the past. Scenario 3b assumes that irrigation would be provided largely by a recycled water project, so that two of the existing irrigation wells can be converted for use as a municipal supply. These two scenarios begin with June 2009 initial head conditions.

5.1. Conceptual Analysis

Because operation of the SFGW Project includes substantial pumping of groundwater, and the wells to be utilized are located relatively close to the Pacific Coast, there is the potential for seawater intrusion in this area. Therefore, additional analysis is necessary to characterize the potential for seawater intrusion in the North Westside Basin. However, because of the distance from the pumping wells to the San Francisco Bay Coast, the potential of seawater intrusion induced by the SFGW Project in the South Westside Basin is low.

5.2. Pacific Coast

The SFGW-only Scenarios (3a and 3b) include substantial additional pumping in the North Westside Basin (3.0 mgd and 2.9 mgd, respectively; see Table 10.3-1), so changes in head would be expected to occur in this area. Figures 10.3-4 through 10.3-12 show head results for these scenarios, as well as the differences in head between these scenarios and Scenario 1. Table 10.3-2 presents the maximum, average, and minimum differences between the results for these scenarios and those of Scenario 1.

5.2.1. Head

Scenario 3a: In general, heads in the North Westside Basin under Scenario 3a decline quickly over the first approximately 10 years of the simulation period, eventually leveling out at a fairly constant offset from Scenario 1 results (Figures 10.3-4 through 10.3-12). This fairly constant offset (as represented by the average difference between the scenario results and those of Scenario 1 from Scenario Years 37 to 47) varies from well to well. In Model Layer 1 (Table 10.3-2a), the average offset varies from 0.1 ft at the Fort Funston cluster to 23.0 ft at the West Sunset Playground well. In Model Layer 4 (Table 10.3-2b), the average offsets varied from 0.3 ft at the Thornton Beach cluster to 18.5 ft at the Zoo cluster. In Model Layer 5 (Table 10.3-2c), the average offsets varied from 0.3 ft at the Thornton Beach cluster to 6.9 ft at the West Sunset well cluster. Note that head decreases more at the West Sunset Playground well because its location is close to a proposed SFGW Project production well. Additionally, it is important to note that this well is about 3,000 feet inland, so results at this location should not be considered typical of head along the coast.

At the North Windmill location and the Fort Funston and Thornton Beach clusters (Figures 10.3-4, 10.3-11, and 10.3-12), the head in all present Model Layers remains at least a bit above sea level at all times during the model simulations. Elsewhere, head drops to sea level and below, up to -11.4 ft msl at the West Sunset Playground well (Figure 10.3-8a) in Model Layer 1, -31.3 ft msl at the Zoo cluster (Figure 10.3-10b) in Model Layer 4, and -32.1 ft msl at the Zoo cluster in Model Layer 5 (Figure 10.3-10c). After head declines slow between Scenario Years 10 and 15, heads are mainly above sea level at all Model Layer 1 locations aside from the West Sunset Playground well, only dropping below sea level at isolated times (particularly during the Design Drought). In Model Layer 4, head hovers around sea level at the South Windmill and Kirkham clusters, and remain below sea level through most of the simulation period at the Ortega, Taraval, and Zoo clusters and the West Sunset Playground well. In Model Layer 5, head is around sea level at the Kirkham cluster, and below sea level at the Ortega, Taraval, and Zoo clusters and the West Sunset Playground well.

Scenario 3b: Scenario 3b is similar to Scenario 3a, except that it includes the assumed recycled water delivered to Golden Gate Park; this means that total groundwater extraction in Golden Gate Park is slightly lower in Scenario 3b than in Scenario 3a, and also slightly lower in the South Sunset Playground and West Sunset Playground wells.

The difference between the results of Scenario 3b and Scenario 3a is generally not large. As might be expected by the scenario construction, head in the Golden Gate Park wells resulting from Scenario 3b is slightly lower at the North Windmill location (Figure 10.3-4a) and the South Windmill cluster (Figure 10.3-5) in Model Layer 1. In Model Layer 4, head at the South Windmill cluster is generally higher than in Scenario 3a, and with much larger seasonal fluctuations. At the Kirkham cluster (Figure 10.3-6b), head is generally slightly higher, with larger seasonal fluctuation, than in Scenario 3a. At the Ortega (Figure 10.3-7b), Taraval (Figure 10.3-9b), and Zoo (Figure 10.3-10b) clusters and the West Sunset Playground well (Figure 10.3-8b), head results for Scenario 3b are slightly higher than those for Scenario 3a. Finally, heads at the Fort Funston (Figure 10.3-11) and Thornton Beach (Figure 10.3-12) clusters are almost equal under Scenarios 3b and 3a.

Seasonal Fluctuations: Seasonal fluctuations are generally somewhat smaller than under Scenario 1 (Table 10.3-4). For Scenario 3a, values range from about 0.5 ft (West Sunset Playground well and Taraval cluster) to 1.6 ft (North Windmill location) in Model Layer 1, from -0.8 ft (South Windmill cluster) to 0.3 ft (Kirkham, Ortega, and Taraval clusters and West Sunset Playground well) in Model Layer 4, and from -0.6 ft (Zoo cluster) to 0.2 ft (Kirkham and Ortega clusters) in Model Layer 5. For Scenario 3b, seasonal fluctuations vary from 0.5 ft (West Sunset Playground well and Taraval cluster) to 1.3 ft (Fort Funston cluster) in Model Layer 1, from 0.0 ft (Fort Funston and Thornton Beach clusters) to 0.3 ft (South Windmill, Kirkham, and Taraval) in Model Layer 4, and from -0.6 ft (Zoo cluster) to 0.2 ft (Kirkham and Ortega clusters) in Model Layer 5. These results indicate that seasonal fluctuations in head would not have a substantial effect on the occurrence of seawater intrusion in this area.

5.2.2. Groundwater Flux

Scenario 3a includes increased pumping in the North Westside Basin envisioned as part of the SFGW Project. As discussed in Section 5.2.1, the general reaction of the aquifers in this part of the Basin is a decline in head, although it is not uniform throughout the area studied. This decline in head indicates that the oceanward freshwater flux could be expected to decrease. Figure 10.3-16 shows the freshwater flux predicted by the numerical model for this scenario. Table 10.3-5 gives the maximum, minimum, and average monthly freshwater fluxes and fluxes relative to Scenario 1 for these scenarios.

Although flux still responds strongly to climatic variation, the fluxes predicted for this scenario are much lower than those of Scenario 1, varying from a maximum of about 370 afm to a minimum of about 10 afm. Additionally, the variance of flux is higher (standard deviation of about 70 afm versus about 50 afm under Scenario 1).

As discussed above, the flux values presented in this analysis represent the total flux for the entire coast, and so can only be used to discuss average conditions along the coast. However, it is probable that, at the extremely low flux totals seen in this scenario, flux is either zero or negative (i.e., inland from the Ocean) at certain locations. Therefore, this analysis indicates that the increased pumping entailed by the SFGW Project would create conditions conducive to the potential inducement of seawater intrusion in localized areas along the coast.

Scenario 3b is identical to Scenario 3a, except as noted above. The results for this scenario are very similar to those of Scenario 3a: a maximum freshwater flux of about 350 afm, and a minimum of about 10 afm. The change in pumping conditions does not have a substantial effect on the flux out of this stretch of coastline compared to Scenario 3a, although the head results (Section 5.2.1) do show some spatial variability in the North Westside Basin. This indicates that the freshwater flux may be decreased in some places and increased in others compared to Scenario 3a, something that this analysis of total flux would not capture. These results indicate that the pumping rates and distribution of pumping under Scenario 3b would not have a substantial effect on seawater intrusion in the North Westside Basin compared to Scenario 3a, although the location and timing of intrusion may be affected.

These results indicate that there is no major difference between Scenarios 3a and 3b in terms of seawater intrusion, except on the coastline directly west of Golden Gate Park, where heads are projected to be slightly higher under Scenario 3b, possibly reducing the rate of intrusion along this part of the coast.

5.2.3. Groundwater Contour Map Analysis

Under Scenario 3a, the model-simulated groundwater head elevations for the Shallow Aquifer at the end of the simulation period (Figure 10.3-19) were lower than under Scenario 1

(Figure 10.3-18). This reflects the effect of the SFGW Project operations in the North Westside Basin. The head was just below sea level in the immediate area around West Sunset Playground and in central Golden Gate Park, representing the drawdown cones around production wells. Head was above sea level through most of the rest of the North Westside Basin, other than the southernmost parts (where head was below sea level in Scenario 1 as well).

Scenario 3b was similar to Scenario 3a, except as noted above. The model-simulated water table elevations in the North Westside Basin under this scenario (Figure 10.3-20) were mostly similar to those of Scenario 3a. The water table was very slightly higher at the western end of Golden Gate Park. The area of the North Westside Basin with groundwater heads below sea level under this scenario was slightly smaller than under Scenario 3a, as the cone of depression in central Golden Gate Park does not reach below sea level.

The map distributions for Scenarios 3a and 3b suggest that the area between the West and South Sunset Playgrounds would have an increased potential for landward migration of the seawater-freshwater interface resulting from groundwater pumping (as noted in Section 2, the groundwater elevation does not have to drop below sea level for seawater intrusion to occur). Areas along the northern part of the Coast are predicted to have higher groundwater head even with the pumping, suggesting a lesser potential for the landward migration of the seawater-freshwater interface in this area compared to the southern part of the Coast.

5.2.4. Evaluation of Analytical Results

Comparing the exclusion heads calculated by the analytical method (see Section 3.5.1) to the head results from the numerical model suggests that conditions near the Pacific Coast of the North Westside Basin under Scenarios 3a and 3b have the potential for seawater intrusion, particularly during periods of drought. Table 10.3-6 provides the percentage of each scenario duration during which head is below the applicable exclusion heads.

- At the North Windmill location (Figure 10.3-4), head in Model Layer 1 is below the single-aquifer exclusion head[4] for much of the simulation after about Scenario Year 10 (57% of the simulation duration for Scenario 3a, 60% for Scenario 3b), and is below the Shallow Aquifer exclusion head during the Design Drought and Scenario Year 27 (5% of the simulation duration for Scenario 3a, 4% for Scenario 3b).

- At the South Windmill cluster (Figure 10.3-5), head in Model Layer 1 is below the single-aquifer exclusion head for the entire simulation duration after about Scenario Year 4 (95% of the Scenario 3a simulation duration, 98% for Scenario 3b), and varies around the Shallow Aquifer exclusion head throughout most of the simulation duration (below the exclusion head for 73% of the simulation duration under Scenario 3a, 85% for

[4] As discussed in Section 3.5.1, this represents the exclusion head for the entire subsurface taken as a single aquifer, rather than discretized into multiple aquifers.

Scenario 3b). In Model Layer 4, head is below the single-aquifer and Primary Production Aquifer exclusion heads for the entire simulation.

- At the Kirkham cluster (Figure 10.3-6), head in Model Layer 1 is below the single-aquifer exclusion head for the entire simulation duration, and is mostly below the Shallow Aquifer exclusion head for most of the simulation after about Scenario Year 8 (77% of the Scenario 3a simulation duration, 75% for Scenario 3b). In Model Layers 4 and 5, head is below both exclusion heads for the entire simulation, although this is also true of Scenario 1.

- At the Ortega cluster (Figure 10.3-7), head in Model Layer 1 is below the single-aquifer exclusion head for the entire simulation duration (as is true of Scenario 1), and below the Shallow Aquifer exclusion head for the bulk of the simulation duration after about Scenario Year 6 (89% of the total simulation duration for both scenarios). In Model Layers 4 and 5, head is below both exclusion heads for the entire simulation, as is true for Scenario 1.

- At the West Sunset Playground Well (Figure 10.3-8), head in Model Layer 1 is below the single-aquifer exclusion head for the entire simulation duration after about Scenario Year 1 (99% of the simulation duration for both scenarios), and below the Shallow Aquifer exclusion head after about Scenario Year 6 (90% of the simulation duration for both scenarios). In Model Layers 4 and 5, head is below both exclusion heads throughout the simulation duration, as is the case for Scenario 1.

- At the Taraval cluster (Figure 10.3-9), head in Model Layer 1 is below the single-aquifer exclusion head throughout the simulation (as is the case for Scenario 1), and below the Shallow Aquifer exclusion head for the entire simulation duration after about Scenario Year 5 (91% of the simulation duration for both scenarios). Head in Model Layers 4 and 5 is below both exclusion heads for the entire simulation period, as is the case for Scenario 1.

- At the Zoo cluster (Figure 10.3-10), head in Model Layer 1 is below the single-aquifer exclusion head throughout the simulation duration (as is the case for Scenario 1), and varies around the Shallow Aquifer exclusion head for the entire simulation duration after about Scenario Year 14 (below for 35% of the simulation duration for Scenario 3a, 30% for Scenario 3b). Head in Model Layers 4 and 5 is below both exclusion heads for the entire simulation, as is the case for Scenario 1.

- At the Fort Funston cluster (Figure 10.3-11), head in Model Layers 1, 4 and 5 is below the single-aquifer exclusion heads for the model simulation, as is the case for Scenario 1. Note that the units at this cluster and at the Thornton Beach cluster do not correlate to the individual aquifers present east of the Serra Fault, so only the single-aquifer exclusion head is considered and presented on the hydrographs.
- At the Thornton Beach cluster (Figure 10.3-12), head in Model Layer 1 varies around the single-aquifer exclusion head throughout the simulation duration (below the exclusion head for 64% of the simulation duration for both scenarios, compared to 63% of the simulation duration for Scenario 1). Head is below the single-aquifer exclusion head for the entire simulation duration for Model Layers 4 and 5, as is true of Scenario 1.

These results indicate that there is the potential for the landward migration of the seawater-freshwater interface under the pumping conditions proposed for the SFGW Project along some parts of the Pacific Coast, but not others. The exclusion head is a way to evaluate the long-term potential for seawater intrusion. It is important to note that groundwater heads below the exclusion head at a location do not necessarily imply that seawater intrusion will reach that location, because there are other hydrogeologic factors that may influence the location of the seawater-freshwater interface. In particular, physical controls may exist, such as low-permeability layers or offshore fault zones, as discussed earlier. Rather, the analytical model indicates that there is an increased potential for the landward migration of the seawater-freshwater interface. Also, seawater intrusion is typically a slow process that may take years to manifest in a production well, and only if the conditions favorable for seawater intrusion are sustained continuously for an extended period of time.

Varying groundwater heads over the year can have a substantial effect on the movement of the seawater-freshwater interface. If groundwater head rises and falls within a similar range from year to year, then the seawater-freshwater interface would move back and forth in a similar fashion. If this were the case, the interface would not continue to advance landward over time, but would establish a new transition zone and remain at that new location over time. If groundwater head declines over a period but become stable at some lower level, then the seawater-freshwater interface would shift to a new equilibrium location, which may still be offshore.

For the most part, seasonal fluctuations in head in Model Layer 1 are not great enough to lower head below exclusion head values during dry parts of the year (Table 10.3-4). In general, seasonal fluctuations, even when they repeatedly cross the exclusion head, are not likely to substantially affect the occurrence of seawater intrusion, because intrusion occurs on a much greater time scale than these annual fluctuations. Therefore, the small inward interface migration that would occur during the low summer heads would be offset by the outward migration that would occur during the higher winter heads. In this conceptual scenario, the seasonal fluctuations would approximately cancel each other out, indicating that the average annual head is the most important factor that relates to the potential for seawater intrusion.

5.2.5. Evaluation

Groundwater head, especially in the southern half of the North Westside Basin, is projected by the model to be below sea level (and the calculated exclusion heads) for some or most of the simulation period. During the operation of the SFGW Project, the model results show lower groundwater heads throughout the northern half of the North Westside Basin. For Scenarios 3a and 3b, the groundwater heads along the Pacific Coast would be depressed and hydrologic conditions may allow for the landward migration of the seawater-freshwater interface in the aquifer in areas where no physical controls exist to prevent intrusion. Based on the groundwater elevation contour maps from the model, these areas would be limited to an area along the Coast. It is unclear how far landward the seawater-freshwater interface may move or at what rate.

Groundwater head responds similarly during drought periods compared to the same drought periods under Scenario 1, except that they are offset by fairly uniform amounts, so the change in head appears to be due almost entirely to the increase in pumping in this area; head also does not rebound to Scenario 1 levels during wet periods, indicating that the extra pumping in the North Westside Basin would have a uniform effect on head in both wet and dry times.

The results of this analysis indicate that the increase in pumping in the North Westside Basin entailed in the SFGW Project would result in the landward migration of the seawater-freshwater interface in the aquifer beyond that which would occur naturally due to climatic fluctuations. Although the flux results quantified by the numerical model are not expected to accurately represent the actual flux everywhere along the coast, the relative changes resulting from the various scenarios are informative for understanding the possible timing of seawater intrusion.

5.3. San Francisco Bay Coast

The SFGW-only Scenarios (3a and 3b) do not include any additional pumping in the South Westside Basin, so large changes in head are not anticipated in this area. Figures 10.3-13 through 10.3-15 show the difference in head for these scenarios versus Scenario 1 (note that the results of these scenarios are nearly identical to those of Scenario 1, so the Scenario 1 results are generally not visible on the hydrographs). Table 10.3-2 presents the maximum, average, and minimum differences between the results for these scenarios and those of Scenario 1.

5.3.1. Head

Scenario 3a: This scenario includes additional pumping in the North Westside Basin, which is far from the Bay monitoring well locations. Therefore, minimal change is expected in these wells. Indeed, the average differences in head in these wells compared to Scenario 1 are all between -0.01 and -0.03 ft (Table 10.3-2). This indicates that the SFGW Project pumping conditions would not have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

Seasonal fluctuations under this scenario are all between +0.1 ft and -0.1 ft (Table 10.3-4), indicating that seasonal head fluctuations would not have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

Scenario 3b: As with Scenario 3a, the situation simulated in this scenario is not expected to affect this area greatly. The average differences in head compared to Scenario 1 are all between -0.01 and -0.03 ft (Table 10.3-2). As such, the Scenario 3b conditions are not expected to have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

Seasonal fluctuations in head under this scenario are all between +0.1 ft and -0.1 ft (Table 10.3-4), indicating that seasonal head fluctuations would not have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

5.3.2. Groundwater Flux

Scenario 3a: This scenario simulates the pumping entailed in the SFGW Project, which increases groundwater extraction in the North Westside Basin. Even though pumping is not modified in the South Westside Basin, the inclusion of the SFGW Project seems to have a slight effect on the freshwater flux along the Bay coast, decreasing it slightly compared to Scenario 1 throughout the simulation period (Figure 10.3-17 and Table 10.3-5). This decrease is not reflected in the heads. The minimum freshwater flux is about 80 afm, a decline of only 2 afm compared to Scenario 1. These results indicate that this configuration of the SFGW Project would not have a substantial effect on the occurrence of seawater intrusion in the South Westside Basin.

Scenario 3b: This scenario is identical to Scenario 3a, except as noted above. Because of the distance to the North Westside Basin and the relatively small change in pumping involved from Scenario 3a, conditions along the Bay Coast are expected to show only minimal changes. The minimum freshwater flux is still about 80 afm (Table 10.3-5). These results indicate that the changes between Scenarios 3a and 3b do not have a substantial effect on the occurrence of seawater intrusion along the Bay coast.

5.3.3. Evaluation

In general, the modeling results suggest that the Bay Coast would not be vulnerable to seawater intrusion due to the operation of the SFGW Project. The freshwater flux out of the aquifer into San Francisco Bay is quite low, and would not be modified to a great degree by the pumping configurations simulated in the numerical model (Figure 10.3-17). As noted previously, the hydrogeological framework in this part of the Basin is not well-known, so these results are considered to be fairly qualitative.

6. Cumulative Scenario Analysis

The Cumulative Scenario (4) includes the assumed operation of both the GSR and SFGW Projects, projected pumping for the PAs and third party pumpers, and other reasonably foreseeable future projects. Reasonably foreseeable projects that are considered under the cumulative scenario include the Daly City Vista Grande Drainage Basin Improvements Project and the Holy Cross cemetery future build-out with its anticipated increase in irrigation pumping.

6.1. Scenario Conditions

Scenario 4 assumes the operations of the GSR (as per Scenario 2) and SFGW Projects with total SFGW Project pumping of 4 mgd (as per Scenario 3b). The model assumptions used for Scenario 4 are summarized in TM-10.1.

The Daly City Vista Grande Drainage Basin Improvements Project is assumed to be a reasonably foreseeable future project under the cumulative scenario. It is assumed that supplemental water to the Lake would be supplied by Daly City storm water from the Vista Grande canal with baseflows being maintained via a wetland (see TM-10.1 for details).

Based on the future land use development projections in the Holy Cross cemetery, irrigation pumping in this cemetery is anticipated to increase under the cumulative scenario by 0.04 mgd, and the associated recharge to groundwater has also been adjusted (see TM-10.1).

6.2. Conceptual Analysis

The Cumulative Scenario includes both the GSR and SFGW Projects. However, since the GSR Project is located in the South Westside Basin, and the SFGW Project is located in the North Westside Basin, it is not anticipated that there would be much interaction between the two projects with respect to seawater intrusion. Scenario 2 showed that the GSR Project conditions did not have a large effect on conditions in the North Westside Basin, while Scenarios 3a and 3b showed that the SFGW Project conditions did not have a large effect on conditions in the South Westside Basin. Therefore, in terms of the potential for seawater intrusion, it is anticipated that the Cumulative Scenario would produce results in the South Westside Basin similar to those of the GSR-only Scenario (2), and in the North Westside Basin similar to those of the SFGW-only Scenarios (3a and 3b).

As shown in TM-10.1, diversion of water from the Vista Grande Canal into Lake Merced would have the effect of raising groundwater head in the Lake Merced area as a result of leakage from the Lake to the aquifer. This localized increase in head may decrease the potential for seawater intrusion along the coast near Lake Merced, but this effect diminishes with distance from the Lake.

The changes to pumping associated with the Cumulative Scenario (such as the pumping increase at the Holy Cross cemetery) are located in the South Westside Basin and are too far from either coast to have a substantial effect on seawater intrusion.

6.3. Pacific Coast

The results of the Cumulative Scenario (4) are shown on Figures 10.3-4 through 10.3-12. These figures show predicted head at the various Pacific Coast monitoring locations as well as the difference in head between this scenario and Scenario 1. Table 10.3-2 presents the maximum, average, and minimum differences between the results for this scenario and those of Scenario 1.

6.3.1. Head

Scenario 4 combines the GSR Project pumping of Scenario 2 with the SFGW Project pumping of Scenario 3b. Because the GSR Project pumping is concentrated in the South Westside Basin, the results of this scenario in the Pacific Coast area are very similar to those of Scenario 3b (Figures 10.3-4 through 10.3-12). At the North Windmill location, and the South Windmill and Kirkham clusters, the average difference between the results of Scenario 3b and those of this scenario in Model Layer 1 is minimal (Table 10.3-2a).

Further to the south, head is slightly higher in this scenario versus Scenario 3b. This reflects the operation of the GSR Project, which is shown (under Scenario 2; see Section 4.2.1) to increase head slightly in this area compared to Scenario 1. At the Ortega Cluster, head in Model Layer 1 (Table 10.3-2a) is on average less than a foot higher than under Scenario 3b. This average difference increases to the south to about 0.8 ft at the Taraval cluster and 4 ft at the Zoo cluster. At the West Sunset Playground well (Figure 10.3-8), head is about 2 ft higher than under Scenario 3b. Head is nearly unchanged at the Fort Funston (Figure 10.3-11) and Thornton Beach (Figure 10.3-12) clusters.

In Model Layer 4 (Table 10.3-2b), the results are similar. At the West Sunset Playground well, the average difference from Scenario 1 is about 3 fthigher than under Scenario 3b, about 3 ft higher at the Taraval cluster, and 6 ft higher at the Zoo cluster.

In Model Layer 5 (Table 10.3-2c), results are similar to those of Model Layer 1, except that the average difference is about 2 ft higher at the Taraval cluster than under Scenario 3b.

Seasonal fluctuations in this area are mostly smaller than under Scenario 1 for the Cumulative Scenario, and similar to those of Scenario 3b (Table 10.3-4). Values for Scenario 4 range from about 0.5 ft (West Sunset Playground well and Taraval cluster) to 1.3 ft (Zoo and Fort Funston clusters) in Model Layer 1, from about 0 ft (Fort Funston and Thornton Beach clusters) to 0.3 ft (South Windmill, Kirkham, and Taraval clusters and West Sunset Playground well) in Model Layer 4, and from -0.5 ft (Zoo cluster) to 0.2 ft (Kirkham and Ortega clusters) in Model Layer 5. These results indicate that seasonal fluctuations in head would not have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

6.3.2. Groundwater Flux

Scenario 4 combines the pumping changes of the GSR and SFGW Projects simulated in Scenarios 2 and 3b. The average flux (and head) conditions are higher than under the SFGW Project Scenarios (3a and 3b), although by only a small amount relative to the total flux (Figure 10.3-16 and Table 10.3-5).

The maximum freshwater flux for this simulation is about 350 afm, while the minimum is about 15 afm. The minimum flux is slightly higher than under Scenarios 3a and 3b, but the difference is not large compared to the total range of fluxes from maximum to minimum. Therefore, the results of this scenario indicate that the combination of the SFGW and GSR Project pumping regimes would not have a substantial effect in the North Westside Basin compared to the SFGW Project alone.

6.3.3. Groundwater Contour Map Analysis

Under Scenario 4, the model-simulated groundwater elevations for the Shallow Aquifer at the end of the simulation period (Figure 10.3-20) are very similar to those of Scenario 3b. The lack of difference between the results of Scenarios 3b and 4 indicate again that the GSR Project would have only a minor effect on groundwater head in the North Westside Basin. The cone of depression around the West Sunset Playground well is very slightly smaller, and areas north of this well see very slightly higher groundwater elevations. South of the West Sunset Playground well, areas of below-sea-level groundwater elevations around Lake Merced disappear, and groundwater elevations just north of Lake Merced are generally around five feet higher, a likely result of the modeled additions of the Daly City Vista Grande Drainage Basin Improvement Project under the Cumulative Scenario.

Compared to Scenario 1, the map distribution for Scenario 4 suggests that the area of the West Sunset Playground well would have an increased potential for landward migration of the seawater-freshwater interface resulting from groundwater pumping, similar to the results of Scenarios 3a and 3b. Areas to the south would have a much smaller extent of decreased groundwater head, suggesting a lesser potential for the landward migration of the seawater-freshwater interface.

6.3.4. Evaluation of Analytical Results

From the Ortega cluster (Figure 10.3-7) south, head is actually higher than predicted for Scenario 3b in Model Layers 1 and 4, likely the result of the Vista Grande additions to Lake Merced. However, the differences are generally quite small, and would only slightly change the degree and rate of seawater intrusion, not its occurrence. Therefore, combined operation of the GSR and SFGW Projects is considered to have the same effect on seawater intrusion as does the SFGW Project alone. The exception to this is in Model Layer 1 at the Zoo cluster (Figure 10.3-10a), where heads are about four feet higher under this simulation and above the Shallow Aquifer exclusion head throughout the simulation duration (compared to Scenario 3b, during which head was below the Shallow Aquifer exclusion head for 30% of the simulation duration).

Seasonal head fluctuations in Model Layer 1 (Table 10.3-4) are similar to those of Scenario 3b, and the same conclusions apply (Section 5.2.4). Even in the southern part of the North Westside Basin, where there is some slight difference between the head values for this scenario and those of Scenario 3b, the seasonal fluctuations are not markedly different.

6.3.5. Evaluation

The Scenario 4 results indicate that some of the groundwater heads in the North Westside Basin for the Cumulative Scenario would be higher than those for the SFGW-only Scenarios (3a and 3b), while other groundwater heads would be similar to Scenarios 3a and 3b. Exceptions are seen in Model Layer 5 in the southern part of the North Westside Basin (from the West Sunset Playground well south). Head values under Scenario 4 drop below the results of Scenarios 3a and 3b during take periods, with the largest declines seen during the Design Drought; these declines follow similar patterns as the Scenario 2 results, indicating that they result from the operation of the GSR Project. As noted in Section 4.2.4, the declines in head seen during the take periods are temporary, and would not have a significant effect on the occurrence of seawater intrusion along this Coast. Taken as a whole, the results of Scenario 4 indicate that the combined effects of the Projects would create conditions less favorable for the landward migration of the seawater-freshwater interface than those seen in Scenarios 3a and 3b.

6.4. San Francisco Bay Coast

The results of the Cumulative Scenario (4) for the Bay side monitoring network locations are shown on Figures 10.3-13 through 10.3-15, which depict the head predictions for this scenario as well as the differences in head between this scenario and Scenario 1. Table 10.3-2 presents the maximum, average, and minimum differences between the results for this scenario and those of Scenario 1.

6.4.1. Head

Scenario 4 combines the pumping changes entailed in the GSR and SFGW Projects. Because neither of these projects would have much of an effect on head in this part of the Basin (see Sections 4.3.3 and 5.3.3), the Cumulative Scenario pumping would not have a large effect either. Indeed, the hydrograph results for the three well clusters in the area (Figures 10.3-13 through 10.3-15) show minimal differences compared to the results of Scenario 2. This finding is confirmed by the statistical evaluation of head (Table 10.3-2). This indicates that the operation of the combined Projects would not have a substantial effect on seawater intrusion in this part of the Basin.

Seasonal fluctuations in head under Scenario 4 are between about -0.1 ft and +0.1 ft (Table 10.3-4). This indicates that seasonal fluctuations in head would not have a substantial effect on the occurrence of seawater intrusion in this part of the Basin.

6.4.2. Groundwater Flux

Scenario 4 combines the pumping conditions of the GSR and SFGW Projects. The average freshwater flux results of this scenario fall below those of the other scenarios (Figure 10.3-17 and Table 10.3-5), with a maximum flux of about 110 afm and a minimum flux of about 50 afm. This minimum flux is substantially lower than under Scenario 2 (minimum flux of 70 afm), indicating that the combined operation of the Projects may have an increased effect on freshwater flux, but the flux remains well above zero throughout the simulation period, and the fine-grained nature of the aquifer deposits may represent a physical control preventing seawater intruson.

6.4.3. Evaluation

In general, the changes to groundwater pumping entailed in the GSR and SFGW Projects would not have a substantial effect on seawater intrusion along the San Francisco Bay Coast compared to what may occur under Scenario 1 conditions. The Burlingame cluster is projected to see a decline in head during Scenario 1, approaching sea level in Model Layer 1 (Figure 10.3-13a). In Model Layer 4 (Figure 10.3-13b), head at the Burlingame cluster begin slightly above sea level, and decline throughout the scenario. At the SFO (Figure 10.3-14) and UAL (Figure 10.3-15) clusters, the head rises throughout the simulation period.

7. Assessment of Areas Susceptible to Seawater Intrusion

The occurrence of seawater intrusion into a freshwater aquifer depends greatly on the connection between the ocean and the aquifers. If the aquifer is isolated from seawater, there is no potential for intrusion, while freshwater aquifers in direct communication with seawater may have no physical barrier preventing the intrusion of seawater. To understand the susceptibility of the various aquifers in the study area to seawater intrusion, it is necessary to understand the configuration of the aquifers offshore. In general, studies suggest that the aquifers present in the North Westside Basin do stretch offshore to some distance, but how far, and whether these aquifers are in direct communication with the ocean, are questions that have not to date been fully resolved.

7.1. Potential Rate of Intrusion

The rate of seawater intrusion into an aquifer can be widely variable, depending on the values of the various parameters that control it. Because groundwater head in the coastal areas of the Westside Basin is not as far below sea level as in some of the examples presented in Section 8.2, the rate of seawater intrusion that would be seen in this basin may be on the low end of the rates determined by other studies.

The timing of seawater intrusion depends on a number of variables. A large inland gradient or high horizontal hydraulic conductivity would hasten seawater intrusion. Seawater intrusion would also occur more quickly if the seawater front is already close to land due to lower onshore head or freshwater flux. Although the thickness of the aquifer does not analytically have an effect on the rate at which seawater intrudes into a freshwater aquifer, a seawater wedge would form earlier in a thicker aquifer because the thicker aquifer requires a larger freshwater head to keep seawater out. An analytical equation can be developed that gives a first approximation of the potential rate of seawater intrusion under various conditions; this is described in Attachment A.

A simplified aquifer was constructed to apply this analytical solution, and the various parameters were chosen to reflect approximate actual values at the South Windmill cluster in Golden Gate Park. The parameter values, and the sources from which they were derived, are given in Table 10.3-7. These values were used to calculate the change in seawater intrusion length over various periods of time (0.25, 0.5, 1, 2, 5, 10, 20, and 50 years) at pumping rates varying from zero to equal to the freshwater flux rate determined by Yates et al. (1990) for the Golden Gate Park area. It should be noted that the aquifer at this location was assumed to be continuous from the top of the sediments to the bedrock surface, due to the lack of large aquifer-bounding clay layers here (LSCE, 2010).

The results of this analysis indicate that the rate of intrusion would be quite low (Figure 10.3-21; note that the vertical axis is logarithmic). The dotted line on this figure represents the equilibrium change in intrusion length (i.e., the equilibrium intrusion length, L_{eq}, minus the pre-pumping intrusion length, L_0) based on the new freshwater flux rate (i.e., the original freshwater flux rate,

Q'_0, minus the pumping rate, Q'_w); this is the intrusion length that would eventually be reached at steady state. The blue dashed line indicates the percentage of the original freshwater flux rate that is left after pumping is increased. The three solid lines indicate the change in intrusion length (i.e., the transient intrusion length, $L(t)$, minus the pre-pumping intrusion length, L_0) at three different values of t: 1, 10, and 50 years. The change in intrusion length, read off the left-hand axis, represents how far the toe of the intrusion wedge would have advanced in the period of time corresponding to each line; for example, at a pumping rate of 5,000 cubic feet per year per foot of shoreline (cfy/ft of shoreline), the intruding wedge would have moved 3 feet in 1 year, 13 feet in 10 years, and 39 feet in 50 years. When a solid line intersects with or is above the red dotted curve representing the equilibrium change in intrusion length, the system would be at equilibrium, and the interface would not progress past L_{eq}.

These results indicate that the rate of seawater intrusion is lower than has been seen in other settings (see Section 8.2). Even if pumping in the Basin were equal to the pre-pumping freshwater flux (an extreme scenario that is not expected to occur), the change in the intrusion length would be 7 feet after 1 year, 33 feet after 10 years, and 96 feet after 50 years (note that the method assumes that the freshwater pumping is small compared to the initial freshwater flux, so these results should be considered approximate). An equilibrium change in intrusion length of 12,600 feet for this pumping rate indicates that it would take many decades for this system to reach equilibrium.

This method can be applied to the pumping rates from the various modeling scenarios. Scenario 1 utilizes an average pumping rate of about 4,830 cfy/ft of shoreline. The proposed total pumping in the North Westside Basin is about 13,640 cfy/ft of shoreline in Scenario 3a, which represents an increase of about 8,810 cfy/ft of shoreline. The analytical method indicates that the change in intrusion length would be 4 feet over the first year, 19 feet over 10 years, and 57 feet over 50 years. The proposed total pumping of 14,050 cfy/ft of shoreline in Scenario 3b represents an increase of about 9,220 cfy/ft of shoreline. At this rate, the change in intrusion length would be 4 feet over 1 year, 20 feet over 10 years, and 59 feet over 50 years. It should be noted that the increased pumping entailed by the SFGW Project represents about 45% of the initial freshwater flux under Scenario 3a and 47% under Scenario 3b, which indicates that one of the assumptions of the analytical method (that pumping be small compared to the initial freshwater flux) is not completely valid. Because of this, these results should be considered approximate. However, the results are still instructive of the general magnitude of the potential seawater intrusion rate, and are useful in providing an independent line of evidence that pertains to the seawater intrusion analysis.

As with the analysis of flux predicted by the numerical model, it should be noted that this rate analysis assumes that the fluxes can be applied in average across the entire Pacific coast. The actual rate of intrusion at Golden Gate Park may be greater or less than that implied by this analysis, depending on how flux in the area is actually modified.

7.2. Physical Conditions Along the Pacific Coast

Previous reports (LSCE, 2002; LSCE, 2010; SFPUC, 2005; SFPUC, 2006) discussed the coastal topography and stratigraphy in relation to the problem of seawater intrusion. These reports considered pre-existing information on the onshore geology (e.g., Clifton and Hunter, 1987) coupled with the results of a study of offshore seismic reflection (Bruns et al., 2002). The information in these reports is summarized in this section. Because no control studies have been performed (i.e., coring offshore to confirm stratigraphy), this discussion of offshore stratigraphy is somewhat speculative.

7.2.1. Offshore Geology

The upper surface of sediments continues offshore at a very gentle slope for a large distance. The water depth in the Ocean is only 60 feet about 2 miles offshore, 100 feet 8 miles offshore, and 300 feet 25 miles offshore, at the edge of the continental shelf; the Ocean bottom drops off steeply further offshore. This indicates that the onshore sedimentary units, if they stretch continuously offshore, may not outcrop on the Ocean floor for some distance. The intersection of the top of each aquifer with the Ocean bottom (i.e., its highest outcrop) is important to the problem of seawater intrusion because this is, theoretically, where freshwater exits the aquifer, and is the location where the uppermost part of the seawater wedge exists within the aquifer (Figure 10.3-3).

Because of the structural complications that exist offshore, the slope of the aquifer boundaries that exist onshore and the depth to the Ocean floor cannot be used to predict the depths of the units offshore and where the aquifers are connected to the Ocean. The San Andreas Fault is present offshore from around Mussel Rock north to Bolinas Lagoon. Further to the west, the San Gregorio Fault Zone also sits offshore. Between these faults exists the extensional San Gregorio Basin, a down-dropped area that results from the structure of the two bounding fault zones. This extensional basin has filled with more than 3,000 feet of sediment that is presumed to correlate to the Merced and Colma Formation sediments further inland (Bruns et al., 2002). However, no control points exist to confirm this. The extensional regime that led to the deepening of this basin likely made this a somewhat different depositional environment from the areas east of the San Andreas Fault, so there may be some differences even between units that correlate exactly in time across the San Andreas Fault. West of the San Gregorio Fault Zone, the stratigraphic sequence revealed by the seismic profiling resembles the units seen in the Santa Cruz Mountains to the southeast, indicating that these units have been translated by strike-slip motion along the San Andreas and San Gregorio Fault Zones (Bruns et al., 2002), and the aquifers that exist in the North Westside Basin therefore cannot be correlated to units west of the San Gregorio Basin. As long as the individual onshore aquifer units do not intersect the Ocean floor before reaching the San Andreas Fault, this fault zone may act as a physical barrier preventing seawater intrusion. The Shallow Aquifer, which is not covered by a confining clay layer, is in direct communication with the Ocean all along the coast.

Faults may represent hydrologic barriers in other parts of the Basin. The Serra Fault makes the Daly City area non-susceptible to seawater intrusion from the Ocean (see Section 7.2.3), and the same might be true of the lower aquifers in the North Westside Basin north of Lake Merced due to the presence of the San Andreas Fault, although no direct evidence of this exists.

An additional factor that may aid in reducing the likelihood of seawater intrusion is the presence of freshwater in offshore sediments (LSCE, 2010). During the Pleistocene glaciations, Ocean levels were about 300 to 400 feet lower, exposing the coastal plain to the atmosphere. During that time, the Sacramento-San Joaquin River system flowed across the coastal plain, depositing river sediments. The presence of this river and the exposure to the atmosphere for a relatively long period of time likely allowed fresh water to flush through most or all of the present-day offshore aquifer system. Provided the fine-grained units that exist between the aquifer layers are continuous offshore, these offshore units may still be filled with fresh water. If this is the case, then even head below sea level in the Primary Production and Deep Aquifers may not lead to seawater intrusion on any near-term time frame (SFPUC, 2006); it may take years to decades of continuously below-sea level onshore freshwater head for seawater to intrude through the miles of aquifer potentially occupied by fresh water. Indeed, about 5.5 mgd of groundwater was pumped from the North Westside Basin from 1930 to 1935, immediately prior to the completion of the Hetch Hetchy aqueduct, without inducing any noticeable degradation of water quality in the production wells (Gilman, 2010; SFPUC, 2006). LSCE (2010) also notes that the boreholes at the Fort Funston and Thornton Beach clusters, both located in deformed Merced Formation sediments west of the Serra Fault, did not encounter any saline water to their total depths of 1,500 feet.

7.2.2. Pacific Coast Northeast of the Serra Fault

The western boundary of the North Westside Basin is the Pacific Ocean. This stretch of the Pacific Coast is considered potentially susceptible to seawater intrusion due to its direct connection to the Pacific Ocean; however, it does not seem to be currently affected by seawater intrusion. Chloride levels in the monitoring wells along the coast have remained steady and fairly low. The shallow well at the South Windmill monitoring well cluster shows relatively high chloride concentrations, up to 154 milligrams per liter (mg/L) in the most recent (2011) samples (J. Gilman, personal communication, April 22, 2012). The California secondary maximum contaminant level (MCL) for chloride is 250 mg/L recommended and 500 mg/L upper limit.

As noted above, three aquifers exist in this part of the Basin, the Shallow, Primary Production, and Deep Aquifers, although the Deep Aquifer pinches out between the Kirkham and South Windmill well clusters (LSCE, 2010). The boundaries between these units tend to dip slightly toward the Ocean, especially in the deepest sediments as noted in TM#1.

The onshore hydrogeology presented in Appendix A of LSCE (2010) provides insights into the structure of the aquifers. Cross-sections J-J’, Z-Z’, and Y-Y’ stretch through this area. According to these cross-sections, the Shallow Aquifer is in direct contact with the Ocean, and so there are no physical controls to prevent the intrusion of seawater should currently-existing hydrologic controls change.

The cross-sections do not stretch far enough off the coast to show where the Primary Production and Deep Aquifers may be in direct contact with seawater. SFPUC (2006) notes that the structural and depositional features that exist in the offshore sediments preclude the intrusion of seawater into the Primary Production and Deep Aquifers north of Lake Merced, but the physical barriers implied by this are not yet proven to exist. Rather, they are suggested by offshore seismic studies (Bruns et al., 2002) and the presence of offshore fault zones.

Cross-section J-J' is located along an west-east transect from the Ocean through Golden Gate Park to Strawberry Hill. In this area, the Shallow and Primary Production Aquifers are present. At the coast, the Shallow Aquifer is about 100 feet thick, while the Primary Production Aquifer may be about 350 feet thick. There is no fine-grained layer between the two aquifers at this location, meaning that they are hydraulically connected, and they can effectively be considered to be one thick aquifer. According to the cross-section, no physical barrier exists here that would prevent intrusion of seawater into the Primary Production Aquifer via the Shallow Aquifer above. As noted above, these cross-sections do not stretch far offshore; the absence of an intervening fine-grained layer onshore does not necessarily imply that no such layer separates the different aquifers offshore.

Cross-section Z-Z' runs from the Ortega cluster approximately east through the West Sunset Playground to the Sunset Reservoir. Along this cross-section, all three aquifers are present, and they are divided by at least some thickness of fine-grained units, although these lenses are fairly thin and could be discontinuous between the existing wells. At the coast, the Shallow Aquifer is about 120 feet thick, while the Primary Production Aquifer is about 310 feet thick and the Deep Aquifer is about 60 feet thick. If the clay layers between the aquifers are continuous as indicated on the cross-section, and if they continue offshore to some physical barrier (e.g., the San Andreas Fault), the Primary Production and Deep Aquifers at this location may be physically protected from seawater intrusion.

Cross-section Y-Y' runs from the San Francisco Zoo area east to Pine Lake Park and beyond. This cross-section, like Z-Z', indicates that there are continuous clay layers present between (and, in some cases, within) the aquifers here. The Shallow Aquifer is about 40 feet thick at the coast, while the Primary Production Aquifer is about 300 feet thick and the Deep Aquifer is about 130 feet thick. As with cross-section Z-Z', the Primary Production and Deep Aquifers may be isolated from the Ocean. It should be noted that the thick clay present between the Shallow and Primary Production Aquifers at the coast (the "-100 clay") is indicated to be possibly discontinuous about 2,000 feet inland of the coast.

From the information summarized above, a conceptual model of the potential route of seawater intrusion can be constructed for the North Westside Basin. The Shallow Aquifer is connected directly to the Ocean everywhere along the coast, indicating that seawater intrusion would occur in this aquifer anywhere that the on-shore freshwater head is low enough that seawater is not excluded from the aquifer. From the Kirkham cluster north, there are no continuous confining layers present that separate the aquifers, indicating that all three aquifers are open to intrusion along this stretch of the coast should head levels permit it.

South of the Kirkham cluster, clay layers are present between the three aquifers. To the extent that these layers are laterally continuous, they present a barrier to seawater intruding into the lower two aquifers from the Shallow Aquifer above. Cross-section D-D’ in LSCE (2010) indicates that the W clay is continuous from the Kirkham cluster south to the Serra Fault, separating the Primary Production Aquifer from the Deep Aquifer below. This indicates that, should seawater enter the Primary Production Aquifer, it would not intrude into the Deep Aquifer except at the rate allowed by the W clay. The -100 clay, which separates the Shallow from the Primary Production Aquifer, is not fully continuous south of the Ortega cluster, and there is a gap in this layer between the Taraval and Zoo clusters. Should seawater intrusion occur in the Shallow Aquifer along the coast in locations where the -100 clay is not present, the Primary Production Aquifer would also be susceptible to seawater intrusion. The -100 clay is continuous from north of the Zoo cluster to the Serra Fault (to the south).

7.2.3. Pacific Coast Southwest of the Serra Fault

The southwestern boundary of the South Westside Basin is made up of the San Andreas Fault, which juxtaposes Merced Formation sediments against the Franciscan bedrock southwest of the Basin. This barrier likely prevents the part of the Basin bounding it from experiencing any ill effects in terms of seawater intrusion due to groundwater development. As with the bedrock high sections along the eastern edge of the North Westside Basin, it is always somewhat possible that connate water (seawater trapped in a formation when the sediments are deposited) could be mobilized out of marine sediments by changes in the head distribution, but this is considered unlikely. Therefore, the areas of the Basin bounded by the San Andreas Fault, from San Andreas Lake to the Pacific Ocean, are considered non-susceptible to seawater intrusion.

The Serra Fault, which runs sub-parallel to the San Andreas Fault, has unknown hydraulic characteristics. While the San Andreas Fault to the south has placed low-permeability bedrock against the sediments of the Merced Formation, the Serra Fault separates Merced Formation sediments from those of the Colma Formation, implying that, if a physical barrier to groundwater flow exists, it must be the fault zone itself rather than the rocks bounding it. LSCE (2002) suggest that, due to their “presence and configuration,” the deformed Merced Formation sediments present along the Serra Fault could act as a barrier to seawater intrusion as far north as Fort Funston, where the fault heads offshore, but no corroborating evidence for this has been found elsewhere. The well cluster at Thornton Beach shows very different groundwater head trends from the other wells in the coastal monitoring network, indicating that this cluster, which is located between the San Andreas and Serra Faults, may be hydraulically disconnected by the Serra Fault from the rest of the Westside Basin. For the purposes of this TM, the portion of the Basin along the Pacific Ocean southwest of the Serra Fault between the San Andreas Fault and Lake Merced is considered to be non-susceptible to seawater intrusion based on the assumption that the Serra Fault represents an effective physical barrier to intrusion.

7.2.4. Pacific Coast Head Monitoring

The coastal monitoring wells are screened in the Shallow, Primary Production, and Deep Aquifers (hydrographs for the wells discussed in this section are presented as Appendix B of TM#1). Within the Shallow Aquifer, head has generally not changed much since monitoring began (2004) at the Ortega (120 ft bls) and Taraval (145 ft bls) well clusters. At the Kirkham cluster, head in the well screened within the Shallow Aquifer (130 ft bls) fluctuates quite a bit on a seasonal basis, and LSCE (2010) suggest that this is due to irrigation cycles in Golden Gate Park. The average head in this well dropped by about 4 feet around the spring of 2006; this drop could be related to a change in the irrigation practices. All available heads in the Shallow Aquifer remain above sea level, currently averaging about +10 ft mean sea level (msl) in the Ortega and Taraval wells and about +8 ft msl in the Kirkham wells.

The recent head trends in the Primary Production Aquifer have shown more spatial variability, although they have generally been fairly steady and above sea level. The South Windmill well (140 ft bls) has seen head dip below sea level repeatedly during the irrigation season, by as much as 20 feet. Of the three wells screened in this aquifer at the Kirkham cluster, head in the upper one (255 ft bls) has fluctuated around an average of about +11 ft msl, that in the middle one (385 ft bls) has fluctuated around an average of +8 ft msl, and has not dropped below sea level, and head in the deeper one (435 ft bls) has generally been about +5 ft msl, and dipped below sea level in September of 2007; at the same time, head in the upper (255 ft bls) and middle (385 ft bls) wells dropped below +3 ft msl for the only time over the period of record. The Ortega cluster also has three wells screened within the Primary Production Aquifer. The upper two (265 and 400 ft bls) show very similar trends in head over time, with little change and values hovering around +12 ft msl for most of the period of record. Head in the lowest well (475 ft bls) has fluctuated quite a bit, with two major excursions below sea level in 2006 and 2007. Two wells screened in the Primary Production Aquifer at the Taraval cluster (240 and 400 ft bls) have had heads averaging around +10 to +13 ft msl, with fairly steady heads and no major trends up or down. At the West Sunset Playground well, head has been fairly steady over the period of record at between +17 and +18 ft msl. At the Zoo cluster, two wells are screened within the Primary Production Aquifer. The upper one (275 ft bls) has shown a generally rising head since 2004, staying consistently above sea level; recent head measurements have ranged between about +6 and +7 ft msl. The lower well (450 ft bls) head has also been highly variable, although it has seen at least three drops slightly below sea level, in 2004, 2006, and 2007. Finally, the Thornton Beach cluster has two wells screened within the Primary Production Aquifer. The upper one (225 ft bls) shows head between +82 and +85 ft msl, with the most recent heads about a foot above the earliest heads. The lower one (360 ft bls) shows head between +13 and +15 feet msl, with no appreciable trend over time.

Head in the Deep Aquifer has generally stayed steady on average, with large seasonal fluctuations. The deepest wells at the Taraval (530 ft bls) and Zoo (565 ft bls) clusters are screened in this aquifer. Head in the Taraval well varies between 4 and -9 ft msl, with the lowest heads recorded during the autumn of 2007. The Zoo well varies between +1 and -14 ft msl, with the timing of the deepest head coincident with that in the Taraval well. Neither of these wells shows an identifiable upward or downward groundwater head elevation trend over the period of record.

7.2.5. Pacific Coast Chemical Monitoring

Within the coastal monitoring network, the clusters at South Windmill, Kirkham, Ortega, and Taraval are sampled for chloride, total dissolved solids (TDS), and specific conductance, while the Zoo cluster and the West Sunset Playground well are measured for nitrate and general minerals (which includes chloride and TDS). Chloride concentrations for selected wells are included on the hydrographs of TM#1, and average concentrations for selected chemical constituents are given in Table 10.3-8.

The wells in the monitoring network are sampled for chloride semi-annually. At the Kirkham, Ortega, and Taraval wells, chloride has varied between about 20 and 40 mg/L, and each well has seen fairly steady concentrations since monitoring began in 2004. The three wells in the Zoo cluster have higher chloride, varying from about 70 mg/L (275 ft bls) to 45 mg/L (450 ft bls) to 50 mg/L (565 ft bls). These wells have shown no appreciable upward or downward trend in concentrations over time. Limited data exist for the cluster at South Windmill, with the shallower well (57 ft bls) concentrations varying from 115 to 193 mg/L, and the deeper well (140 ft bls) concentrations varying between 48 and 70 mg/L. The concentrations in this shallower well increased with every measurement from when monitoring began in 2006 through 2009, but have since decreased to 154 mg/L in November 2011.

The highest chloride concentrations measured in the North Westside basin have been at LMMW-1S, screened in the Shallow Aquifer and located between Lake Merced and the Pacific Ocean along the west side of John Muir Drive (data are available for April and November of 2009 and 2010). The highest chloride concentration measured was 393 mg/L in November 2009, with the lowest concentration being 129 mg/L in April 2010 (SFPUC, 2011). The ultimate cause of these high chloride concentrations is unknown. The co-located well LMMW-1D, screened in the Primary Production Aquifer, yielded samples with chloride concentrations of 104 and 106 mg/L in April and November of 2010. The proximity of these wells to the Pacific Ocean (approximately 1,300 feet to the west) indicates that the Ocean is a potential source for elevated chloride; however, LMMW-1S is separated from the Ocean by the Serra Fault, which is interpreted to be a barrier to groundwater flow and seawater intrusion in this area, as discussed further in TM#1. In addition, some other chemical constituents are not typical of Ocean water; in particular, the pH (average of 6.8) is well below the average pH of seawater (about 7.8 to 8.4; see, for example, Krauskopf and Bird, 1995) and below the values seen in the other wells within the North Westside Basin (averages for wells monitored by SFPUC vary from 7.2 to 8.6), perhaps indicating that some other source is affecting the chemistry of groundwater at LMMW-1S. These observations indicate that the elevated chloride concentrations seen in LMMW-1S likely result from a source other than seawater intrusion.

Other previous studies have also presented chloride data in the North Westside Basin that could potentially provide useful information on the occurrence of seawater intrusion along the Pacific coast. AGS (1994) presented results of production well sampling in November and December of 1993 at various wells around the North Westside Basin. Chloride varied from 21 to 68 mg/L, with the highest value at the Oceanside Water Pollution Control Plant (just south of the Zoo cluster and LMMW-4S on Figure 10.3-1); outside of this sample, the highest chloride concentration was 42 mg/L at Sunset Well #7. Samples were obtained from a few locations studied in detail in this TM: North Windmill, South Windmill, and the San Francisco Zoo. At these production wells, chloride concentrations varied from 37 to 39 mg/L. High capacity, deep production wells have been pumping at the west end of Golden Gate Park since the 1920s and at the San Francisco Zoo since the 1930s.

Yates et al. (1990) and Phillips et al. (1993) provided the results of sampling for various constituents (including chloride) at several wells, mostly in the North Westside Basin. Chloride concentrations in all of the wells sampled varied from 21 to 210 mg/L (this highest value was seen at the Elk Glen-S monitoring well in central Golden Gate Park; the highest value along the coast was 130 mg/L at HLA E). Samples from the North Windmill, South Windmill, and Zoo locations (including both production and monitoring wells) had chloride concentrations of 35 to 54 mg/L, except a sample from the shallowest monitoring well at South Windmill, which had a chloride concentration of 100 mg/L. Yates et al. (1990) offered the following explanation for the chloride concentrations in shallow groundwater: “Most of the chloride in shallow ground water is probably derived from near-surface sources. For example, the average concentration of chloride during 1987 in sewage flowing out of the Richmond-Sunset Water Pollution Control Plant was 145 mg/L.” Phillips et al. (1993) offered the following explanation for the elevated chloride concentrations seen at the Elk Glen-S and the South Windmill-S (now known as MW57) monitoring wells: “The apparent saltwater contamination in shallow wells at Golden Gate Park probably is a result of leakage of seawater used at Steinhart Aquarium, either from the supply pipe or exfiltration of saltwater discharge to the sewer system.”

The data presented in the reports discussed above indicate that there have not been appreciable trends over time in the coastal chloride concentrations in the North Westside Basin. Further, the recent sample results have been in line with historical data. The generally stable chloride concentrations along the Pacific Coast indicate that substantial seawater intrusion has not occurred to date, despite long-operating irrigation wells in the areas of Golden Gate Park and the San Francisco Zoo.

Additional groundwater chemistry monitoring has been performed on a short-term basis as part of construction projects in the North Westside Basin. An important and instructive example occurred during dewatering associated with construction at the Oceanside Water Pollution Control Plan (WPCP) from 1989 to 1994 (dewatering started in May of 1990, and continued until April 1991). Oceanside WPCP is located south of the San Francisco Zoo, between the Pacific Ocean and Lake Merced. ESA (1994) presented monitoring data collected in the Oceanside WPCP area during the construction activities. Observation wells were installed surrounding the site, including along the Great Highway along the Pacific Coast (OB-3, OB-6, and OB-7), along the northern end of the site (OB-1, OB-2, and OB-5), and along the eastern boundary of the site where it borders Lake Merced (OB-4). Well OB-3, screened in the Shallow Aquifer, was directly west of the field of dewatering wells, and saw 19 feet of water table decline during dewatering operations, but rebounded to pre-pumping levels within a month of the cessation of dewatering. Water quality was also monitored during construction activities; chloride in OB-3 rose quickly from background concentrations, eventually reaching a maximum of 10,500 mg/L. Monitoring of chloride continued after the cessation of dewatering, and the groundwater in OB-3 remained brackish throughout the period of post-dewatering monitoring, at least to 1994 when ESA reported these results. The monitoring results indicate several important things relevant to this TM:

- Based on the speed with which seawater reached OB-3 after dewatering began, the freshwater-seawater interface in the Shallow Aquifer must be located just offshore in this aquifer, and the Shallow Aquifer is in direct contact with the Ocean here.
- Seawater intrusion can affect coastal monitoring wells within a span of just a few months.
- Once seawater intrusion does occur, it is difficult to reverse the process and return aquifer water quality to its pre-intrusion state, even when head has rebounded to this pre-intrusion state.
- Intrusion, especially when it is caused by highly localized pumping in the vicinity of the coast, can be localized (none of the other monitoring wells saw any decline in water quality during dewatering operations) and temporary (SFPUC, 2005).

The results of the dewatering operations are not expected to exemplify the reaction of the aquifer system to pumping associated with either the GSR or SFGW Projects, which would involve pumping further away from the Coast, and would derive groundwater from deeper, confined aquifers that are not expected to experience seawater intrusion on the short timescales demonstrated for the Shallow Aquifer by ESA (1994).

7.3. Physical Conditions Along the San Francisco Bay Coast

The portion of the Westside Basin along the San Francisco Bay is the easternmost part of the South Westside Basin. This is another area potentially susceptible to seawater intrusion, and may in fact currently be affected by seawater intrusion. Chloride concentrations in this area vary from 42 to 13,000 mg/L, with the highest values seen in the shallowest wells. The chloride-bromide ratios for the sampling events in November 2006 and April 2007 (WRIME, 2007) are fairly similar to that of water collected from a nearby location in the San Francisco Bay (Cl:Br = 327), also in April 2007.

As noted in WRIME (2007), both the Bay Mud and the artificial fill were emplaced in the environment of the saline Bay, meaning that these deposits likely contain substantial connate water. While the similarity of chloride concentrations and chloride-bromide ratios to those of Bay water may seem indicative of seawater intrusion into this area, similar concentrations could be due to the presence of connate Bay water in the sediments of the area, which may be expected to be fairly similar chemically to today's Bay water and would therefore have a similar effect on aquifer water quality as would intruding seawater. Because the available reservoir of connate water is determined by the porosity of the Bay Mud, this reservoir can be assumed to be much smaller than the effectively infinitely large reservoir of Bay water nearby; therefore, the flux of connate water into the freshwater aquifer would likely be lower than would be the flux of seawater intrusion from the Bay if the aquifer were in direct communication with the Bay.

7.3.1. San Francisco Bay Geology

In the San Bruno area, the deposits closest to the Bay are made up of Bay Mud overlain by artificial fill deposited into the Bay (WRIME, 2007). LSCE (2010) produced two cross-sections that stretch through the South Westside Basin toward the Bay, although neither provides a representation of the sediments at the Bay Coast. These cross-sections (N-N' and O-O' in Appendix A of LSCE, 2010) show Colma Formation deposits on the surface inland, interfingering with Bay deposits closer to the Bay. A subsurface bedrock ridge is also shown that provides some protection to the southern portion of the South Westside Basin from potential seawater intrusion from San Francisco Bay.

Cross-section O-O' runs from San Andreas Lake northeast towards San Francisco Bay. Based on the inferred geologic correlations, the Colma Formation sediments that are present on this cross-section inland are not continuous to the Bay, being separated from it by deposits of low-permeability Bay Mud that likely stretch from the land surface to the bedrock surface below. If true, this would present a physical barrier, likely precluding seawater intrusion in this area. The Bay deposits are very fine-grained, and are considered by some to be a physical control on seawater intrusion into the freshwater aquifers. However, TM#1 notes the presence of some sands within this unit that could be conduits for seawater intrusion. The properties of the artificial fill deposited over the Bay Mud are not noted in WRIME (2007), although it is likely that it contains a wide variety of grain sizes.

7.3.2. San Francisco Bay Head Monitoring

Head in the Bay side monitoring well network is available for the Shallow and Primary Production Aquifers (hydrographs for the wells discussed in this section are presented as Appendix B of TM#1). At the UAL site, one well (MW13D) is screened within the Shallow Aquifer (SFPUC, 2010). Head in this well hovered around +2.5 ft msl from late 2003 to early 2006, after which head dropped to around -0.5 ft msl through at least late 2009. At the SFO and Burlingame sites, the shallowest wells (SFO-S and Burlingame-S) are both screened within the Shallow Aquifer; these two wells show very similar head results (with fairly sparse data). Each well shows a seasonal variation, with high values (around +2.3 ft msl at SFO and +3.5 ft msl at Burlingame) in the winter and low values (around +1.9 ft msl at SFO and +1.8 ft msl at Burlingame) in the summer.

At the UAL site, one well (MW13C) is screened within the Primary Production Aquifer. This well shows head varying between -29 and -33 ft msl from 2004 to 2009. At the SFO and

Burlingame sites, the deepest wells (SFO-D and Burlingame-D) are both screened within the Primary Production Aquifer. These wells show a similar seasonal fluctuation to the co-located wells screened within the Shallow Aquifer. SFO-D head varies from about -30 ft msl in the summer to about -29 ft msl in the winter. Burlingame-D head varies from about -5 ft msl in the summer to about -4 ft msl in the winter.

7.3.3. San Francisco Bay Chemical Monitoring

The wells in the Bay side monitoring network are sampled for general minerals, nitrate, bromide, boron, and orthophosphate (see Table 10.3-8 for average concentrations of selected constituents for each well). The Burlingame cluster contains three wells. Samples from the shallowest (Burlingame-S) well have chloride concentrations varying from 110 to 518 mg/L, with the highest values measured in February, 2009. The middle well (Burlingame-M) has shown concentrations ranging from 63 to 140 mg/L, while the deep well (Burlingame-D) has shown concentrations between 41 and 140 mg/L; these two wells have both shown a decreasing trend in chloride concentration over the sampling period. In the SFO cluster, the shallow well (SFO-S) has shown the most elevated values of chloride, between 8,400 and 12,400 mg/L, with increasing chloride over time. The deep well (SFO-D) has shown chloride values between 240 and 2,210 mg/L, with highly variable concentrations that don’t seem to have a specific trend. Chloride results from the UAL cluster indicate that concentrations in the deeper well (MW-13C) are slightly over 500 mg/L, while one sample in the shallower well (MW-13D) shows a chloride concentration of 13,000 mg/L (WRIME, 2007). Bay water near the site was reported to have a chloride concentration of 17,000 mg/L. The high chloride concentrations observed in the Bay side monitoring network wells may result from the mobilization of or mixing with connate water with high salt concentrations (see Section 7.3).

Bromide results are also available for the Burlingame and SFO clusters from two sampling events (WRIME, 2007). At Burlingame, bromide concentrations were 0.22 and 0.36 mg/L in Burlingame-D, 0.24 and 0.38 mg/L in Burlingame-M, and 0.26 and 0.66 mg/L in Burlingame-S. At SFO, bromide concentrations were 0.79 and 1.7 mg/L in SFO-D and 27 and 32 mg/L in SFO-S. Bay water near the site was reported to have a bromide concentration of 52 mg/L.

Chloride:bromide ratios represent a better method for detecting seawater intrusion than simple chloride concentrations. In the Burlingame well cluster, this ratio was 389 and 427 in Burlingame-D, 368 and 458 in Burlingame-M, and 333 and 423 in Burlingame-S. At the SFO cluster, the ratio was 259 and 342 in SFO-D and 291 and 311 in SFO-S (WRIME, 2007). The ratio in Bay water near the site was reported to be 327. Salinity in the southern Bay changes on a seasonal basis due to changes in the inflows, reaching a maximum in October and a minimum in February (Figure 10.3-22). Because this salinity change is the result of the mixing of two very different waters, the chloride:bromide ratio may be expected to change seasonally as well, so a single measurement should not be taken as the definitive representation of Bay water.

8. Seawater Intrusion Monitoring and Management

In addition to evaluating the conceptual model and the results of the analytical and MODFLOW models, other evaluations were conducted to add insight into potential seawater intrusion issues.

8.1. Drinking Water Standards

For the purpose of managing water resources to minimize the occurrence of seawater intrusion, a set of performance measures must be defined. Although this is a complex issue, it is helpful to put the problem in terms that are easily understood. CH2M HILL (1995) defined seawater intrusion as “significant migration (based upon an intermediate composition of fresh water and salt water) of salt water into the potable aquifer and/or extraction of salt water by production wells.” However, this definition is fairly subjective, and represents a definition of seawater intrusion that is reactionary, rather than preventative, in nature.

For effects on the freshwater aquifer, it is useful to define some level of chloride (and other constituents) that represents degradation of the groundwater resource. Although various levels can be defined, management agencies generally use pre-existing maximum contaminant level (MCL) values. The Environmental Protection Agency (EPA) publishes a secondary drinking water standard of 250 milligrams per liter (mg/L) for chloride (EPA, 2009); there is no primary MCL for chloride as high chloride levels are not dangerous to health, but rather cause aesthetic degradation (e.g., taste or odor). This level has been used as a threshold for defining seawater intrusion in other basins, including Soquel Creek in California (Hydrometrics, 2009) and those around the City of Honolulu in Hawaii (Todd, 2004). Performance measures could be defined for other constituents based on EPA MCL values, but chloride is the most commonly utilized one for seawater intrusion.

8.2. Summary of Seawater Intrusion Rate Studies

The rate at which the seawater-freshwater interface enters the aquifer depends on a number of parameters, and is difficult to determine except by direct measurement or numerical simulation. This section summarizes the results of previous studies in other parts of the world, where geophysical, chemical, or modeling techniques were used to estimate a rate of seawater intrusion.

Izbicki (1996) summarized the occurrence of seawater intrusion into the Oxnard and Mugu aquifers of southern California. Seawater intrusion into these aquifers occurred as the result of extended groundwater overdraft in the coastal zone, with head levels dropping to below sea level in large parts of the aquifer system. Seawater began intruding into the coastal freshwater aquifers as early as the mid-1950’s. Using a time-series of chloride measurements, Izbicki (1996) was able to estimate the total extent of seawater intrusion from 1955 to 1992 as being 2.7 miles in the Oxnard aquifer and 1.9 miles in the Mugu aquifer, implying rates of 375 and 264 feet per year (ft/yr), respectively.

Yakirevich et al. (1998) used the SUTRA computer model code to predict the rate of seawater intrusion in the coastal aquifer along the Gaza Strip. Seawater intrusion is currently occurring in this aquifer, where groundwater is heavily over-used. Yakirevich et al. (1998) predicted that seawater intrusion over the ten-year period from 1997 to 2006 would occur at a rate of 66 to 148 ft/yr.

Kennedy/Jenks (2004) studied the intrusion of seawater into the Salinas Valley groundwater basin by constructing a three-dimensional hydrogeologic conceptual model to assess the susceptibility of the different aquifers to seawater intrusion. An analysis of the movement of chloride fronts was based on a time-series of chloride concentration from a system of monitoring wells. It was concluded that the rate of intrusion into the coastal aquifer varied between 202 and 673 ft/yr, depending on location in the aquifer.

8.3. Typical Monitoring Procedures

To monitor whether seawater intrusion is occurring, an extensive monitoring system is typically employed. A network of groundwater monitoring wells is typically employed that monitors groundwater head and water quality at different depth intervals within the aquifer (or aquifers). Monitoring different depth ranges is necessary because, since seawater intrusion occurs as a wedge, the presence of vertical variations in water quality is important to understanding the extent of intrusion. Also, aquifer heterogeneity may cause seawater intrusion to find preferential pathways through the aquifer that a single well screen might miss.

The primary parameter that is monitored is groundwater head, as this represents the driving mechanism for seawater intrusion. Based on the Ghyben-Herzberg ratio, seawater is kept out of the freshwater aquifer if the groundwater elevation above sea level is at least about 1/38th of the thickness of the aquifer. For example, if the aquifer is 380 feet thick, a freshwater head of 10 feet is required to keep the aquifer at that location free of seawater at the bottom of that aquifer. Therefore, at each location an aquifer thickness must be defined, and then divided by 38 to determine the threshold above which freshwater head should be maintained.

Water quality parameters are also monitored, primarily chloride (Cl) and total dissolved solid (TDS) concentrations. Because of the contrast in marine and typical continental anion matrices, the clearest indication of possible seawater intrusion is an increase in Cl concentration as a proxy for salinity (although other processes may lead to a similar phenomenon; see below). In those coastal aquifers where continuous over-exploitation causes a reduction of groundwater head levels, intrusion of seawater would result in an increase in salinity. Thus, a time-series of chloride concentrations can help provide early indications of seawater intrusion.

In addition to the lateral infiltration of seawater through aquifers that communicate directly with the ocean, there are several possible sources of increased salinity of freshwater aquifers (DWR, 1958). The best way to differentiate intruding seawater from degradation through some other cause is to employ an extensive monitoring network to track the spatial and temporal variability in groundwater chemistry. If saline water can be observed progressing steadily inland and upward in the formerly freshwater aquifer, causes other than seawater intrusion can be discounted. In situations where salinity increases are observed in a monitoring network, more intensive monitoring may be initiated, using other ionic constituent concentrations or stable isotope values to identify seawater intrusion and differentiate it from other potential sources of increased salinity. These approaches exploit the differences in geochemistry and transport processes between seawater intrusion and other sources of salinity. In summary, these include (modified from Jones et al., 1999):

- **Chloride-bromide (Cl/Br) ratios:** These ratios can be used as a reliable tracer as both constituents usually behave conservatively (i.e., they are not particularly subject to retardation through reaction or sorption, and therefore are transported almost entirely by advection alone). Seawater is distinguished from anthropogenic sources like sewage effluents (which have higher Cl/Br ratios) or agriculture-return flows (which have lower Cl/Br ratios). This and the other geochemical methods listed here rely on the fact that seawater chemistry is quite uniform in time and space.
- **Sodium-chloride (Na/Cl) ratios:** Na/Cl ratios of intruding seawater are usually lower than the values in ocean water due to the fact that sodium interacts with aquifer sediments more strongly than does chloride. The low Na/Cl ratio of seawater intrusion is distinguishable from the higher Na/Cl ratios typical of anthropogenic sources like domestic wastewaters.
- **Calcium-anion (Ca/X) ratios:** One of the most conspicuous features of seawater intrusion is the enrichment of Ca over its concentration in seawater. High Calcium-Magnesium (Ca/Mg) and Calcium-Bicarbonate-Sulfate ($Ca/(HCO_3 + SO_4)$) ratios are further indicators of seawater intrusion.
- **Oxygen and hydrogen stable isotopes:** Linear correlations are expected from mixing of seawater with ^{18}O-depleted groundwater when comparing $\delta^{18}O$[5] to $\delta^{2}H$ or Cl because all three behave conservatively (so a straightforward mixture of seawater and freshwater would fall along a line between the seawater and freshwater end-members). Salinity introduced to an aquifer by sources enriched by evaporative processes (e.g., agriculture-return flows) would result in mixing lines with different slopes from the seawater-freshwater mixing line, which could generally be expected to follow a meteoric water line.
- **Boron isotopes:** The boron isotopic composition of groundwater can be useful in distinguishing seawater intrusion from anthropogenic salinity sources such as domestic wastewater or non-seawater salinity sources such as hydrothermal fluids (Vengosh and Spivack, 1999). The $\delta^{11}B$ value of seawater is about 39‰, distinctly different from the more depleted values in sewage effluents (0-10‰) and non-marine hydrothermal fluids (-10-5‰). Because of the significant differences between seawater and other potential

[5] Stable isotope measurements are expressed in delta (δ) notation, calculated as the difference between the abundance of a specific isotope to that in a reference standard divided by the abundance in the reference standard. This is a much more accurate measure than the actual abundance. See Clark and Fritz, 1997.

salinity sources, boron isotopes may be one of the most useful constituents to include in a monitoring program.

- **Residence time tracers:** The above constituents are measured to monitor for the intrusion of saline water, and to differentiate intruding seawater from domestic effluents and evaporatively enriched groundwater. Radioactive and other residence time tracers can be used to differentiate between recently-intruded seawater and connate water (seawater trapped in a formation when the sediments are deposited) that may have been present in the sediments for thousands of years. The specific tracer chosen would depend on the expected residence time of the connate water.

8.4. Potential Control Measures for Seawater Intrusion

Various control methods can be utilized to prevent, slow, or reverse seawater intrusion into coastal aquifers. These methods have been developed in areas that have experienced significant intrusion. Control measures have been summarized elsewhere (e.g., DWR, 1975; van Dam, 1999), and will only be briefly discussed here. Two categories of control methods exist, corresponding to two types of controls on seawater intrusion discussed in Section 2.3: physical and hydrological methods.

Physical controls entail the installation of actual physical barriers in the subsurface to block the flow of ocean water. These barriers are only useful when intrusion occurs on a fairly small scale, where the area of intrusion is limited. Barriers can be constructed of grout, slurry, or some kind of membrane, anything that is low enough in permeability to effectively exclude seawater. In thick or complex aquifer systems, physical barriers would have to be very long and extend very deep into the aquifer to prevent seawater intrusion, making them impractical.

Hydrologic controls are more widely employed, and are better suited to large aquifers. As discussed in Section 2.3, the two important factors for preventing seawater intrusion are freshwater flux into the ocean and the freshwater head just landward of the coast. Hydrologic methods of control consist of enhancing one or both of these. The simplest method is conservation, where extraction of groundwater is reduced. This can be considered a “natural” approach to control, as it seeks to prevent intrusion by returning the hydrologic system closer to its “natural” (or pre-development) state. However, this method may not be practical in systems where the groundwater extraction is necessary. Similarly, active management of groundwater extraction, where pumping is shifted around in the basin so that individual locations are not pumped too heavily, is used to allow the aquifer to recover when not pumped; this requires the installation of extra wells, and could greatly increase the cost required to build a groundwater extraction network.

Seawater intrusion can also be controlled hydrologically through artificial means. Attempts to limit or prevent seawater intrusion through engineering often focus on creating a head barrier near the shoreline through injection of freshwater. Commonly, this involves the injection of freshwater into the aquifer landward of the intrusion wedge, and seaward of production wells.

The injected freshwater can be locally-sourced groundwater, imported surface water, or reclaimed wastewater. The goal of this method is to build up a mound of freshwater with sufficient head to prevent seawater from intruding into the base of the aquifer.

A similar effect can be achieved by pumping groundwater on the seaward side of the seawater intrusion wedge, although this is necessarily temporary (since the goal is to get the wedge to move toward, and eventually past, these extraction wells), and the produced water must be disposed of somehow; as the wedge is moved back toward the pumping wells, much of the extracted water would be made up of useful freshwater that is mixed with the saline water, and this freshwater may have to be wasted by simply discharging it to an appropriate location.

The control method (or methods) used depends on the exact conditions under which seawater intrusion occurs. This would require an analysis to be made before seawater intrudes into the freshwater aquifer, through the investigation of various mitigation alternatives.

9. Summary

This section summarizes the results of the conceptual model, empirical data, numerical modeling, and analytical approaches with respect to seawater intrusion.

9.1. Assessment of Susceptible Areas

The two areas of the Westside Basin that were determined to be susceptible to seawater intrusion are (1) the Pacific Coast from the south side of Lincoln Park to Lake Merced, and (2) the San Francisco Bay Coast from the Visitacion Valley Basin to the San Mateo Plain Basin (Figure 10.3-1).

Along the Pacific Coast, sediments are more permeable, and reductions in head along the Coast could move the seawater wedge inland. There is no physical barrier to seawater intrusion into the Shallow Aquifer because the sediments here are fairly coarse-grained and in direct communication with the Ocean offshore. The offshore San Andreas Fault may represent a physical control on seawater intrusion into the Primary Production and Deep Aquifers, although discontinuities in the -100-foot clay may serve as locations where seawater could intrude into the Primary Production Aquifer from the Shallow Aquifer above.

In general, the San Francisco Bay Coast is not particularly susceptible to seawater intrusion due to the presence of the Bay Mud and a subsurface bedrock ridge that provides some protection to the southern portion of the South Westside Basin from potential seawater intrusion from San Francisco Bay. Chloride levels in the Shallow Aquifer at the SFO cluster are very high, near those of Bay water. However, this could be due to the presence of connate water in the Bay Mud itself, which may be easier to mobilize locally than it would be for seawater to intrude from the Bay to the freshwater aquifer through the Bay Mud. It should be noted that the chloride concentrations in the Primary Production Aquifer, where head levels are well below sea level and seawater intrusion would occur more quickly, are much lower than in the Shallow Aquifer.

Non-susceptible parts of the basin are areas where some sort of physical control precludes the current and future intrusion of seawater into the Basin. The inland parts of the basin, separated from the coast by the mountain ranges located on the northeastern and southwestern boundaries of the basin, are not susceptible to seawater intrusion. Parts of the North Westside Basin where the bedrock surface is above sea level are also not susceptible. The southern part of the Basin’s Pacific Coast, where the Serra Fault represents a barrier between the Ocean and inland areas, seems to not be susceptible to seawater intrusion.

9.2. GSR-Only Scenario

The GSR Project is a conjunctive use project that would allow for increased groundwater supplies in the Westside Basin during periods of drought and emergencies (MWH, 2008). The conjunctive use project is based on the concept of providing available surplus surface water from the SFPUC Regional Water System to the Partner Agencies (PAs). This water would be used by the PAs instead (or “in-lieu”) of pumping groundwater from the Westside Basin.

The project is planned to provide up to 60,500 af of in-lieu recharge. During the take cycle, both SFPUC and the PAs would be pumping groundwater; however, SFPUC would not take more than the amount of in-lieu recharge available in the SFPUC Storage Account.

Pumping in the South Westside Basin for the GSR-only Scenario (2) would have a minimal effect on head in the North Westside Basin. South of Lake Merced the Serra Fault likely presents a physical barrier to seawater intrusion. The operation of the GSR Project would not change the potential for seawater intrusion relative to Scenario 1 because groundwater head at wells in the North Westside Basin along the Pacific Coast would not substantially change.

Along the San Francisco Bay Coast, the changes to groundwater pumping do not show a substantial effect on seawater intrusion compared to what may occur under Scenario 1 conditions. The freshwater flux out of the aquifer into the San Francisco Bay is quite low under existing conditions, and is not modified to any great degree by the pumping configurations simulated in the MODFLOW model.

Based on this analysis, the likelihood of seawater intrusion resulting from the GSR Project would be considered low along either the Pacific Coast or the San Francisco Bay Coast.

9.3. SFGW-Only Scenarios

The SFGW Project would construct up to four wells (along with conversion of two irrigation wells) and associated facilities in the western part of San Francisco and extract an annual average of up to 4 mgd of water from the North Westside Basin (SFPUC, 2009a). The SFGW wells would pump at this rate on a near-continuous basis over periods of many years.

Two model scenarios incorporate the pumping of the SFGW Project (3a and 3b). The results of these scenarios indicate that there is the potential for the landward migration of the seawater-freshwater interface along the Pacific Coast as a result of increased groundwater pumping from the SFGW Project. Many of the heads, especially in the southern half of the North Westside Basin, are projected by the numerical model to be below sea level for some to most of the simulation period; even in the northern half of the North Westside Basin, head would drop everywhere near and along the Pacific coast, possibly low enough to induce seawater intrusion.

It is important to note that the groundwater head in the Deep Aquifer at the Zoo monitoring well cluster has been almost uniformly below sea level since monitoring began in 2003. Despite this, and despite the fact that the cluster is only about 300 feet from the Ocean, the chloride concentration has remained steady between 50 and 60 mg/L over the same time period, indicating that this location has not yet been affected by seawater intrusion. This indicates one or more of the following: 1) that conditions ideal for seawater intrusion (i.e., groundwater head below sea level) must be present for some time (in this case more than at least 9 years) before the intrusion actually occurs; 2) the assumption of a coastal location for the discharge point is not applicable for these aquifers (i.e., the discharge point is further offshore); and 3) the Deep Aquifer is separated from the Ocean by a physical barrier, such as the W-clay. Without more knowledge of offshore geologic structures and their ability to act as physical controls, and the locations where freshwater discharges from the different aquifers, the exact reason that seawater has not shown itself to be intruding into the freshwater aquifer is unknown.

Similarly, measured head elevations in wells along the west end of Golden Gate Park have repeatedly dipped below the single-aquifer and Shallow Aquifer exclusion heads in the recent past (TM#1), and this area has been subject to relatively continuous groundwater pumping for irrigation since the 1920's. Despite this, there has been no appreciable increase in chloride concentrations in the production wells at the North Windmill and South Windmill locations over many years of monitoring. Unlike the Deep Aquifer at the Zoo monitoring well cluster (see above), the aquifers along the west end of Golden Gate Park seem to be in fairly direct contact with seawater (see Figure 10.3-2), so there does not seem to be a specific physical control that would prevent seawater intrusion. The fact that seawater intrusion does not seem to have had an effect on chloride concentrations in this area may indicate that the seasonal rebound in head that occurs in the winter (when head in the Shallow Aquifer is above the single-aquifer and Shallow Aquifer exclusion heads) effectively compensates for seasonal excursions below the exclusion heads, or that the small fine-grained layers present in the area break the sediments into multiple thin aquifers, which are theoretically less susceptible to seawater intrusion than would be a single thick aquifer.

Along the San Francisco Bay coast, the freshwater aquifer would not be vulnerable to seawater intrusion due to the operation of the SFGW Project primarily because of the distance from the SFGW groundwater pumping to the San Francisco Bay. The freshwater flux out of the aquifer into the San Francisco Bay is quite low, and would not be modified to any great degree by the pumping configurations for the SFGW Project. Therefore, the model results indicate that there is not a substantial change in the potential for seawater intrusion along the San Francisco Bay as a result of the SFGW Project.

9.4. Cumulative Scenario

The cumulative scenario (4) assumes the operations of the GSR and SFGW Projects at the same time. The cumulative scenarios also include other reasonably foreseeable future projects, such as the Daly City Vista Grande Drainage Basin Improvements Project and Holy Cross cemetery future build-out.

The Daly City Vista Grande Drainage Basin Improvements Project involves diverting stormwater from the Vista Grande Canal into Lake Merced with baseflow to Lake Merced being maintained via a wetland. The addition of water to Lake Merced to maintain lake levels would have the net effect of recharging the groundwater system locally.

Because the GSR Project pumping is concentrated in the South Westside Basin, the results of cumulative Scenario 4 are very similar to those of Scenario 3b.

Similar to both the GSR and SFGW Projects, the changes to groundwater pumping under the Cumulative Scenario do not show a substantial effect on seawater intrusion along the San Francisco Bay Coast compared to what may occur under Scenario 1 conditions. The freshwater flux out of the aquifer into the San Francisco Bay is quite low, and is not modified to any great degree by the pumping configurations simulated in the MODFLOW model.

These results indicate that there is the potential for the landward migration of the seawater-freshwater interface along the Pacific Coast as a result of increased groundwater pumping from the SFGW Project under the cumulative scenario. In addition,, the results of the Cumulative Scenario generally do not indicate an increased risk of seawater intrusion along the San Francisco Bay Coast.

9.5. Analytical Evaluation Along the Pacific Coast

The exclusion head analysis was performed to evaluate the potential for the landward migration of the seawater-freshwater interface under the Westside Basin Groundwater-Flow Model Results for Scenarios 3a, 3b, and 4. The results suggest that the lowering of groundwater head along the coast would increase the potential for the landward migration of the seawater-freshwater interface along several portions of the Pacific Coast. However, the rate analysis suggests that any seawater intrusion would occur at rates on the order of feet per year. It should be noted that the analytical method employed assumes a horizontal aquifer base, and that the actual intrusion into the sloped aquifers of the North Westside Basin would be slightly smaller than shown by the method.

The potential rate of seawater intrusion was estimated for the North Westside Basin using analytical equations. These results indicate that the rate of possible seawater intrusion would be on the order of 4 feet after 1 year, about 20 feet after 10 years, and about 60 feet after 50 years under implementation of the SFGW Project, a very slow rate of intrusion. Therefore, careful groundwater monitoring would be able to indicate the potential for seawater intrusion to occur with sufficient time to take proper actions to correct the situation.

Therefore, seawater intrusion along the Pacific Coast would occur slowly and would be recognizable in the Coastal Groundwater Monitoring Network before it could affect the beneficial use of pumping wells in the North Westside Basin. Historical data have shown that chloride levels along the Pacific Coast have remained low, even when there have been periods of relatively substantial groundwater pumping in the North Westside Basin in the past (5.5 mgd from 1930 to 1935; note that this rate is higher than the 3.0 to 4.0 mgd of municipal pumping proposed for the SFGW Project). This confirms that, although the potential for seawater intrusion exists, there may be other geologic factors that are limiting both the occurrence and rate of seawater intrusion along the Pacific Coast.

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Yates, E.B., S.N. Hamlin, and L.H. McCann, 1990, Geohydrology, water quality, and water budgets of Golden Gate Park and the Lake Merced area in the western part of San Francisco, California, *U.S. Geological Survey Water-Resources Investigations Report 90-4080*, U.S. Geological Survey, Sacramento, CA, 50p.

Figure List

Table List

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Figures

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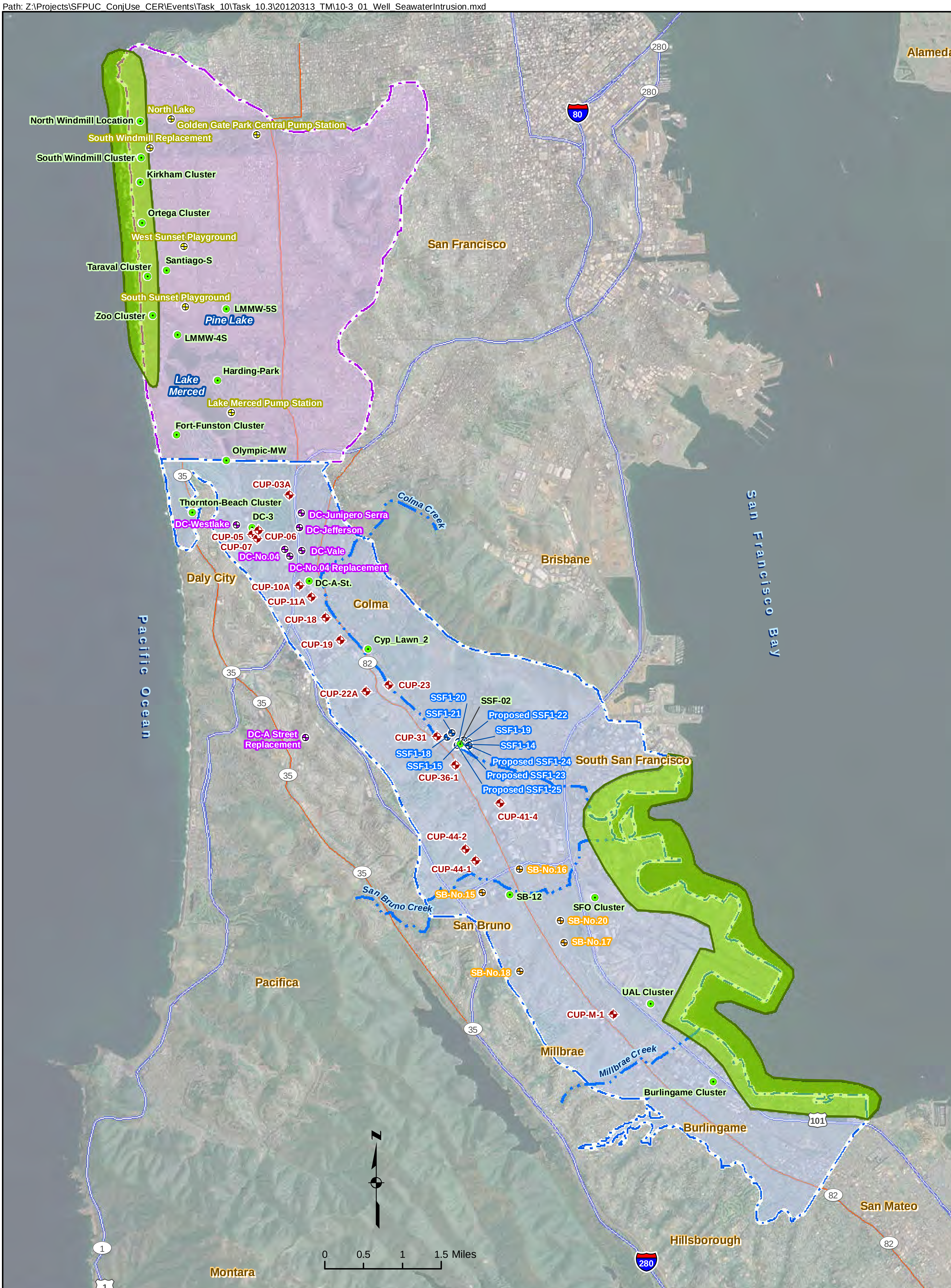

Aerial Photo Source: World Imagery from ESRI. Copyright:© 2009 ESRI, AND, TANA, UNEP-WCMC

Note:
The North Windmill Location is a location used by the Westside Basin Groundwater-Flow Model to track the model-simulated groundwater head. It represents a historical well location, but is not the current location of an active monitoring well.

Legend

- GSR Proposed Municipal Wells
- SFGW Proposed Municipal Wells
- Selected Representative Monitoring Location
- Cal Water Municipal Wells
- Daly City Municipal Wells
- San Bruno Municipal Wells
- North Westside Groundwater Basin
- South Westside Groundwater Basin
- Approximate Areas Susceptible to Seawater Intrusion

CITY AND COUNTY OF SAN FRANCISCO
PUBLIC UTILITIES COMMISSION
ENGINEERING MANAGEMENT BUREAU

WELL LOCATIONS AND AREAS POTENTIALLY SUSCEPTIBLE TO SEAWATER INTRUSION

Kennedy/Jenks Consultants
303 Second Street, Suite 300 South
San Francisco, CA 94107

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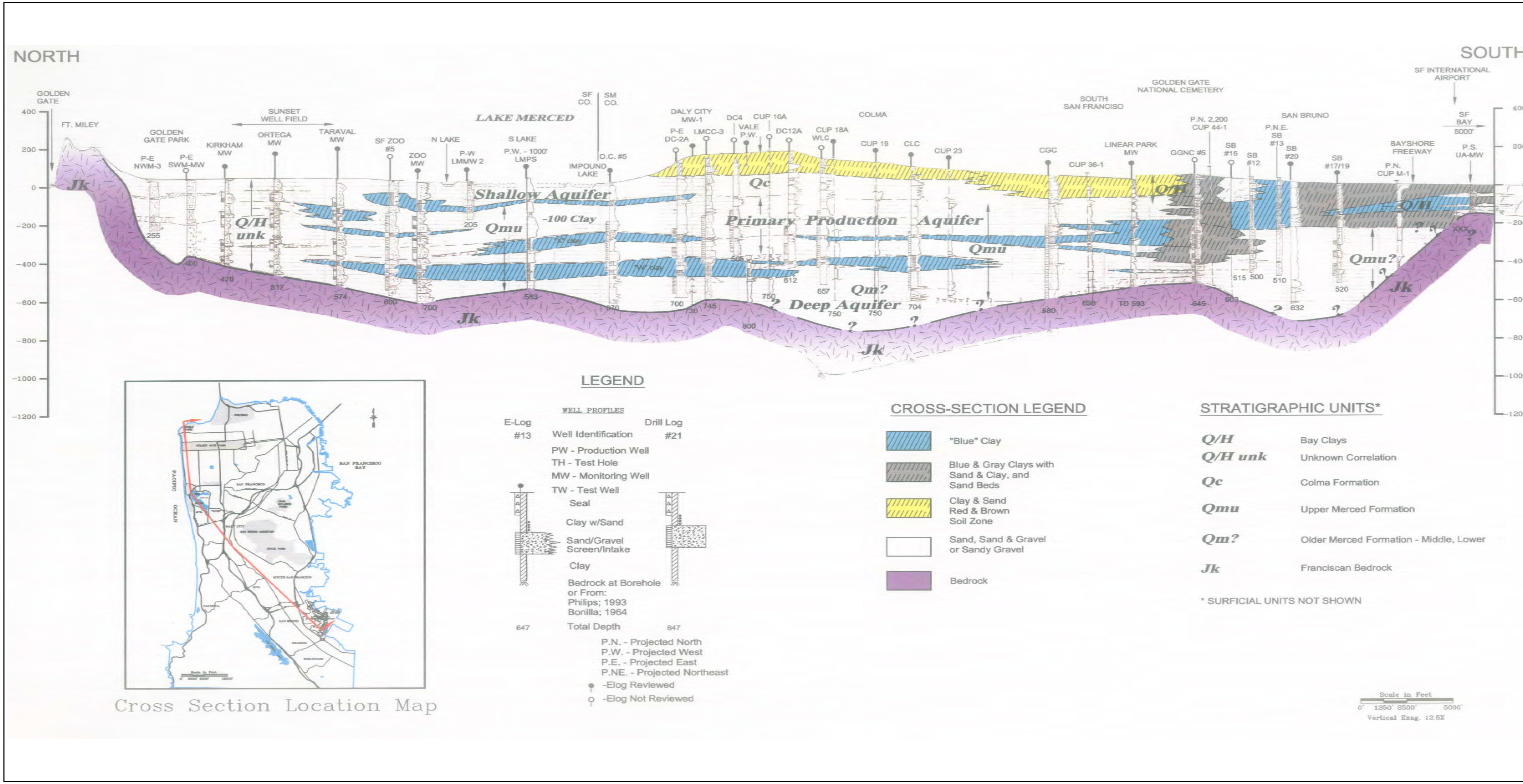
Figure **10.3-1**

Date April 2012



Source: Final Task 8B Technical Memorandum No.1, Hydrologic Setting of the Westside Basin, LSCE, May 2010.

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Westside Basin Regional Subsurface Hydrogeology

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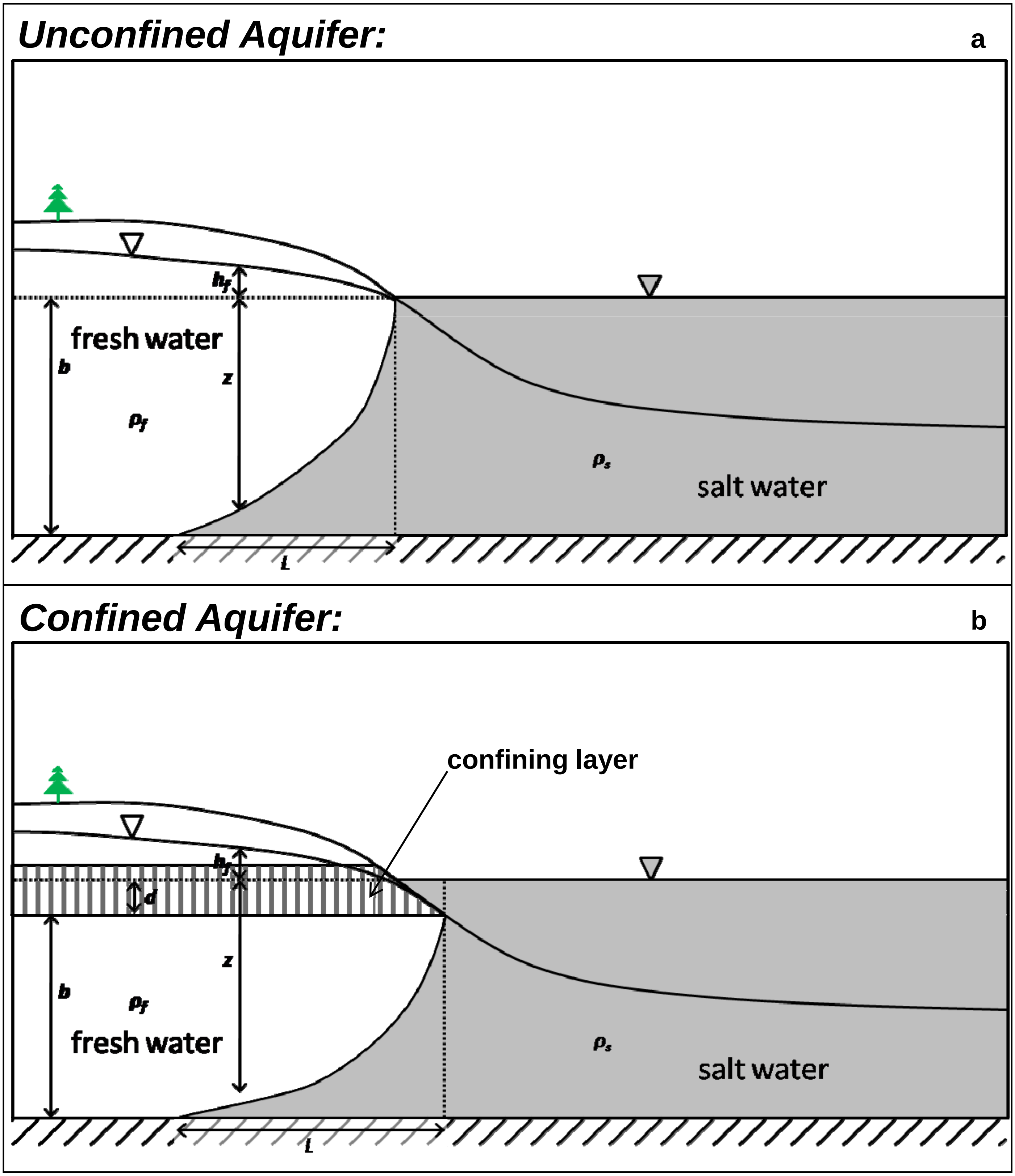
Figure 10.3-2



Explanation of Variables:

- ρ_f = density of freshwater (mass/volume)
- ρ_s = density of seawater (mass/volume)
- z = depth of freshwater-seawater interface below sea level (length)
- h_f = freshwater head above sea level (length)
- b = depth below sea level to aquifer base (length); unconfined conditions
- b = aquifer thickness (length); confined conditions
- d = depth below sea level of base of confining layer (length)
- L = length of intruding wedge (length)

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Seawater Intrusion Schematics for Unconfined and Confined Aquifers

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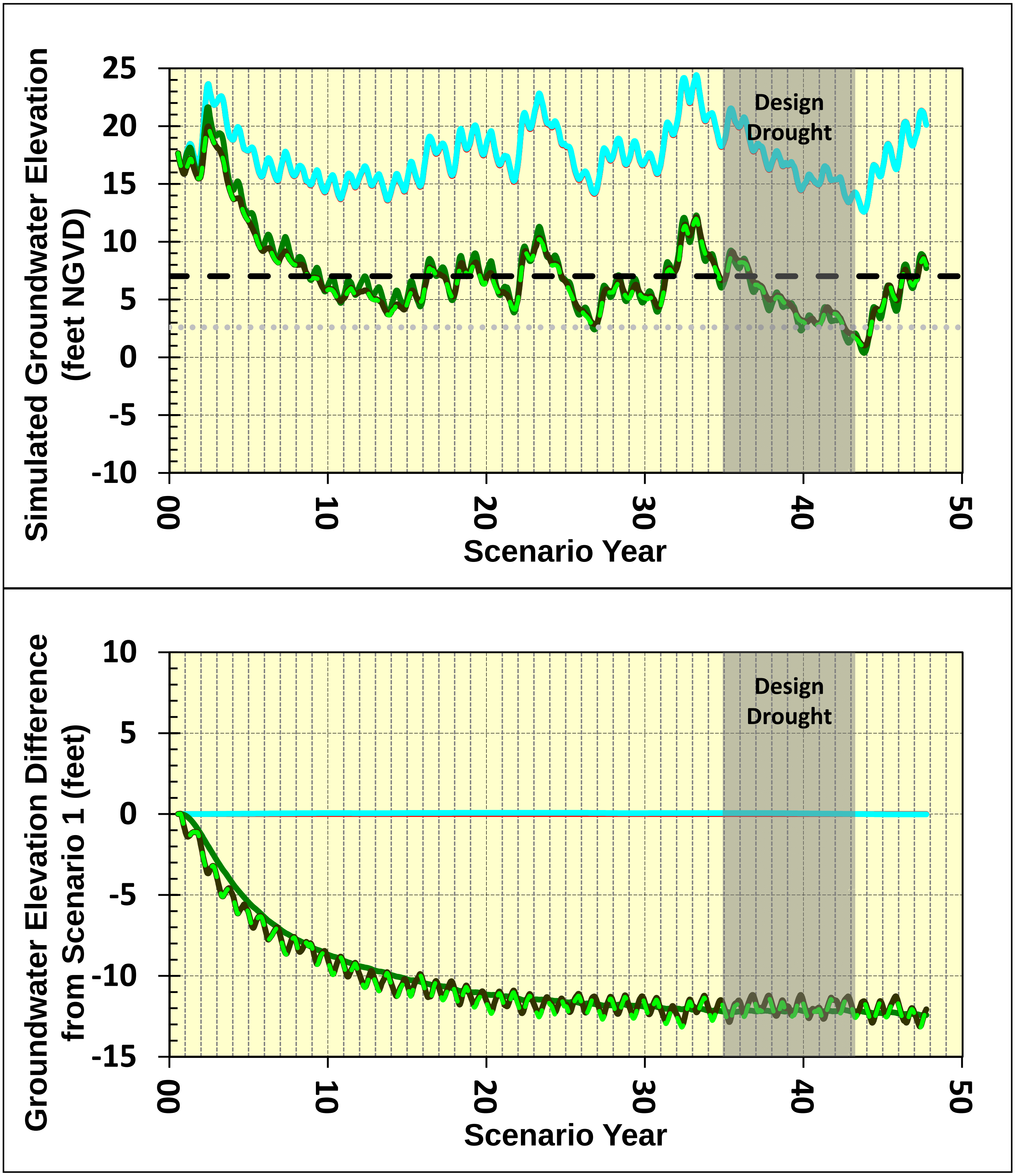
Figure 10.3-3



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

- **Scenario 1**
- **Scenario 2**
- **Scenario 3a**
- **Scenario 3b**
- **Scenario 4**

Exclusion Heads:

- **Single-Aquifer**
- **Shallow Aquifer**

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Model Layer 1 Hydrographs for North Windmill Location

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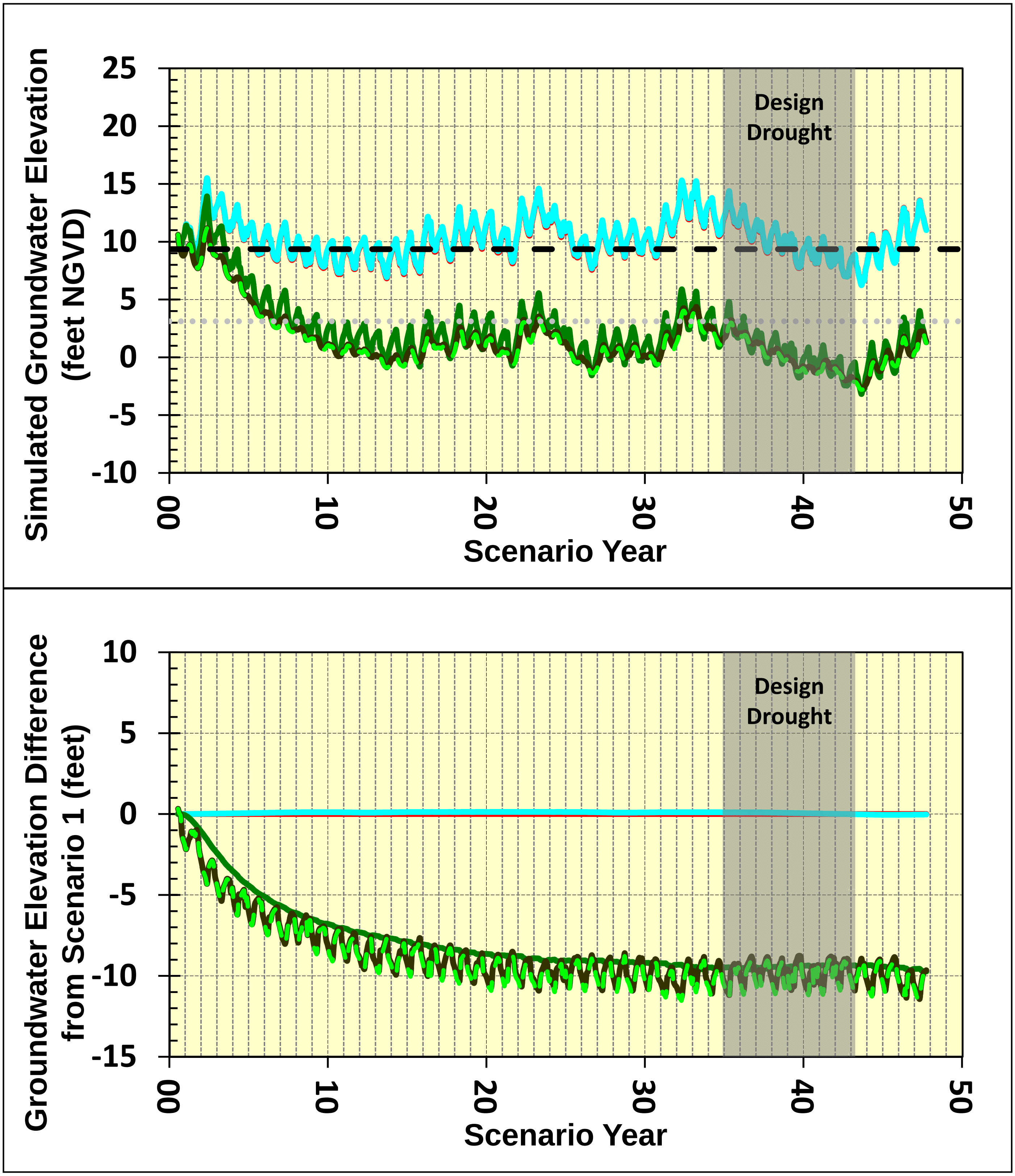
Figure 10.3-4



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4

Exclusion Heads:

Single-Aquifer
Shallow Aquifer

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Model Layer 1 Hydrographs for South Windmill Cluster

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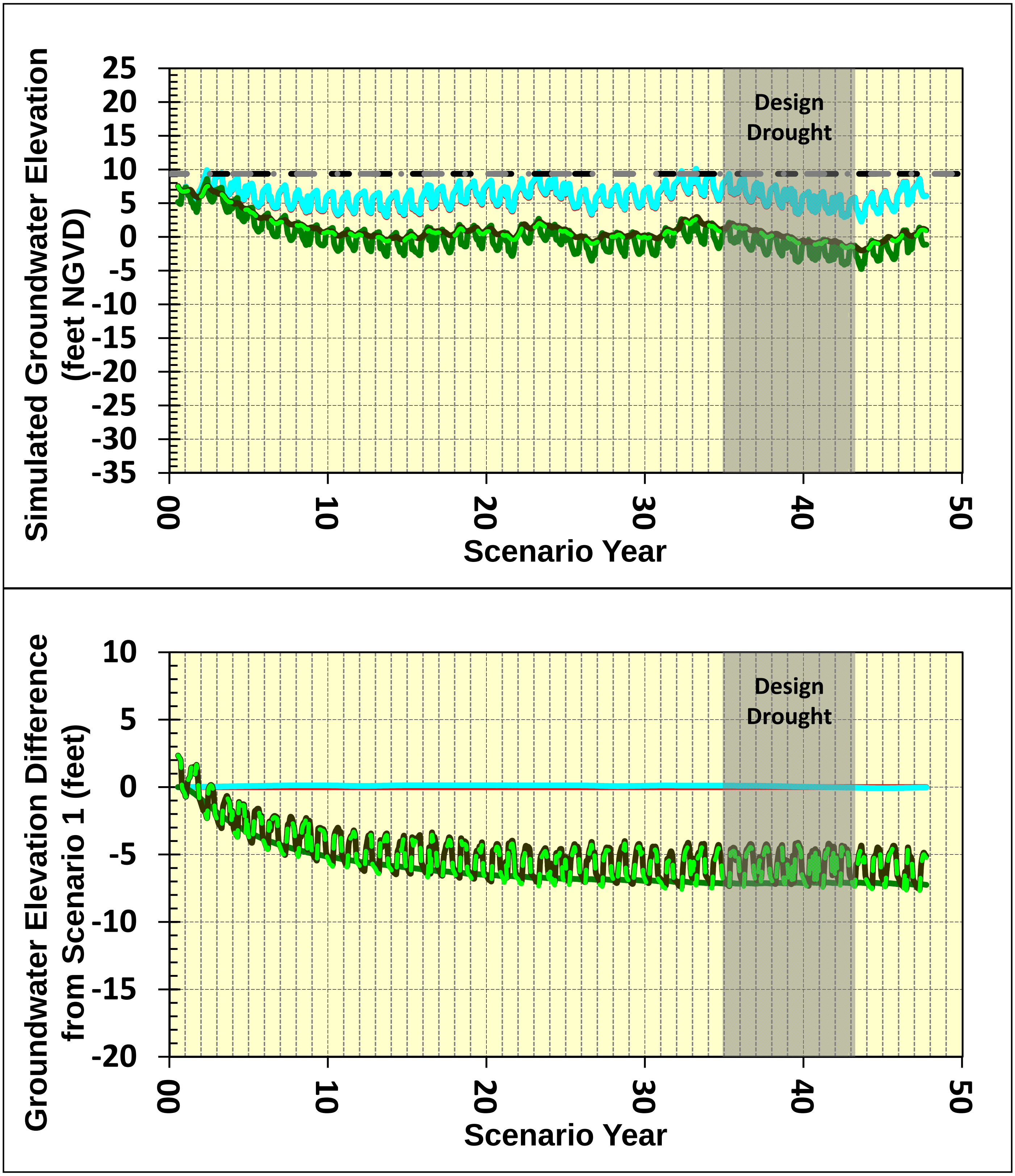
Figure 10.3-5a



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4

Exclusion Heads:

Single-Aquifer
Primary Production Aquifer

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Model Layer 4 Hydrographs for South Windmill Cluster

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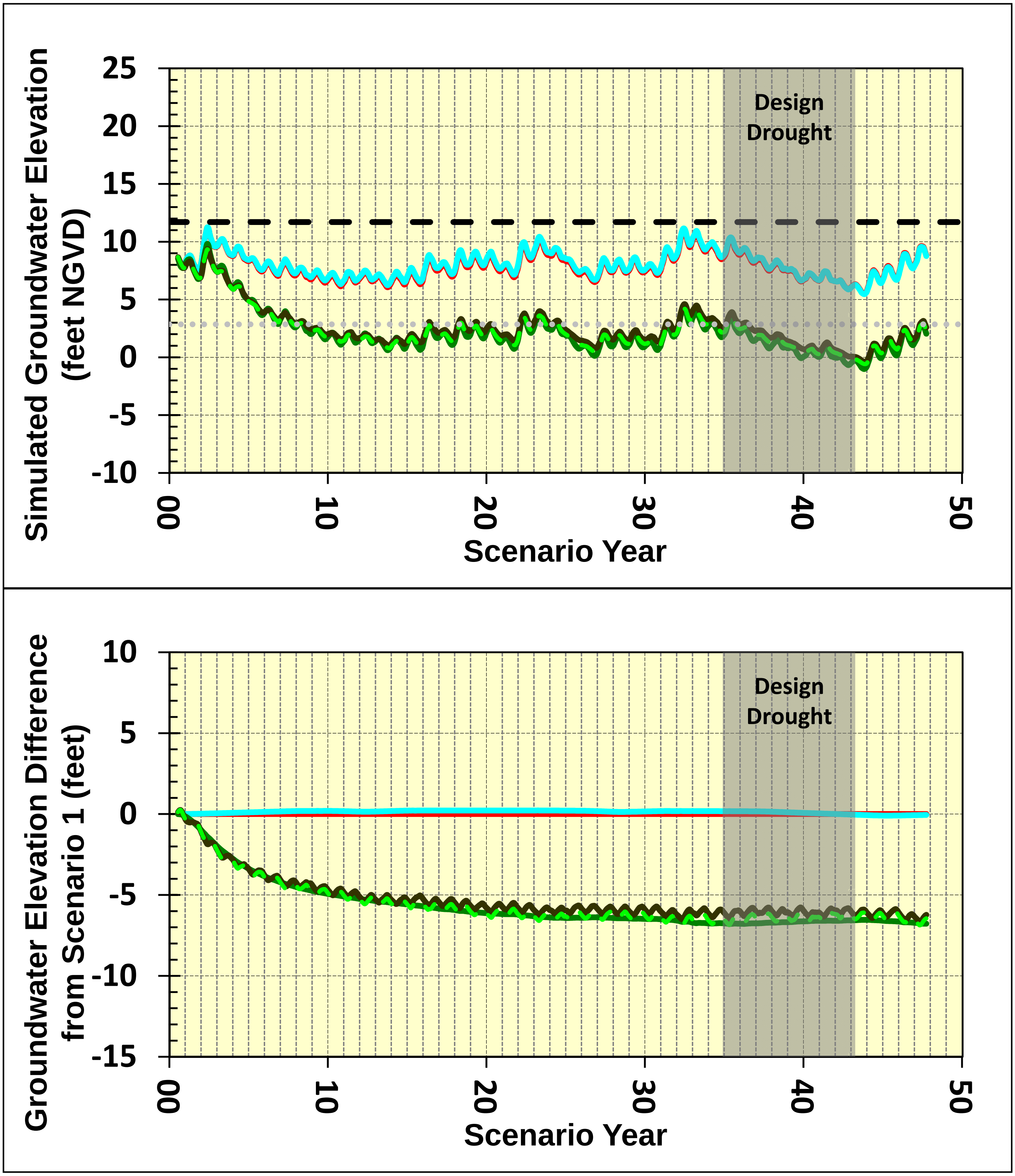
Figure 10.3-5b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:

- Single-Aquifer
- Shallow Aquifer

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Model Layer 1 Hydrographs for Kirkham Cluster

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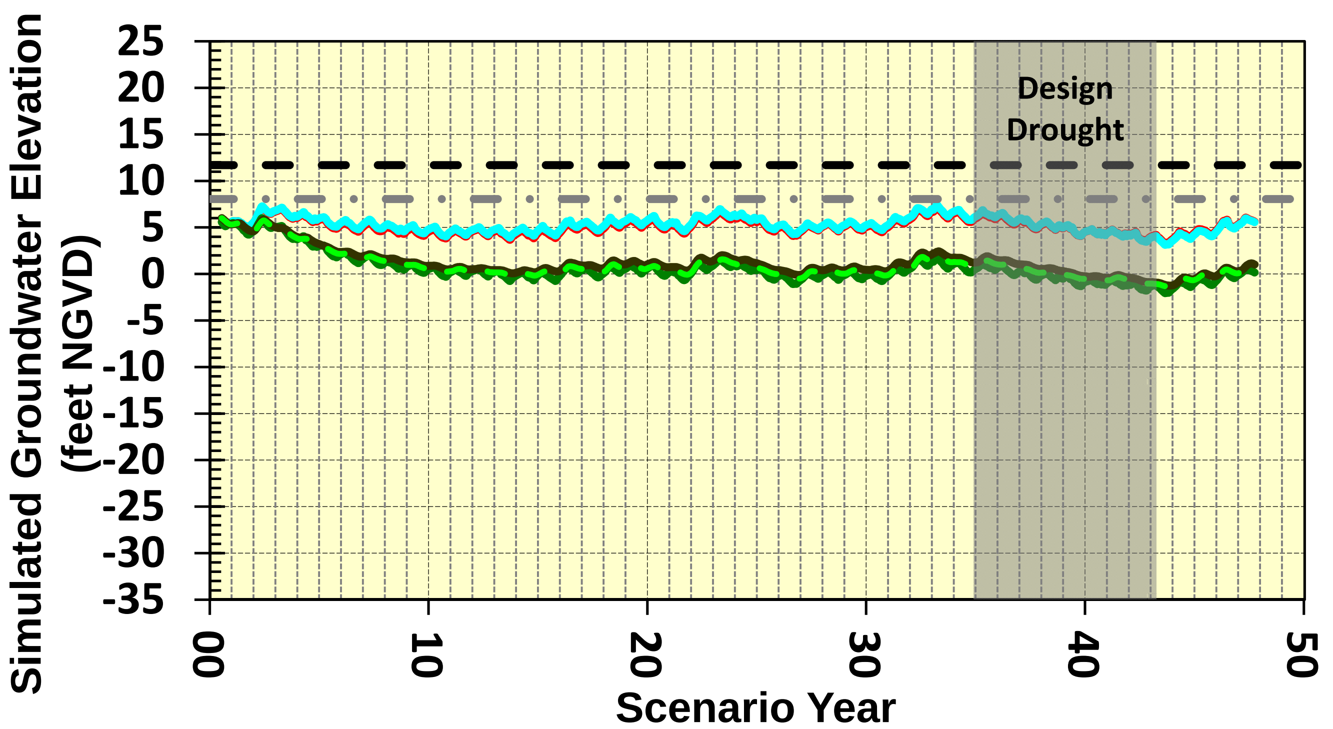
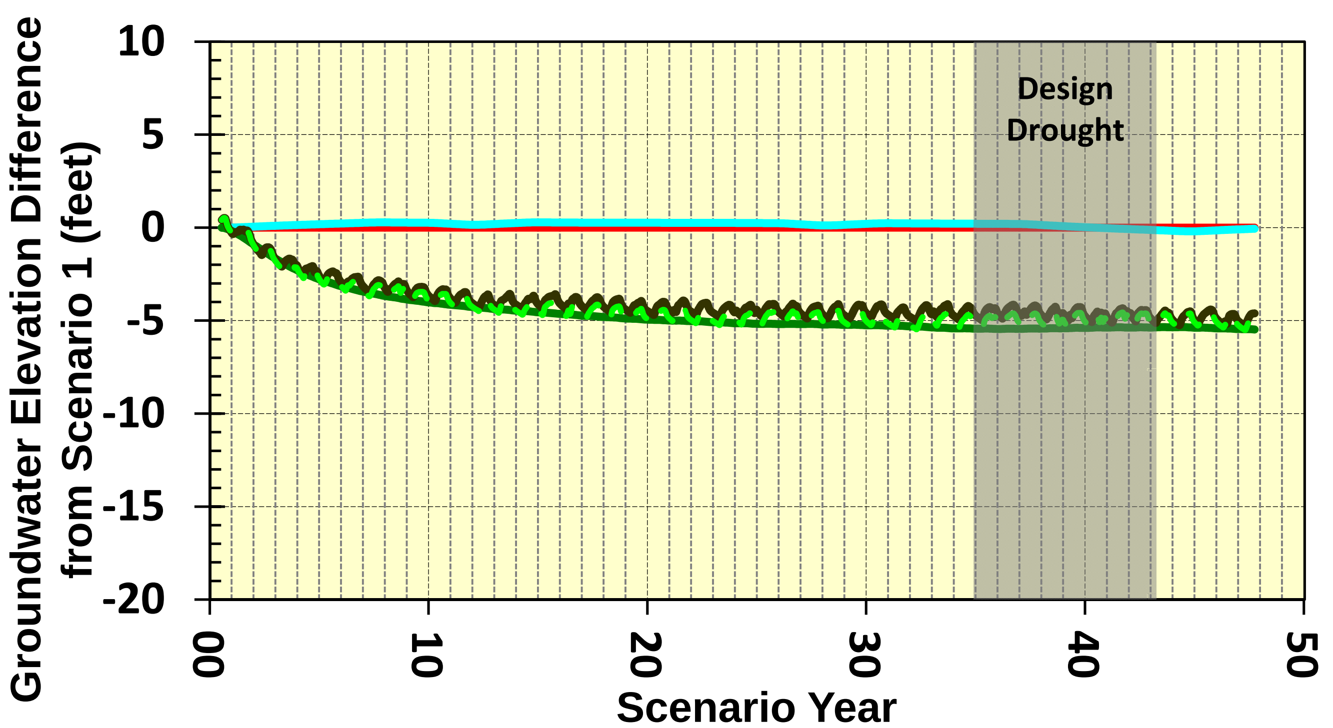
Figure 10.3-6a





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1 | Scenario 2
Scenario 3a | Scenario 3b
Scenario 4

Exclusion Heads:

Single-Aquifer | Primary Production Aquifer

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Model Layer 4 Hydrographs for Kirkham Cluster

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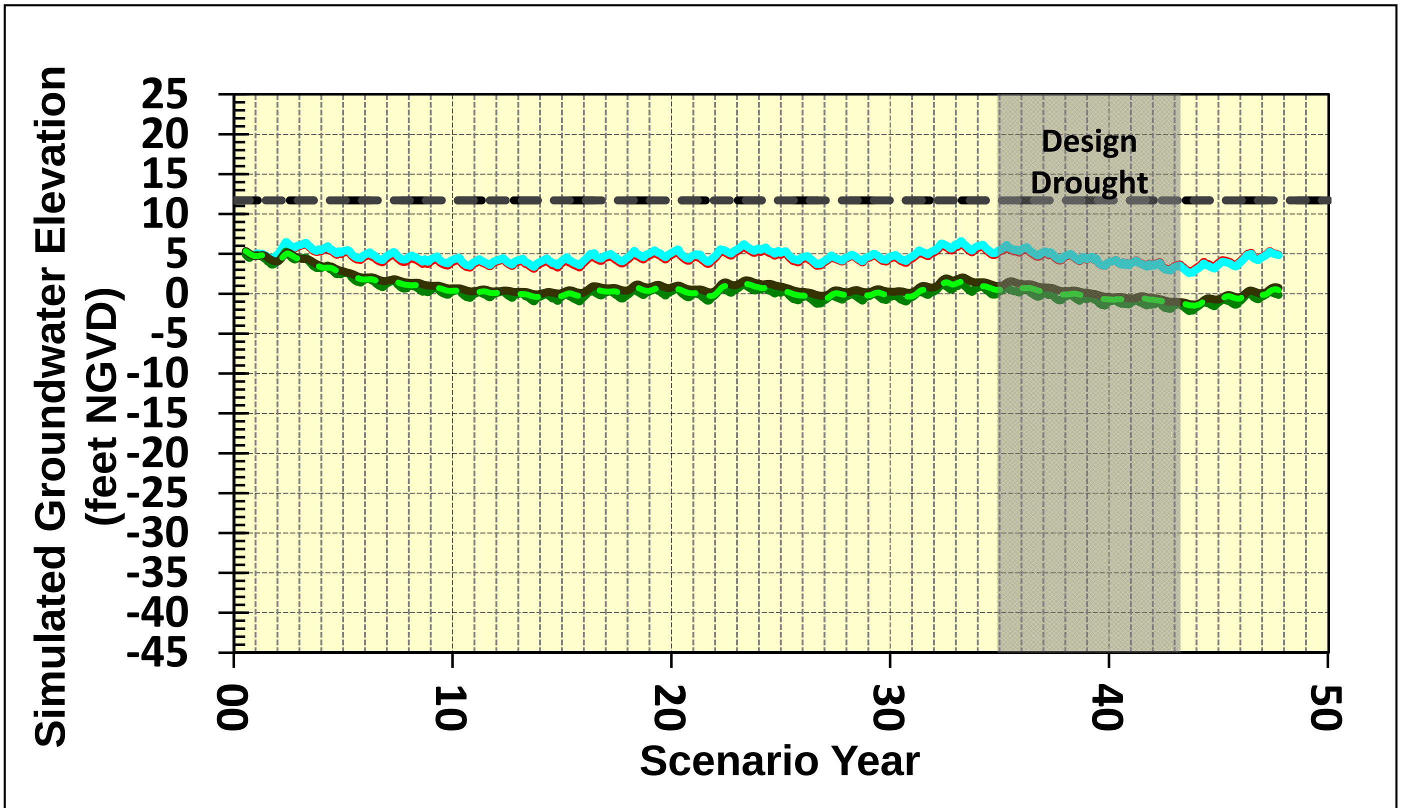
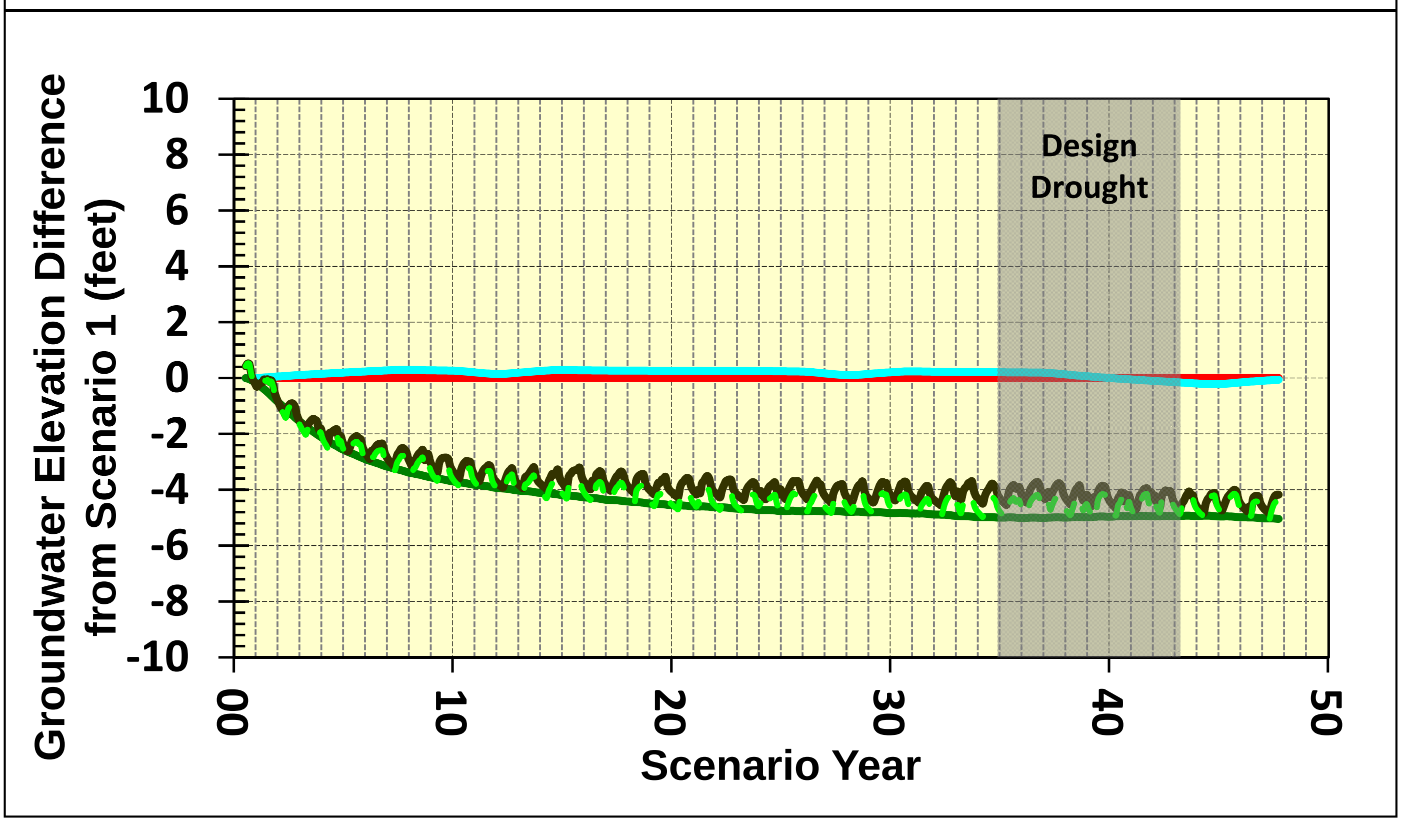
April 2012
Figure 10.3-6b





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4

Exclusion Heads:
Single-Aquifer
Deep Aquifer

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Model Layer 5 Hydrographs for Kirkham Cluster

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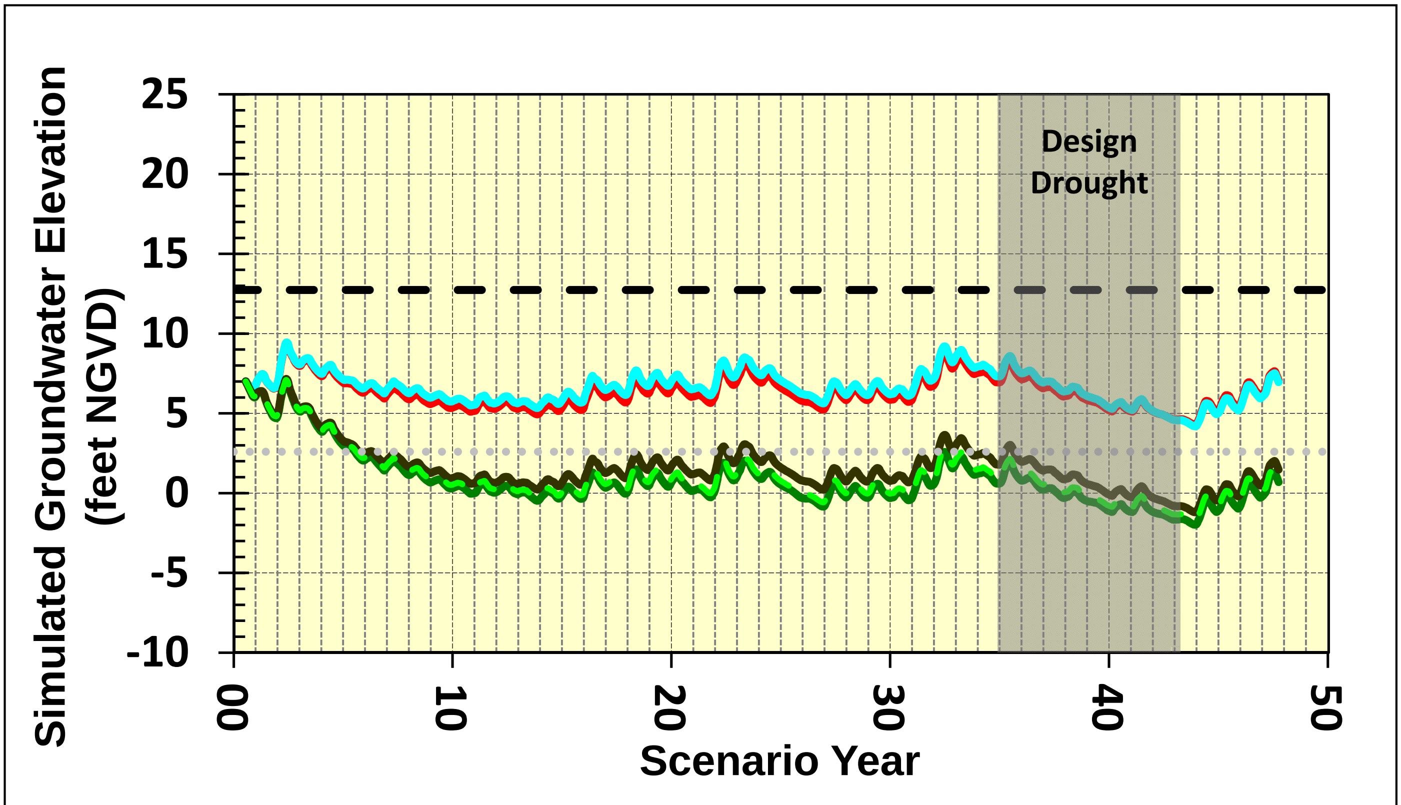
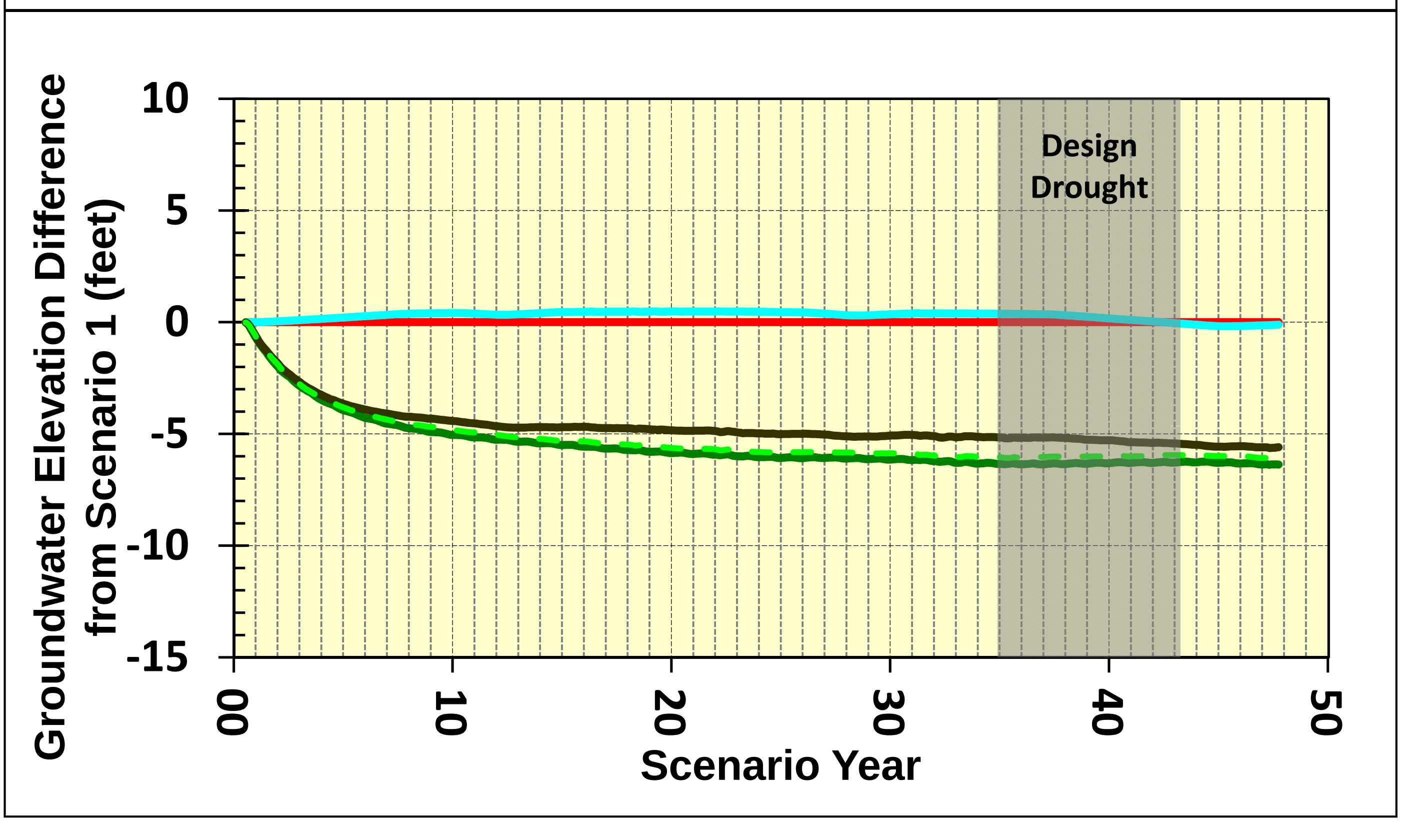
Figure 10.3-6c





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:

- Single-Aquifer
- Shallow Aquifer

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Model Layer 1 Hydrographs for Ortega Cluster

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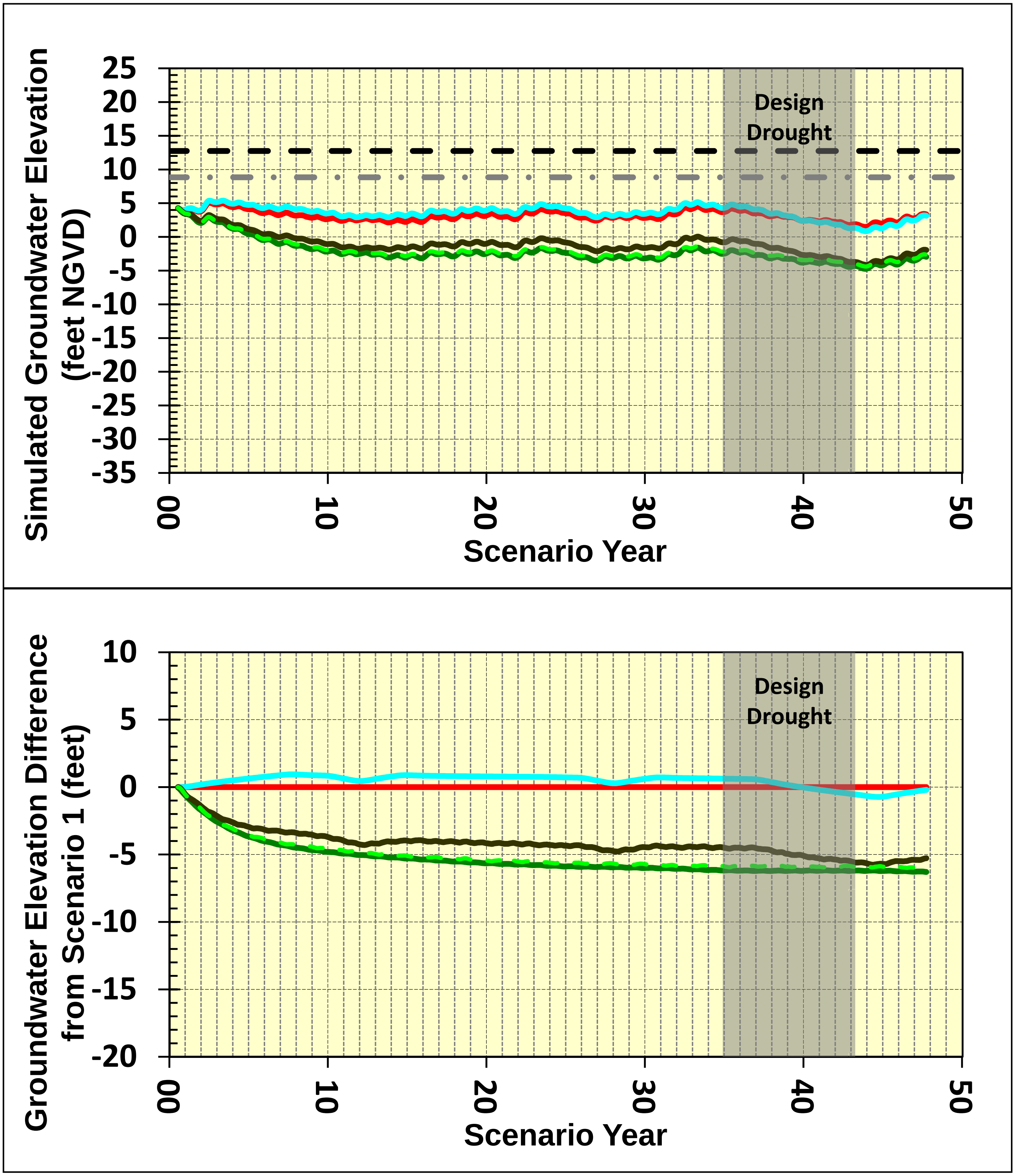
Figure 10.3-7a



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4

Exclusion Heads:
Single-Aquifer
Primary Production Aquifer

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Model Layer 4 Hydrographs for Ortega Cluster

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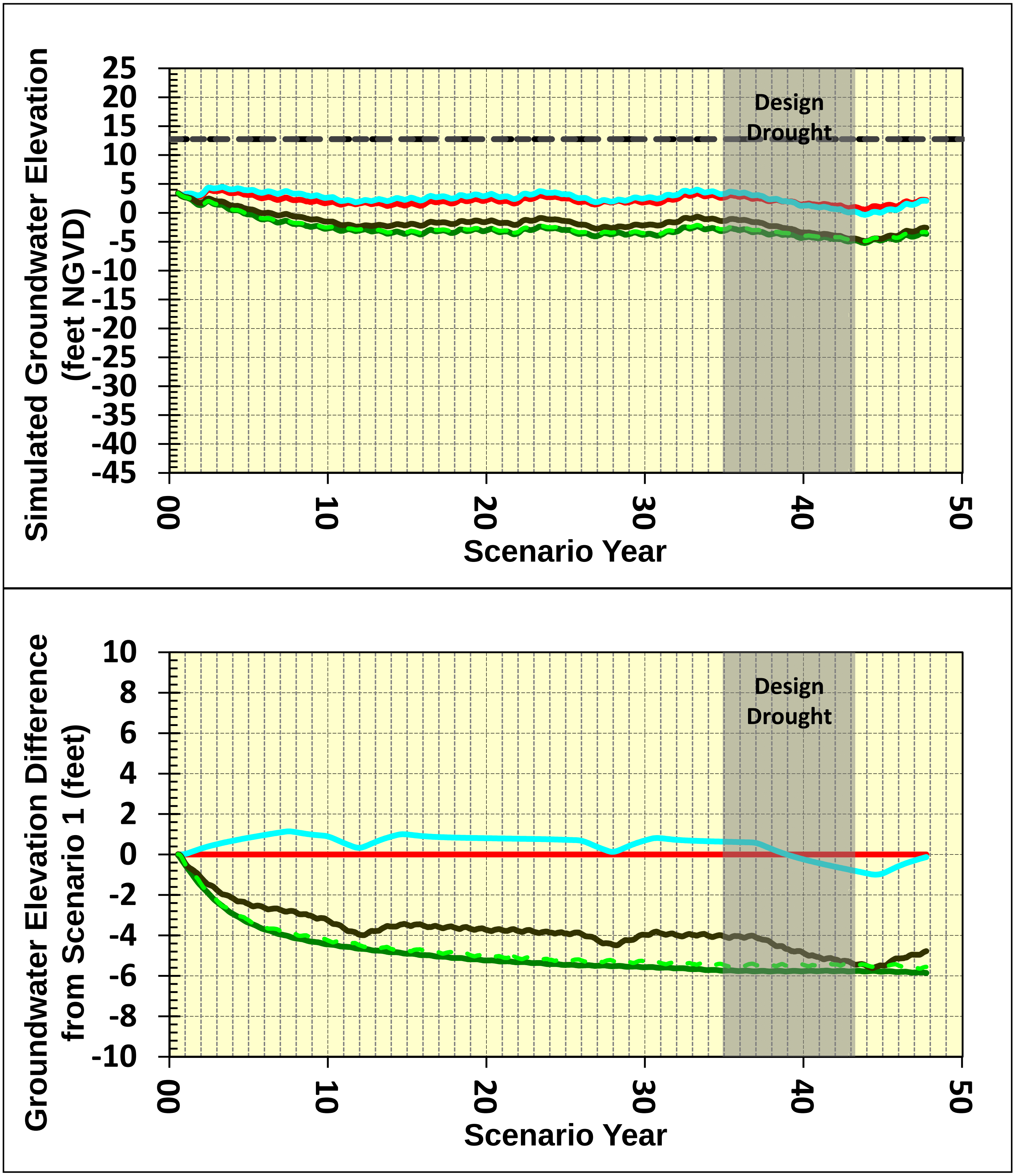
Figure 10.3-7b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer
- Deep Aquifer

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Model Layer 5 Hydrographs for Ortega Cluster

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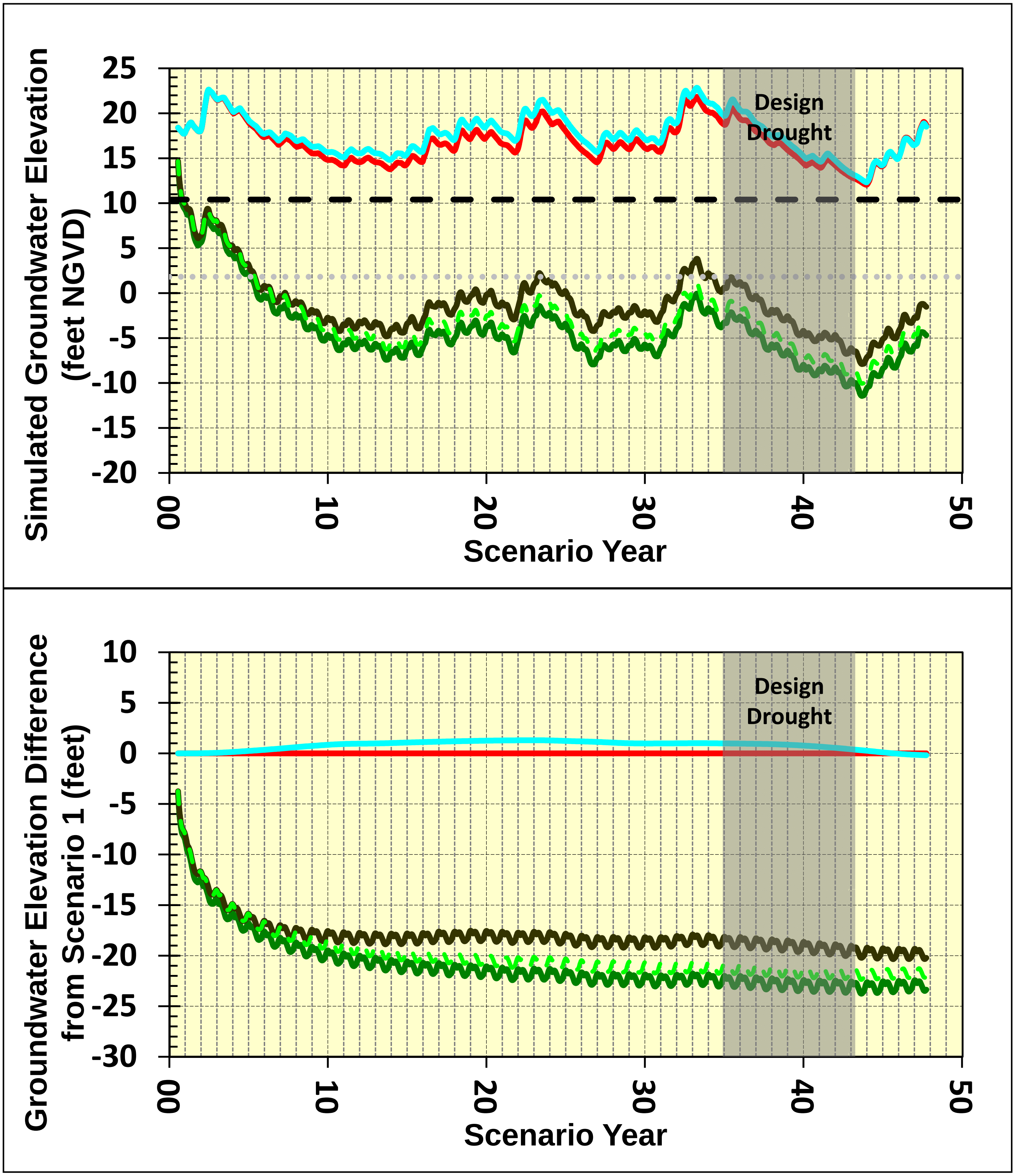
Figure 10.3-7c



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer
- Shallow Aquifer

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Model Layer 1 Hydrographs for West Sunset Playground Well

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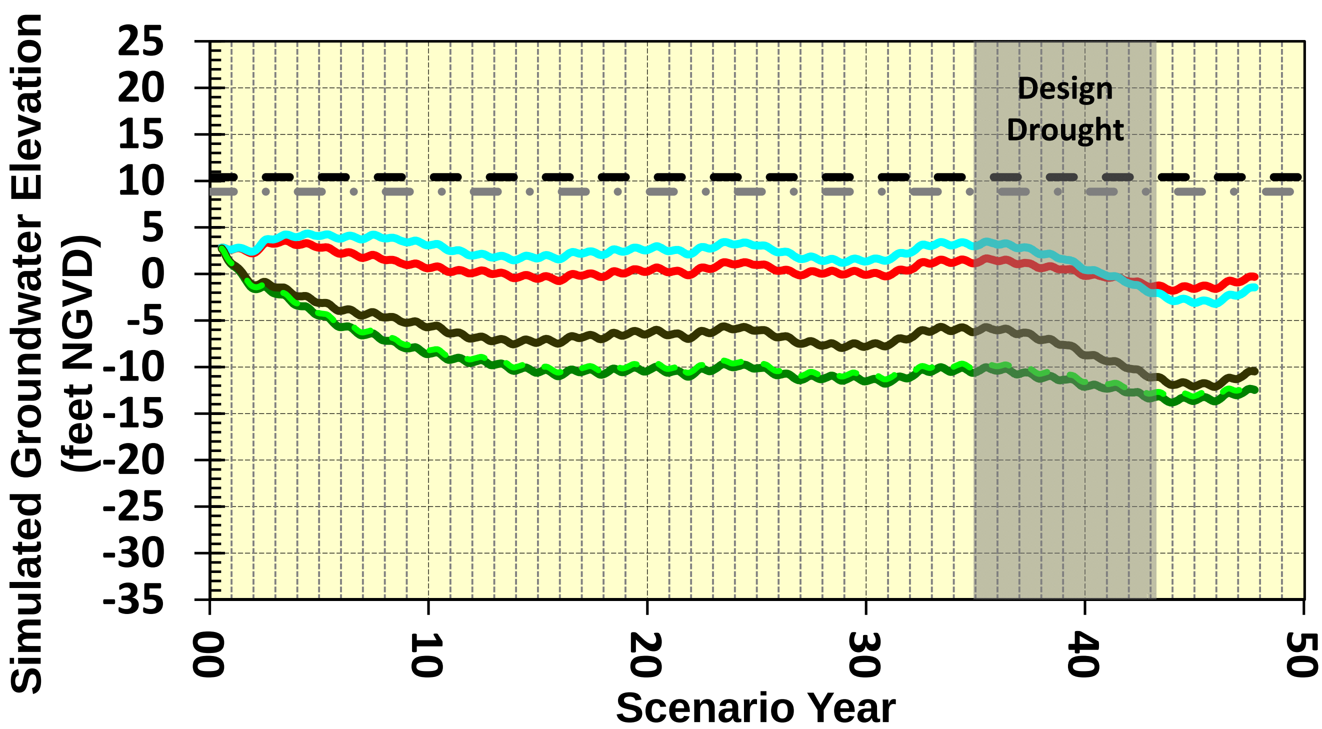
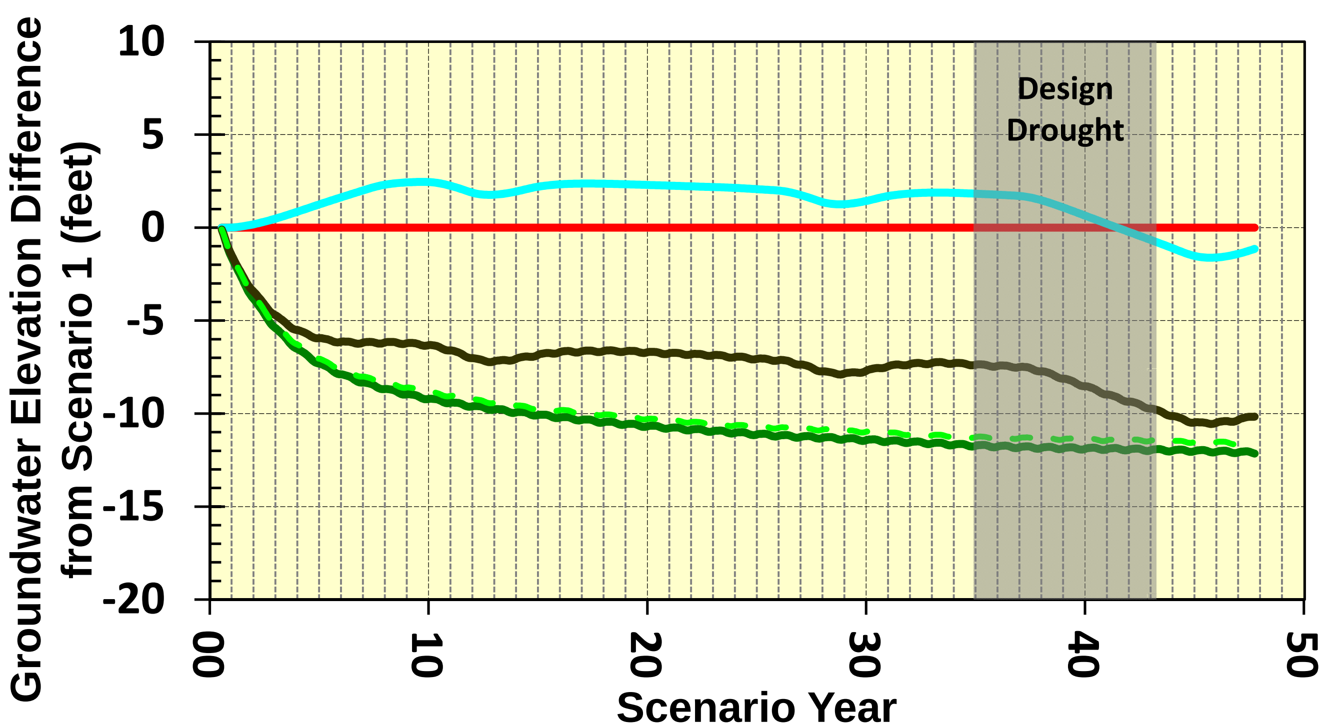
Figure 10.3-8a





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- **Scenario 1**
- **Scenario 2**
- **Scenario 3a**
- **Scenario 3b**
- **Scenario 4**

Exclusion Heads:
- **Single-Aquifer**
- **Primary Production Aquifer**

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Model Layer 4 Hydrographs for West Sunset Playground Well

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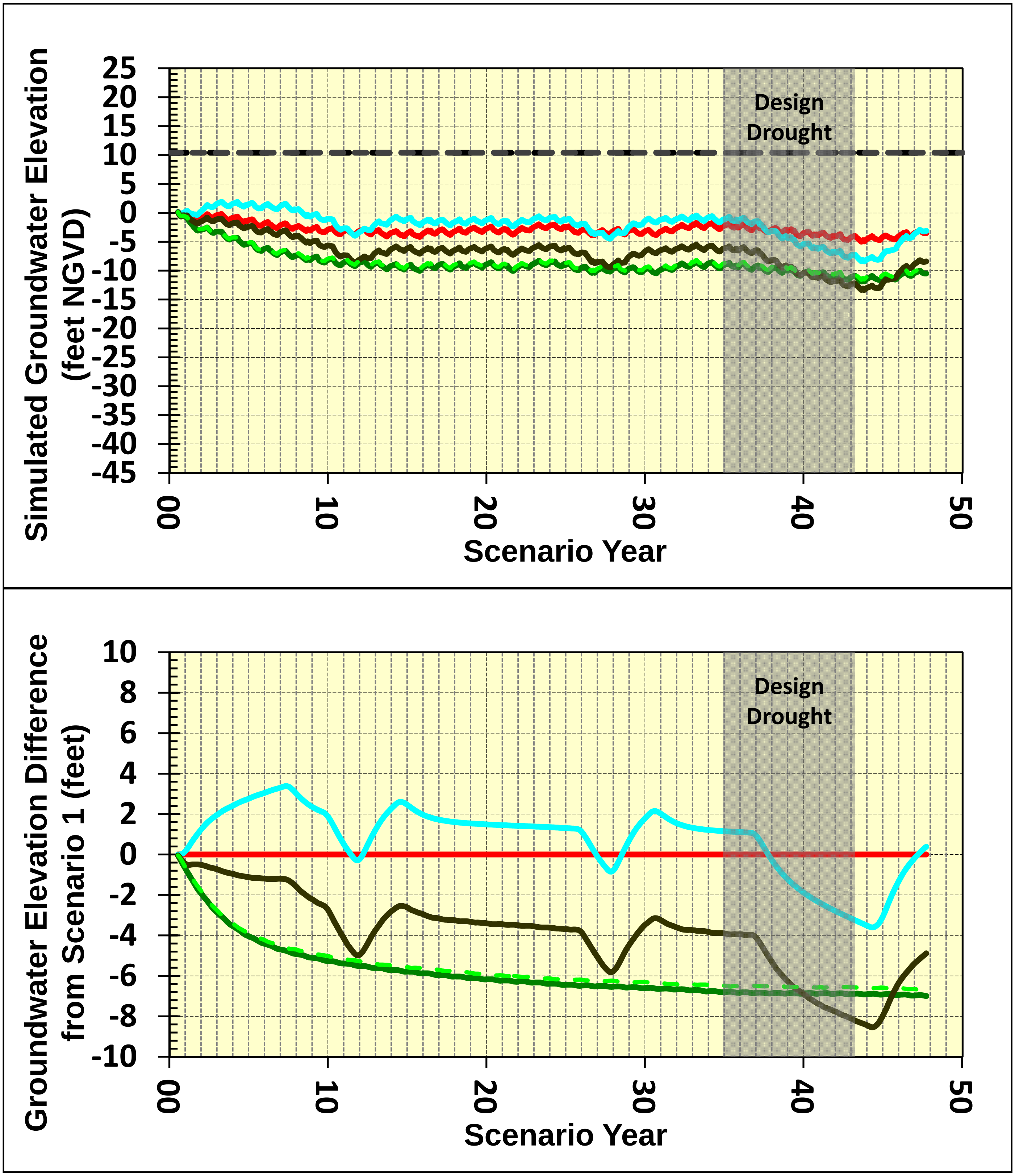
April 2012
Figure 10.3-8b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:

- Single-Aquifer
- Deep Aquifer

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Model Layer 5 Hydrographs for West Sunset Playground Well

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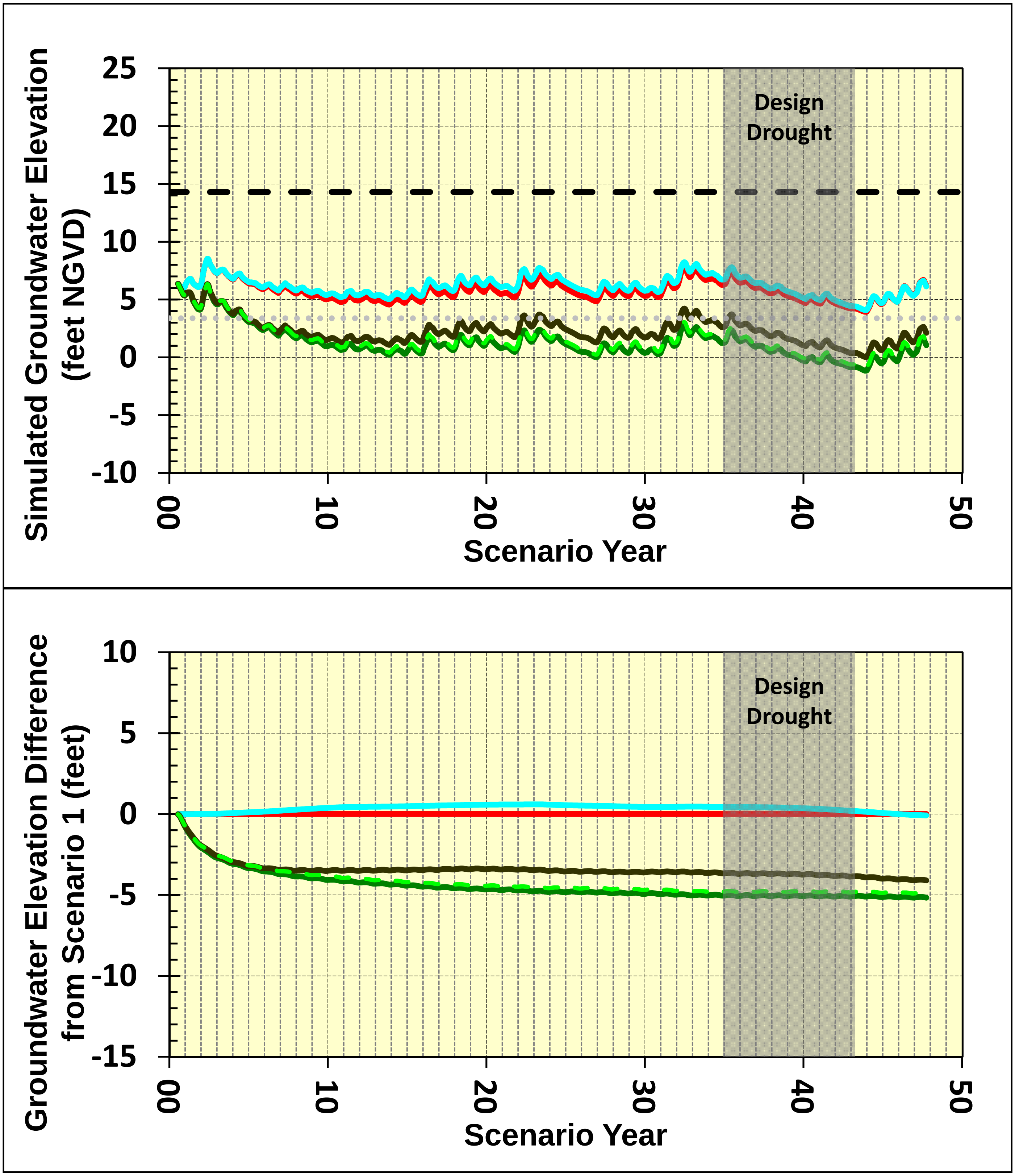
Figure 10.3-8c



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer
- Shallow Aquifer

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Model Layer 1 Hydrographs for Taraval Cluster

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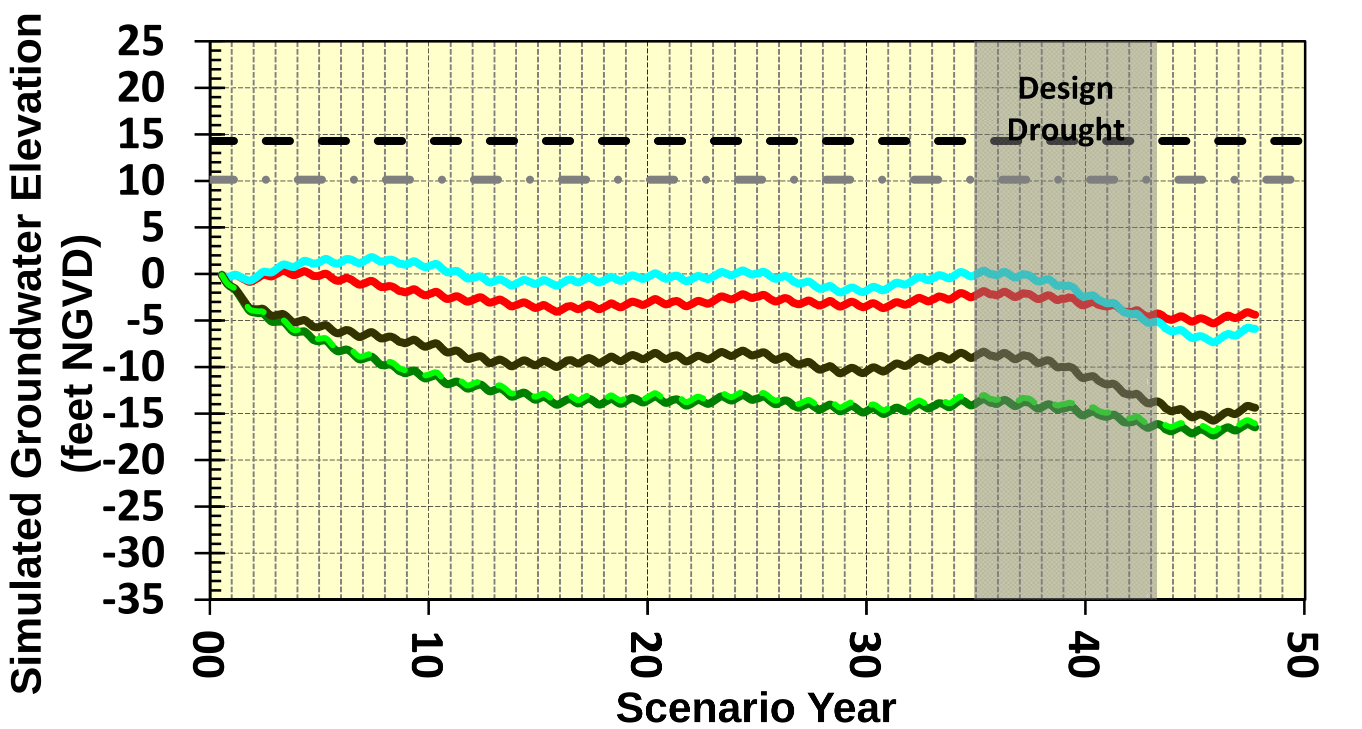
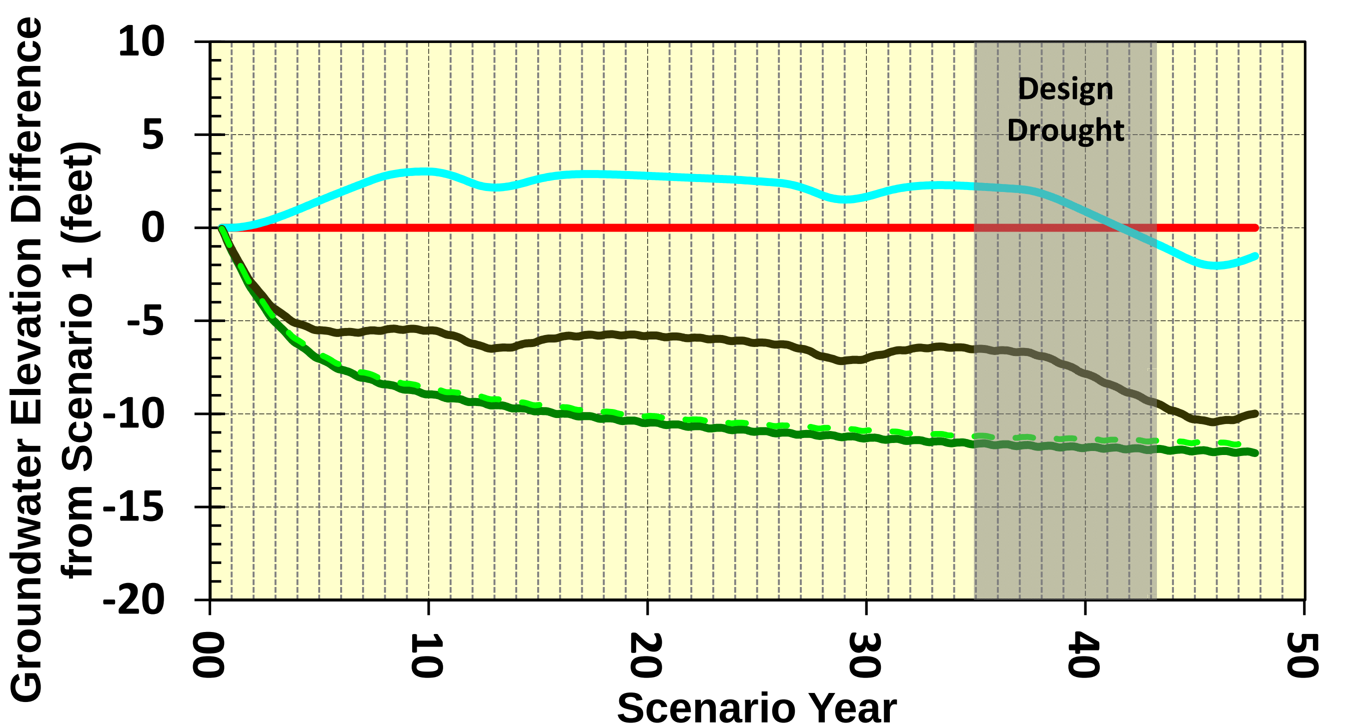
Figure 10.3-9a





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1 **Scenario 2**

Scenario 3a **Scenario 3b**

Scenario 4

Exclusion Heads:

Single-Aquifer **Primary Production Aquifer**

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Model Layer 4 Hydrographs for Taraval Cluster

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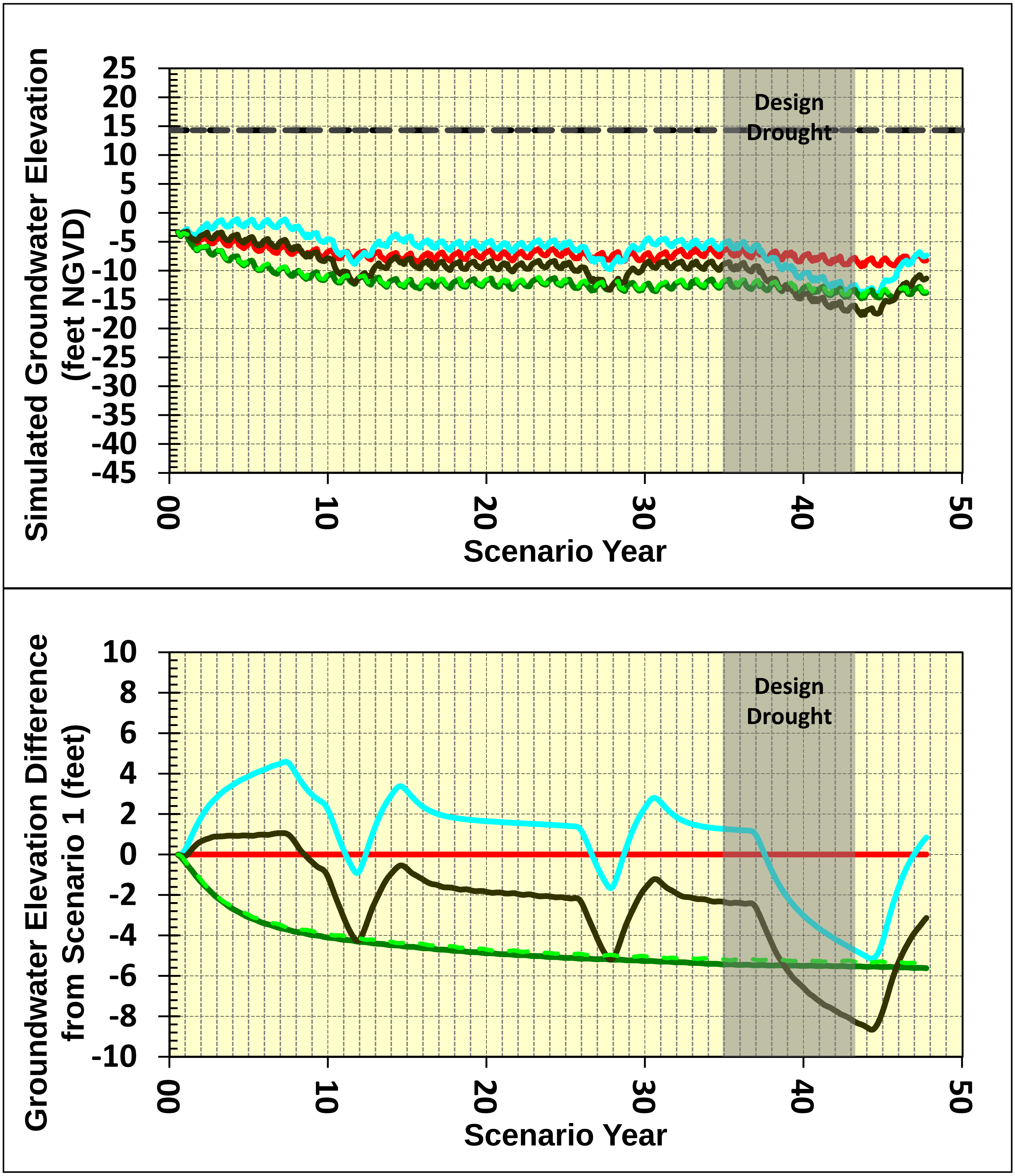
Figure 10.3-9b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1 **Scenario 2**
Scenario 3a **Scenario 3b**
Scenario 4

Exclusion Heads:

Single-Aquifer **Deep Aquifer**

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Model Layer 5 Hydrographs for Taraval Cluster

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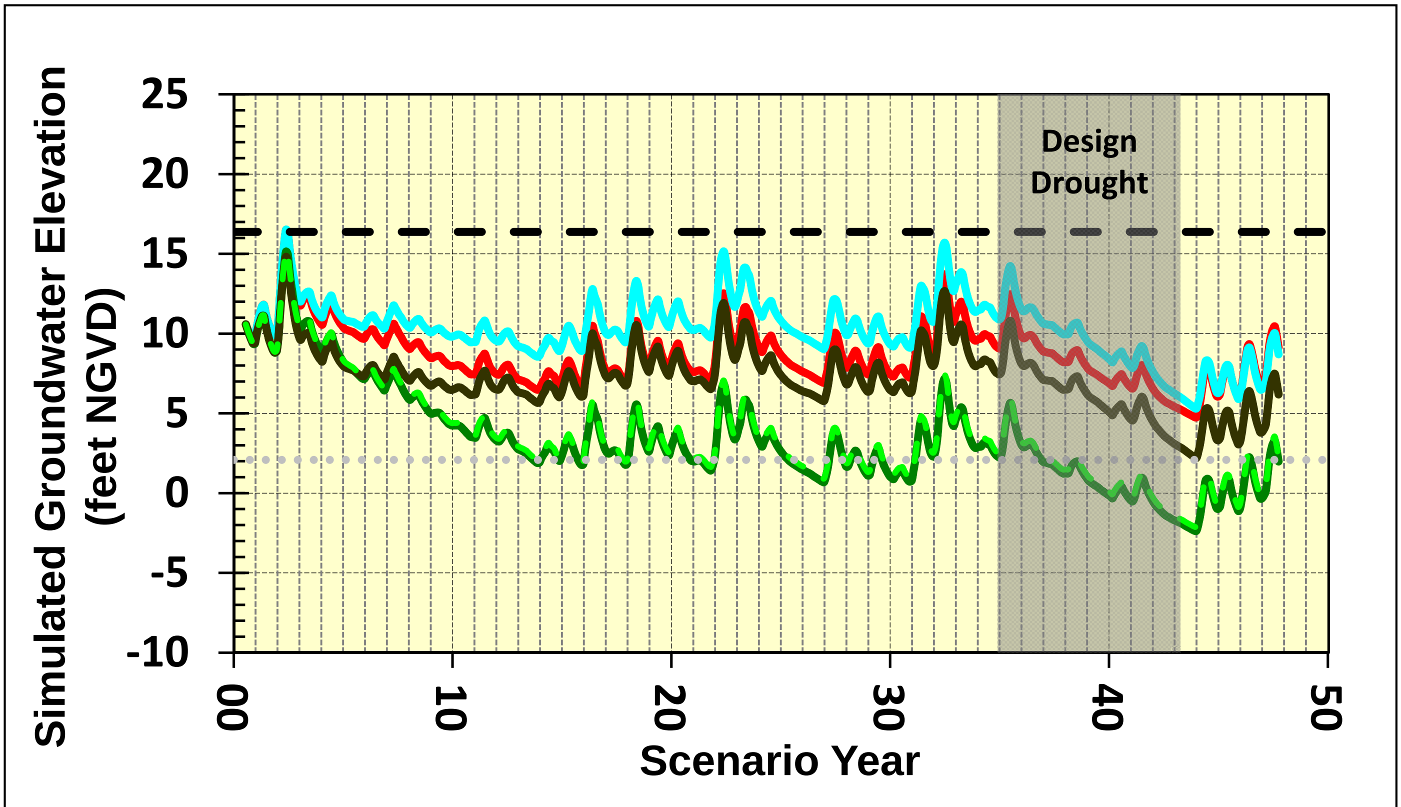
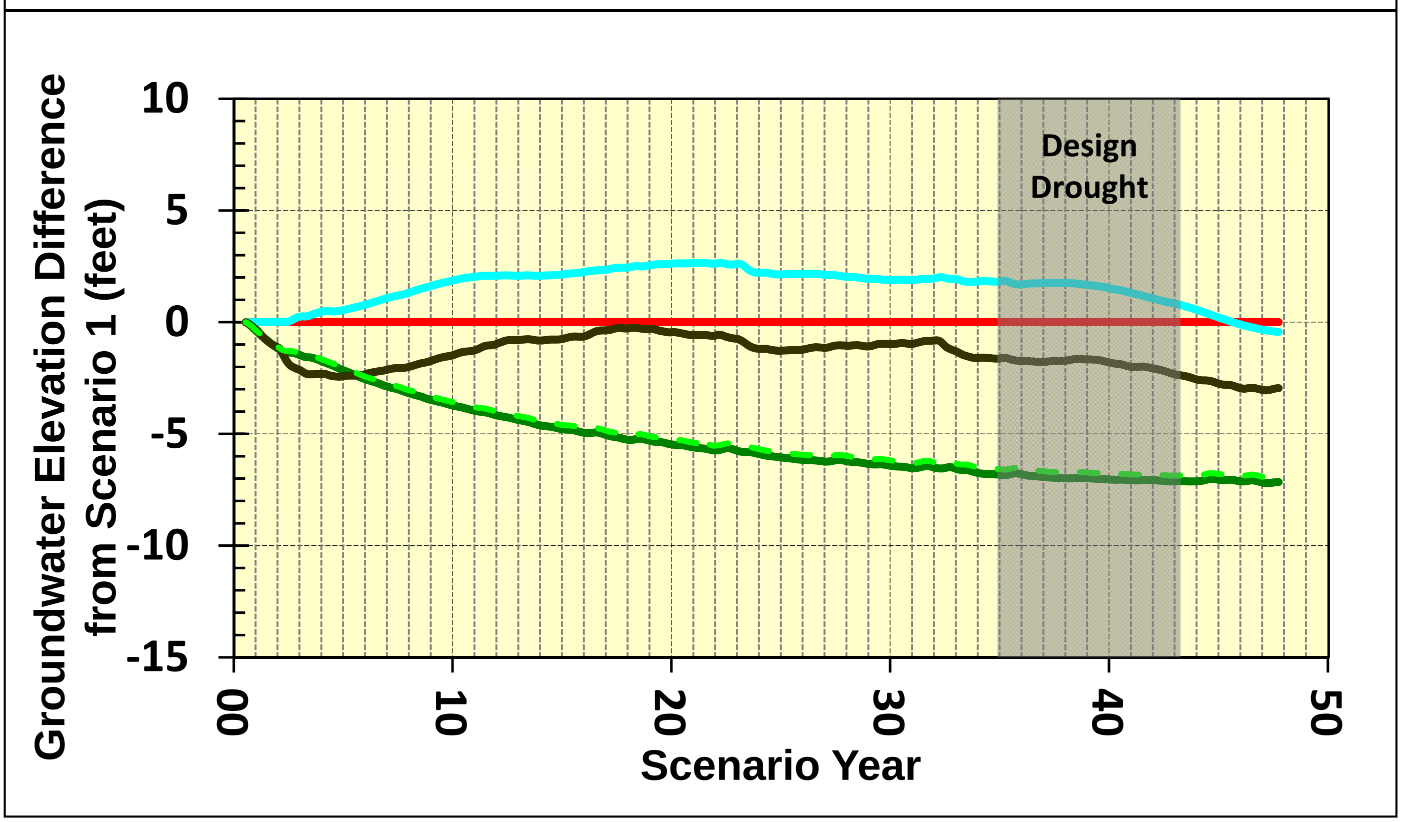
Figure 10.3-9c





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer
- Shallow Aquifer

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Model Layer 1 Hydrographs for Zoo Cluster

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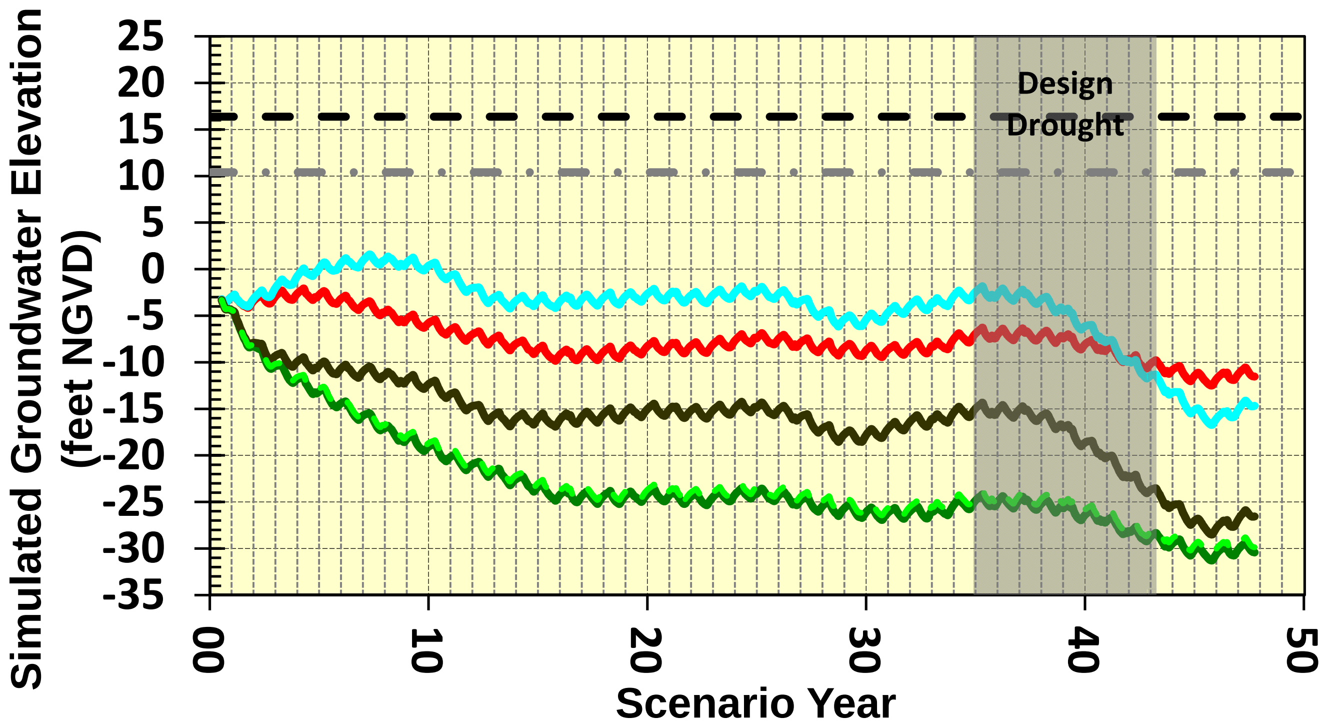
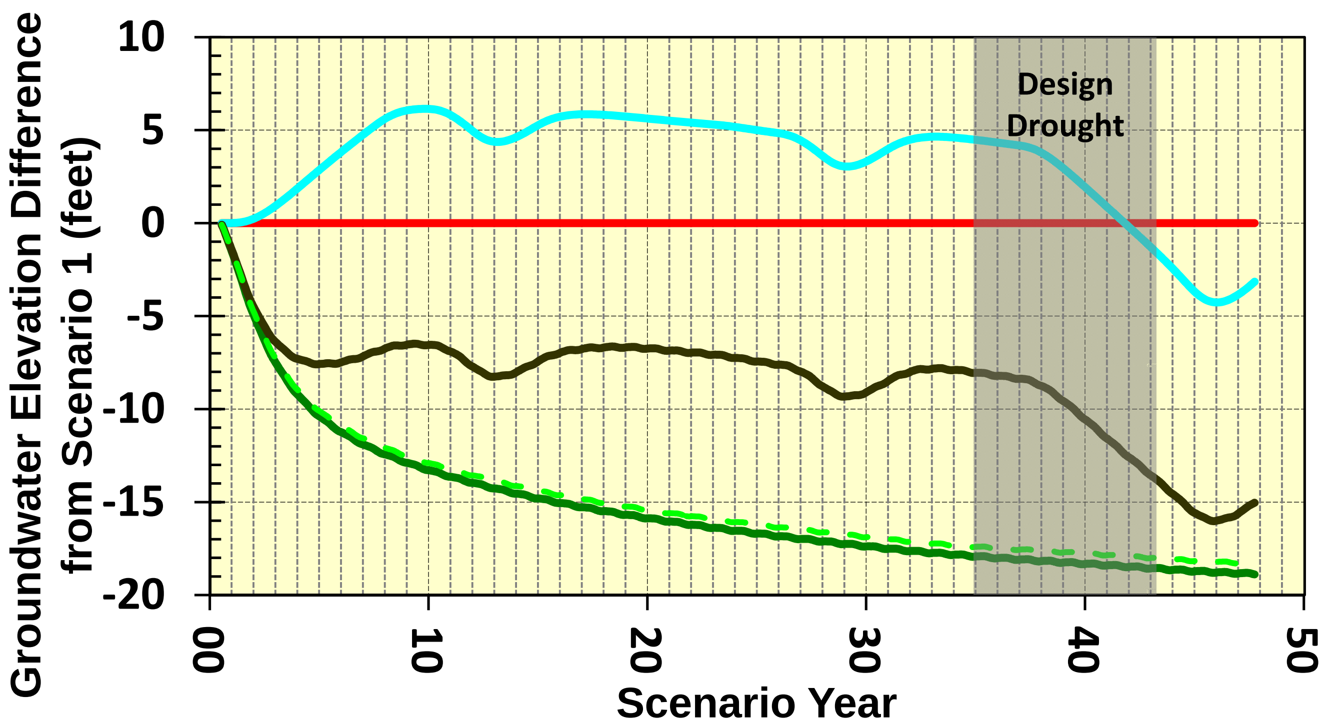
Figure 10.3-10a





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

- **Scenario 1**
- **Scenario 2**
- **Scenario 3a**
- **Scenario 3b**
- **Scenario 4**

Exclusion Heads:

- **Single-Aquifer**
- **Primary Production Aquifer**

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Model Layer 4 Hydrographs for Zoo Cluster

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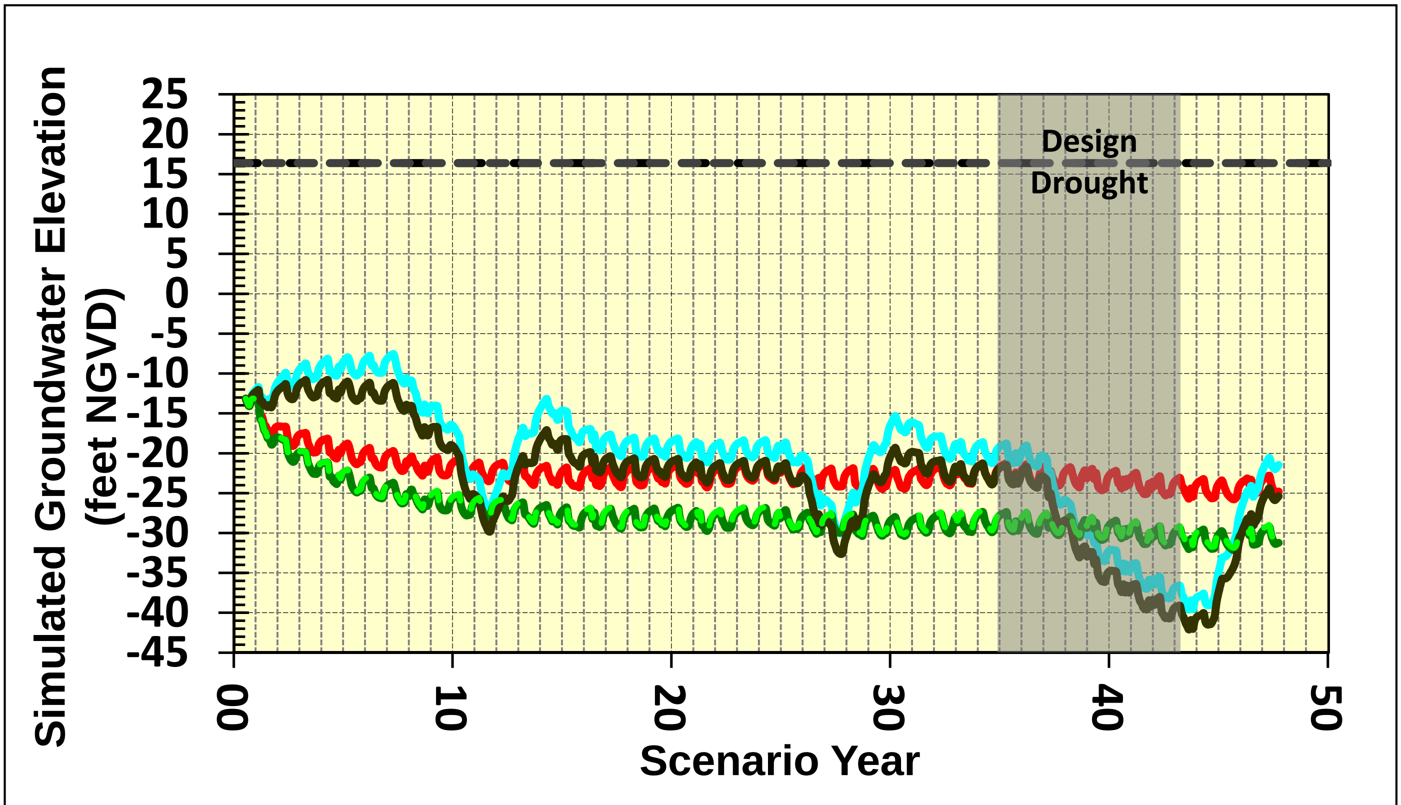
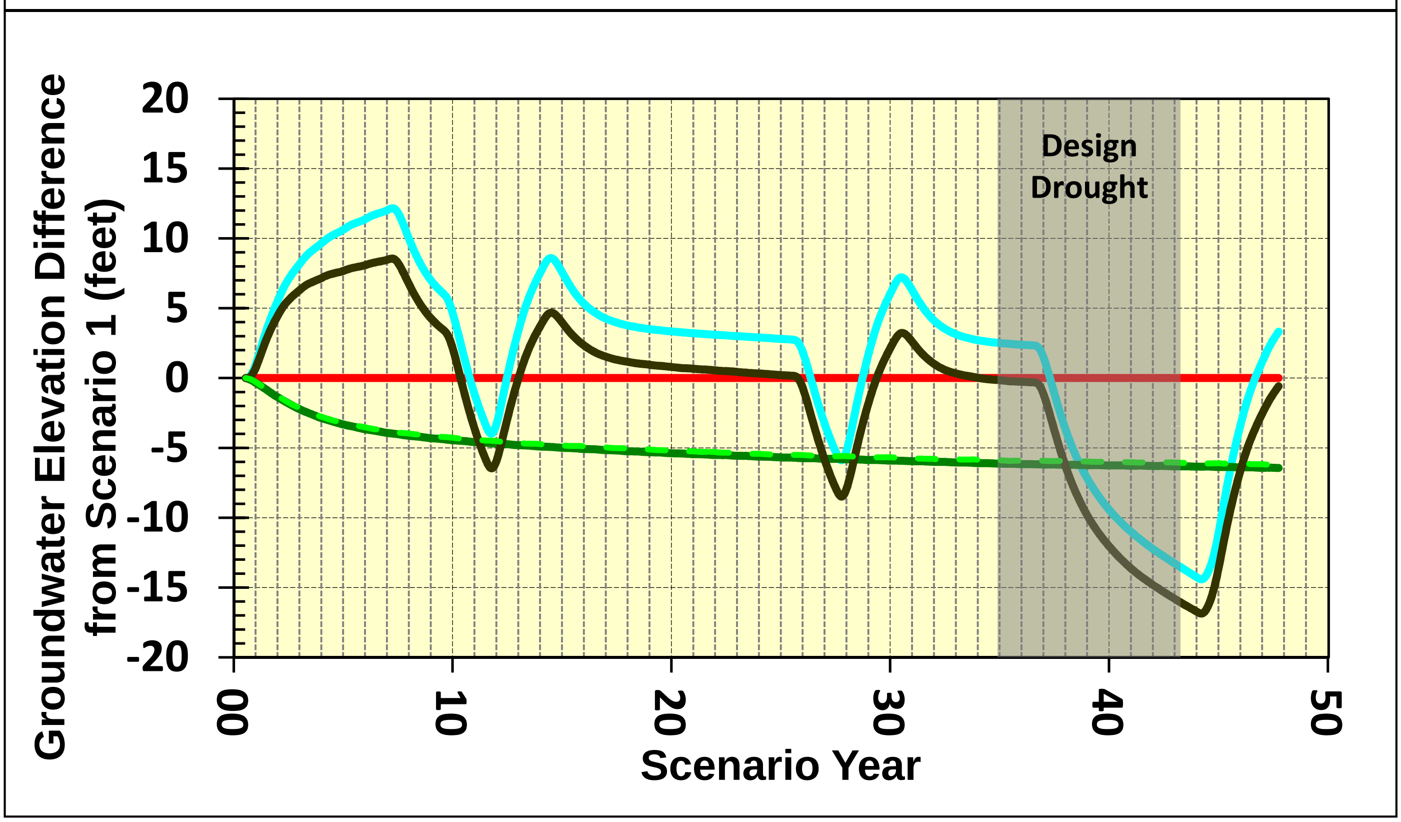
Figure 10.3-10b





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4
Exclusion Heads:
Single-Aquifer
Deep Aquifer

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Model Layer 5 Hydrographs for Zoo Cluster

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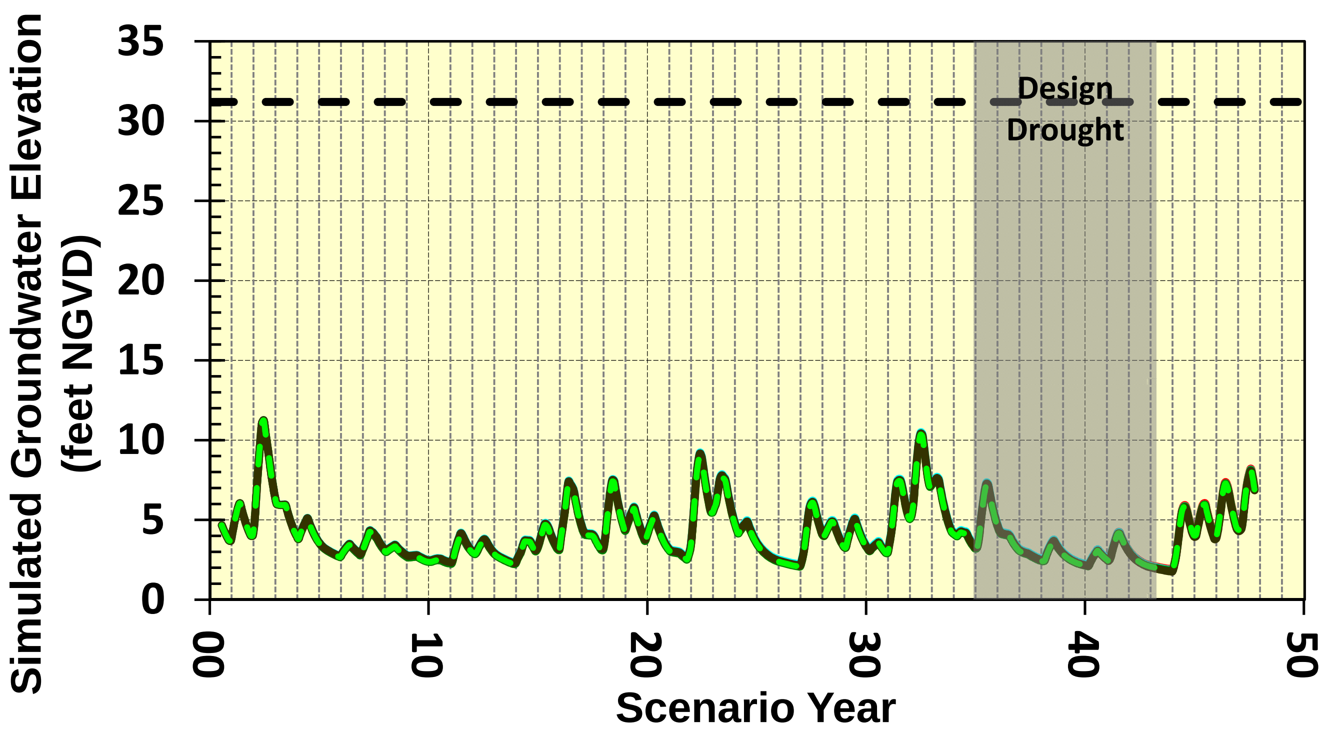
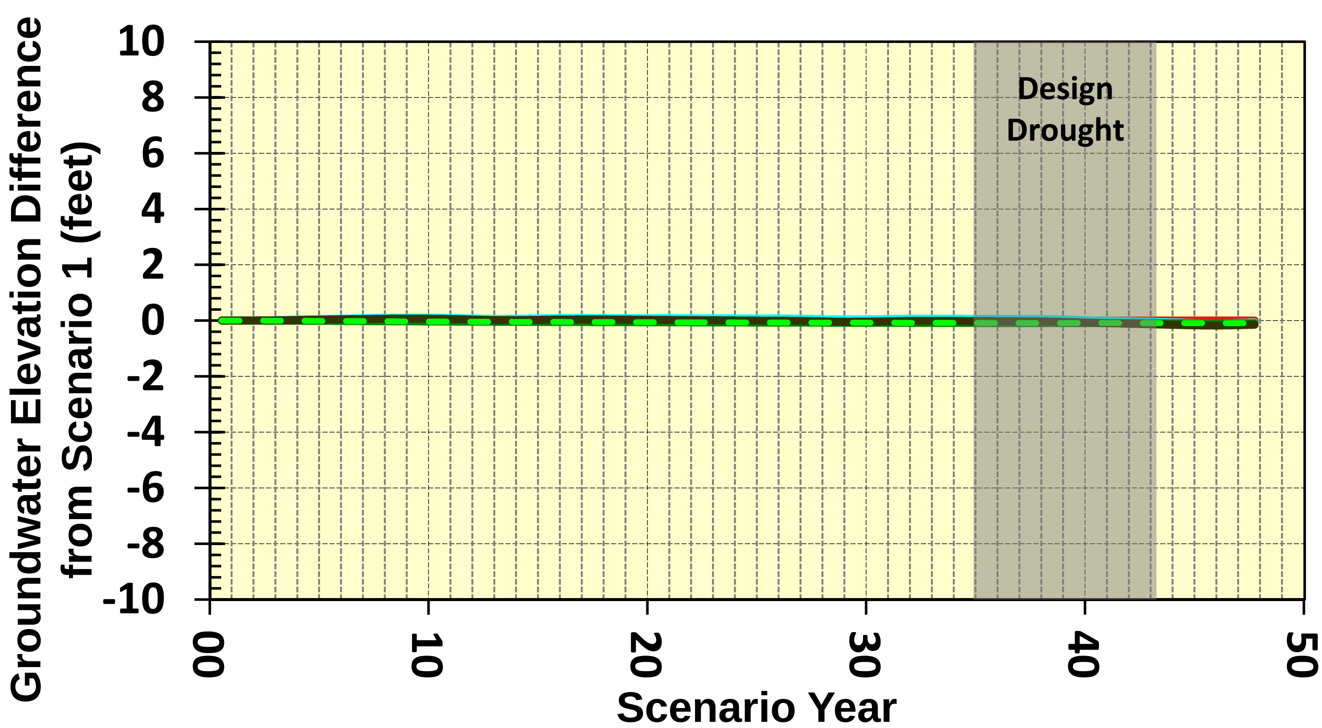
Figure 10.3-10c





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- **Scenario 1**
- **Scenario 2**
- **Scenario 3a**
- **Scenario 3b**
- **Scenario 4**

Exclusion Heads:
- **Single-Aquifer**

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Model Layer 1 Hydrographs for Fort Funston Cluster

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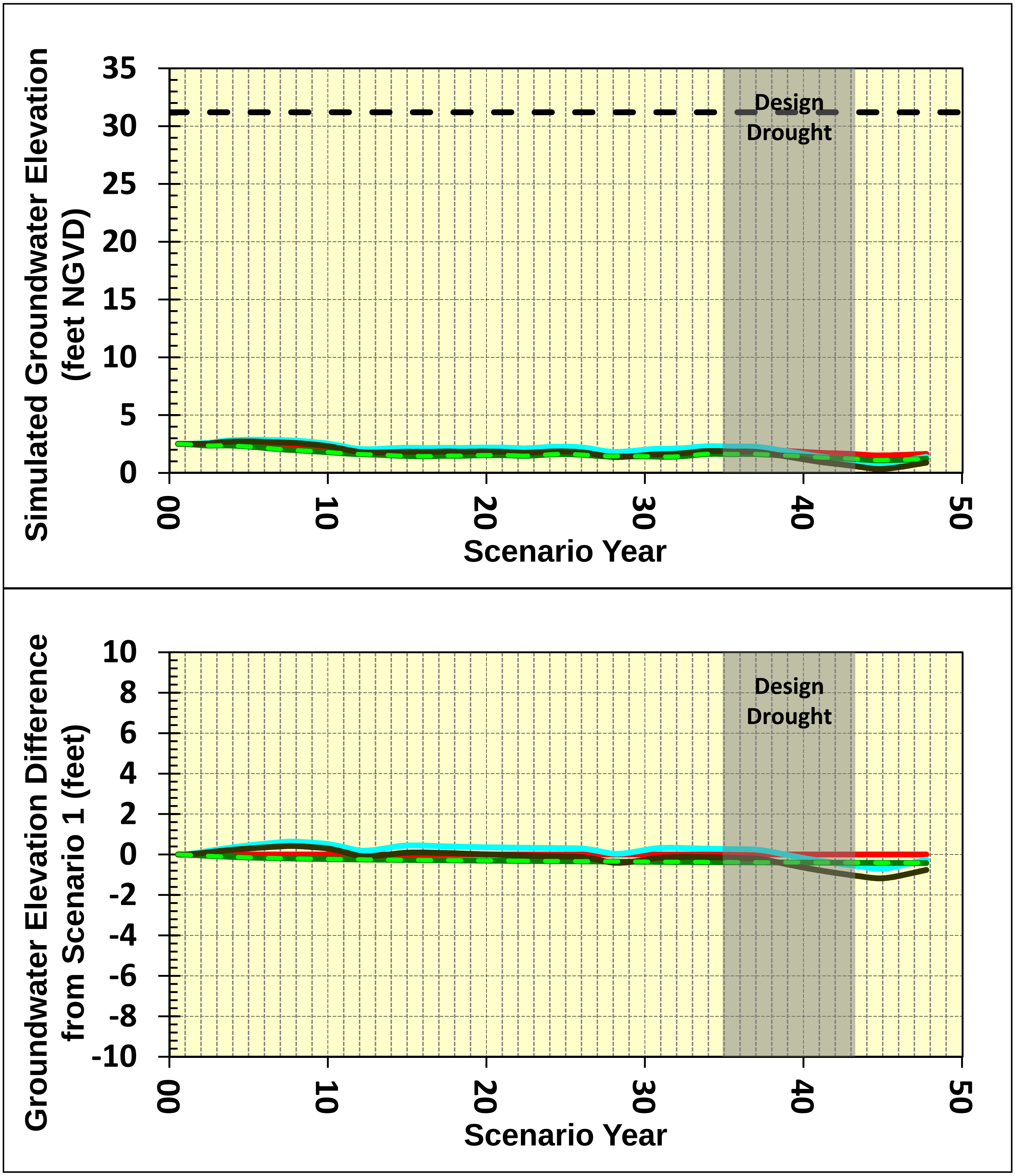
Figure 10.3-11a



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4
Exclusion Heads:
Single-Aquifer

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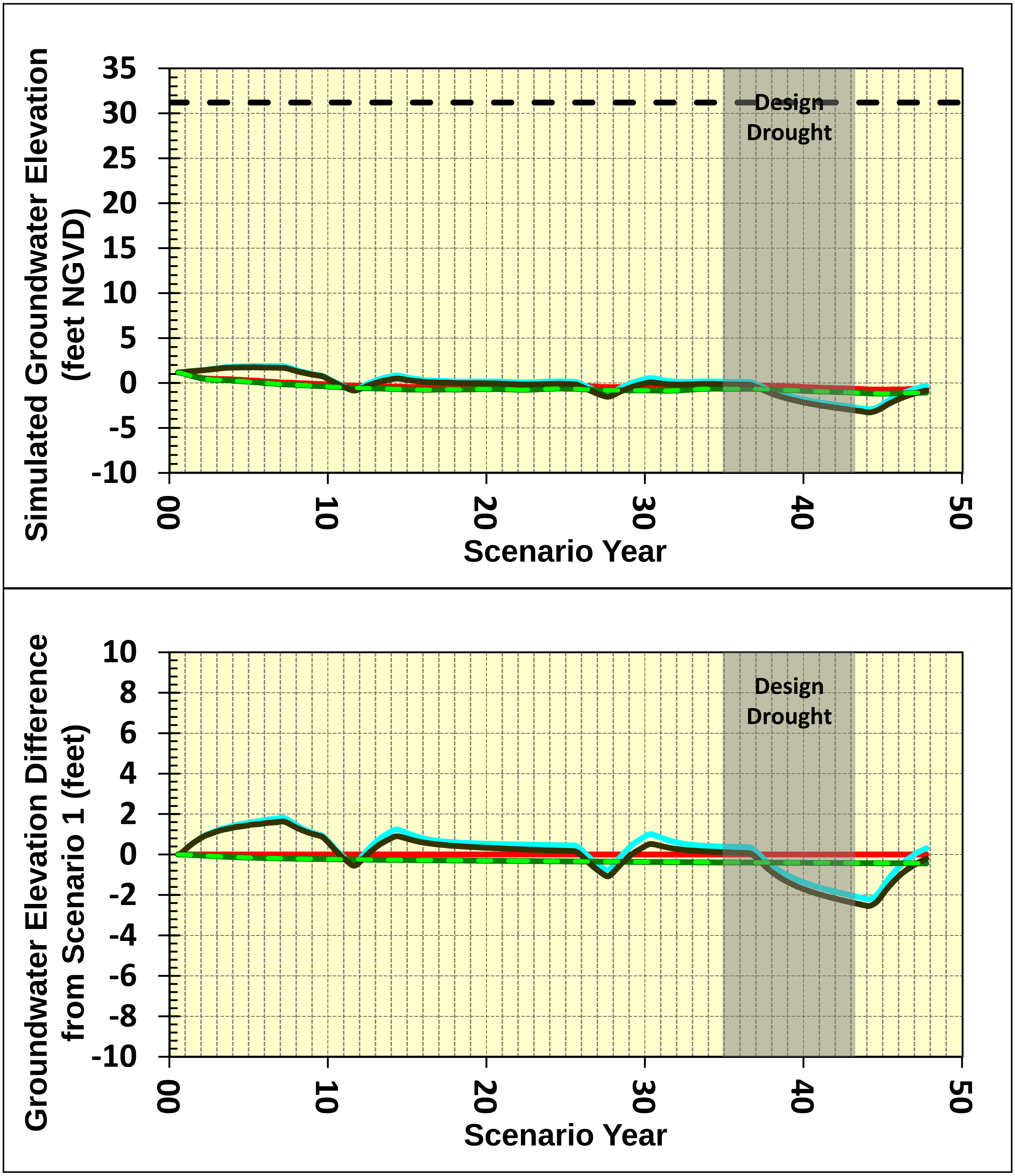
Model Layer 4 Hydrographs for Fort Funston Cluster

K/J 0864001
April 2012
Figure 10.3-11b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1

Scenario 2

Scenario 3a

Scenario 3b

Scenario 4

Exclusion Heads:

Single-Aquifer

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Regional Groundwater Storage and Recovery Project
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Model Layer 5 Hydrographs for Fort Funston Cluster

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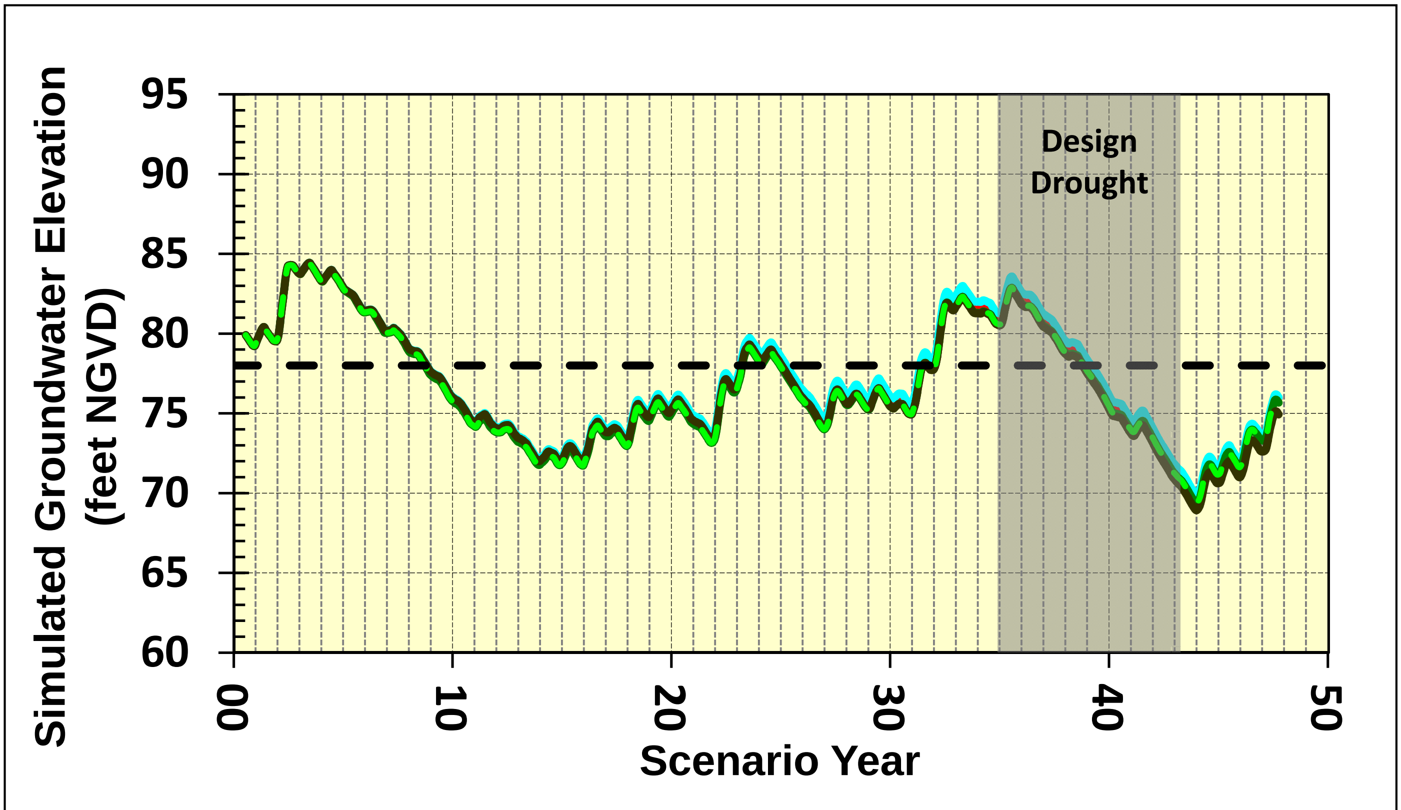
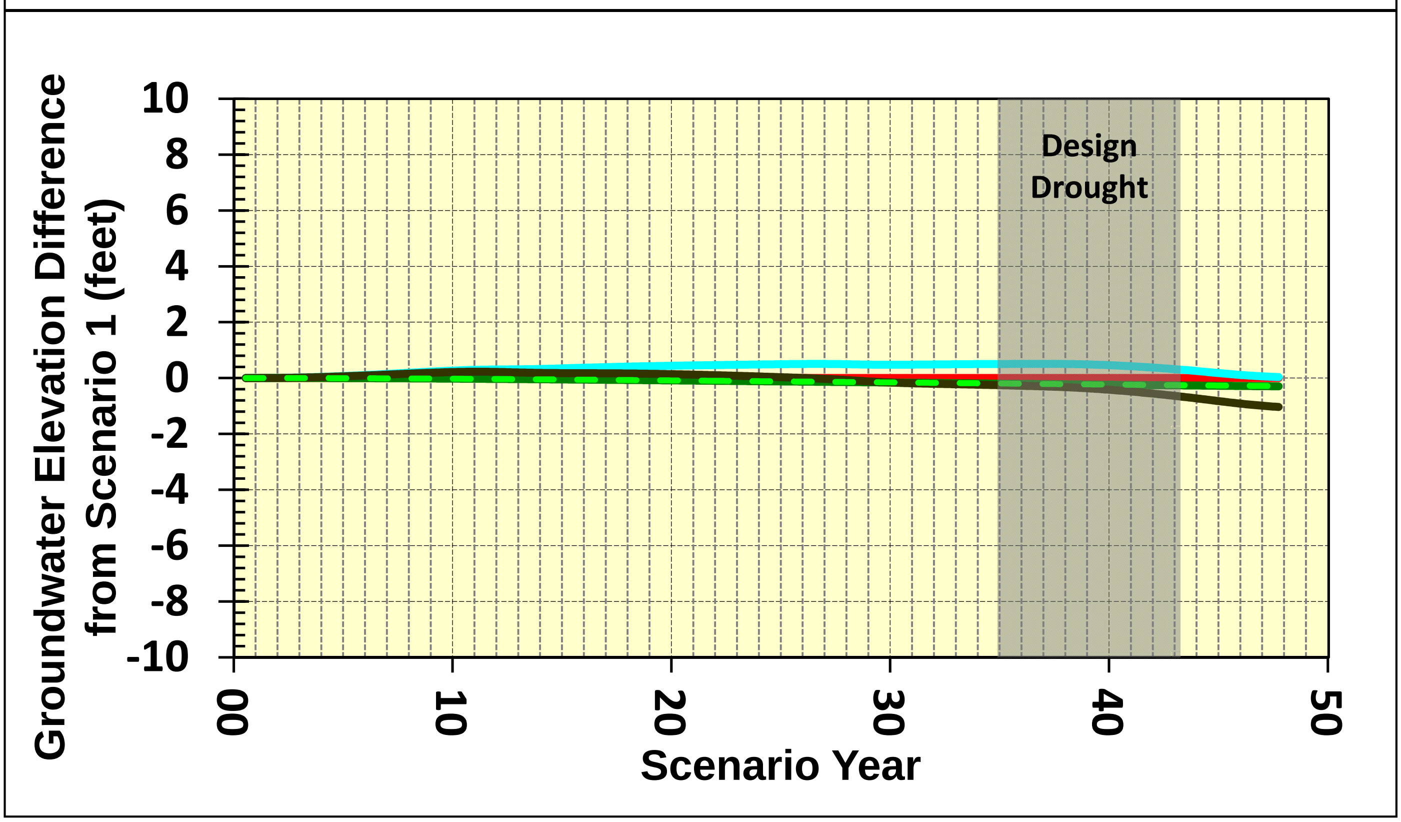
Figure 10.3-11c





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
Scenario 1
Scenario 2
Scenario 3a
Scenario 3b
Scenario 4
Exclusion Heads:
Single-Aquifer

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Model Layer 1 Hydrographs for Thornton Beach Cluster

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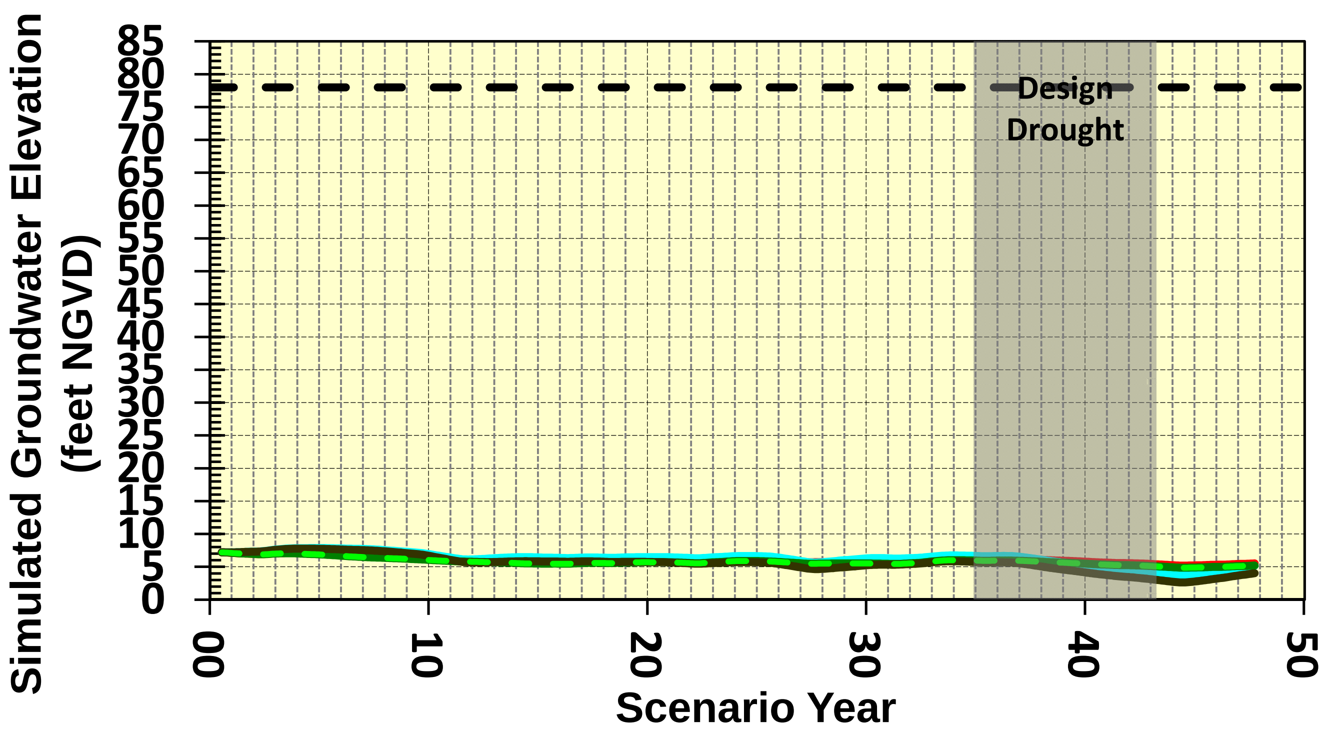
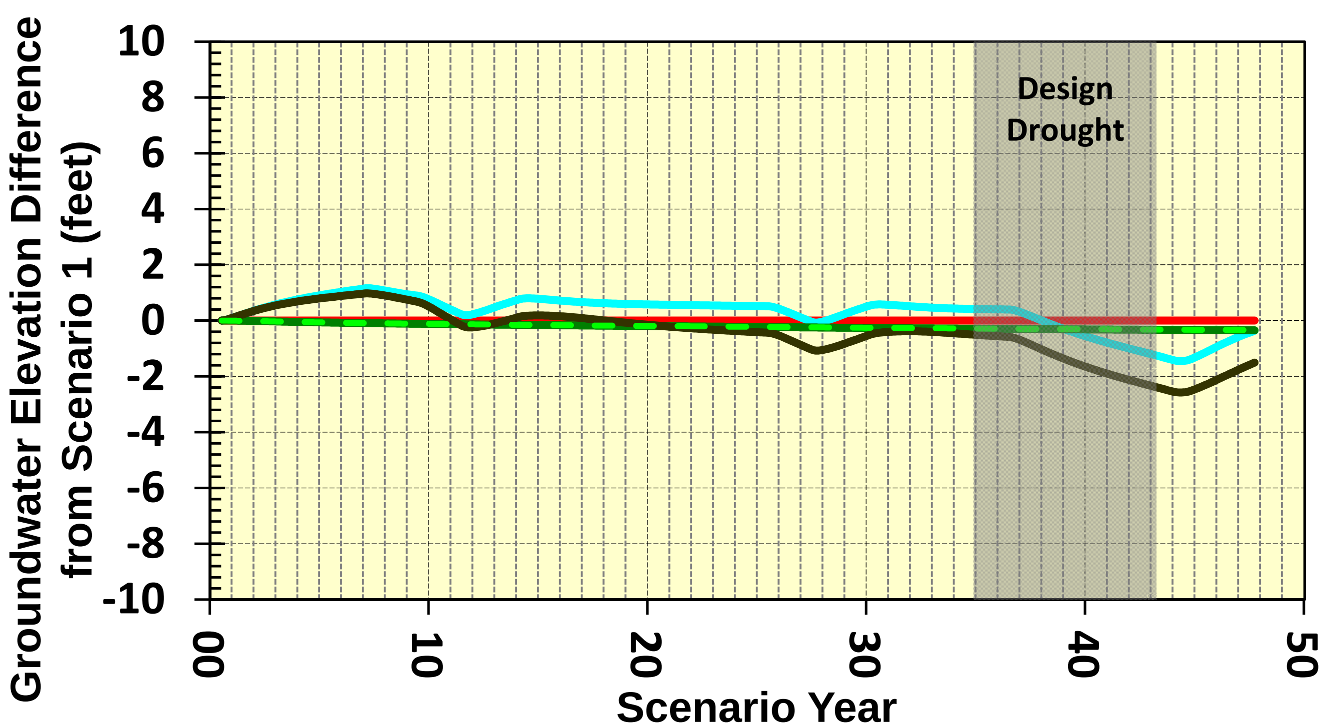
April 2012
Figure 10.3-12a





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:

- Single-Aquifer

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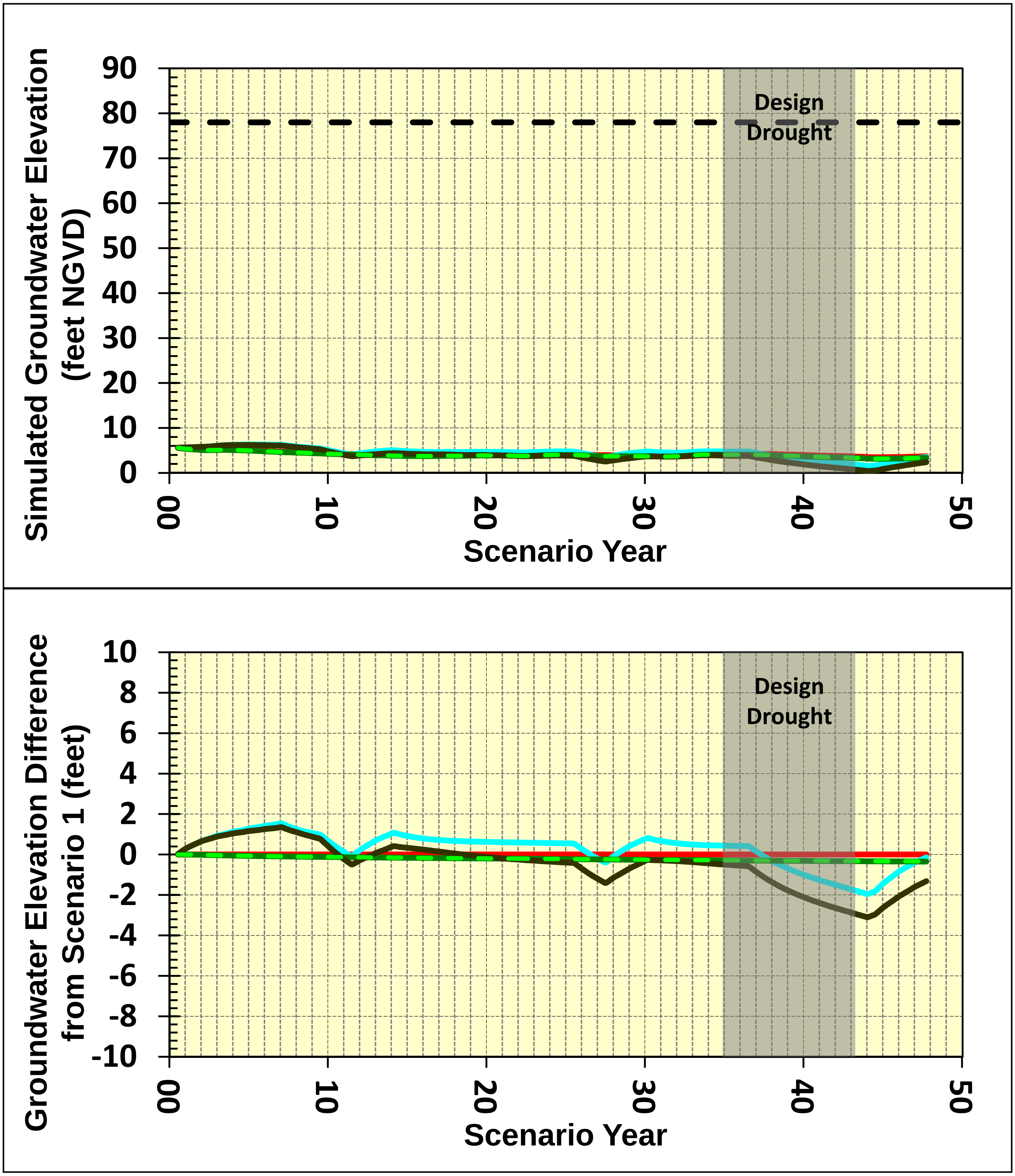
and San Francisco Groundwater Supply Project
San Francisco Public Utilities Commission

Model Layer 4 Hydrographs for Thornton Beach Cluster

K/J 0864001
April 2012
Figure 10.3-12b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:

Scenario 1

Scenario 2

Scenario 3a

Scenario 3b

Scenario 4

Exclusion Heads:

Single-Aquifer

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Model Layer 5 Hydrographs for Thornton Beach Cluster

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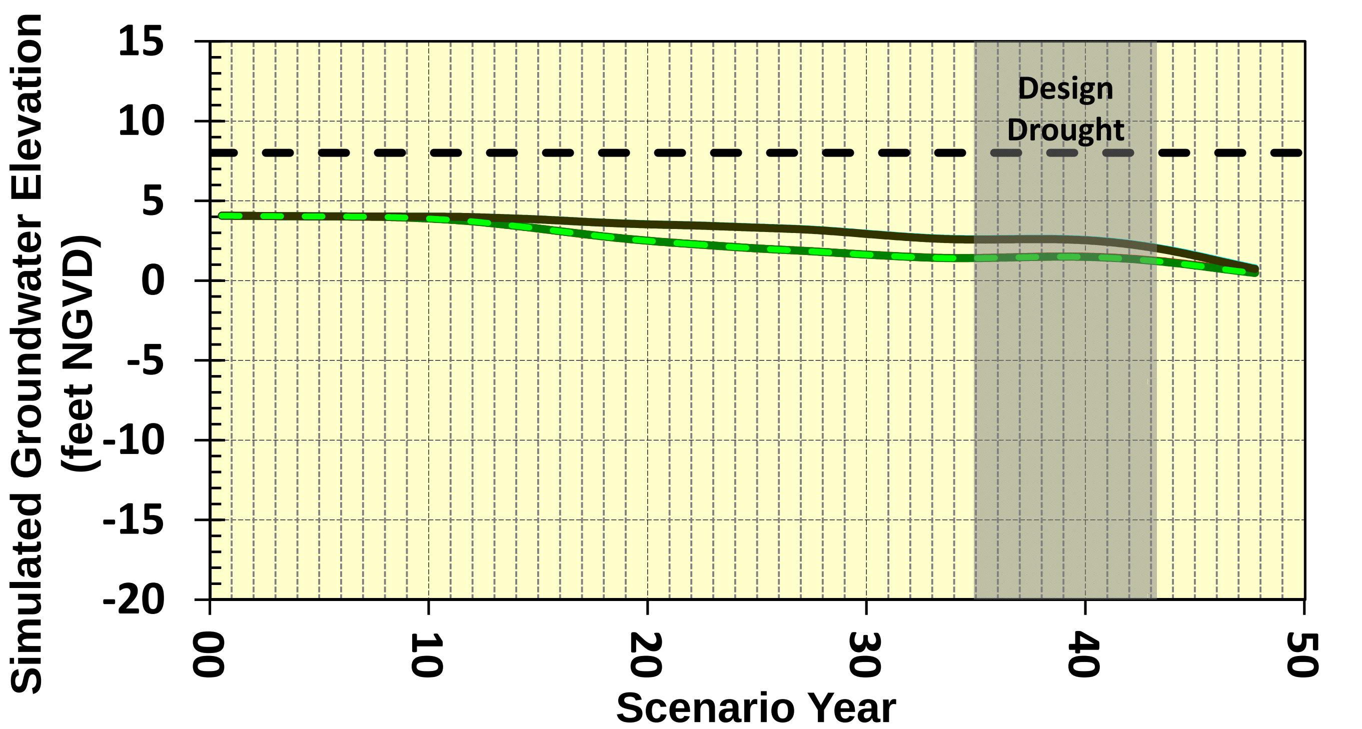
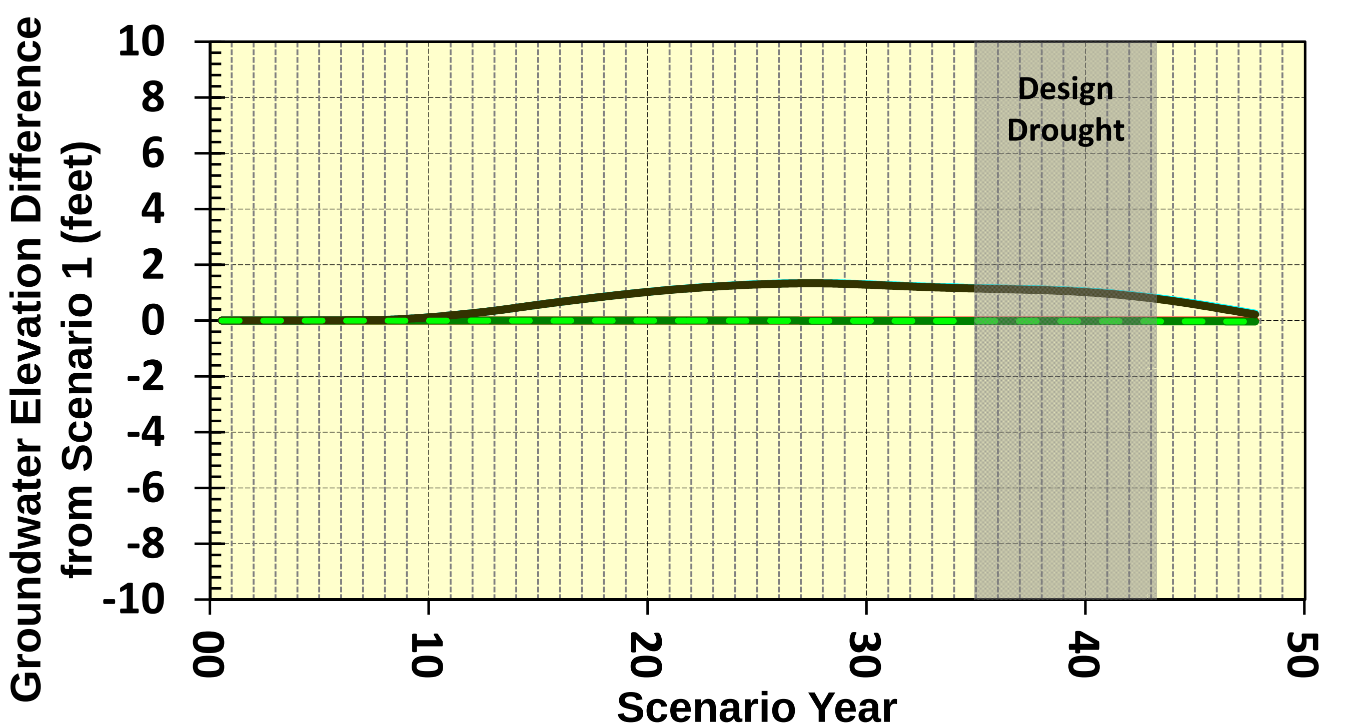
Figure 10.3-12c





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer

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Model Layer 1 Hydrographs for Burlingame Cluster

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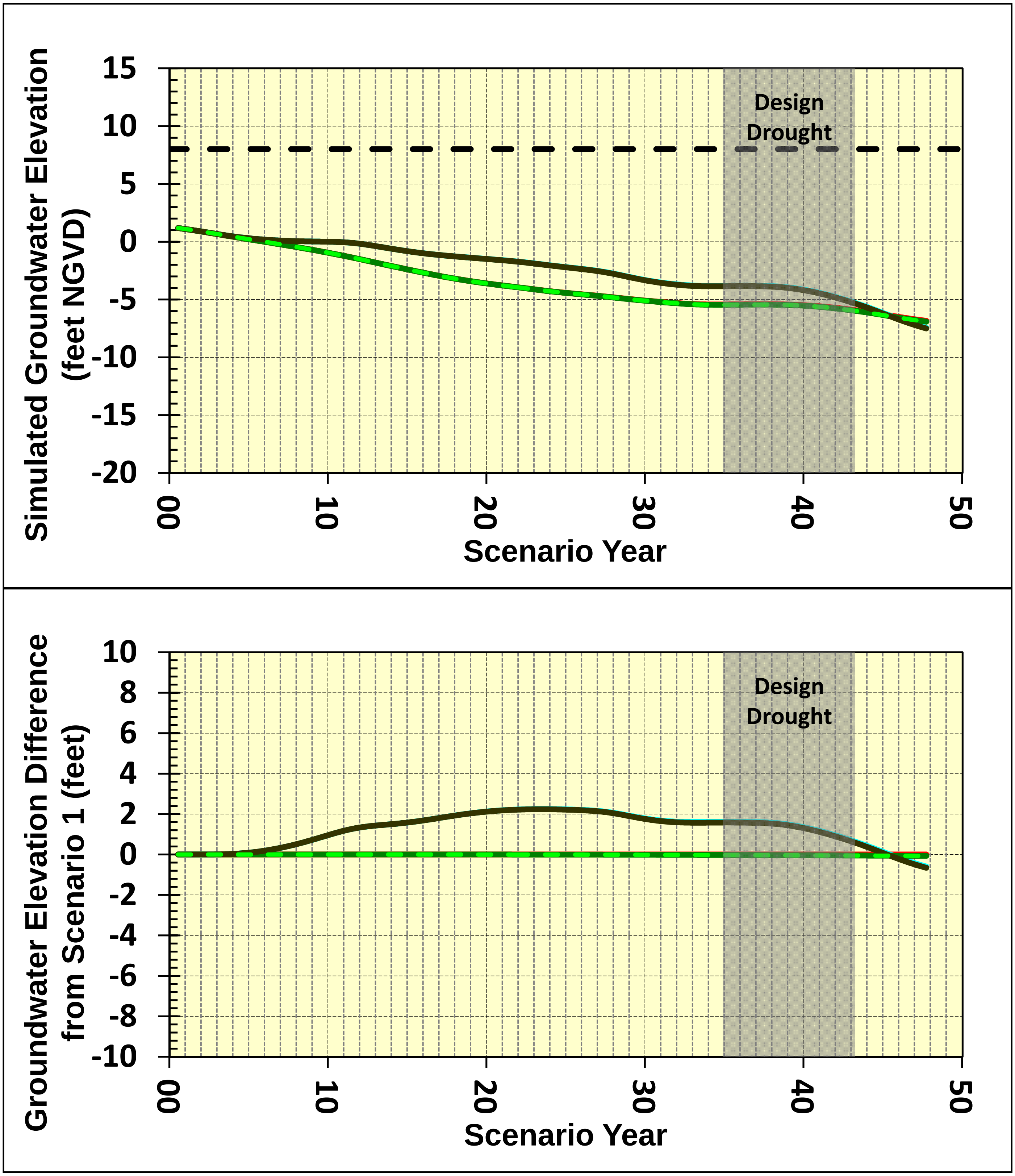
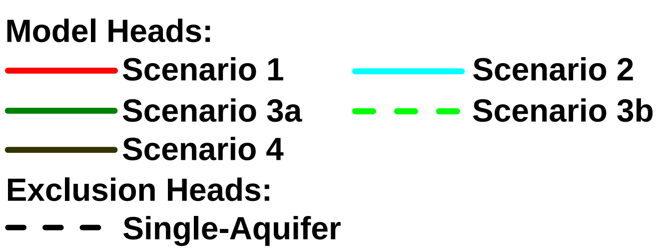
Figure 10.3-13a



Note: Zero elevation is equivalent to mean sea level NGVD.



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Model Layer 4 Hydrographs for Burlingame Cluster

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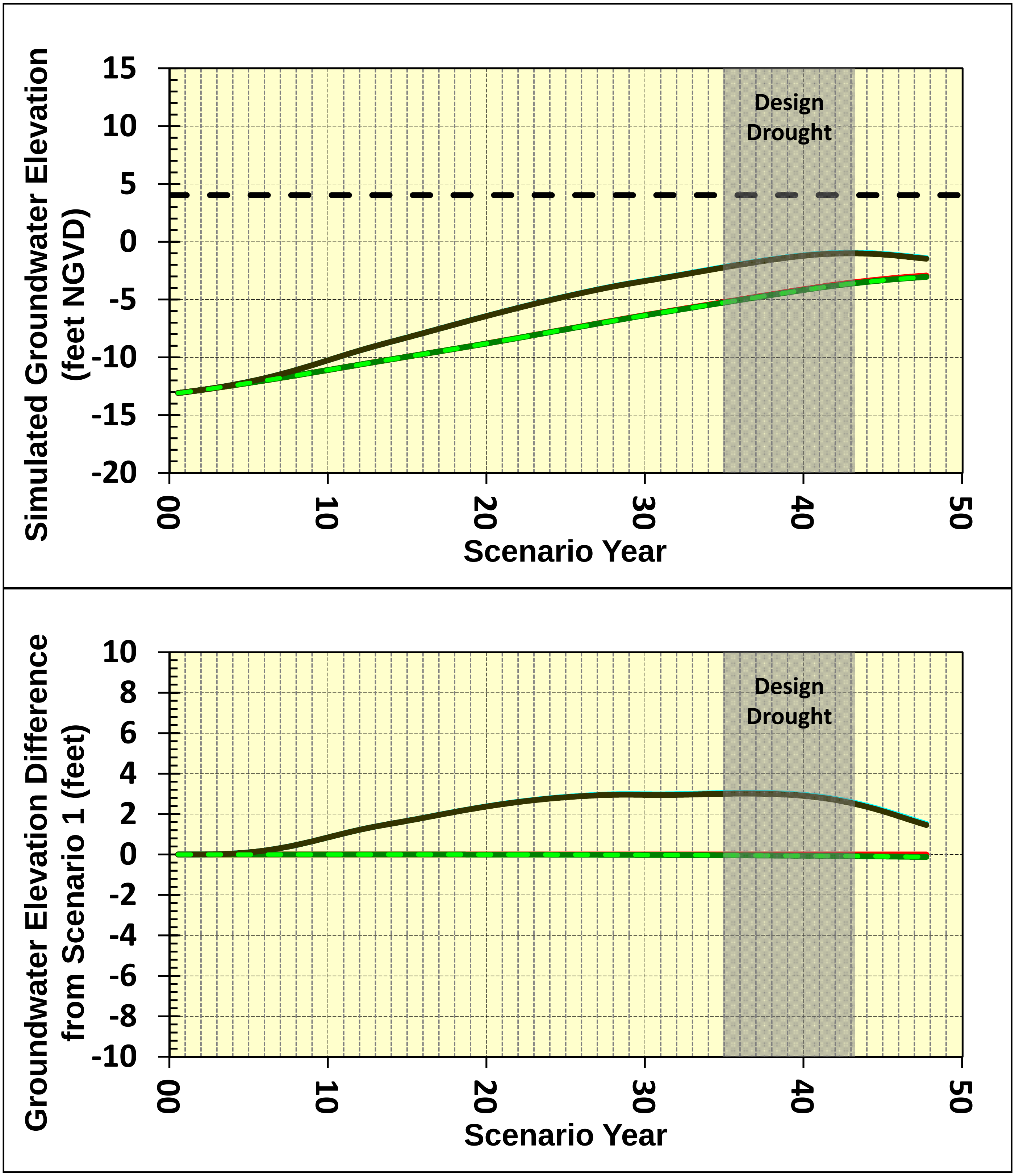
Figure 10.3-13b



Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer

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Model Layer 1 Hydrographs for SFO Cluster

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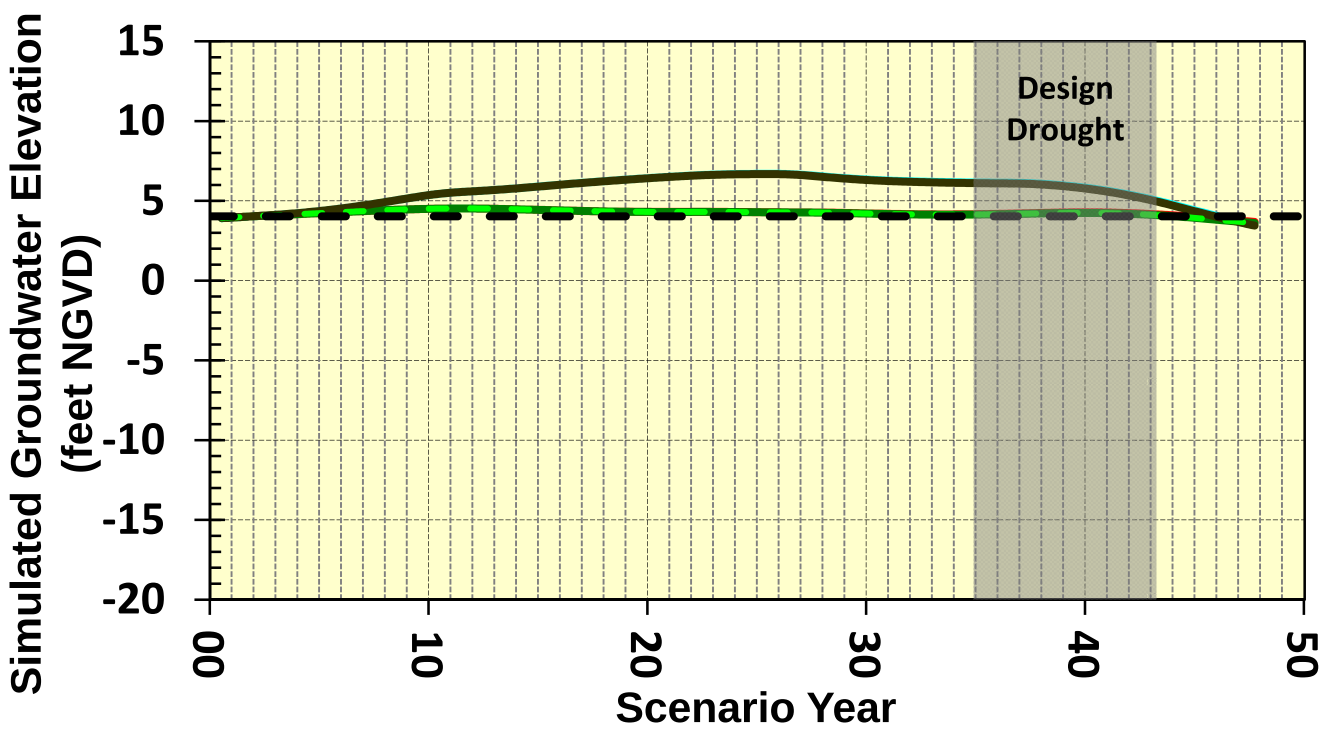
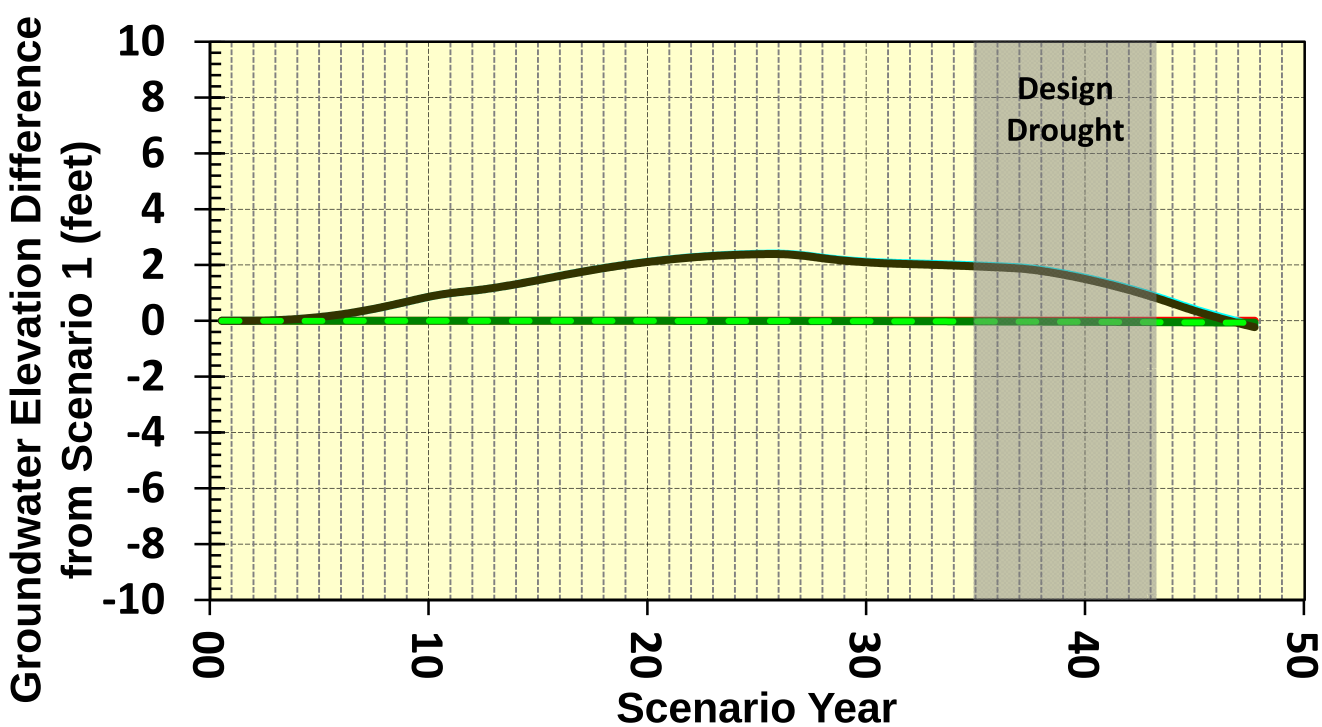
Figure 10.3-14





Note: Zero elevation is equivalent to mean sea level NGVD.

Model Heads:
- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

Exclusion Heads:
- Single-Aquifer

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Model Layer 1 Hydrographs for UAL Cluster

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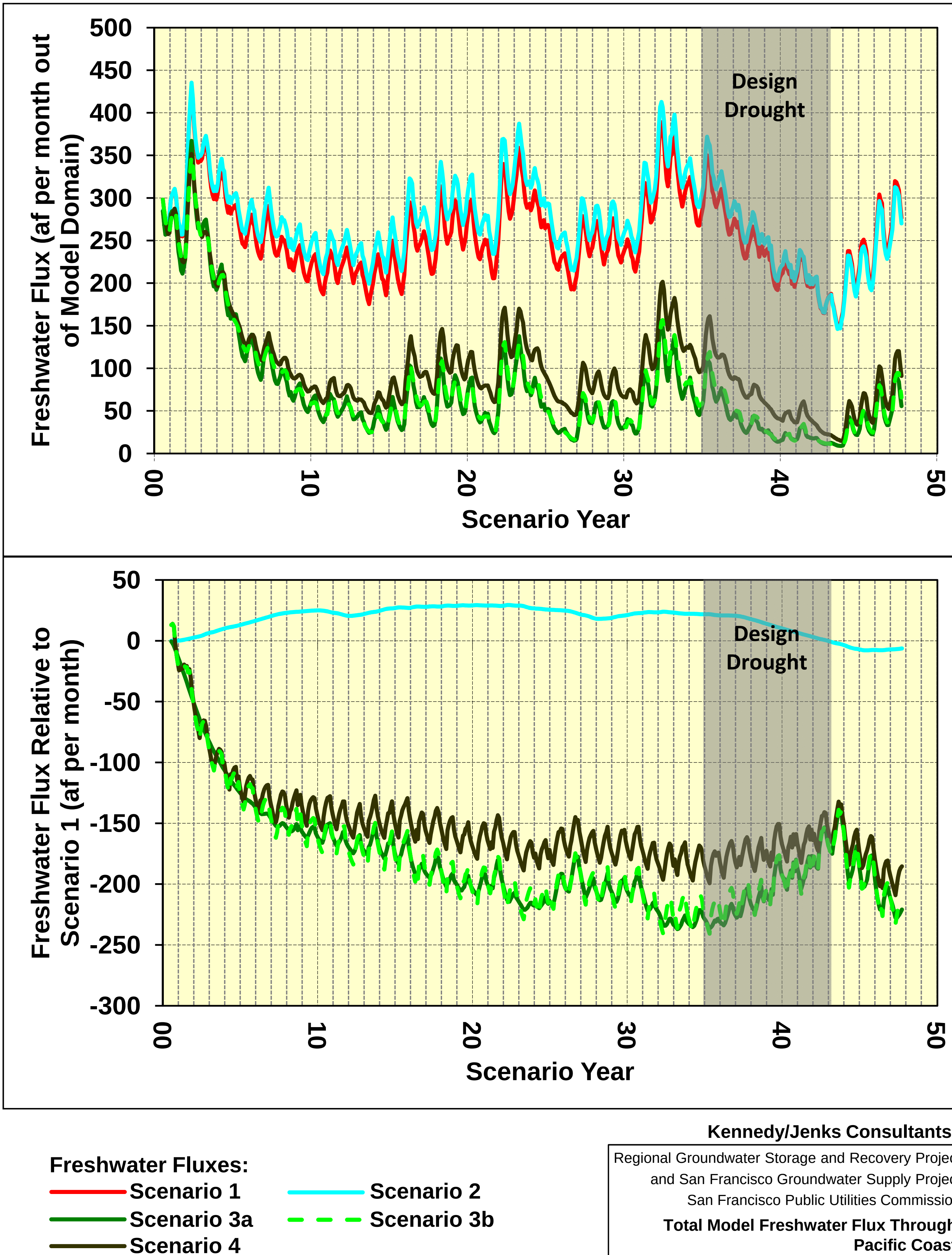
Figure 10.3-15



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Total Model Freshwater Flux Through Pacific Coast

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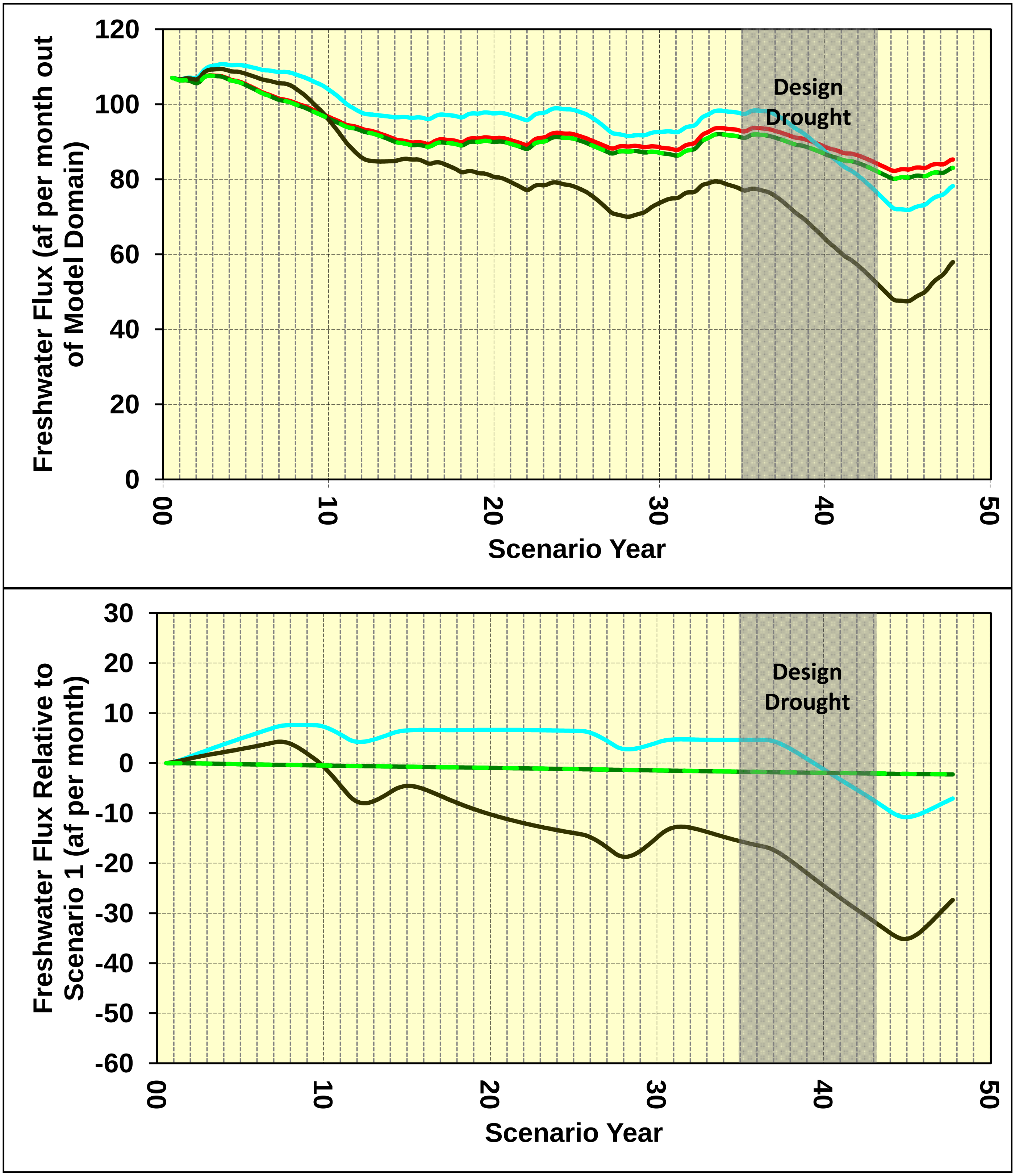
April 2012
Figure 10.3-16



Freshwater Fluxes:

- Scenario 1
- Scenario 2
- Scenario 3a
- Scenario 3b
- Scenario 4

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Total Model Freshwater Flux Through Bay Coast

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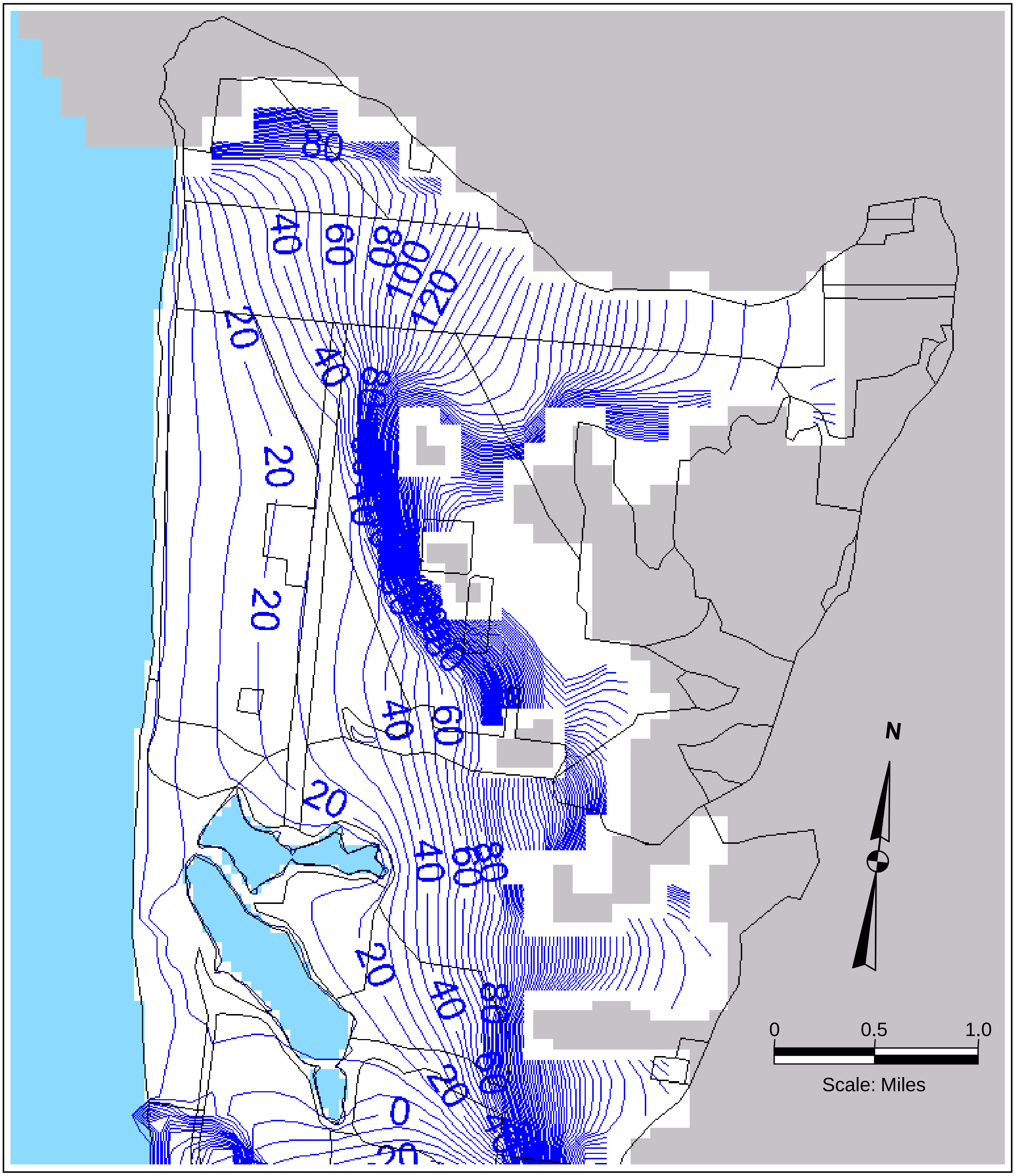
Figure 10.3-17



Note: Elevations are in feet NGVD 29. Contour interval is 5 feet.

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Water Table Elevation at End of Scenario 1 (Model Layer 1)

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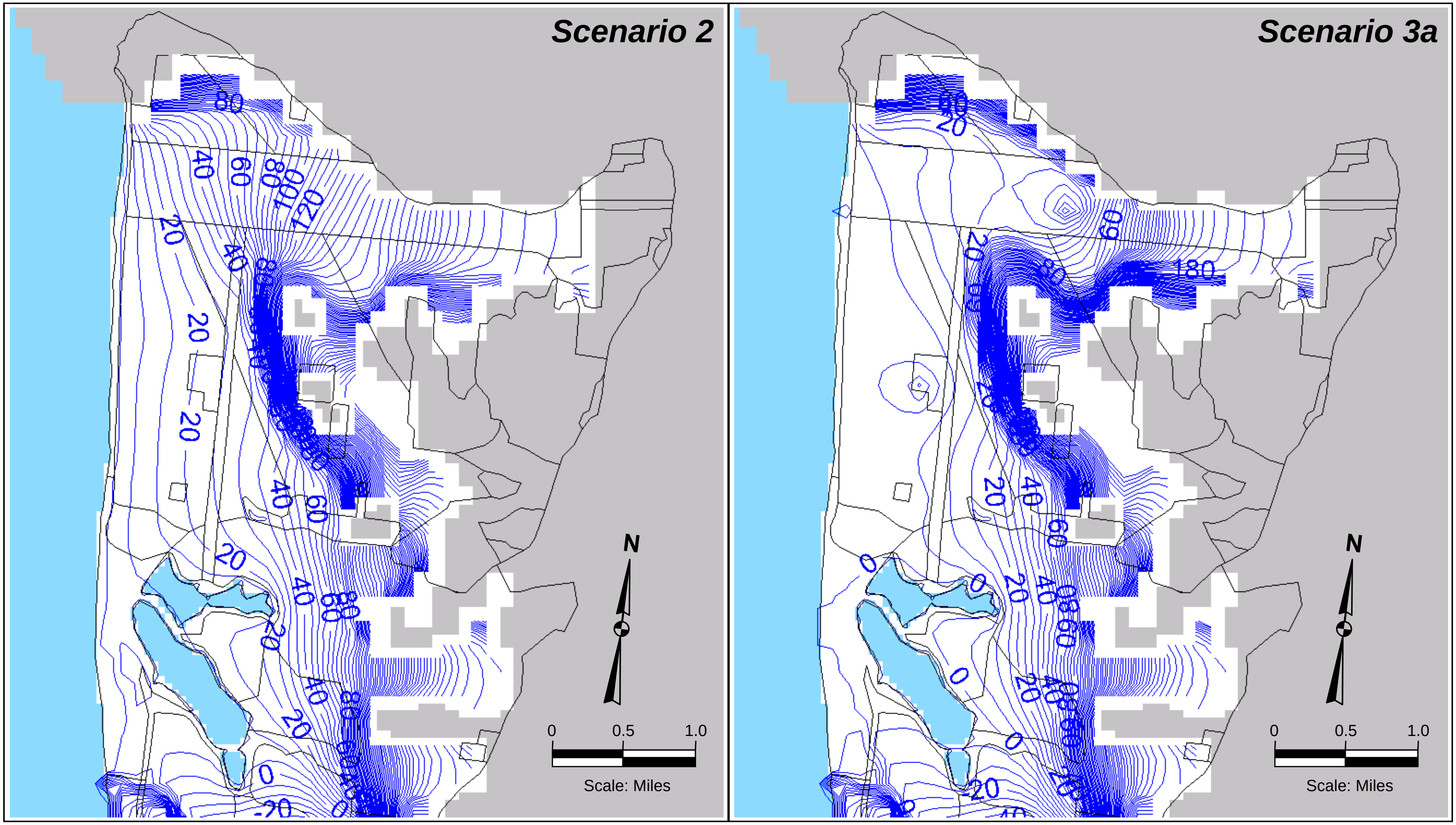
Figure 10.3-18



Note: Elevations are in feet NGVD 29. Contour interval is 5 feet.

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Water Table Elevation at End of Scenarios 2 and 3a (Model Layer 1)

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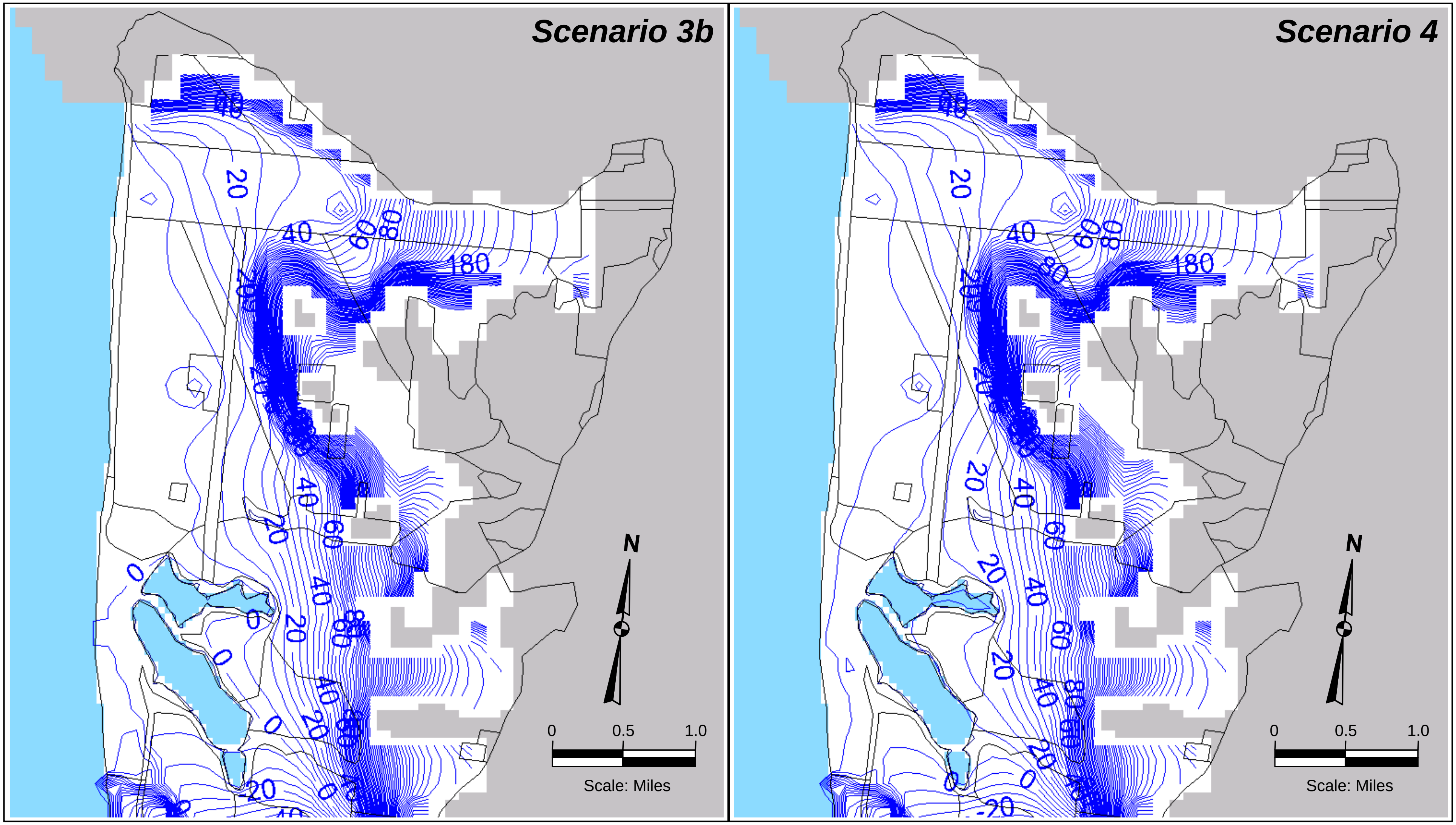
April 2012
Figure 10.3-19



Note: Elevations are in feet NGVD 29. Contour interval is 5 feet.

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Water Table Elevation at End of Scenarios 3b and 4 (Model Layer 1)

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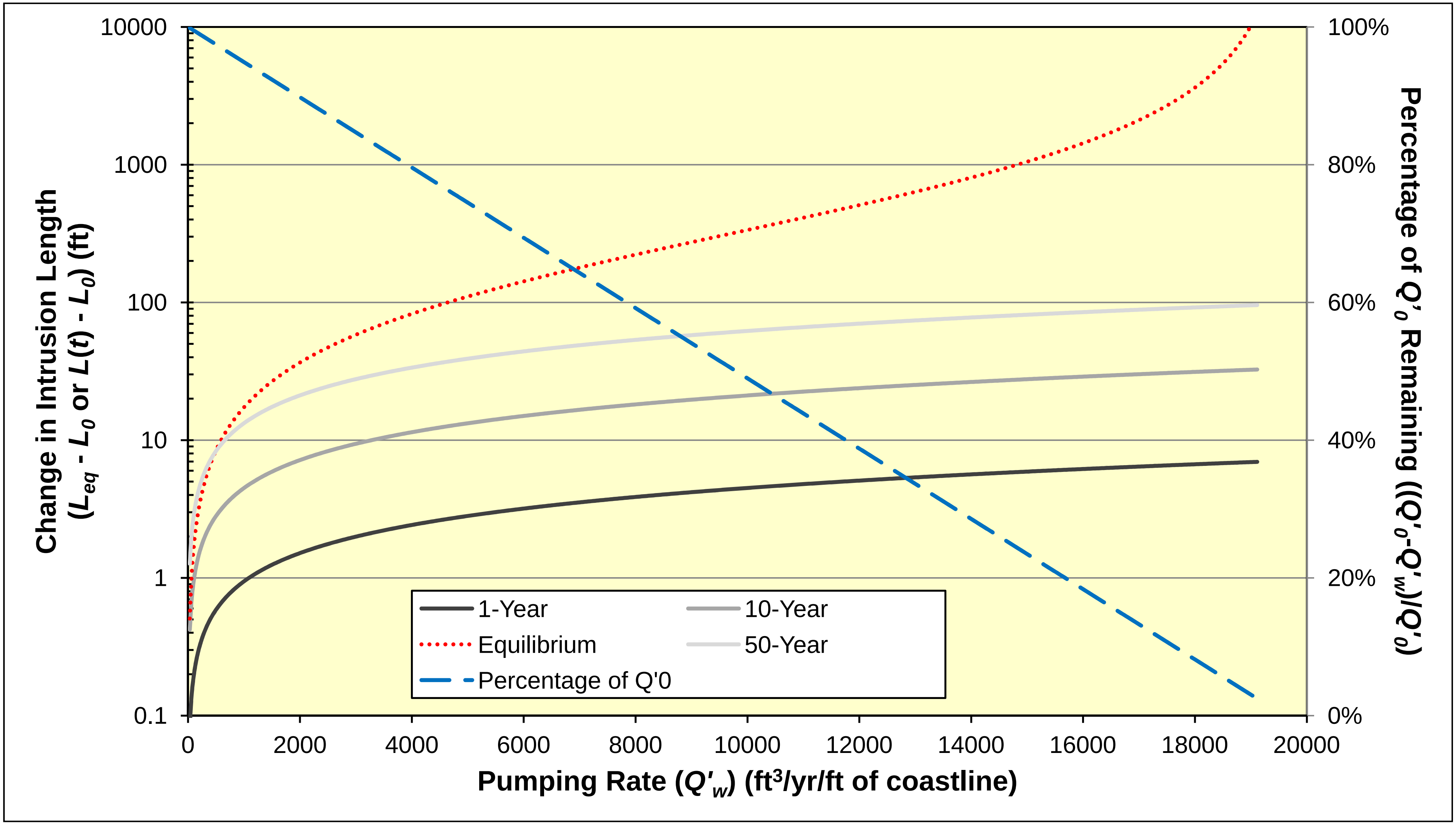
Figure 10.3-20



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Analytical Model of Rate of Change of Intrusion Length versus Pumping

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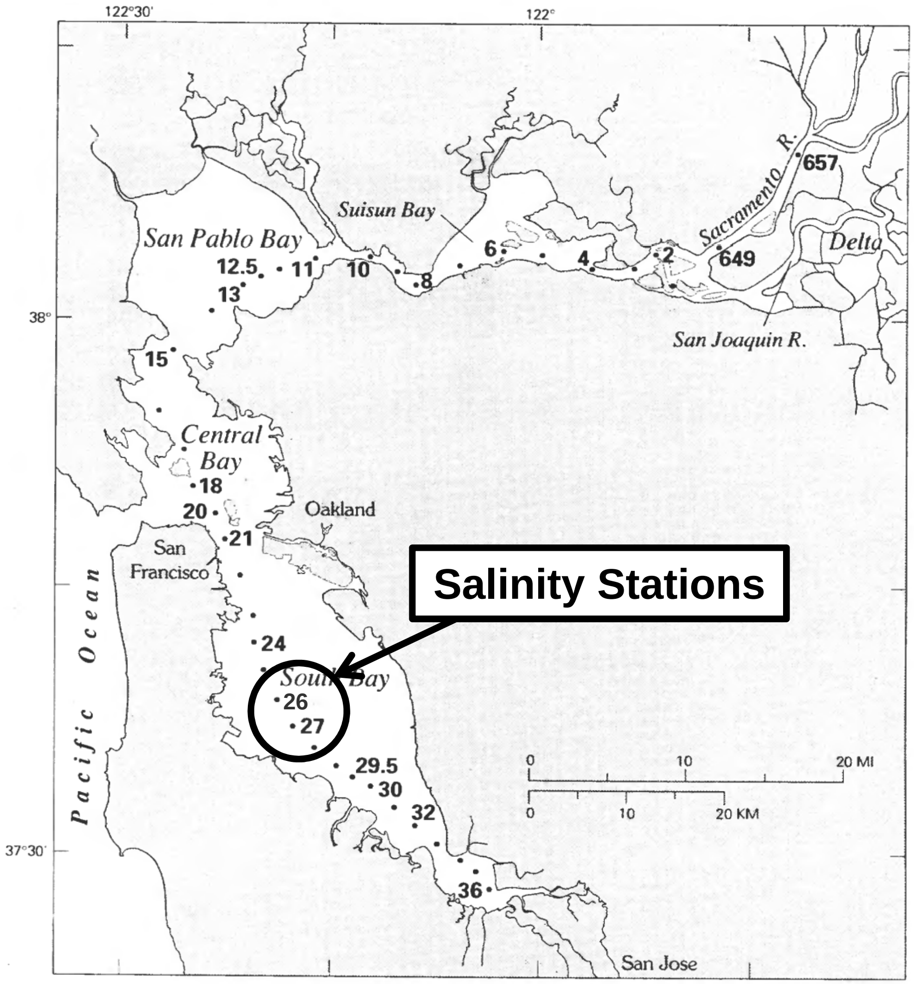
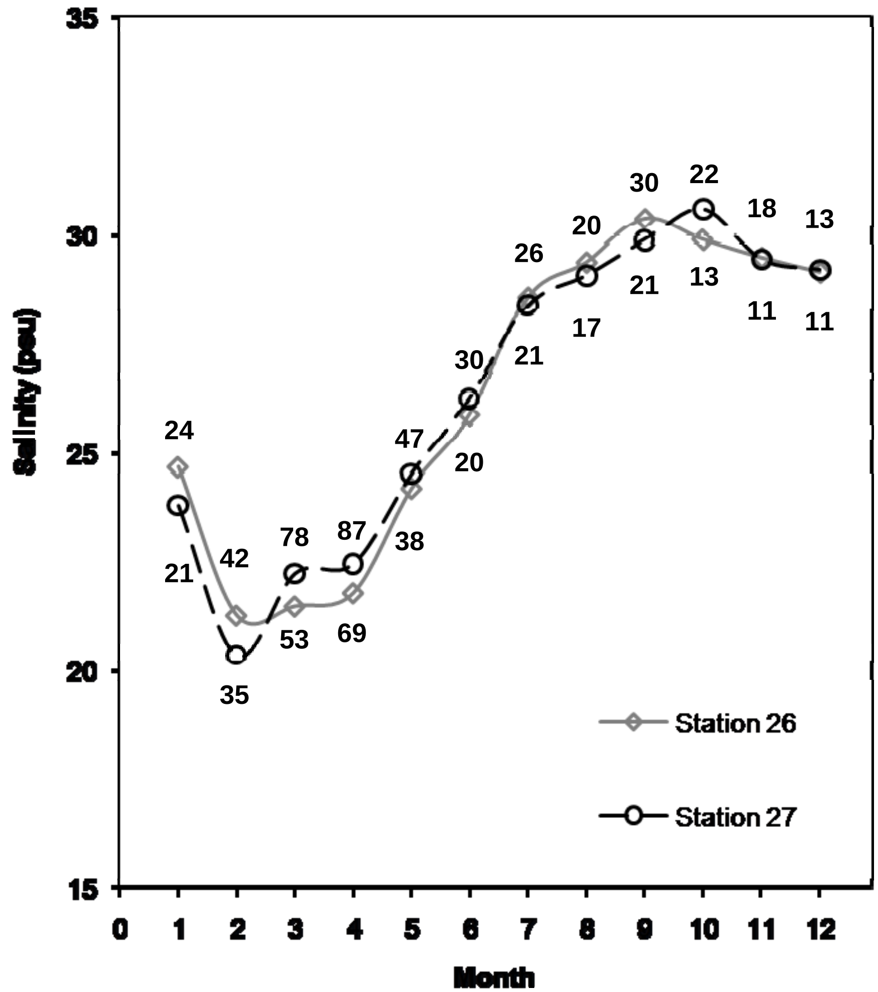
Figure 10.3-21





Note: Data from the U.S. Geological Survey; see for example Baylosis et al. (1998). Period of record is 1969 to 1998. Readings are from 1 meter depth. Numbers above the data are the number of records for Station 26, while numbers below the data are the number of records for Station 27. Map is modified from Baylosis et al. (1998).

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Monthly Salinity in the South San Francisco Bay

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Figure 10.3-22

Tables

Table 10.3-1: Summary of Model Scenario Pumping Assumptions

Model Scenarios		Scenario 1 Existing Conditions	Scenario 2 GSR	Scenario 3a SFGW	Scenario 3b SFGW	Scenario 4 Cumulative
Establish Initial Conditions		Hydrologic Sequence	Hydrologic Sequence	Hydrologic Sequence	Hydrologic Sequence	Hydrologic Sequence
	June 2009 Condition	√	√	√	√	√
Model Scenario Simulation Period						
	47.25 years (including Design Drought) Hydrologic Sequence: July 1996 to September 2003 -> October 1958 to November 1992 -> December 1975 to June 1978 -> July 2003 - September 2006		√	√	√	√
Pumping Assumptions for Municipal Use						
PA Municipal Wells (mgd)						
	"Take" Periods	6.84	6.90	6.84	6.84	6.90
	"Put" Periods	6.84	1.38	6.84	6.84	1.38
	"Hold" Periods	6.84	6.90	6.84	6.84	6.90
GSR Project Proposed Municipal Wells (mgd)						
	"Take" Periods	0.0	7.23	0.0	0.0	7.23
	"Put" Periods	0.0	0.04	0.0	0.0	0.04
	"Hold" Periods	0.0	0.04	0.0	0.0	0.04
SFGW Project Proposed Municipal Wells (mgd)						
	Year-Round Pumping	0.0	0.0	3.0	4.0	4.0
Total Municipal Pumping (PA + GSR + SFGW)						
	"Take" Periods	***6.84***	***14.13***	***9.84***	***10.84***	***18.13***
	"Put" Periods	***6.84***	***1.42***	***9.84***	***10.84***	***5.42***
	"Hold" Periods	***6.84***	***6.94***	***9.84***	***10.84***	***10.94***
Irrigation and Other Non-Potable Pumping Assumptions (mgd)(1)						
Golden Gate Park	Elk Glen (GGP)	0.081	0.081	0.081	0.000	0.000
	South Windmill (GGP)	0.498	0.498	0.498	0.000	0.000
	North Lake (GGP)	0.563	0.563	0.563	0.000	0.000
	Sub-Total	***1.142***	***1.142***	***1.142***	***0.000***	***0.000***
Golf Courses	Burlingame Golf Club	0.150	0.150	0.150	0.150	0.150
	California Golf No. 02	0.192	0.192	0.192	0.192	0.192
	Green Hills No. 05	0.099	0.099	0.099	0.099	0.099
	Lake Merced Golf No. 01	0.004	0.004	0.004	0.004	0.004
	Lake Merced Golf No. 02	0.004	0.004	0.004	0.004	0.004
	Lake Merced Golf No. 03	0.010	0.010	0.010	0.010	0.010
	Olympic Club No. 09(2)	0.002	0.002	0.002	0.002	0.002
	SF Golf West	0.035	0.035	0.035	0.035	0.035
	Sub-Total	***0.495***	***0.495***	***0.495***	***0.495***	***0.495***
Cemeteries	Cypress Lawn No. 02	0.020	0.020	0.020	0.020	0.020
	Cypress Lawn No. 03	0.144	0.144	0.144	0.144	0.144
	Eternal Home	0.013	0.013	0.013	0.013	0.013
	Hills of Eternity No. 02	0.020	0.020	0.020	0.020	0.020
	Holy Cross No. 03(3)	0.190	0.190	0.190	0.190	0.230
	Home of Peace No. 02	0.039	0.039	0.039	0.039	0.039
	Italian Cemetery	0.033	0.033	0.033	0.033	0.033
	Olivet	0.098	0.098	0.098	0.098	0.098
	Woodlawn No. 02	0.085	0.085	0.085	0.085	0.085
	Sub-Total	***0.641***	***0.641***	***0.641***	***0.641***	***0.681***
Other	Hillsborough Residents No. 1-12	0.291	0.291	0.291	0.291	0.291
	Edgewood Development Ctr.	0.009	0.009	0.009	0.009	0.009
	Zoo No.05	0.321	0.321	0.321	0.321	0.321
	Stern Grove	0.004	0.004	0.012	0.013	0.013
	Sub-Total	***0.626***	***0.626***	***0.634***	***0.635***	***0.635***
Total Irrigation and Other Non-Potable Pumping		***2.90***	***2.90***	***2.91***	***1.77***	***1.81***

Key:
afy - acre-feet per year
mgd - million gallons per day
PA - Partner Agencies
GGP - Golden Gate Park
GSR - Regional Groundwater Storage and Recovery
SFGW - San Francisco Groundwater Supply
SFPUC - San Francisco Public Utilities Commission

Notes:
(1) Pumping wells that are listed identify the wells in the model scenarios whose pumping assumptions were modified compared to the 2008 No-Project Scenario by HydroFocus (May, 2011, ver. 3.1), as a result of revised Soil Moisture Budget (SMB). Pumping rates for the three wells in GGP and the California Golf No. 02, Edgewood Development Center, Zoo No. 05, and Stern Grove wells were further modified compared to the results of revised SMB.
(2) Olympic Club No. 09 values include pumping for both Olympic Golf Club wells.
(3) Holy Cross No. 3 well irrigation pumping for Scenarios 1, 2, 3a, and 3b is based on the results of revised SMB. Based on the projected future build-out at the Holy Cross cemetery, an additional pumping of 0.04 mgd (45 afy) was estimated to occur under Scenario 4 (Cumulative).

Table 10.3-2a: Statistics for Relative Differences Between Model Scenario Groundwater Head and Scenario 1 Head in Model Layer 1

	Scenario	2				3a				3b				4			
	Location	Maximum Difference[a]	Minimum Difference[b]	Avgerage Difference[c]	Average Offset[d]	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset
Pacific Coast	North Windmill	0.1	0.0	0.0	0.0	0.0	-12.4	-10.2	-12.2	0.0	-13.2	-10.5	-12.1	0.0	-13.1	-10.4	-12.0
	South Windmill	0.1	-0.1	0.1	0.0	0.0	-9.7	-7.9	-9.5	0.3	-11.5	-8.9	-10.1	0.3	-11.4	-8.7	-9.9
	Kirkham	0.2	-0.1	0.1	0.0	0.0	-6.8	-5.6	-6.6	0.2	-6.9	-5.5	-6.4	0.2	-6.7	-5.3	-6.1
	Ortega	0.5	-0.2	0.3	0.0	0.0	-6.4	-5.5	-6.3	0.0	-6.1	-5.3	-6.0	0.0	-5.6	-4.7	-5.4
	West Sunset Playground	1.3	-0.2	0.8	0.5	-4.0	-23.8	-20.9	-23.0	-3.7	-22.4	-19.8	-21.6	-3.7	-20.3	-18.0	-19.4
	Taraval	0.6	-0.1	0.4	0.2	0.0	-5.2	-4.4	-5.1	0.0	-4.9	-4.2	-4.8	0.0	-4.1	-3.4	-3.8
	Zoo	2.7	-0.4	1.6	0.9	0.0	-7.2	-5.3	-7.1	0.0	-6.9	-5.1	-6.8	0.0	-3.0	-1.4	-2.3
	Fort Funston	0.1	-0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	-0.1	0.1	-0.2	0.0	-0.1
	Thornton Beach	0.5	0.0	0.3	0.3	0.0	-0.3	-0.1	-0.3	0.0	-0.3	-0.1	-0.3	0.2	-1.0	-0.1	-0.6
Bay Coast	Burlingame	1.3	0.0	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.7	0.8
	SFO	3.1	0.0	2.0	2.5	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.1	3.0	0.0	2.0	2.5
	UAL	2.4	-0.2	1.4	1.0	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	0.0	2.4	-0.2	1.4	1.0

Notes: (a) Maximum positive difference from Scenario 1. If this value is negative, the head was lower than Scenario 1 at all times.
(b) Maximum negative difference from Scenario 1. If this value is positive, the head was higher than Scenario 1 at all times.
(c) Average difference from Scenario 1.
(d) Average difference from Scenario 1 over Scenario Years 37 to 47.

Table 10.3-2b: Statistics for Relative Differences Between Model Scenario Groundwater Head and Scenario 1 Head in Model Layer 4

	Scenario	2				3a				3b				4			
	Location	Maximum Difference[a]	Minimum Difference[b]	Avgerage Difference[c]	Average Offset[d]	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset
Pacific Coast	North Windmill	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	South Windmill	0.1	-0.1	0.1	0.0	0.0	-7.3	-6.0	-7.1	2.3	-7.7	-5.1	-6.0	2.3	-7.6	-4.9	-5.8
	Kirkham	0.3	-0.2	0.2	0.0	0.0	-5.5	-4.6	-5.4	0.5	-5.5	-4.3	-5.0	0.5	-5.3	-4.0	-4.7
	Ortega	0.9	-0.7	0.5	-0.2	0.0	-6.3	-5.3	-6.2	0.0	-6.0	-5.1	-5.9	0.0	-5.8	-4.2	-5.3
	West Sunset Playground	2.5	-1.6	1.3	-0.2	-0.1	-12.2	-10.2	-11.9	-0.1	-11.7	-9.8	-11.5	-0.1	-10.6	-7.2	-9.3
	Taraval	3.0	-2.0	1.6	-0.2	-0.1	-12.1	-10.1	-11.9	-0.1	-11.7	-9.7	-11.4	-0.1	-10.4	-6.5	-8.8
	Zoo	6.1	-4.3	3.3	-0.4	-0.1	-18.9	-15.4	-18.5	-0.1	-18.3	-14.9	-17.9	-0.1	-16.0	-8.5	-12.6
	Fort Funston	0.6	-0.7	0.2	-0.3	0.0	-0.4	-0.3	-0.4	0.0	-0.4	-0.3	-0.4	0.4	-1.2	-0.2	-0.8
	Thornton Beach	1.2	-1.4	0.3	-0.7	0.0	-0.3	-0.2	-0.3	0.0	-0.3	-0.2	-0.3	1.0	-2.6	-0.5	-1.8
Bay Coast	Burlingame	2.3	-0.6	1.3	0.7	0.0	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	2.2	-0.7	1.2	0.7
	SFO	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	UAL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Notes: (a) Maximum positive difference from Scenario 1. If this value is negative, the head was lower than Scenario 1 at all times.
(b) Maximum negative difference from Scenario 1. If this value is positive, the head was higher than Scenario 1 at all times.
(c) Average difference from Scenario 1.
(d) Average difference from Scenario 1 over Scenario Years 37 to 47.

Table 10.3-2c: Statistics for Relative Differences Between Model Scenario Groundwater Head and Scenario 1 Head in Model Layer 5

	Scenario	2				3a				3b				4			
	Location	Maximum Difference[a]	Minimum Difference[b]	Avgerage Difference[c]	Average Offset[d]	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset	Maximum Difference	Minimum Difference	Avgerage Difference	Average Offset
Pacific Coast	North Windmill	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	South Windmill	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Kirkham	0.3	-0.2	0.2	-0.1	0.0	-5.0	-4.2	-5.0	0.5	-5.1	-3.9	-4.5	0.5	-4.8	-3.6	-4.3
	Ortega	1.1	-1.0	0.5	-0.4	0.0	-5.9	-4.9	-5.8	0.0	-5.6	-4.7	-5.5	0.0	-5.6	-3.8	-5.0
	West Sunset Playground	3.4	-3.6	0.8	-1.7	-0.1	-7.0	-5.9	-6.9	0.0	-6.7	-5.6	-6.6	0.0	-8.5	-3.9	-6.8
	Taraval	4.6	-5.2	0.8	-2.6	0.0	-5.6	-4.7	-5.5	0.0	-5.4	-4.5	-5.3	1.1	-8.7	-2.6	-6.2
	Zoo	12.2	-14.4	1.5	-7.5	0.0	-6.4	-5.2	-6.3	0.0	-6.2	-5.0	-6.1	8.5	-16.9	-1.3	-10.3
	Fort Funston	1.8	-2.2	0.2	-1.2	0.0	-0.4	-0.3	-0.4	0.0	-0.4	-0.3	-0.4	1.6	-2.5	0.0	-1.5
	Thornton Beach	1.5	-2.0	0.3	-1.0	0.0	-0.3	-0.2	-0.3	0.0	-0.3	-0.2	-0.3	1.4	-3.1	-0.5	-2.1
Bay Coast	Burlingame	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	SFO	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	UAL	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Notes: (a) Maximum positive difference from Scenario 1. If this value is negative, the head was lower than Scenario 1 at all times.
(b) Maximum negative difference from Scenario 1. If this value is positive, the head was higher than Scenario 1 at all times.
(c) Average difference from Scenario 1.
(d) Average difference from Scenario 1 over Scenario Years 37 to 47.

Table 10.3-3: Aquifer Thicknesses and Exclusion Head Values at Westside Basin Coastal Monitoring Points

	Well or Cluster	Single Aquifer		Multi-Aquifer					
				Shallow		Primary Production		Deep	
		b [a]	E_h [b]	*b*	E_h	*b+d* [c]	E_h	*b+d*	E_h
Pacific Coast	North Windmill	270	7.0	100	2.6	270	7.0	--	--
Pacific Coast	South Windmill	360	9.4	120	3.1	360	9.4	--	--
Pacific Coast	Kirkham	450	11.7	110	2.9	310	8.1	450	11.7
Pacific Coast	Ortega	490	12.7	100	2.6	340	8.8	490	12.7
Pacific Coast	West Sunset Playground	400	10.4	70	1.8	340	8.8	400	10.4
Pacific Coast	Taraval	550	14.3	130	3.4	390	10.1	550	14.3
Pacific Coast	Zoo	630	16.4	80	2.1	400	10.4	630	16.4
Pacific Coast	Fort Funston	1200	31.2	--	--	--	--	--	--
Pacific Coast	Thornton Beach	3000	78.0	--	--	--	--	--	--
Bay Coast	Burlingame	308	8.0	--	--	--	--	--	--
Bay Coast	SFO	155	4.0	--	--	--	--	--	--
Bay Coast	UAL	155	4.0	--	--	--	--	--	--

Notes:

(a) *b* = Depth (below sea level) of aquifer bottom (for Single-Aquifer and Shallow Aquifer cases), or aquifer thickness (for Primary Production and Deep Aquifer cases) (see Figure 10.3-3).
(b) *Eh* = Exclusion head, defined in Section 3.5.1.
(c) *d* = Depth (below sea level) of bottom of the confining unit (see Figure 10.3-3).

Table 10.3-4: Seasonal Fluctuation in Head for Model Layers 1, 4, and 5 at the Pacific Ocean and San Francisco Bay Monitoring Network Wells

Scenario	1			2			3a			3b			4		
Model Layer / Location	1	4	5	1	4	5	1	4	5	1	4	5	1	4	5
North Windmill	1.7	--	--	1.7	--	--	1.6	--	--	0.8	--	--	0.8	--	--
South Windmill	0.7	-0.7	--	0.7	-0.7	--	0.6	-0.8	--	0.7	0.3	--	0.7	0.3	--
Kirkham	0.9	0.3	0.3	0.9	0.3	0.3	0.9	0.3	0.2	0.6	0.3	0.2	0.6	0.3	0.2
Ortega	0.6	0.3	0.3	0.6	0.3	0.3	0.6	0.3	0.2	0.6	0.2	0.2	0.6	0.2	0.2
West Sunset Playground	0.7	0.3	0.1	0.7	0.3	0.1	0.5	0.3	0.1	0.5	0.2	0.0	0.5	0.3	0.1
Taraval	0.5	0.4	-0.1	0.5	0.3	-0.1	0.5	0.3	-0.1	0.5	0.3	-0.2	0.5	0.3	-0.2
Zoo	1.3	0.3	-0.5	1.3	0.2	-0.5	1.2	0.1	-0.6	1.2	0.1	-0.6	1.3	0.2	-0.5
Fort Funston	1.3	0.0	0.0	1.3	0.0	0.0	1.3	0.0	0.0	1.3	0.0	0.0	1.3	0.0	0.0
Thornton Beach	0.6	0.0	0.0	0.6	0.0	0.0	0.6	0.0	0.0	0.6	0.0	0.0	0.6	0.0	0.0
Burlingame	0.0	-0.1	--	0.0	-0.1	--	0.0	-0.1	--	0.0	-0.1	--	0.0	-0.1	--
SFO	0.1	--	--	0.1	--	--	0.1	--	--	0.1	--	--	0.1	--	--
UAL	0.0	--	--	0.0	--	--	0.0	--	--	0.0	--	--	0.0	--	--

Note:
Table cells containing "--" indicate that this Model Layer is not present in this location. Seasonal fluctuation is defined as the average difference between May head (generally representing the highest head annually) and November head (generally representing the lowest head annually).

Table 10.3-5: Model-Predicted Flux Through the Pacific Ocean and San Francisco Bay Coasts, Both Absolute and Relative to Scenario 1 (in acre-feet per month)

	Location	Scenario	1	2	3a	3b	4
Absolute	Pacific	AMax[a]	432	435	367	351	352
		AMin[b]	149	146	9	9	15
		AAvg[c]	255	273	75	77	103
	Bay	AMax	108	111	108	108	109
		AMin	82	72	80	80	47
		AAvg	93	96	91	91	80
Relative	Pacific	RMax[d]	--	29	-1	14	14
		RMin[e]	--	-8	-237	-241	-209
		RAvg[f]	--	17	-181	-179	-153
	Bay	RMax	--	8	0	0	4
		RMin	--	-11	-2	-2	-35
		RAvg	--	3	-1	-1	-13

Notes:

(a) Maximum absolute freshwater flux.

(b) Minimum absolute freshwater flux.

(c) Average absolute freshwater flux.

(d) Maximum flux difference from Scenario 1; if this value is negative, flux is always lower than in Scenario 1.

(e) Minimum flux difference from Scenario 1; if this value is positive, flux is always higher than in Scenario 1.

(f) Average flux difference from Scenario 1.

Table 10.3-6a: Percentage of Simulation Duration Below the Freshwater Exclusion Head (Model Layer 1)

Single-Aquifer Case

	Location	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b	Scenario 4
Pacific Coast	North Windmill	0%	0%	**57%**	**60%**	**59%**
	South Windmill	**33%**	**31%**	**95%**	**98%**	**98%**
	Kirkham	100%	100%	100%	100%	100%
	Ortega	100%	100%	100%	100%	100%
	West Sunset Playground	0%	0%	**99%**	**99%**	**99%**
	Taraval	100%	100%	100%	100%	100%
	Zoo	100%	100%	100%	100%	100%
	Fort Funston	100%	100%	100%	100%	100%
	Thornton Beach	**63%**	**61%**	**64%**	**64%**	**64%**
Bay Coast	Burlingame	100%	100%	100%	100%	100%
	SFO	100%	100%	100%	100%	100%
	UAL	**10%**	**7%**	**11%**	**11%**	**7%**

Shallow Aquifer

	Location	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b	Scenario 4
Pacific Coast	North Windmill	0%	0%	**5%**	**4%**	**4%**
	South Windmill	0%	0%	**73%**	**85%**	**83%**
	Kirkham	0%	0%	**77%**	**75%**	**66%**
	Ortega	0%	0%	**89%**	**89%**	**83%**
	West Sunset Playground	0%	0%	**90%**	**90%**	**85%**
	Taraval	0%	0%	**91%**	**91%**	**86%**
	Zoo	0%	0%	**35%**	**30%**	**0%**
	Fort Funston	--	--	--	--	--
	Thornton Beach	--	--	--	--	--
Bay Coast	Burlingame	--	--	--	--	--
	SFO	--	--	--	--	--
	UAL	--	--	--	--	--

Notes:

(1) Percentage represents the percentage of timesteps (i.e. months) with head below the exclusion head (see Section 3.5.1).

(2) -- = Model Layer is not present at this location.

Table 10.3-6b: Percentage of Simulation Duration Below the Freshwater Exclusion Head (Model Layer 4)

Single-Aquifer Case

	Location	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b	Scenario 4
Pacific Coast	North Windmill	--	--	--	--	--
	South Windmill	**99%**	**99%**	100%	100%	100%
	Kirkham	100%	100%	100%	100%	100%
	Ortega	100%	100%	100%	100%	100%
	West Sunset Playground	100%	100%	100%	100%	100%
	Taraval	100%	100%	100%	100%	100%
	Zoo	100%	100%	100%	100%	100%
	Fort Funston	100%	100%	100%	100%	100%
	Thornton Beach	100%	100%	100%	100%	100%
Bay Coast	Burlingame	100%	100%	100%	100%	100%
	SFO	--	--	--	--	--
	UAL	--	--	--	--	--

Primary Production Aquifer

	Location	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b	Scenario 4
Pacific Coast	North Windmill	--	--	--	--	--
	South Windmill	**99%**	**99%**	100%	100%	100%
	Kirkham	100%	100%	100%	100%	100%
	Ortega	100%	100%	100%	100%	100%
	West Sunset Playground	100%	100%	100%	100%	100%
	Taraval	100%	100%	100%	100%	100%
	Zoo	100%	100%	100%	100%	100%
	Fort Funston	--	--	--	--	--
	Thornton Beach	--	--	--	--	--
Bay Coast	Burlingame	--	--	--	--	--
	SFO	--	--	--	--	--
	UAL	--	--	--	--	--

Notes:

(1) Percentage represents the percentage of timesteps (i.e. months) with head below the exclusion head (see Section 3.5.1).

(2) -- = Model Layer is not present at this location.

Table 10.3-6c: Percentage of Simulation Duration Below the Freshwater Exclusion Head (Model Layer 5)

Single-Aquifer Case

	Location	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b	Scenario 4
Pacific Coast	North Windmill	--	--	--	--	--
	South Windmill	--	--	--	--	--
	Kirkham	100%	100%	100%	100%	100%
	Ortega	100%	100%	100%	100%	100%
	West Sunset Playground	100%	100%	100%	100%	100%
	Taraval	100%	100%	100%	100%	100%
	Zoo	100%	100%	100%	100%	100%
	Fort Funston	100%	100%	100%	100%	100%
	Thornton Beach	100%	100%	100%	100%	100%
Bay Coast	Burlingame	--	--	--	--	--
	SFO	--	--	--	--	--
	UAL	--	--	--	--	--

Deep Aquifer

	Location	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b	Scenario 4
Pacific Coast	North Windmill	--	--	--	--	--
	South Windmill	--	--	--	--	--
	Kirkham	100%	100%	100%	100%	100%
	Ortega	100%	100%	100%	100%	100%
	West Sunset Playground	100%	100%	100%	100%	100%
	Taraval	100%	100%	100%	100%	100%
	Zoo	100%	100%	100%	100%	100%
	Fort Funston	--	--	--	--	--
	Thornton Beach	--	--	--	--	--
Bay Coast	Burlingame	--	--	--	--	--
	SFO	--	--	--	--	--
	UAL	--	--	--	--	--

Notes:

(1) Percentage represents the percentage of timesteps (i.e. months) with head below the exclusion head (see Section 3.5.1).

(2) -- = Model Layer is not present at this location.

Table 10.3-7: Descriptions, Values, and Sources for Parameters Used in Analytical Rate Estimation Model (see Section 7.1)

Parameter	Type	Description	Value	Units	Source
b_u	parameter	Thickness of the unconfined aquifer below sea level	360	feet	LSCE, 2010
b_c	parameter	Thickness of the confined aquifer	240	feet	LSCE, 2010
d	parameter	Depth to the top of the confined aquifer below sea level	120	feet	LSCE, 2010
n_e	parameter	Effective (or available) porosity	0.2	--	CH2MHILL, 1995
x	variable	Horizontal location within the aquifer	--	feet	--
h_f	calculated	Freshwater head above sea level at location x	--	feet	--
K_h	parameter	Horizontal hydraulic conductivity of the aquifer	3652.5	ft/yr	CH2MHILL, 1995
ρ_f	constant	Density of fresh water	1	g/cm^3	Standard
ρ_s	constant	Density of salt water	1.026	g/cm^3	Standard
α	constant	Elasticity of the aquifer materials	1.00E-08	Pa^{-1}	Freeze and Cherry, 1979
β	constant	Compressibility of water	4.40E-10	Pa^{-1}	Freeze and Cherry, 1979
S_s	parameter	Specific storage of the confined aquifer	0.00002	ft^{-1}	Yates et al., 1990
Q'_0	parameter	Freshwater flux to the ocean per foot of shoreline prior to pumping	19600	ft^3/yr/ft of coastline	Yates et al., 1990
Q'_w	input	Rate of pumping per foot of shoreline	--	ft^3/yr/ft of coastline	--
Δt	input	Time period over which pumping is applied	--	years	--
z	calculated	Depth to saltwater interface below sea level	--	feet	--
L	calculated	Length from the discharge point to the toe of the wedge	--	feet	--

Table 10.3-8: Average Water Quality for Westside Basin Monitoring Wells

	Calcium	n	Magnesium	n	Sodium	n	Potassium	n	Total Alkalinity	n	Chloride	n	Sulfate	n	Specific Conductance	n	Total Dissolved Solids	n	Hardness as $CaCO_3$	n	pH	n
North Westside Basin																						
Kirkham MW-130	28.5	3	25.8	3	26.3	3	1.5	3	123	3	33.3	13	33.5	3	447	14	258	14	172	4	8.0	4
Kirkham MW-255	28.1	3	30.3	3	22.4	3	1.4	3	133	3	36.3	13	30.0	3	460	14	274	14	196	4	7.9	4
Kirkham MW-385	56.1	3	7.4	3	25.8	3	4.9	3	119	3	34.6	13	64.2	3	455	14	285	14	166	4	8.1	4
Kirkham MW-435	46.9	3	4.0	3	35.2	3	7.4	3	113	3	31.2	13	60.3	3	445	14	277	14	132	4	8.2	4
Ortega MW-125	26.8	3	22.1	3	26.3	3	1.3	3	106	3	30.8	14	36.3	2	436	14	257	13	147	4	7.9	4
Ortega MW-265	14.4	3	12.4	3	20.9	3	1.0	3	81	2	26.1	14	12.2	2	353	13	210	12	86	3	8.1	3
Ortega MW-400	16.2	3	12.7	3	22.7	3	1.4	3	90	2	23.0	14	10.7	3	274	14	178	14	92	3	8.2	3
Ortega MW-475	13.3	3	1.9	3	43.2	3	3.1	3	78	3	28.9	14	14.1	3	285	14	173	14	42	4	8.3	4
Taraval MW-145	29.4	3	25.8	3	29.6	3	1.8	3	132	2	36.6	13	24.4	3	483	14	296	14	171	3	7.9	3
Taraval MW-240	21.8	3	20.1	3	23.1	3	1.7	3	104	2	34.2	14	18.9	3	376	14	228	14	137	3	7.8	3
Taraval MW-400	18.4	3	15.4	3	21.9	3	1.6	3	90	2	27.2	14	26.3	2	308	14	189	12	116	3	8.2	3
Taraval MW-530	11.7	2	5.4	2	51.1	2	2.4	2	120	2	24.6	14	8.8	2	326	14	199	14	56	3	8.4	3
Zoo MW-275	20.4	5	18.7	4	37.3	4	4.4	5	115	4	67.0	12	7.3	4	466	14	264	13	116	5	8.6	5
Zoo MW-450	22.5	5	25.4	5	41.7	5	2.6	5	134	4	43.8	12	18.8	5	483	14	287	14	142	5	8.4	5
Zoo MW-565	27.6	4	10.2	4	67.5	4	3.4	4	167	3	53.2	13	7.3	3	503	13	293	13	103	4	8.3	4
SWM MW-57	--	0	--	0	--	0	--	0	--	0	160.1	8	53.0	1	1191	8	667	7	--	0	--	0
SWM MW-140	--	0	--	0	--	0	--	0	--	0	60.8	8	39.0	1	675	8	381	7	--	0	--	0
Edgewood School	24.7	2	25.3	2	25.2	3	1.4	2	116	4	30.5	4	35.9	4	448	4	258	3	170	4	7.4	4
Elk Glen 2	34.6	5	37.1	5	27.1	5	1.0	4	142	5	40.2	6	52.4	6	575	6	367	6	227	6	7.7	6
LMMW1S	60.4	4	90.4	4	102.1	4	2.8	4	317	4	252.5	4	108.3	4	1545	4	853	4	568	4	6.8	4
LMMW1D	30.0	2	45.0	2	47.5	2	3.2	2	161	2	105.0	2	27.5	2	781	2	435	2	265	2	7.9	2
LMMW-2S	40.0	4	32.7	4	59.5	4	2.9	4	214	4	95.0	4	30.5	4	777	4	417	4	260	4	7.5	4
LMMW-2D	41.1	4	33.6	4	58.9	4	3.2	4	222	4	95.3	4	30.4	4	790	4	432	4	258	4	7.5	4
LMMW3S	45.5	11	50.6	10	46.1	11	1.8	10	310	10	51.9	10	28.5	10	786	10	453	10	287	9	7.2	10
LMMW3D	29.8	11	32.1	11	42.0	11	1.9	10	180	10	76.5	11	13.3	11	600	11	339	11	204	10	7.6	11
LMMW4SS	37.1	2	41.5	2	33.0	2	1.7	2	194	1	55.5	1	44.5	1	624	1	464	1	244	1	7.3	1
LMMW6D	27.8	11	28.4	10	36.9	11	1.4	10	127	10	52.7	11	32.5	11	556	11	334	11	186	10	8.0	11
LMMW7SS	43.2	3	44.4	3	55.6	3	1.4	3	240	2	44.4	2	46.4	2	753	2	476	2	271	2	7.6	2
(NE) Windmill	28.6	1	36.2	1	30.6	1	1.7	1	174	2	48.0	2	36.0	2	575	2	269	2	221	2	7.5	2
New GG Park (N) Lake	26.0	4	31.6	4	27.8	4	1.1	4	143	4	42.7	4	27.5	4	505	4	304	4	193	4	7.6	4
New GG Park (S) Windmi	29.5	4	35.8	4	28.0	4	1.5	4	149	5	42.8	4	43.7	3	562	4	340	4	234	4	7.9	4
(NW) Windmill	20.0	1	24.3	1	24.6	1	1.3	1	140	3	42.7	3	20.0	3	467	3	173	2	174	3	7.8	3
Olympic Club #8	38.5	1	39.7	1	46.0	1	2.0	1	189	1	84.0	1	30.5	1	685	1	--	0	--	0	8.1	1
Pine Lake Prod Well	32.7	1	33.4	1	36.4	1	1.1	1	144	1	35.3	1	37.0	1	565	1	336	1	244	1	7.2	1
(S) Windmill	26.5	3	29.1	3	26.1	3	1.4	3	133	4	40.3	5	26.7	5	476	5	262	4	185	5	7.7	5
West Sunset Playground	17.5	9	18.1	9	23.0	9	1.0	9	88	8	28.1	9	28.7	9	353	9	222	9	124	9	8.5	9
(S) Sunset Playground	30.2	3	32.6	3	36.8	3	1.3	3	159	2	41.7	3	33.0	3	573	3	366	3	205	3	7.4	3
CPS MW-190	44.2	3	44.7	3	44.4	3	1.5	3	267	3	42.3	3	44.0	3	725	3	413	3	295	3	7.6	3
CPS MW-270	29.9	3	23.0	3	46.0	3	1.5	3	171	3	70.3	3	9.7	3	552	3	297	3	168	3	7.9	3
LMPS MW-155	26.7	4	25.0	4	36.5	3	2.2	4	106	4	38.6	3	45.7	3	492	2	317	4	175	3	7.7	4
LMPS MW-270	24.2	4	17.6	4	55.9	4	1.5	4	127	4	43.7	3	34.7	3	522	3	323	4	134	4	7.8	3
LMPS MW-440	19.3	4	21.2	4	30.8	4	1.3	4	109	4	50.3	3	8.0	3	412	3	247	4	135	4	8.2	4
South Westside Basin																						
Burlingame-S	49.5	9	33.3	9	423	9	5.0	9	240	9	342	9	448	9	2,401	8	1,393	9	--	0	7.3	8
Burlingame-M	31.4	9	19.0	9	69.7	9	3.1	9	181	9	82.3	9	61.9	9	656	8	464	9	--	0	7.2	8
Burlingame-D	35.6	9	20.9	9	83.2	9	4.6	9	206	9	64.1	9	43.3	9	596	8	402	9	--	0	7.3	8
SFO-D	55.0	9	34.3	9	179	8	9.2	9	234	9	609	9	76.4	9	2,036	9	1,202	9	--	0	7.5	8
SFO-S	423.7	9	519.7	9	4,689	9	66.9	9	610	9	9,910	9	802	9	30,757	7	16,300	8	--	0	7.3	9

Notes:

(1) Data from SFPUC 2010 Annual Groundwater Monitoring Report (SFPUC, 2011). Data marked "anomalous or questionable result" were removed from these averages.

(2) n is the number of samples included in the average.

(3) All analytes except Specific Conductance and pH are reported in units of milligrams per liter; Specific Conductance is reported in micromhos per centimeter, while pH is reported in pH units.

Attachment A

Analytical Approach

Attachment A: Analytical Approach

A. Analytical Approach

Because the numerical groundwater model is not perfectly suited to simulating the occurrence of seawater intrusion, an analytical approach to the problem of seawater intrusion is also applied in this section. This method combines a physical treatment of the relation between freshwater head and the depth to the seawater interface with a Darcy's Law approach to relating freshwater flux to the location of the interface. This approach does not explicitly deal with the problem of the transition zone (i.e., it assumes a sharp interface). It should be noted that the analytical solutions presented here deal with simplified aquifer constructions, and are not meant to exactly model reality, but rather provide another useful estimate of the future occurrence of seawater intrusion under a variety of conditions.

A.1. Ghyben-Herzberg Relation

The analytical solution to seawater intrusion was first developed in the late nineteenth (Badon-Ghyben, 1888) and early twentieth (Herzberg, 1901) centuries. Independently of each other, these two investigators found that the seawater-freshwater interface in coastal aquifers occurs at a depth below sea level about 38 times the freshwater head at a given location (Cheng and Ouazar, 1999). This is due to the difference in densities between seawater and freshwater.

Assuming that the seawater and freshwater zones are in approximate hydrostatic equilibrium, the pressure in each zone is defined based on the head in the aquifer:

$$p_s = zg\rho_s$$

$$p_f = g\rho_f\left(z + h_f\right)$$

where p_s is the pressure on the seawater side of the interface, z is the depth (below msl) to the interface, g is the acceleration due to gravity, ρ_s is the density of seawater, p_f is the pressure on the freshwater side of the interface, ρ_f is the density of freshwater, and h_f is the water table elevation (height above msl). Because the pressure must be the same on both sides of this interface, these two equations can be related:

$$zg\rho_s = g\rho_f\left(z + h_f\right)$$

$$z = \frac{\rho_f}{\rho_s - \rho_f} h_f$$

With standard values of density for freshwater (1.0 g/cm^3) and seawater (1.026 g/cm^3), this equates to:

$$z = 38h_f$$

With this proportionality in mind, a schematic of a simplified aquifer can be constructed (Figure 10.3-3). The shape of the head profile in this schematic is dictated by the flux through the aquifer and the hydraulic conductivity (see Section A.3.4); the seawater-freshwater interface and the freshwater head gradient both steepen approaching the discharge point because the freshwater flux (which is assumed to be equal at all horizontal locations up to the discharge point) must pass through a progressively smaller thickness of freshwater aquifer. According to Darcy's law (see Section A.3.4), the flux is proportional to the product of the aquifer thickness and the head gradient, so as the freshwater aquifer thickness declines the head gradient must increase to compensate.

For this simplified treatment of a coastal aquifer, a number of assumptions are made:

- Flow is steady, i.e., flow does not change over time.
- The interface between the seawater and freshwater sections of the aquifer is sharp, i.e., there is no transition zone.
- The seawater portion of the aquifer is under hydrostatic conditions, i.e., there is no flow within this section of the aquifer.
- Flow in the freshwater aquifer is essentially horizontal, which amounts to the Dupuit-Forchheimer assumption in an unconfined aquifer.
- The aquifer top (where applicable) and base (whether a fine-grained layer or the bedrock surface) are horizontal.

The first assumption listed, that of steady flow, runs counter to the purpose of this TM, i.e., determining how changes in the flow regime will affect seawater intrusion. However, considering the timescales involved in seawater intrusion, the assumption of steady flow is safe for a screening-level analysis.

A.2. Upconing of the Seawater-Freshwater Interface

While the Ghyben-Herzberg relationship can predict the depth to the interface between freshwater and salt water in the aquifer away from active wells, in the vicinity of these wells the relationship does not hold. If a well is screened over only a portion of the aquifer, the reduced pressure around the screen leads to upward movement of groundwater below the well. The Ghyben-Herzberg relationship assumes horizontal flow, while, with a well that is not screened across the entire aquifer thickness, a significant component of vertical flow exists in the vicinity of the well. If a seawater-freshwater interface exists below the well, the upward movement of groundwater deflects this interface upward, a process called "upconing."

Bouwer (1978) developed a solution to the location of the interface below a well when upconing is occurring. This method starts with the results of the Ghyben-Herzberg solution (i.e., the depth to the interface at the well location), and modifies them slightly to determine the extent of upconing:

$$Z = \frac{\rho_f}{\rho_s - \rho_f} \frac{Q}{2\pi K z_i}$$

where Z is the height of the cone beneath the center of the well (measured from the location of the interface determined by the Ghyben-Herzberg relationship), Q is the discharge in the well, K is the horizontal hydraulic conductivity, and z_i is the depth of the Ghyben-Herzberg interface below the bottom of the well.

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A.3. Key Data Sets

The specifics of the analytical method are described in Section A.4 below. For the solutions provided below, the pertinent data are the freshwater head, the flux of freshwater into the ocean, the horizontal hydraulic conductivity of the aquifer, the thickness of the aquifer, and the location of the discharge of freshwater into the ocean. Most of these numbers can be derived directly from the numerical groundwater model, but the purpose of this section is to provide an analysis of the issue of seawater intrusion that is as independent of the numerical model as possible. Therefore, values for these variables and parameters will be based on independent estimates from previously published reports or actual field observations. The numerical model will be used to provide values of freshwater head under the various model scenarios, as the effects of the changes in the pumping regime have not been independently quantified.

A.3.1. Freshwater Head

The freshwater head in the aquifer is determined based on field measurements of depth to groundwater in the various monitoring wells present throughout the Basin. These measurements are not a perfect method for determining the head in the aquifer for several reasons. For this analysis, horizontal flow is assumed, meaning that there is no vertical head gradient within the aquifer. In any column of an actual aquifer, the head is not the same everywhere, and the wells in the monitoring network sample across a fairly tightly constrained thickness of the aquifer. Head can also vary significantly between layers in a stacked aquifer structure such as that present in the Westside Basin, although the monitoring well network was constructed carefully to not sample multiple layers. The monitor well network also does not sample all horizontal locations in the aquifer. The monitor well is a discrete point within a continuous and extensive aquifer, and the data measured within a network of monitor wells must not be considered to capture all variability within the aquifer.

With these caveats in mind, head must be defined for this analysis based on actual measurements from the existing monitoring well network, the details of which are summarized in Section 2.2.2 above. Head has been measured in the North Westside Basin since 2002 for the Zoo cluster, 2003 for the Thornton Beach cluster, 2004 for the Kirkham, Ortega, and Taraval clusters, and 2006 for the South Windmill cluster. Hydrographs for these wells are presented in the annual groundwater monitoring reports for the Westside Basin (i.e., SFPUC, 2011). These hydrographs, along with head values measured at some wells further inland (e.g., the West Sunset Playground well), are used to assess current conditions according to the analytical method.

In addition to the current conditions, future conditions will be assessed. To do so, head levels predicted by the numerical model will be considered in relation to the freshwater head needed at each monitoring location to prevent seawater intrusion to occur at that point.

A.3.2. Horizontal Hydraulic Conductivity

Horizontal hydraulic conductivity (K_h) is an empirical proportionality constant that dictates the degree to which an aquifer allows water to pass through it. This parameter is not easily predicted based solely on the physical properties of the aquifer, although numerous hydrologic textbooks provide ranges of values for typical rocks and unconsolidated deposits (i.e., Freeze and Cherry, 1979, p.29). Instead, K_h is usually determined at individual wells using aquifer tests, calculated based on established time-drawdown relationships. These tests have been performed at a number of locations in the Basin in the past, and this section summarizes those published values.

In the North Westside Basin, K_h values were collected from various references by Phillips et al. (1993). These values, measured mostly in Golden Gate Park or along the Pacific coast between Golden Gate Park and Lake Merced, varied from 5 to 31 ft/d, with an average value of 17.3 ft/d, an arithmetic mean of 16.5 ft/d, and a geometric mean of 15.4 ft/d.

CH2M HILL (1995) performed a seawater intrusion model analysis on the North Westside Basin. K_h was determined for three model layers, roughly corresponding (from lowest to highest) with the Merced Formation, the Colma Formation, and the surficial dune sands (plus unconfined portions of the Colma Formation). While initial estimates were based on the values presented in Phillips et al. (1993), calibration of the model resulted in values of K_h of 10 ft/d for the upper two layers and 8 ft/d for the lowest layer. While these calibrated values are useful for giving additional insight into the likeliness of values within the existing range, they cannot be considered to be exact, due to the non-uniqueness inherent in a numerical solution within a complex model domain.

LSCE (2005) presented the results of an aquifer test performed at the South Sunset Playground well. The constant-rate test was run for 4.6 days at an average discharge rate of 409 gallons per minute. Using the Cooper-Jacob method, the aquifer transmissivity was determined to be about 27,100 gallons per day per foot (gpd/ft). No aquifer thickness is reported, so K_h cannot be calculated (transmissivity, T, is equal to the product of K_h and the aquifer thickness, B).

Rather than choose a single value of K_h for the Pacific Coast, a range of values (5 to 31 ft/d) will be used. The part of the analytical method that uses values of K_h (see Section A.6) was not performed for the Bay Coast due to the lack of an independent estimate for freshwater flux (see Section A.3.4).

A.3.3. Aquifer Thickness

The aquifer thickness is likely the most likely parameter to determine accurately. The aquifer materials are well-defined at the individual well locations and can be interpolated in between. The movement of a seawater-freshwater interface through a real aquifer happens in a very complex manner, due to the heterogeneity of the aquifer.

Seawater tends to intrude along the base of an aquifer, atop a relatively impermeable layer (Figure 10.3-3). In a complex aquifer, with multiple low-permeability lenses, the seawater may intrude at multiple levels, depending on the continuity of these lenses; for a seawater intrusion front to intrude along a low-permeability lens surrounded on both top and bottom by higher-permeability aquifer layers, that lens must stretch continuously into the saline portion of the aquifer (i.e., Figure 5.2 in Bear, 1999). Until the intrusion front comes on-land, the area where it resides (i.e., offshore) is very poorly understood because no sediment profiles have been constructed beneath the Ocean or the Bay. Low-permeability layers that are very extensive onshore may be assumed to be continuous to the ocean floor, but this is unsure.

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According to the cross-sections presented in LSCE (2010), all of the clay layers are discontinuous in the North Westside Basin (i.e., Figure 8 in Appendix A of LSCE, 2010). In the northernmost two cross-sections perpendicular to the coast (J-J' and Z-Z'), clay layers are either specifically discontinuous (i.e., J-J') or thin enough that they are unlikely to be continuous from the Great Highway a significant distance offshore. The southernmost cross-section north of Lake Merced (Y-Y') does have a thick, seemingly continuous clay layer present between the Shallow and Primary Production Aquifers, as well as a series of clay layers between the Primary Production and Deep Aquifers, so the analysis may have to consider the aquifer in three sections in this southern area. For completeness, both a sectioned aquifer and a non-sectioned aquifer will be considered. At the coast, the aquifer thickness varies from 450 ft at Golden Gate Park to 510 ft at the Ortega cluster to 630 ft at the Zoo cluster. If the area of the Zoo cluster is partitioned into three aquifers, their thicknesses are approximately 60, 290, and 120 ft (Shallow, Primary Production, and Deep Aquifers, respectively).

The same cross-sections do not extend all the way into the Bay (LSCE, 2010). However, the two southernmost cross-sections perpendicular to the Bay (N-N' and O-O') indicate that most or all of the subsurface sediments are made up of fine-grained sediments from at least the Bay Plain into the San Francisco Bay. Again, as with the North Westside Basin, there are no sediment profiles beneath the Bay itself, but it is safe to assume that the deposits in this area are continuous. Because the cross-sections do not stretch offshore, the aquifer thicknesses given here are measured at South Airport Boulevard. At cross-section N-N', the aquifer thickness is about 170 ft, while the thickness at cross-section O-O' is about 130 ft.

A.3.4. Freshwater Flux

The flux of freshwater toward the Ocean (or Bay) is important for keeping the seawater-freshwater interface offshore. Unlike the groundwater head elevation, this flux is not monitored directly anywhere in the Basin. Few estimates have been made of the flux. Yates et al. (1990) used a water budget calculation for 1988 to determine that a total of 0.45 acre-feet (af) (19,600 cubic feet) of outflow occurred per foot of coastline in the Golden Gate Park area, while about 640 af of freshwater flowed into the Ocean in the Lake Merced area. Outflows have not previously been estimated for the coastline between these two areas. Outflows have also not been independently estimated for the Bay Coast.

Flux can also be calculated based on Darcy's Law, which is an empirical relationship between the head gradient in an aquifer and the flux through it:

$$Q' = -KBi$$

where Q' is the flux through the aquifer [L^3/T], K is the hydraulic conductivity [L/T], B is the aquifer thickness [L], and i is the head gradient [L/L]. The values of K and B are discussed in Sections A.3.2 and A.3.3 above. Values of i can be determined based on values of head (see Section A.3.1).

A.4. Seawater Wedge Toe Location Methodology

An analytical solution can be created for the location of the toe of the seawater intrusion wedge under both unconfined and confined conditions using a combination of the Ghyben-Herzberg solution and Darcy's Law. This analytical solution has previously been developed in various sources, for example Bear (1972) and Strack (1976).

A.4.1. Unconfined Solution

A schematic of seawater intrusion into an unconfined aquifer is shown in Figure 10.3-3a. At any location within the freshwater aquifer, Darcy's Law can be used to relate the head gradient to the flux through the aquifer. To do this, the basic version of Darcy's Law presented in Section A.3.4 is modified by replacing the aquifer thickness (*B* in the above equation) with the thickness of freshwater above the seawater wedge in the interface area and expressing the head gradient in terms of the change in freshwater head over distance:

$$Q' = -K\left(z + h_f\right)\frac{dh_f}{dx}$$

where Q' is the freshwater flux through the aquifer and x is measured as the distance seaward from the toe of the seawater wedge ($x = 0$). The Ghyben-Herzberg solution relates z to h_f using the relationship between ρ_s and ρ_f, and can be used to remove z from this equation:

$$Q' = -Kh_f\left(\frac{\rho_s}{\rho_s - \rho_f}\right)\frac{dh_f}{dx}$$

which can be rearranged to:

$$Q' = -\frac{K}{2}\left(\frac{\rho_s}{\rho_s - \rho_f}\right)\frac{dh_f^2}{dx}$$

This equation can be solved by integrating over x (and rearranged):

$$\frac{\rho_s - \rho_f}{\rho_s}\frac{2Q'x}{K} = -h_f^2 + const$$

The constant in this equation is the freshwater head at $x = 0$, the location of the toe of the wedge:

$$\frac{\rho_s - \rho_f}{\rho_s}\frac{2Q'x}{K} = h_f^2\Big|_{x=0} - h_f^2$$

Evaluated at $x = L$, the assumed location of freshwater discharge (and the point where the freshwater head (h_f) and aquifer thickness diminish to zero), the equation becomes:

$$h_f^2\Big|_{x=0} = \frac{\rho_s - \rho_f}{\rho_s}\frac{2Q'L}{K}$$

The Ghyben-Herzberg solution also contains a relationship for the value of h_f at $x = 0$ (because at this point the value of z is by definition to the aquifer thickness, as thickness of the seawater

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wedge in the freshwater aquifer is equal to zero), which can then replace the left-hand side of the equation:

$$h_f^2\Big|_{x=0} = \left(\frac{\rho_s - \rho_f}{\rho_f}\right)^2 b^2$$

$$\left(\frac{\rho_s - \rho_f}{\rho_f}\right)^2 b^2 = \frac{\rho_s - \rho_f}{\rho_s}\frac{2Q'L}{K}$$

where b is the thickness of the aquifer lying below sea level (note the difference from the entire aquifer thickness, B, introduced above; $b = B - h_f$). Finally, this equation can be rearranged to solve for L as a function of Q':

$$L = \frac{\rho_s}{\rho_f}\frac{\rho_s - \rho_f}{\rho_f} b^2 \frac{K}{2Q'}$$

It should be noted that this solution does not depend on the freshwater head, except as its gradient affects the value of Q'. The values of ρ_s and ρ_f are constant, so applying this simplified solution requires knowledge of K (Section A.3.2), b (Section A.3.3), and Q' (Section A.3.4).

A.4.2. Confined Solution

A schematic for seawater intrusion in a confined aquifer is given in Figure 10.3-3b. In terms of the parameters involved in the analytical solution, the difference between the two aquifer constructions is that the thickness of the confined aquifer changes only due to the shape of the seawater wedge at the base of the aquifer, whereas the thickness of the unconfined aquifer also changes due to the changing water table surface. Because the entire thickness of the aquifer is, by definition, at or below the elevation of the assumed discharge point of the aquifer, b in the following equation is equal to B in Section A.3.3.

The Darcy's Law application for a confined aquifer is given by the equation:

$$Q' = -K(z - d)\frac{dh_f}{dx}$$

where d is the depth from msl to the top of the aquifer. The Ghyben-Herzberg solution can then be used to replace the value of z:

$$Q' = -K\left(\frac{\rho_f}{\rho_s - \rho_f} h_f - d\right)\frac{dh_f}{dx}$$

This equation can then be integrated over x:

$$Q'x = -K\left(\frac{\rho_f}{\rho_s - \rho_f}\frac{h_f^2}{2} - h_f d\right) + const$$

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Again, this constant is defined by solving for the value of h_f at $x = 0$:

$$Q'x = K\frac{\rho_f}{\rho_s - \rho_f}\frac{h_f^2\big|_{x=0} - h_f^2}{2} - Kd\left(h_f\big|_{x=0} - h_f\right)$$

Solving at $x = L$:

$$Q'L = K\frac{\rho_f}{\rho_s - \rho_f}\frac{h_f^2\big|_{x=0} - h_f^2\big|_{x=L}}{2} - Kd\left(h_f\big|_{x=0} - h_f\big|_{x=L}\right)$$

The Ghyben-Herzberg solution equates the freshwater head with the various vertical aquifer parameters. This changes depending on location. At $x = 0$, the location of the toe of the wedge, the depth to the interface is equal to about 38 times the freshwater head above msl; this depth is equal to the aquifer thickness (b) plus the depth to the top of the aquifer (d):

$$h_f\big|_{x=0} = \frac{\rho_s - \rho_f}{\rho_f}(b + d)$$

At the coast, the depth to the interface is equal to the depth of the aquifer, as the freshwater thickness diminishes to zero:

$$h_f\big|_{x=L} = \frac{\rho_s - \rho_f}{\rho_f}d$$

These values can be substituted into the equation above:

$$Q'L = \frac{K}{u}\frac{[u(b+d)]^2 - [ud]^2}{2} - Kd[u(b+d) - ud]$$

where:

$$u = \frac{\rho_s - \rho_f}{\rho_f}$$

Rearranging the above equation and simplifying yields:

$$Q'L = Ku\frac{(b+d)^2 - d^2}{2} - Kubd$$

$$Q'L = Ku\left(\frac{b^2 + 2bd + d^2 - d^2}{2} - bd\right)$$

$$Q'L = Ku\left(\frac{b^2}{2} + bd - bd\right)$$

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Rearranging this equation can be used to express the intrusion length (*L*) in terms of the freshwater flux (*Q'*):

$$L = \frac{\rho_s - \rho_f}{\rho_f} b^2 \frac{K}{2Q'}$$

It should be noted that the depth to the top of the aquifer (*d*) does not appear in the solution for intrusion length for a confined aquifer. As with the unconfined solution, the values of *K*, *Q'*, and *b* must be known to use this solution.

A.5. Exclusion Head Methodology

As implied by the analytical solutions presented in Section A.4, there is a simple relationship between freshwater head (h_f) and aquifer thickness (*b*) at the location of the most extensive intrusion of the seawater wedge into an unconfined freshwater aquifer, termed the toe of the wedge:

$$h_{f,toe} = \frac{\rho_s - \rho_f}{\rho_f} b$$

It should be remembered that the value of *b* used in this formulation is the thickness of the aquifer below sea level only. For a confined aquifer, the freshwater head is:

$$h_{f,toe} = \frac{\rho_s - \rho_f}{\rho_f} (b + d)$$

where b is the aquifer thickness and d is the depth below sea level of the top of the aquifer.

This simple relationship for freshwater head at the toe can be used as a management tool; to prevent intrusion from reaching any given location in the freshwater aquifer, the toe of the seawater wedge must be kept seaward of the location. To do so, the freshwater head at that location must be kept above the level at which it would be were the toe of the wedge to reach that location. This head is here termed the "exclusion head," and is equivalent to the "potential constraint" used in a management study by Mantoglou (2003), which showed this approach to be a conservative management tool.

To apply the exclusion head methodology, the parameter *b* (and *d* where conditions are confined) must be defined. The exclusion head is then calculated using assumed values of the densities of seawater and freshwater (see Section A.1).

A.6. Rate of Seawater Intrusion at Golden Gate Park

In an effort to quantify the rate of seawater intrusion into the freshwater aquifer under various pumping conditions, a simplified mathematical model was created to estimate the change in the position of the toe of the seawater wedge over time. This mathematical model is based on the analytical model presented in Section A.4. The model was developed by assuming that the movement of the wedge could be described by assuming that the interface moves in the short

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term due to changes in the amount of freshwater present in the aquifer. This section describes the development of the model and its application to an idealized case designed to resemble conditions at the South Windmill Cluster in Golden Gate Park. A similar analysis was not performed for the Bay Coast because of the lack of an independent estimate of freshwater flux (see Section A.3.4).

The theory behind this method is that the movement of the seawater-freshwater interface can be described by assuming that the well pumping over a given time period can be converted to a volume of water removed. This approach makes a number of assumptions, most of which are similar to the analytical method for estimating the intrusion length (see Section A.4). Additional assumptions include:

- The pumping rate is a small percentage of the freshwater flux.
- The aquifer thickness landward of the intrusion wedge toe is approximately constant.
- The discharge point does not move from the coast.
- The system is unconfined and functions as a single aquifer.

The second assumption greatly simplifies the mathematical solution. Implicit in this assumption is that the head gradient landward of the wedge toe is approximately flat; this does not introduce substantial error into the analysis because head gradients in permeable alluvial sediments are typically very flat compared to the total aquifer thickness; Yates et al. (1990) reported a maximum gradient in the North Westside Basin of 0.035 ft/ft in the Lake Merced area, with typical gradients on the order of 0.010 ft/ft, including in the Golden Gate Park area). It should be noted that the analytical solution presented below does not depend on the head or head gradient directly, so the assumption of a constant aquifer thickness (and therefore flat gradient) does not preclude freshwater flux toward the ocean and is an appropriate approximation.

The last assumption is required because the confined solution is much more complicated than is the unconfined solution, due to the effects of aquifer elasticity and water compressibility (together contributing to the specific storage of the confined aquifer). This assumption is applicable at the western end of Golden Gate Park because the -100 foot clay is absent, leaving the Shallow and Primary Production Aquifers in direct communication; this implies that they can be considered a single aquifer. Elsewhere in the North Westside Basin, where the clay layers are present, this assumption would not apply.

As shown in Section A.4, the intrusion length into the aquifer (i.e., the distance from the discharge point to the toe of the wedge) is equal to:

$$L = \frac{K}{2Q_0'} \frac{\rho_s}{\rho_f} \frac{\rho_s - \rho_f}{\rho_f} b^2$$

where Q'_0 is the initial freshwater flux per foot of coastline before modification by pumping (all other terms are defined in Section A.4). The volume of water within any slice of the aquifer of infinitesimal width dx is equal to:

$$dV' = h_f n_e \frac{\rho_s}{\rho_s - \rho_f} dx$$

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where n_e is the effective porosity of the aquifer[6]. Integrating from the coast to the toe of the wedge, the total initial volume of freshwater per foot of coastline above the wedge is equal to:

$$V_0' = -\left(\frac{\rho_s}{\rho_s - \rho_f}\right)^2 \frac{n_e K}{3Q_0'}\left[\left[\left(\frac{\rho_s - \rho_f}{\rho_f}\right)^2 b^2 - \frac{\rho_s - \rho_f}{\rho_f}\frac{2Q_0' L_0}{K}\right]^{3/2} - \left[\left(\frac{\rho_s - \rho_f}{\rho_f}\right)^2 b^2\right]^{3/2}\right]$$

which, when substituting the above equation for computing L, simplifies to:

$$V_0' = \frac{n_e K}{3Q_0'}\left(\frac{\rho_s}{\rho_f}\right)^2 \frac{\rho_s - \rho_f}{\rho_f} b^3$$

Pumping removes a volume of water from the aquifer (V'_w) that is equal to the product of the pumping rate and the time over which it is applied:

$$V_w'(t) = Q_w'(t - t_0)$$

where Q'_w is the pumping rate, t is the time, and t_0 is the time when pumping was initiated. In this case, the pumping rate must be converted to an equivalent flux per foot of shoreline, which implies that the pumping in the basin results in a uniform decrease in the freshwater flux rate. This pumping from the aquifer induces some movement of the intrusive wedge inland (as extra recharge would move the wedge closer to the ocean). The volume of water removed from the aquifer from the new location of the toe of the wedge to the coast is equal to the volume of water removed from the aquifer. The volume of freshwater contained in the aquifer from the location of the new toe to the coast prior to pumping is equal to the volume of freshwater above the seawater-freshwater interface plus the volume of water in the stretch of aquifer that becomes intruded by the wedge during its movement. Assuming that the freshwater head is approximately flat landward of the toe of the wedge, the freshwater head is equal everywhere to its value at the toe of the wedge, which is equal to:

$$h_{f,toe} = \frac{\rho_s - \rho_f}{\rho_f} b$$

The volume of freshwater in the aquifer that becomes intruded by the wedge is equal to:

$$V_i' = n_e b \frac{\rho_s}{\rho_f}\left(L(t) - L_0\right)$$

where $L(t)$ is the distance from the coast to the toe of the wedge at time t. The total volume of freshwater in the aquifer from the coast to the new location of the wedge of the toe prior to pumping is:

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[6] Note that this assumes that the intruding seawater does not interact with the non-effective porosity of the aquifer, i.e. $n - n_e$. In reality, this non-effective porosity will lead to (very slightly) lower salinity behind an intruding wedge, and the leaving of salts behind by a retreating wedge.

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$$V'_{0,Total} = V'_0 + V'_i = \frac{n_e K}{3Q'_0}\left(\frac{\rho_s}{\rho_f}\right)^2 \frac{\rho_s - \rho_f}{\rho_f} b^3 + n_e\left(L(t) - L_0\right)\frac{\rho_s}{\rho_f} b$$

The wedge at time *t* has a volume equal to:

$$V'_t = V'_{0,Total} - V'_w(t)$$

Combining this with earlier equations produces an equation for the total volume of freshwater above the transient wedge at time *t*:

$$V'_t = \frac{n_e K}{3Q'_0}\left(\frac{\rho_s}{\rho_f}\right)^2 \frac{\rho_s - \rho_f}{\rho_f} b^3 + n_e\left(L(t) - L_0\right)\frac{\rho_s}{\rho_f} b - Q'_w\left(t - t_0\right)$$

Assuming the value of Q'_0 is not significantly changed by the pumping, this volume can also be computed by:

$$V'_t = -\left(\frac{\rho_s}{\rho_s - \rho_f}\right)^2 \frac{n_e K}{3Q'_0}\left[\left[\left(\frac{\rho_s - \rho_f}{\rho_f}\right)^2 b^2 - \frac{\rho_s - \rho_f}{\rho_f}\frac{2Q'_0 L(t)}{K}\right]^{3/2} - \left[\left(\frac{\rho_s - \rho_f}{\rho_f}\right)^2 b^2\right]^{3/2}\right]$$

The assumption that Q'_0 is not changed significantly is only applicable if the value of Q'_w is small compared to Q'_0, i.e., most of the initial freshwater flux is not captured by the wells. Results based on values of Q'_w that represent a significant fraction of Q'_0 should be used with caution. The value of Q'_0 reported by Yates et al. (1990) was 19,600 ft^3/yr per foot of coastline; the pumping entailed by the SFGW Project is about 8,810 ft^3/yr per foot of coastline above the pumping reported by Yates et al. (1990) for Scenario 3a, and about 9,220 ft^3/yr per foot of coastline above for Scenario 3b; the large magnitude of these changes relative to the initial freshwater flux indicates that this assumption is not completely valid in this case, and the results should be considered approximate.

These two values for the total volume of freshwater can be equated to each other. The equation for the value of L_0 can be substituted into this equation to simplify it to:

$$Q'_w\left(t - t_0\right) - n_e b\frac{\rho_s}{\rho_f} L_0 = \left(\frac{\rho_s}{\rho_f}\right)^2 \frac{2n_e b^2}{3L_0^{1/2}}\left[L_0 - L(t)\right]^{3/2} - n_e b\frac{\rho_s}{\rho_f} L(t)$$

or

$$\frac{Q'_w\left(t - t_0\right)}{n_e b}\frac{\rho_f}{\rho_s} = \frac{\rho_s}{\rho_f}\frac{2b}{3L_0^{1/2}}\left(L_0 - L(t)\right)^{3/2} + \left(L_0 - L(t)\right)$$

This equation cannot be solved for $L(t)$ using separation of variables. Instead, this model must be solved iteratively. This iterative solution can be performed in any spreadsheet software

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(e.g., Microsoft Excel) by minimizing the difference between the specified pumping rate and the pumping rate calculated using the equation above by optimizing values of $L(t)$.

A.7. Effect of a Sloping Aquifer Base

The above analytical methods assume a horizontal aquifer. As shown in LSCE (2010), the actual aquifer bases in the North Westside Basin have been shown to be sloped toward the Ocean. A similar analytical method assuming a sloping aquifer base could not be constructed because the solution is inseparable. Abarca et al. (2007) performed numerical simulations that investigated the effect of a sloping aquifer boundary, both parallel and perpendicular to the coastal boundary. Their results indicated that a slope toward the Ocean slightly decreases the intrusion length into an aquifer, but not substantially. The presence of a slope parallel to the coast, on the other hand, can greatly increase the length of seawater intrusion into the lowest parts of the aquifer base. Mulligan et al. (2007) demonstrate that freshwater flux tends to be concentrated in paleochannels, which would represent the low points in the aquifer base demonstrated by Abarca et al. (2007) to be locations of greater intrusion; the concentration of freshwater flux into these same areas may keep this intrusion at bay.