CHAPTER 2
BASIN SETTING

2.1 INTRODUCTION TO BASIN SETTING

Physical Setting and Characteristics

The Oxnard Subbasin of the Santa Clara River Valley Groundwater Basin is located near the western edge of the Transverse Ranges Geomorphic Province, which extends from the San Bernardino Mountains in the east to the San Miguel, Santa Rosa, and Santa Cruz Islands in the west (Figure 2-1; CGS 2002). The Transverse Ranges Geomorphic Province is characterized by a series of east-to-west-trending mountain ranges and valleys that are formed by north–south compression across a restraining bend in the San Andreas Fault (Hadley and Kanamori 1977; Bohannon and Howell 1982; Zoback et al. 1987; Eberhart-Philips et al. 1990; Nicholson et al. 1994). Compression across this restraining bend is responsible for rapid, ongoing uplift of the mountain ranges (Yeats 1988; Feigl et al. 1993; Marshall et al. 2008) and extensive folding and faulting of the Pleistocene and older geologic formations in the province (Rockwell et al. 1988; Huftile and Yeats 1995).

The Oxnard Subbasin underlies the Oxnard Plain, an approximately 58,000-acre coastal plain formed by deposition of sediments from the Santa Clara River and Calleguas Creek, in southwestern Ventura County (DWR 1965, 2006). The northern boundary of the Oxnard Subbasin is the Oak Ridge Fault, and the southern boundary is the contact between permeable alluvium and semipermeable rocks of the Santa Monica Mountains (SWRCB 1956; DWR 2006). The eastern boundary of the Oxnard Subbasin lies against the Las Posas Valley and Pleasant Valley Basins. The western boundary of the Oxnard Subbasin is the Pacific Ocean (SWRCB 1956; DWR 2006).

The stratigraphic sequence underlying the Oxnard Plain comprises an upper unit of active and older alluvial deposits that unconformably overlies the San Pedro and Santa Barbara Formations (Table 2-1). The San Pedro Formation is a lower to middle Pleistocene shallow marine deposit that grades upward from a white gray sand and gravel basal layer into an overlying series of interbedded silts, clays, and gravels. The Santa Barbara Formation is a lower Pleistocene marine sand and clay deposit (SWRCB 1956; Weber and Kiessling 1976; Turner 1975). The primary water-bearing units in the Oxnard Subbasin are the alluvial deposits that compose the Oxnard and Mugu Aquifers and the white gray sand and gravel layer of the San Pedro Formation that composes the Fox Canyon Aquifer (FCA; Table 2-1). In addition to these primary aquifers, wells in the Oxnard Subbasin also produce water from the Hueneme Aquifer in the upper San Pedro Formation and the Grimes Canyon Aquifer in the Santa Barbara Formation.

Table 2-1
Oxnard Subbasin Stratigraphic and Hydrostratigraphic Nomenclature

Geologic Period	Geologic Epoch	Mukae and Turner (1975)	Kew (1924); Bailey (1951)	Weber et al. (1976)	Dibblee (1992a, 1992b)	Mukae and Turner (1975); DWR (2006)		
		Lithologic Units and Formations				*Hydrostratigraphy*		
Quaternary	Holocene	**Alluvium:** Active stream deposits, sand, and gravel; stream, swamp, and lagunal deposits of clay, sand, and gravel	**Recent Alluvium**: Active lagoonal, beach, river, and floodplain and alluvial deposits			**Oxnard**	**Semi-Perched**	**Upper Aquifer System**
	Upper Pleistocene		**Terrace deposits**: Deformed river deposits	**Older Alluvium**: Deformed beach, river, floodplain, and terrace deposits			**Oxnard**	
		Older Alluvium: Clays silts, sands, and gravels from the Santa Clara River				**Mugu**		
			Saugus Formation: Terrestrial and marine sand and gravel	**Saugus Formation**: Terrestrial fluvial	**Saugus Formation**: Terrestrial			
				San Pedro Formation: Marine clays and sand and terrestrial sediment		**Hueneme**		**Lower Aquifer System**
	Lower Pleistocene	**San Pedro Formation**: Marine and nonmarine clay, sand, and gravel			**Las Posas Sand**: Shallow marine sand	**Fox Canyon**		
		Santa Barbara Formation: Marine clay, sand, and gravel		**Santa Barbara Formation**: Shallow marine sand		**Grimes Canyon**		
Tertiary	Pliocene	**Pico Formation**: Shale, sandstone, and conglomerate	**Fernando Group**			**Non-Water Bearing**		
	Miocene	**Santa Margarita and Modelo Formations**	**Modelo Formation**: Marine mudstones		**Monterey Formation**			
		Topanga Formation and Volcanics	**Conejo Volcanics**: Terrestrial and marine extrusive and intrusive igneous rocks					
	Oligocene/ Eocene	**Older Rocks**	**Sespe Formation**: Sandstone and cobble conglomerate					

The shallowest aquifer in the Oxnard Subbasin is a semi-perched aquifer comprising sands and gravels deposited by the Santa Clara River. This unit is underlain by a clay layer, commonly referred to as the "clay cap," that is nearly continuous throughout the subbasin, with the notable exception of an approximately 10-square-mile area in the northeastern part of the subbasin, adjacent to and south of the Santa Clara River, referred to as the "Forebay area" (Figure 2-1; Mukae and Turner 1975). In this region, the Oxnard and underlying Mugu Aquifers are unconfined. In the areas where the clay cap separates the semi-perched aquifer from the underlying Oxnard Aquifer, the Oxnard Aquifer is confined. The area in which the Oxnard Aquifer is confined is referred to as the "pressure plain area" of the Oxnard Subbasin (Figure 2-1; Mukae and Turner 1975).

The majority of the Oxnard Subbasin lies within the jurisdiction of the Fox Canyon Groundwater Management Agency (FCGMA), with two exceptions (Figure 2-1). These exceptions include an area in the northeastern corner of the Oxnard Subbasin, at the western end of South Mountain, and along the southeastern edge of the Oxnard Subbasin adjacent to the foothills of the Santa Monica Mountains. The reason for the discrepancy is that the FCGMA boundary was established based on a vertical projection of the FCA as defined by the Fox Canyon Groundwater Management Agency Act in 1982, whereas the Oxnard Subbasin boundary is based on the surface extent of the alluvium in the Oxnard Plain, the location of both geologic structures and facies changes that impede flow between the Oxnard Subbasin and neighboring groundwater basins (DWR 2006). The geologic and hydrologic descriptions of the Oxnard Subbasin in this Groundwater Sustainability Plan are based on the boundaries of the Oxnard Subbasin, including the areas to the northeast and southeast of the FCGMA jurisdictional boundaries.

2.2 HYDROGEOLOGIC CONCEPT MODEL

The five commonly recognized water-bearing units in the Oxnard Subbasin are the Oxnard, Mugu, Hueneme, Fox Canyon, and Grimes Canyon Aquifers (DWR 1965, 2006; Turner 1975). These aquifers are grouped into an upper aquifer system (UAS) and lower aquifer system (LAS), with the Oxnard and Mugu Aquifers composing the UAS and the Hueneme, Fox Canyon, and Grimes Canyon Aquifers composing the LAS. The UAS primarily comprises recent to upper Pleistocene-age alluvial deposits of the Santa Clara River system.

The Forebay area is the primary recharge area for all the aquifers in the Oxnard Subbasin. In this area, the UAS rests directly on the folded and eroded upper surface of the FCA and Hueneme Aquifer. Water that recharges the UAS in the Forebay area is able to migrate throughout the subbasin. Both the lithologic units and geologic structures present in the Oxnard Subbasin affect the hydrology of the subbasin. These features are discussed in more detail in the following text.

2.2.1 Geology

Geologic Units and Variation

Tertiary Sedimentary and Igneous Formations

Tertiary sedimentary and igneous rocks that underlie the Oxnard Subbasin are generally considered semipermeable or non-water-bearing (Turner and Mukae 1975). These tertiary formations include the Oligocene/Eocene-age Sespe Formation, the lower Miocene Conejo Volcanics, the upper Miocene Modelo and Monterey Formations, and the Pliocene Pico Formation (Table 2-1; Weber and Kiessling 1976; Diblee 1992a, Diblee 1992b). These formations have been sampled in deep wells drilled in the Oxnard Subbasin (Figure 2-2; Turner 1975; Weber and Kiessling 1976). These formations are not considered an important source of groundwater in the Oxnard Subbasin (Turner 1975).

Quaternary Sedimentary Formations

Santa Barbara Formation (Lower Pleistocene; Marine)

The Santa Barbara Formation typically comprises laminated, poorly indurated blue-gray marine mud- and siltstone with sand and gravel (Table 2-1; Turner and Mukae 1975). The upper clay-rich sediments act as an aquitard between the Santa Barbara Formation and the overlying San Pedro Formation (Weber and Kiessling 1976). The localized basal conglomerate within the upper member of the Santa Barbara Formation hosts the Grimes Canyon Aquifer (Weber and Kiessling 1976).

San Pedro Formation (Lower to Middle Pleistocene; Marine and Nonmarine)

The San Pedro Formation is an interbedded, poorly lithified fine marine, silty sandstone, shale, and mudstone with local pebble conglomerate and an extensive basal sand unit that unconformably overlies the Santa Barbara Formation in the Oxnard Subbasin (Mukae and Turner 1975; Weber and Kiessling 1976). The pebbles are plutonic, metamorphic, and metavolcanic clasts.

The upper and lower parts of the San Pedro Formation are separated by a laterally extensive clay marker bed (Turner 1975). Overlying the clay marker bed are lenticular layers of sand, gravel, and silt (Mukae and Turner 1975). The lenticular deposits of sand and gravel in the upper San Pedro Formation are known as the Hueneme Aquifer in the Oxnard Subbasin. The sediments of the upper San Pedro Formation coarsen to the west, with a larger percentage of sand and gravel in the western part of the subbasin and a larger percentage of fines in the eastern part of the subbasin, particularly in the area adjacent to the boundary with the Las Posas Valley Basin.

In contrast, the basal unit of the San Pedro Formation fines to the west. This unit comprises a 100- to 600-foot-thick continuous white or gray fine to medium marine sand with stringers of gravel and local silt and clay lenses (Turner 1975).[1] The lower part of the San Pedro Formation hosts the FCA, which is an important source of groundwater supply in the Oxnard Subbasin (Turner 1975).

Older Alluvium (Upper Pleistocene; Terrestrial)

The older alluvium, which comprises gravel, sand, silt, and clay, unconformably overlies the upper San Pedro Formation. The older alluvium was deposited in river, floodplain, and beach environments. The older alluvium has been gently folded (Mukae and Turner 1975). The older alluvium can be divided into two units: an upper clay zone and a lower sand and gravel zone (Mukae and Turner 1975). The Mugu Aquifer occurs in the sand and gravel zone at the base of the older alluvium (Mukae and Turner 1975).

Recent Alluvium (Holocene; Terrestrial)

The recent alluvium in the Oxnard Subbasin comprises sands and gravels interbedded with silt and clay (DWR 1965). These sediments, which unconformably overlay the older alluvium, reach a thickness of up to 300 feet. The basal unit includes coarse sands and gravels intercalated with clay layers (Mukae and Turner 1975). Overlying the basal unit throughout much of the subbasin is a laterally continuous clay layer that reaches a thickness of up to 160 feet locally. The Oxnard aquifer occurs in the sand and gravel layer below the clay. Above the clay is the "semi-perched" aquifer.

Geologic Structure

Wright Road Fault

The Wright Road Fault is an active oblique right reverse fault that generally parallels the eastern jurisdictional boundary of the Oxnard Subbasin, separating the Las Posas Valley Basin to the east from the Oxnard Subbasin to the west (Figure 2-2; DeVecchio et al. 2007). The fault trace is characterized by a 20-meter-high topographic scarp with up to the east displacement along the north/northwest-trending fault (DeVecchio et al. 2007). There is no evidence that the Wright Road Fault impacts groundwater flow between the Oxnard Subbasin and the Las Posas Valley Basin.

[1] This marine sand has been identified as both the Saugus Formation (Kew 1924; Jakes 1979) and the Las Posas Sand (Pressler 1929; Dibblee 1992a; Dibblee 1992b; DeVecchio et al. 2012). The term "San Pedro Formation" is used here for consistency with California Department of Water Resources nomenclature (DWR 2006).

Oak Ridge and McGrath Faults

The Oak Ridge Fault is a high-angle, south-dipping, left-lateral reverse fault that juxtaposes water-bearing alluvium and older, semipermeable formations in the subsurface (Figure 2-2; SWRCB 1956). To the east of the Oxnard Subbasin, anticlinal folding in the hanging wall of the Oak Ridge Fault resulted in the Oak Ridge and South Mountain uplift (Yeats 1988). In the Oxnard Subbasin, the western extent of the Oak Ridge Fault is concealed beneath the recent alluvium (Mukae and Turner 1975).

The McGrath Fault, located approximately 1 mile south of the Oak Ridge Fault along the coast in the Oxnard Subbasin, is a branch of the Oak Ridge Fault system with the same sense of motion (Mukae and Turner 1975). The McGrath Fault defines the northerly limit of the Forebay area (Turner 1975). Together, the McGrath and Oak Ridge Faults limit hydraulic communication between the Oxnard Subbasin to the south and the Mound and Santa Paula Subbasins of the Santa Clara River Valley Groundwater Basin to the north.

Bailey Fault

Along the northern edge of the Santa Monica Mountains, the Bailey Fault Zone trends northeast–southwest through the Oxnard Subbasin (Figure 2-2; Turner 1975). The Bailey Fault is a near-vertical fault with up to the south displacement in the subsurface that offsets quaternary sedimentary formations to the north with non-water-bearing older formations to the south (Turner 1975). Groundwater elevation differences and chloride ion concentration differences across the fault suggest that it is a barrier to groundwater movement (Turner 1975).

Las Posas Syncline

The Las Posas syncline causes thickening and downwarping of the San Pedro Formation and older formations in the central part of the Oxnard Subbasin (Figure 2-2). The axis of the Las Posas syncline trends northeast from its western mapped extent at the intersection of West 5th Avenue and Harbor Boulevard, through El Rio, and into the Las Posas Valley (Turner 1975). At the deepest part of the Las Posas syncline, the upper San Pedro Formation reaches a thickness of approximately 1,150 feet (Mukae and Turner 1975).

Montalvo Anticline

Deformation in the hanging wall of the Oak Ridge and McGrath Faults has resulted in anticlinal structures on the northern boundary of the Oxnard Subbasin, including the Montalvo anticline (Figure 2-2). The upper San Pedro Formation has been eroded away in the Forebay area of the Oxnard Subbasin along the axis of the anticline (Turner 1975). Erosion of the upper San Pedro

Formation results in direct communication between the alluvium and the white and gray marine sands of the lower San Pedro Formation that compose the FCA.

2.2.2 Boundaries

The western boundary of the Oxnard Subbasin is the Pacific Ocean. The northern boundary is the Oak Ridge Fault and associated McGrath Fault, which are high-angle reverse faults that juxtapose the San Pedro Formation to the north and older, semipermeable formations to the south (SWRCB 1956; Turner 1975). The southern boundary of the Oxnard Subbasin is the contact between permeable alluvium and semipermeable rocks of the Santa Monica Mountains (SWRCB 1956; DWR 2006). The eastern boundary of the subbasin lies against the Las Posas Valley and Pleasant Valley Basins (SWRCB 1956; DWR 2006).

2.2.3 Basin Bottom

The bottom of the Oxnard Subbasin generally corresponds to the base of the San Pedro Formation and the base of the FCA in the northern and western parts of the subbasin, where the Santa Barbara Formation is absent (Figures 2-2 and 2-3; Turner 1975). In the southern and eastern parts of the subbasin, where the Santa Barbara Formation is present, the bottom of the subbasin is defined by the contact between the upper member of the Santa Barbara Formation, the Grimes Canyon Aquifer, and the underlying strata that have poor water quality (Figure 2-4).

In general the bottom of the Oxnard Subbasin is shallower in the east and deeper in the west. Along the eastern margin of the subbasin, the basin bottom has been mapped at depths between 0 and 1,200 feet below mean sea level (Turner 1975). Along the western edge of the basin, the depth to the basin bottom ranges from 400 to over 1,800 feet below mean sea level (Turner 1975). The deepest part of the subbasin occurs along the axis of the Las Posas syncline in the north-central part of the subbasin.

2.2.4 Principal Aquifers and Aquitards

Semi-Perched Aquifer

River-deposited sands and gravels interbedded with minor silt and clay compose the "semi-perched" aquifer in the Oxnard Subbasin (DWR 1965; Turner 1975). The term "semi-perched" aquifer is used in this Groundwater Sustainability Plan as the name for the aquifer that overlies the extensive clay cap in the pressure plain area of the Oxnard Subbasin (Figure 2-2 and Table 2-1). This name was used in Bulletin 12 of the State Water Resources Control Board (SWRCB 1956) to distinguish the water-bearing sedimentary units in the pressure plain area from those in the Forebay area, and this terminology has been adopted by subsequent investigators (Mukae and Turner 1975; Turner 1975; Hanson et al. 2003; DWR 2006). Water-level data indicate that the sediments underlying the semi-perched aquifer are saturated. Therefore, the term "semi-perched aquifer" is used in this Groundwater Sustainability Plan to denote the limited migration of water from the uppermost aquifer to the underlying confined aquifer in the pressure plain area. It is not used to denote a discontinuity in saturation.

The semi-perched aquifer is part of the recent alluvium described in Section 2.2.1. This aquifer extends from the base of developed soil horizons to a depth of approximately 75 feet throughout most of the subbasin (Turner 1975). Notably, this aquifer is absent in the Forebay area of the Oxnard Subbasin adjacent to and south of the present course of the Santa Clara River. The permeable sand and gravel deposits of the semi-perched aquifer tend to be continuous in a northeast–southwest orientation, which is similar to the present orientation of the Santa Clara River and lenticular to the northwest and southeast (Turner 1975).

The lenticular shape of the semi-perched aquifer deposits limits flow in the northwest–southeast direction and facilitates flow in the northeast–southwest direction. These deposits have not been affected by faulting or folding in the basin, and there are no structural restrictions to flow through the semi-perched aquifer.

Agricultural return flows, saline connate water and coastal flooding affect both groundwater quality and groundwater elevation in the semi-perched aquifer (Mukae and Turner 1975). The highest water levels in the aquifer, which are typically within a few feet of land surface, are found in heavily irrigated areas (Turner 1975). Tile drains are used throughout the Oxnard Subbasin to alleviate the high groundwater conditions. Agricultural return flows that cause the high water conditions, combined with seawater intrusion, have resulted in high concentrations of total dissolved solids and chloride in the semi-perched aquifer (Turner 1975). Chloride concentrations have been as high as 23,000 milligrams per liter in samples from this aquifer (USGS 1996). Few production wells are screened solely in the semi-perched aquifer. Water quality is highly variable in the semi-perched aquifer (UWCD 1999).

Clay Cap

Underlying the semi-perched aquifer is a clay layer that separates the semi-perched aquifer from the Oxnard Aquifer below (Turner 1975). The thickness of the clay cap is approximately 160 feet adjacent to the Pacific Ocean. The clay cap is absent in the Forebay area (DWR 1968; Mukae and Turner 1975). Although the clay cap functions as an aquitard, water can migrate vertically through the clay cap under conditions of differential head (Turner 1975), and in some cases, through casings of wells that have been improperly abandoned.

Oxnard Aquifer

The Oxnard Aquifer is a laterally continuous layer of upper Plesitocene and Holocene nonmarine gravel and cobbles (up to 6 inches in diameter); coarse to fine sand; and interbedded clay, silty clay, and silt lenses (Turner 1975). The deposits that compose this aquifer are part of the recent alluvium and are found beneath the entire Oxnard Subbasin and extend offshore, where they are exposed in the walls of the Hueneme and Mugu submarine canyons (DWR 1965, 1968). The deposits tend to be finer near the coast and coarsen to the east (Turner 1975; DWR 2006). The local silty clay and silt lenses restrict both horizontal and vertical movement of water through the aquifer, and distinct permeable horizons have been identified in logs (DWR 1963).

The top of the Oxnard Aquifer has been shaped by differential erosion and sedimentation of the Santa Clara River (Turner 1975). Throughout much of the Oxnard Subbasin, a clay-rich aquitard that ranges in thickness from 10 to 100 feet separates the Oxnard Aquifer system from the underlying Mugu Aquifer (Mukae and Turner 1975). The basal surface of the clay is more uniform than the upper surface and generally deepens to the west–southwest (DWR 1968). The thickness of the Oxnard Aquifer also generally increases to the west–southwest, with a minimum thickness of less than 50 feet in the vicinity of the Forebay area and reaching a maximum thickness of greater than 150 feet in the vicinity of Point Mugu (DWR 1968; Turner 1975).

Flow of groundwater through the Oxnard Aquifer is controlled by lithologic variability. There are no documented structural features that restrict flow in this aquifer (Turner 1975; DWR 2006). The Oxnard Aquifer crops out offshore in the Hueneme and Mugu canyons, making it susceptible to seawater intrusion. The chloride concentration of native water in the Oxnard Aquifer is approximately 40 milligrams per liter (USGS 1996). In the vicinity of the Hueneme and Mugu canyons, however, chloride concentrations were as high as 17,000 milligrams per liter when last measured (Izbicki et al. 2005).

The specific yield of the gravels of the Oxnard Aquifer is about 16% in the Forebay area where there are few clay deposits and the aquifer is unconfined (SWRCB 1956; DWR 2006). Wells screened in the Oxnard Aquifer are typically screened in multiple aquifers, including the underlying Mugu Aquifer. (For information on well construction requirements intended to prevent degradation of water quality of the aquifers in the LAS [referred to as requirements for “sealing zone”], see DWR 1968). The California Department of Water Resources reports that the average well yield in the Oxnard Aquifer is about 900 gallons per minute (DWR 2006). Aquifer test results for two wells screened solely within the Oxnard Aquifer, however, have a higher average well yield of approximately 1,500 gallons per minute, with an average specific capacity of 47 gallons per minute per foot (Hopkins, pers. comm. 2016). Storage coefficients of 6.18×10^{-4} and 3×10^{-4} were estimated from pumping test data at these two wells, and the transmissivity was estimated to be approximately 20,400 feet squared per day (Hopkins, pers. comm. 2016). The well yield and specific capacity were measured at three additional wells screened solely in the Oxnard Aquifer, although aquifer tests were not performed at these wells. The average well yield and specific capacity for these wells is 2,450 gallons per minute and 108 gallons per minute per foot. Based on these measurements, the average transmissivity is approximately 32,000 feet squared per day (Hopkins, pers. comm. 2016).

Water quality in the Oxnard Aquifer has been degraded by seawater intrusion and leakage of agricultural return flows through the clay cap separating the Oxnard Aquifer from the overlying semi-perched aquifer. Seawater intrusion has been documented in both the Port Hueneme and Port Mugu areas (Turner 1975; UWCD 2016a). Water produced from this aquifer is used for agricultural, municipal, and industrial purposes.

Mugu Aquifer

The sediments that compose the Mugu Aquifer are upper Pleistocene-age fine to coarse sands and gravels (DWR 1965; Turner 1975). These sand and gravel deposits are laterally extensive throughout the subbasin and represent the basal deposits of the older alluvium. In general, the sediments of the Mugu Aquifer are finer near the coast and coarsen to the east (Turner 1975). A low-permeability clay deposit that ranges in thickness from 10 to 100 feet separates the Mugu Aquifer from the overlying Oxnard Aquifer throughout much of the Oxnard Subbasin. However, the clay layer is absent in the Forebay area of the subbasin near the Santa Clara River (DWR 1965; SWRCB 1979; Turner 1975). The Mugu Aquifer ranges in thickness from approximately 30 feet in the Forebay to approximately 270 feet in the vicinity of Point Mugu (DWR 1965; Turner 1975).

The Mugu Aquifer crops out offshore in the Hueneme and Mugu canyons, making it susceptible to seawater intrusion. The chloride concentration of native water in the Mugu Aquifer is approximately 40 milligrams per liter (USGS 1996).

The base of the Mugu Aquifer was deposited over an irregular surface that has been affected by both folding and erosion (Turner 1975). The extensive folding of the aquifers underlying the Mugu Aquifer, however, has not been documented within the sediments of the Mugu Aquifer. There are no known structural boundaries to flow within the aquifer.

Wells screened in the Mugu Aquifer are typically screened in multiple aquifers, including the overlying Oxnard Aquifer. The California Department of Water Resources does not report aquifer properties specifically for the Mugu Aquifer (DWR 2006). In the Forebay, well 02N22W36E04S, screened solely within the Mugu Aquifer has a well yield of 1,500 gallons per minute, a specific capacity of 17.8 gallons per minute per foot, and an estimated transmissivity of 7,900 feet squared per day (Hopkins, pers. comm. 2016). For wells screened in both the Oxnard and Mugu Aquifers, the average yield is 2,300 gallons per minute, the average specific capacity is 110 gallons per minute per foot, and the average estimated transmissivity is 29,000 feet squared per day (Hopkins, pers. comm. 2016). Water produced from this aquifer is used for agricultural, municipal, and industrial purposes.

Hueneme Aquifer

The Hueneme Aquifer comprises a series of lenticular silts, sands, and gravels in the upper San Pedro Formation. This aquifer is present in the northern part of the Oxnard Subbasin but is absent to the south of Etting and Hueneme Roads (Mukae and Turner 1975). The Hueneme Aquifer is up to 1,150 feet thick along the axis of the Las Posas syncline (Turner 1975).

Changes in lithologic composition, with the aquifer generally containing a higher percentage of fine materials adjacent to the Las Posas and Pleasant Valley Basins, affect flow through the aquifer. The change in composition is accompanied by an increase in the lenticular nature of the deposits that compose the Hueneme Aquifer along the eastern boundary of the Oxnard Subbasin. These changes limit subsurface flow between the Oxnard Subbasin and the Las Posas Valley and Pleasant Valley Basins to the east.

In addition to changes in lithology, structural folding of the Hueneme Aquifer also affects subsurface flow (Turner 1975). Folding, subsequent erosion, and recent deposition have resulted in a direct hydraulic connection between the Hueneme Aquifer and the overlying Mugu Aquifer throughout much of the Oxnard Subbasin (Turner 1975). However, in the southwestern portion of the basin, where seawater intrusion has affected the Mugu Aquifer, the Mugu and Hueneme Aquifers are not in direct hydraulic communication. As a result, water quality in the Hueneme Aquifer has not been affected by seawater intrusion in this area (Turner 1975; USGS 2003). The chloride concentration of native water in the Hueneme Aquifer is approximately 40 milligrams per liter (USGS 1996).

Wells screened solely within the Hueneme Aquifer have an average yield of approximately 2,500 gallons per minute and an average specific capacity of 38 gallons per minute per foot (Hopkins, pers. comm. 2016). Storage coefficients of $2x10^{-4}$ and $3x10^{-4}$ were estimated from pumping test data at two wells and the transmissivity was estimated to be approximately 13,400 feet squared per day (Hopkins, pers. comm. 2016). Water produced from this aquifer is used for agricultural, municipal, and industrial purposes.

Fox Canyon Aquifer

The FCA is a 100- to 600-foot-thick marine sand and gravel deposit in the lower San Pedro Formation (Mukae and Turner 1975). The water-bearing deposits of the FCA fine toward the west (Turner 1975). This unit is laterally continuous throughout the Oxnard Subbasin, except at the western tip of South Mountain, where the Santa Barbara Formation is in direct contact with the Mugu Aquifer, and in the southwestern part of the basin, where uplift and erosion have removed the FCA (Turner 1975). In the northern and western parts of the subbasin, the FCA defines the base of the fresh water zone.

In the Oxnard Subbasin, the FCA is thickest along the axis of the Las Posas syncline. In this area, the FCA reaches thickness in excess of 500 feet, and the base of the aquifer is below 2,000 feet below sea level (Turner and Mukae 1975; Turner 1975). The primary source of recharge to the FCA is infiltration through the Oxnard and Mugu Aquifer systems in the Forebay area (Turner 1975; FCGMA 2007).

Water quality in the FCA is generally good, with the native water having a chloride concentration of 40 milligrams per liter (USGS 1996). Chloride concentration measured in 2002 from a well in the southeastern part of the subbasin ranged from 183 to 367 milligrams per liter (Izbicki et al. 2005).

Well 02N22W20J02S, also in the northern Oxnard Subbasin, is screened in both the FCA and overlying Hueneme Aquifer. This well has a yield of 3,030 gallons per minute, a specific capacity of 95.3 gallons per minute per foot, and a transmissivity of 40,100 feet squared per day (Hopkins, pers. comm. 2016). Water produced from this aquifer is used for agricultural, municipal, and industrial purposes.

Grimes Canyon Aquifer

The Grimes Canyon Aquifer comprises lower Pleistocene-age sand with minor amounts of gravel. This aquifer corresponds with the basal conglomerate within the upper member of the Santa Barbara Formation and is only found underlying the southern and eastern parts of the Oxnard Subbasin (Turner 1975). In the southern part of the subbasin, the Grimes Canyon Aquifer is found in a band approximately 5 miles wide along the base of the Santa Monica Mountains from the Pacific Ocean to the boundary with the Pleasant Valley Basin to the east (Turner 1975). Throughout the rest of the subbasin, the Grimes Canyon member of the Santa Barbara Formation is absent.

The Grimes Canyon Aquifer, where present in the Oxnard Subbasin, is in hydraulic communication with the overlying FCA, and there are no production wells perforated solely in the Grimes Canyon Aquifer (Turner 1975; VCWPD 2013). As a result, there is little information on the water quality or aquifer properties of the Grimes Canyon Aquifer. In general, in the Oxnard Subbasin, the Grimes Canyon Aquifer has water of poor quality, and some basal portions of the aquifer have brackish water that is likely a result of limited flushing since deposition and upward migration of brines from underlying formations (Mukae and Turner 1975; Turner 1975; Hanson et al. 2003). In addition, seawater intrusion may have impacted some wells screened in the Grimes Canyon Aquifer (see Section 2.3.3). Aquifer properties data specific to the Grimes Canyon Aquifer are not currently available.

2.2.5 Data Gaps and Uncertainty

The primary data gaps in the hydrogeologic conceptual model are:

- Distributed measurements of aquifer properties from wells screened solely in a single aquifer
- Distributed measurements of groundwater quality from wells screened solely in a single aquifer
- Measurements of groundwater quality that distinguish the sources of high total dissolved solids (TDS) concentrations in the Fox Canyon Aquifer and Grimes Canyon Aquifer.

The data gaps listed above create uncertainty in the understanding of the impacts of water level changes on change in storage in the aquifer and on the inland extent of seawater intrusion in the aquifers. Additional aquifer tests and groundwater quality sampling in the future would help reduce the uncertainty associated with these data gaps.

2.2.6 Maps and Cross-Sections

A geologic map is provided in Figure 2-2, and cross-sections are provided in Figures 2-3 and 2-4.

2.3 GROUNDWATER CONDITIONS

2.3.1 Groundwater Elevation Data

Groundwater elevations in the Oxnard Subbasin were first measured in agricultural wells in the 1930s, and multiple entities, including UWCD, DWR, and the County of Ventura (the County), have recorded water elevations in the Oxnard Subbasin over the intervening decades. In the early 1990s, after the U.S. Geological Survey (USGS) installed a series of nested monitoring wells during the Regional Aquifer System Analysis (or "RASA Study"; Densmore 1996), an annual groundwater monitoring program was initiated in the Subbasin by the County, United Water Conservation District (UWCD), and USGS (FCGMA 2007). The groundwater monitoring programs conducted by the County Watershed Protection District (WPD) and other agencies, including UWCD, includes production wells and multiple-completion nested monitoring wells. Many of the production wells included in the monitoring program are screened across multiple aquifers. Historically, the FCGMA annual reports have included potentiometric surface maps for wells screened in the UAS and wells screened in the LAS (FCGMA 2015).

To conform with Title 23 of the California Code of Regulations (CCR) Section 354.14, the following discussion of groundwater elevation is limited to production and monitoring wells screened in a single aquifer. Water level measurements collected between March 2 and March 29, 2015, are used to represent groundwater elevations in spring 2015. Water level measurements collected between October 2 and 29, 2015, are used to represent groundwater elevations in fall 2015.

Because many production wells within the Subbasin are screened across multiple aquifers and there are a limited number of dedicated monitoring wells, the depiction of representative regional potentiometric surfaces in each aquifer is limited. Groundwater pumping data for the year 2015 were mapped to provide context for interpreting the potentiometric surfaces presented in this section (see Figures 2-5 and 2-6). Self-reported groundwater extraction data for 2015 are shown in Figures 2-5 and 2-6 for wells screened in the UAS and LAS, respectively. In the UAS, the location of the greatest amount of extraction is within the Forebay, with additional extraction areas both west and southeast of the City of Oxnard (Figure 2-5). The majority of the production from the LAS is in the southeastern portion of the Subbasin (Figure 2-6). The volume of groundwater extracted from the LAS is greater than that extracted from the UAS.

Current and historical groundwater elevations are discussed below by aquifer. Full hydrographs for all Oxnard Subbasin wells in which five or more water level measurements have been recorded are included in Appendix A.In general, climate cycles, management actions, and the construction of water conservation facilities have impacted water elevations in the Oxnard Subbasin. The Freeman Diversion, completed in 1991, allows UWCD to divert surface water from the Santa Clara River to spreading basins, where it can infiltrate into the aquifers of the UAS and be transported via pipelines to other areas. This additional recharge enhanced aquifer recovery in the 1990s after a period of drought (FCGMA 2007). Additionally, UWCD's Pumping Trough Pipeline (PTP), constructed in 1986, which delivers surface water from the Forebay to agricultural parcels on the Oxnard Plain in lieu of groundwater production from this area, resulted in rising groundwater elevations during the late 1980s. In 1991, Ventura County adopted Ordinance 3991, which prohibited the drilling of new wells in the UAS, which also contributed to water elevation recovery in the UAS in the 1990s.

2.3.1.1 Oxnard Aquifer

Spring and Fall 2015 Groundwater Elevations

In the spring of 2015, recorded groundwater elevations in the Oxnard Aquifer wells ranged from -27.2 to 46.3 feet above mean sea level (amsl; Figure 2-7). In the fall of 2015, recorded groundwater elevations ranged from -30.7 to 37.9 feet amsl (Figure 2-8).

Groundwater flows from areas of high groundwater elevation to areas of low groundwater elevation. The highest groundwater elevations in the Oxnard Aquifer are found in the Forebay in both the fall and spring of 2015, despite the groundwater production from this area (Figures 2-5 and 2-7). The hydraulic gradient in the Forebay in the spring of 2015 was approximately 0.005 feet/feet with groundwater flowing to the south and southwest, toward the pumping centers west and southeast of the City of Oxnard. In the fall of 2015, the hydraulic gradient was approximately 0.005 feet/feet with groundwater flowing to the southwest and southeast.

Away from the Forebay, groundwater elevations in the Oxnard Aquifer are higher on the western and eastern boundaries of the Subbasin than they are in the center of the Subbasin. In this central area, groundwater elevations are more than 20 feet below sea level in both the spring and fall of 2015, though the areal extent of lower elevations is much greater in fall than in spring (Figures 2-7 and 2-8). In general, elevations in the UAS in the central Oxnard Subbasin are above sea level during wet climatic periods and fall below sea level during droughts (UWCD 2016a). Artesian conditions can occur in the western Oxnard Subbasin during wet climatic cycles (UWCD 1999).

The central area of low elevations reflects the groundwater production from wells southeast of the City of Oxnard in the central Oxnard Subbasin (Figure 2-5). The hydraulic gradient, directed toward the production wells, was less than approximately 0.001 feet/feet in both the spring and fall of 2015. Coastal elevations were measured below or near sea level in both spring and fall of 2015, and consequently, the hydraulic gradient was generally landward at the coast (Figures 2-7 and 2-8).

There is uncertainty associated with the groundwater elevation contours, hydraulic gradient, and groundwater flow direction in the Oxnard Aquifer in the spring and fall of 2015. Fewer wells are screened solely within the Oxnard Aquifer than are producing groundwater from the Oxnard Aquifer. The majority of the wells that produce groundwater in the Oxnard Aquifer are screened across multiple aquifers. These wells were not used to create the contour maps in order to conform with Title 23 of CCR Section 354.14. The uncertainty in hydraulic gradient, flow direction, and groundwater elevation within the Oxnard Aquifer is particularly pronounced in the southern Oxnard Subbasin where there are few wells screened solely within the Oxnard Aquifer but several production wells screened in multiple aquifers (Figures 2-7 and 2-8).

Vertical Gradients

Groundwater elevations in the Oxnard Aquifer are higher than those in the underlying Mugu Aquifer, resulting in a downward vertical gradient from the Oxnard Aquifer to the Mugu Aquifer in all areas of the Oxnard Subbasin for which Mugu-specific elevation data is available (Table 2-2). The magnitude of the vertical gradient varies with distance from the coast. The downward vertical gradient between the Oxnard and Mugu Aquifers was calculated for five wells in the fall of 2015 (Table 2-2). The wells in Table 2-2 were selected from a larger group of nested groundwater monitoring wells to represent the vertical gradient at different geographic locations in the Subbasin.

In the spring of 2015, the vertical gradient from the Oxnard Aquifer to the underlying Mugu Aquifer ranged from 0.004 feet/feet at the coast near Port Hueneme to 0.278 feet/feet inland of Point Mugu (Table 2-2). In the fall of 2015, the vertical gradient from the Oxnard Aquifer to the underlying Mugu Aquifer ranged from 0.002 feet/feet at the coast near Port Hueneme to 0.468

feet/feet inland of Point Mugu (Table 2-2). The vertical gradients along the coast are lower than they are inland, possibly reflecting the influence of seawater in the aquifer, moderating water levels at the coast. Alternatively, the vertical gradients may be lower at the coast because there is less pumping near the coast (Figures 2-5 and 2-6), and gradients may be higher in some inland areas that are closer to the Forebay area, as recharge in the Forebay affects water pressure in the Oxnard Aquifer more than the other aquifers.

The vertical gradient between the Oxnard and Mugu Aquifers was higher in the fall than in the spring, except at the coast where it was the same in the spring and fall (wells 01N22W20M02S and -03S), and in the Forebay where the gradient was higher in the spring than in the fall (wells 02N22W23B07S and -08S). The vertical gradient in the Forebay was higher in the spring because of surface water spreading grounds in the Forebay that are primarily utilized during periods of higher flow in the Santa Clara River.

Vertical gradients within the Oxnard Aquifer were determined from monitoring well clusters 01N21W19L, 02N22W23B, and 01N22W28G, which have two screen intervals within the Oxnard Aquifer (Table 2-2). For each of these locations, the vertical hydraulic gradient within the Oxnard Aquifer was directed downward. The downward vertical hydraulic gradient ranged from 0.009 to 0.278 feet/feet in the spring of 2015. In the fall of 2015, the downward vertical gradient ranged from 0.016 to 0.643 feet/feet. The downward vertical hydraulic gradient was larger in the fall than in the spring, and the largest downward vertical hydraulic gradient was in the Forebay. The smallest downward vertical hydraulic gradient within the Oxnard Aquifer was adjacent to the coast (Table 2-2; Figure 2-8).

Table 2-2
Vertical Gradient

Location	Nested group (First 9 digits of SWN)	Well (Penultimate 2 digits of SWN)	Screen Interval		Spring 2015 Elevation (feet amsl)	Spring 2015 Gradient (feet/ feet)[1]	Fall 2015 Elevation (feet amsl)	Fall 2015 Gradient (feet/ feet)[1]	Aquifer[2]
			Top	*Bottom*					
Forebay	02N22W23B	09	75	95	NA	-	10.41	-0.643	Oxnard
		08	135	155	-13.06	-0.057	-28.19	-0.019	Oxnard
		07	260	300	-20.72	-0.012	-30.81	-0.028	Mugu
		06	460	500	-23.2	-0.114	-36.43	-0.107	Hueneme
		05	830	870	-65.53	-0.036	-75.84	-0.039	Hueneme
		04	1110	1150	-75.59	-0.014	-86.77	0.032	Hueneme
		03	1210	1250	-77	-	-83.55	-	Fox
Forebay	02N21W07L	06	135	155	8.2	-0.012	-12.07	-0.042	Mugu
		04	500	540	3.88	-0.014	-27.9	0.022	Fox
		03	640	700	1.84	-	-24.59	-	Fox—
North - Coastal	01N23W01C	05	120	145	1.18	-0.040	-0.92	-0.048	Oxnard
		04	630	695	-20.03	-0.009	-26.52	-0.010	Hueneme
		03	965	1065	-23.24	-0.014	-29.95	-0.010	Hueneme
		02	1390	1490	-29.31	—	-34.34	—	Fox
Port Hueneme	01N22W20M	06	50	70	1.27	-0.071	1.8	-0.131	Semi-perched
		05	150	170	-5.78	-0.004	-11.27	-0.002	Oxnard
		04	280	300	-6.26	-0.033	-11.55	-0.039	Mugu
		03	520	560	-14.6	-0.017	-21.3	-0.019	Hueneme
		02	700	740	-17.57	-0.040	-24.8	-0.048	Hueneme
		01	900	940	-25.65		-34.47		Fox
Port Hueneme	01N22W28G	5	180	200	-7.4	-0.009	-12.4	-0.016	Oxnard
		4	255	275	-8.1	-0.030	-13.6	-0.032	Oxnard
		3	720	760	-22.3	-0.039	-28.8	-0.051	Hueneme
		2	995	1095	-34.2	0.010	-44.2	0.019	Fox
		1	1295	1395	-31.3	-	-38.6	-	Grimes

Table 2-2
Vertical Gradient

Location	Nested group (First 9 digits of SWN)	Well (Penultimate 2 digits of SWN)	Screen Interval		Spring 2015 Elevation (feet amsl)	Spring 2015 Gradient (feet/ feet)[1]	Fall 2015 Elevation (feet amsl)	Fall 2015 Gradient (feet/ feet)[1]	Aquifer[2]
			Top	*Bottom*					
Point Mugu	01N22W36K	09	175	195	-13.07	-0.110	-24.14	-0.156	Oxnard
		08	310	330	-27.89	-0.220	-45.17	-0.561	Mugu
		07	410	450	-52.06	-0.005	-106.82	-0.019	Fox
		06	540	580	-52.71	-0.025	-109.32	-0.014	Fox
		05	680	720	-56.26	-	-111.34	-	Grimes
South/ Central	01N21W19L	14	18	38	11.97	-0.278	10.1	-0.331	Semi-perched
		13	110	130	-13.63	-0.048	-20.33	-0.096	Oxnard
		12	200	220	-17.93	-0.109	-28.96	-0.119	Oxnard
		11	300	320	-28.85	-0.390	-40.87	-0.620	Mugu
		10	394	414	-65.55	-	-99.19	-	Fox
South	01N21W32Q	06	275	285	-41.21	-0.278	-65	-0.468	Oxnard
		07	180	220	-12.7	-0.356	-20.24	-0.560	Mugu
		05	330	370	-60.7	-0.021	-97.74	-0.028	Mugu
		04	600	640	-66.3	-0.047	-105.38	-0.044	Fox Canyon
		03	800	840	-75.6	0.084	-114.17	0.084	Grimes
		02	930	970	-64.7	-	-103.2	-	Grimes

Notes: SWN = State Well Number; amsl = above mean sea level
1 Negative gradients are directed downward.
2 The Oxnard and Mugu Aquifers compose the UAS, and the Hueneme, Fox, and Grimes Aquifers compose the LAS. Aquifer designations were provided by UWCD.

Historical Groundwater Elevation Trends

Groundwater elevations in the Oxnard Aquifer have declined and recovered over climatic cycles since the 1930s (Figure 2-9a). Management policies and the construction and operation of water conservation facilities have also impacted historical groundwater elevations (see Section 2.3.1). Full hydrographs for Oxnard Subbasin wells with five or more groundwater elevation measurements are included in Appendix A.

Groundwater elevation trends in well 01N21W07H01S, the well with the longest historical groundwater elevation record in the Oxnard Subbasin, track with the trends observed in the record of cumulative departure from the mean precipitation on the Oxnard Plain (Figure 2-9a). Declines in groundwater elevation occurred between 1941 and 1966, 1970 and 1977, 1984 and 1990, and 2011 and 2016, coincident with periods of drought shown in the declining limb of the cumulative departure from the mean precipitation curve (Figure 2-9a). Groundwater elevations recover after each drought period. The amount of recovery depended on the length of time between droughts and the amount of precipitation received in each of the water years between the droughts, as well as management measures operative during the various time periods. By 1980, the groundwater elevation recovered to within 10 feet of the previous maximum measured in 1941, and by 1999, water levels exceeded the 1941 maximum (Figure 2-9a), likely due to several wet years during the 1990s and the influence of management actions taken, and water conservation facilities constructed, in the 1980s and 1990s (see Section 2.3.1). In the late 1990s, artesian conditions were documented in the western Oxnard Subbasin (UWCD 1999). Since 2011, groundwater elevations in this well have declined approximately 40 feet.

The patterns of water level decline and recovery observed in well 01N21W07H01S are observed in Oxnard Aquifer wells throughout the Oxnard Subbasin, although absolute changes in water level vary geographically within the Oxnard Subbasin (Figures 2-9a and 2-9b). Wells in the Forebay area and northeastern Oxnard Subbasin have experienced water level declines of approximately 90 feet since 2011 (Figure 2-9b), while water levels in wells adjacent to the coast and in wells farther south have declined between 18 and 40 feet over the same time period (Figure 2-9a). The larger water level changes observed in the northeastern Oxnard Subbasin reflect the influence of UWCD's managed aquifer recharge activities in the Forebay area; additionally, water level changes at the coast may be smaller due to the fact that seawater may be intruding and occupying volume within the aquifer as freshwater recedes.

Although groundwater elevations in the Oxnard Subbasin recover to some degree after each drought period, elevations in coastal wells do not always recover to mean sea level. Historical elevations of coastal wells over time in relation to sea level are discussed in Section 2.3.3.

2.3.1.2 Mugu Aquifer

Spring and Fall 2015 Groundwater Elevations

In the spring of 2015, recorded groundwater elevations in the Mugu Aquifer in the Oxnard Subbasin ranged from -60.7 to 8.2 feet amsl (Figure 2-10). In the fall of 2015, groundwater elevations ranged from -97.7 to -12.1 feet amsl (Figure 2-11).

The highest groundwater elevations in the Mugu Aquifer are found in the Forebay in both the fall and spring of 2015 (Figures 2-10 and 2-11). The hydraulic gradient in the Forebay in the spring of 2015 was approximately 0.003 feet/feet with groundwater flowing to the south and southwest. In the fall of 2015, the hydraulic gradient was approximately 0.002 feet/feet with groundwater flowing to the south and southwest. These gradients are based on the wells that are screened solely within the Mugu Aquifer, which are primarily located in the eastern part of the Subbasin. Groundwater elevations in the Mugu Aquifer are lowest in the southeastern area of the Subbasin. In general, elevations in the UAS in the southernmost corner of the Subbasin tend to be lower than in the central Subbasin (by as much as 40 to 80 feet), regardless of climatic cycles (FCGMA 2013).

In the southeastern area of the Subbasin, groundwater elevations are 30 to 100 feet below sea level in 2015 (Figures 2-10 and 2-11). The hydraulic gradient, directed toward the area of low groundwater elevations, was approximately 0.002 feet/feet to the southeast in the spring of 2015. In the fall of 2015, the hydraulic gradient directed toward the area of low groundwater elevations ranged from approximately 0.004 to 0.009 feet/feet to the east–southeast. Coastal groundwater elevations were measured below or near sea level in both spring and fall of 2015, creating a presumably landward hydraulic gradient at the coast (Figures 2-10 and 2-11).

There is uncertainty associated with the groundwater elevation contours, hydraulic gradient, and groundwater flow direction in the Mugu Aquifer in the spring and fall of 2015. The gradient is unknown in the northwestern area of the Subbasin, where there are no wells screened solely within the Mugu Aquifer. Additionally, fewer wells are screened solely within the Mugu Aquifer than are producing groundwater from the Mugu Aquifer. The majority of the wells that produce groundwater in the Mugu Aquifer are screened across multiple aquifers. These wells were not used to create the contour maps in order to conform with Title 23 CCR Section 354.14. For the areas of the Subbasin in which there are well data in the Mugu Aquifer, the uncertainty in hydraulic gradient, flow direction, and groundwater elevation within the aquifer is particularly pronounced in the central and eastern Oxnard Subbasin. In this area, groundwater appears to flow to the south–southeast from the Oxnard Subbasin to the Pleasant Valley Basin (Figures 2-10 and 2-11).

Vertical Gradients

Groundwater elevations in the Mugu Aquifer are lower than those in the overlying Oxnard Aquifer, resulting in a downward vertical gradient from the Oxnard Aquifer to the Mugu Aquifer throughout the Oxnard Subbasin (Table 2-2; Section 2.3.1.1). Groundwater elevations in the Mugu Aquifer are higher than those in the underlying Hueneme Aquifer, resulting in a downward vertical gradient from the Mugu Aquifer to the Hueneme Aquifer in the Forebay and adjacent to Port Hueneme (Table 2-2). At monitoring well cluster 01N22W20M, adjacent to Port Hueneme, the downward vertical hydraulic gradient was 0.033 feet/feet in the spring of 2015 and 0.039 feet/feet in the fall of 2015. At monitoring well cluster 02N22W23B, in the Forebay, the downward vertical hydraulic gradient was 0.012 feet/feet in the spring of 2015 and 0.028 feet/feet in the fall of 2015.

Within the Mugu Aquifer, a downward vertical gradient of 0.365 feet/feet was calculated in the spring of 2015 between wells 01N21W32Q07S and 01N21W32Q05S (Figure 2-10). In the fall of 2015, the downward vertical gradient was 0.560 feet/feet (Table 2-2; Figure 2-11).

Historical Groundwater Elevation Trends

Groundwater elevations in the Mugu Aquifer have declined and recovered over climatic cycles since the 1970s (Figure 2-12). Management policies and the construction and operation of water conservation facilities have also impacted historical groundwater elevations (see Section 2.3.1 above). Full hydrographs for Oxnard Subbasin wells with five or more groundwater elevation measurements are included in Appendix A.

Groundwater elevation trends in well 02N22W24P01S, the well with the longest historical groundwater elevation record in the Mugu Aquifer, track with the trends observed in the record of cumulative departure from the mean precipitation on the Oxnard Plain (Figure 2-12). Declines in groundwater elevation occurred between 1974 and 1977, 1984 and 1990, and 2011 and 2016, coincident with periods of drought shown in the declining limb of the cumulative departure from the mean precipitation curve (Figure 2-12). Groundwater elevations recovered after each drought period. The amount of recovery depends on the length of time between droughts and the amount of precipitation received in each of the water years between the droughts, as well as management measures operative during the various time periods. In 1996, water levels exceeded the previous maximum in 1980 (Figure 2-12), likely due to several wet years during the 1990s and the influence of management actions taken, and water conservation facilities constructed in the 1980s and 1990s (see Section 2.3.1 above). In the late 1990s, artesian conditions were documented in the western Oxnard Subbasin (UWCD 1999). Since 2011, groundwater elevations in this well have declined approximately 100 feet.

The patterns of water level decline and recovery observed in well 02N22W24P01S are observed in Mugu Aquifer wells throughout the Oxnard Subbasin, although absolute changes in water level vary geographically within the subbasin (Figure 2-12). Well 02N22W24P01S is located near the Forebay area. Other wells in the Forebay area experienced similar water level declines and recoveries to those observed in well 02N22W24P01S (Figure 2-12). Water levels in wells adjacent to the coast and in wells farther south, however, tend to have larger intra-annual variation in water level, but a smaller drought response (e.g., wells 01N21W32Q05S and 01N21W19L11S; Figure 2-12). The groundwater elevation in these wells declined between 20 and 80 feet between 2011 and 2015, whereas the groundwater elevation in wells in the Forebay area declined approximately 100 feet over the same time period. The larger water level changes observed in the northeastern Oxnard Subbasin likely reflect the influence of groundwater recharge from spreading basins in the Forebay area; additionally, water level changes at the coast may be smaller due to the fact that seawater may be intruding and occupying volume within the aquifer as freshwater recedes.

Although groundwater elevations in the Oxnard Subbasin recover after each drought period, groundwater elevations in coastal Mugu-specific wells in the southern Subbasin typically remain below mean sea level. Historical elevations of coastal wells over time in relation to sea level are discussed in Section 2.3.3.

2.3.1.3 Hueneme Aquifer

Spring and Fall 2015 Groundwater Elevations

In the spring of 2015, recorded groundwater elevations in the Hueneme Aquifer in the Oxnard Subbasin ranged from -89.4 to 10.2 feet amsl (Figure 2-13). In the fall of 2015, groundwater elevations ranged from -115.5 to 2.1 feet amsl (Figure 2-14). There are fewer wells screened solely in the Hueneme Aquifer than are screened in the Oxnard, Mugu, or Fox Canyon Aquifers in the Oxnard Subbasin. The small number of wells screened solely within the Hueneme Aquifer creates uncertainty in the groundwater elevation contours, hydraulic gradient, and groundwater flow direction (Figures 2-13 and 2-14). This aquifer is present in the northern part of the Oxnard Subbasin but is absent to the south of Etting and Hueneme Roads (Mukae and Turner 1975).

The highest groundwater elevations in the Hueneme Aquifer are found in the Forebay in both the fall and spring of 2015 (Figures 2-13 and 2-14). The hydraulic gradient in the Forebay in the spring of 2015 was approximately 0.008 feet/feet with groundwater flowing to the southwest. In the fall of 2015 the hydraulic gradient was approximately 0.007 feet/feet with groundwater flowing to the south–southwest.

Groundwater elevations in the Hueneme Aquifer are lowest south of the Forebay and west of Central Avenue (Figures 2-13 and 2-14). In this area, groundwater elevations are 80 to 100 feet below sea level in 2015 (Figures 2-13 and 2-14). This area of lower groundwater elevations coincides with the location of several production wells that are screened solely within the Hueneme Aquifer (Figure 2-6). The hydraulic gradient, directed toward the area of low groundwater elevations, ranged from approximately 0.003 feet/feet to the southeast in the spring of 2015 to approximately 0.008 feet/feet to the east–southeast in the fall of 2015. Coastal groundwater elevations were below or near sea level in both spring and fall of 2015, resulting in a landward hydraulic gradient at the coast (Figures 2-13 and 2-14).

Vertical Gradients

Groundwater elevations in the Hueneme Aquifer are lower than those in the overlying Mugu Aquifer, resulting in a downward vertical gradient from the Mugu Aquifer to the Hueneme Aquifer (Table 2-2; Section 2.3.1.2). Groundwater elevations in the Hueneme Aquifer are higher than those in the underlying Fox Canyon Aquifer, in both the spring and fall of 2015, except in the Forebay at wells 02N22W23B03 and -04. In these wells, the groundwater elevation in the Hueneme Aquifer is higher than it is in the Fox Canyon Aquifer in the spring of 2015, and lower than that in the Fox Canyon Aquifer in the fall of 2015 (Table 2-2). In the spring of 2015, the downward vertical hydraulic gradient between the Hueneme and Fox Canyon Aquifers ranged from 0.014 feet/feet to 0.040 feet/feet. In the fall of 2015, the vertical hydraulic gradient between the Hueneme and Fox Canyon Aquifers ranged from 0.050 feet/feet downward adjacent to the coast, to 0.032 upward in the Forebay (Table 2-2).

Within the Hueneme Aquifer, a downward vertical gradient of 0.017 feet/feet was calculated for wells 01N22W20M03S and 01N22W20M02S, in the spring of 2015 (Figure 2-13). In the fall of 2015, the gradient in these wells is 0.019 feet, which is the same as in the spring. Farther north, in wells 01N23W01C03S and 01N23W01C04S, the vertical gradient within the Hueneme Aquifer is similar to that calculated for wells 01N22W20M03S and 01N22W20M02S. In the spring of 2015, the downward vertical hydraulic gradient was 0.009 feet/feet in wells 01N23W01C03S and 01N23W01C04S. In the fall, the downward vertical hydraulic gradient was 0.010 feet/feet between wells 01N23W01C03S and 01N23W01C04S (Table 2-2).

In wells 02N22W23B07S and 02N22W23B08S, in the Forebay, the downward vertical gradient is greater in the upper Hueneme aquifer than in the lower Hueneme aquifer (Table 2-2). The gradients within the Hueneme aquifer in the Forebay are similar to those within the Hueneme aquifer along the coast.

Historical Groundwater Elevation Trends

Groundwater elevations in the Hueneme Aquifer have declined and recovered over climatic cycles (Figure 2-15). Management policies and the construction and operation of water conservation facilities have also impacted historical groundwater elevations (see Section 2.3.1 above). Full hydrographs for Oxnard Subbasin wells with five or more groundwater elevation measurements are included in Appendix A.

Groundwater elevation trends in well 02N21W31P03S, the well with the longest historical groundwater elevation record in the Hueneme Aquifer, track with the trends observed in the record of cumulative departure from the mean precipitation on the Oxnard Plain (Figure 2-15). Declines in groundwater elevation occurred between 1974 and 1977, 1984 and 1990, and 2011 and 2016, coincident with periods of drought shown in the declining limb of the cumulative departure from the mean precipitation curve (Figure 2-15). Groundwater elevations largely recovered after each drought period. The amount of recovery depends on the length of time between droughts and the amount of precipitation received in each of the water years between the droughts, as well as the management measures operative during the various time periods. Since 2011, groundwater elevations in this well have declined approximately 60 feet (Figure 2-15).

The patterns of water level decline and recovery observed in well 02N21W31P03S are also observed in Hueneme Aquifer wells 01N22W03F05S and 01N22W26M03S, although the magnitude of the change water levels varies between the wells (Figure 2-15). Ignoring seasonal variations reflecting pumping, the spring high elevations between 1996 and 2010 were relatively stable in well 01N22W26M03S and declined by approximately 32 feet in well 01N22W03F05S. Between 2011 and 2015, during a period of drought, groundwater elevations declined approximately 47 feet in well 01N22W26M03S and approximately 55 feet in well 01N22W03F05S (Figure 2-15).

Although groundwater elevations in the Oxnard Subbasin recover after each drought period, groundwater elevations in coastal wells can remain below mean sea level, resulting in a landward gradient near the coast.

2.3.1.4 Fox Canyon Aquifer

Spring and Fall 2015 Groundwater Elevations

In the spring of 2015, recorded groundwater elevations in the Fox Canyon Aquifer in the Oxnard Subbasin ranged from -107.3 to 3.9 feet amsl (Figure 2-16). In the fall of 2015, groundwater elevations ranged from -156.3 to -24.6 feet amsl (Figure 2-17).

The highest groundwater elevations in the Fox Canyon Aquifer are found Forebay in both the fall and spring of 2015 (Figures 2-16 and 2-17). The lowest recorded groundwater elevations are found at well 01N21W06J05S, south of 5th Street, west of Pleasant Valley Road (Figures 2-16 and 2-17). The low groundwater elevations in this well reflects the production from the Fox Canyon Aquifer in this location (Figure 2-6). However, there are several wells in the surrounding areas that produced more groundwater in 2015, but are screened across multiple aquifers in the LAS. The hydraulic gradient in the Fox Canyon Aquifer is directed toward well 01N21W06J05S in both the spring and fall of 2015. In the spring of 2015, the hydraulic gradient was approximately 0.001 to 0.002 feet/feet. In the fall of 2015 the hydraulic gradient ranged from approximately 0.002 to approximately 0.005 feet/feet. These gradients may not fully depict the direction and magnitude of flow within the Fox Canyon Aquifer because more production wells are screened across multiple aquifers in the LAS than are screened solely within the Fox Canyon Aquifer, and consequently production is occurring in areas of the aquifer that lack aquifer-specific groundwater elevation data. Coastal groundwater elevations were measured below or near sea level in both spring and fall of 2015, resulting in a landward hydraulic gradient (Figures 2-16 and 2-17).

Vertical Gradients

Groundwater elevations in the Fox Canyon Aquifer are, generally, lower than those in the overlying aquifers (Figures 2-16 and 2-17; Table 2-2). In the spring of 2015, the downward vertical gradient from the Mugu Aquifer to the Fox Canyon Aquifer ranged from 0.012 feet/feet in the Forebay to 0.390 feet/feet adjacent to Highway 1 (Figure 2-16; Table 2-2). In the fall of 2015, the downward vertical gradient from the Mugu Aquifer to the Fox Canyon Aquifer ranged from 0.620 feet/feet in the Forebay to 0.028 feet/feet south of Hueneme Road.

In the spring of 2015, the downward vertical gradient from the Hueneme Aquifer to the Fox Canyon Aquifer was similar geographically, ranging from 0.014 feet/feet in the Forebay and along the coast north of Port Hueneme to 0.040 feet/feet adjacent to the coast at Port Hueneme (Table 2-2). In the fall of 2015, the vertical hydraulic gradient between the Hueneme and Fox Canyon Aquifers ranged from 0.050 feet/feet downward along the coast near Port Hueneme to 0.032 feet/feet upward in the Forebay (Table 2-2).

Within the Fox Canyon Aquifer, a downward vertical gradient of 0.005 feet/feet was calculated for wells 01N22W36K06S and 01N22W36K07S in the spring of 2015. The vertical hydraulic gradient in these wells, near Point Mugu, was 0.019 feet/feet downward in the fall of 2015. In the Forebay area, the vertical hydraulic gradient within the Fox Canyon Aquifer is 0.014 feet/feet downward in the spring of 2015 and 0.022 feet/feet upward in the fall of 2015 (Table 2-2; wells 02N21W07L04S and 02N21W07L06S).

Groundwater elevations in the Fox Canyon Aquifer are higher than those in the underlying Grimes Canyon Aquifer, except adjacent to Port Hueneme in wells 01N22W28G04S and 01N22W28G05S (Table 2-2).

Historical Groundwater Elevation Trends

Groundwater elevations in the Fox Canyon Aquifer have declined and recovered over climatic cycles (Figure 2-18). Management policies and the construction and operation of water conservation facilities have also impacted historical groundwater elevations (see Section 2.3.1 above). Full hydrographs for Oxnard Subbasin wells with five or more groundwater elevation measurements are included in Appendix A.

Groundwater elevation trends in well 01N22W26K04S, the well with the longest historical groundwater elevation record in the Fox Canyon Aquifer, track with the trends observed in the record of cumulative departure from the mean precipitation on the Oxnard Plain (Figure 2-18). Declines in groundwater elevation occurred between 1974 and 1977, and 1984 and 1990, and 2011 and 2016, coincident with periods of drought shown in the declining limb of the cumulative departure from the mean precipitation curve (Figure 2-18). Groundwater elevations recovered after each drought period. The amount of recovery depends on the length of time between droughts and the amount of precipitation received in each of the water years between the droughts, as well as management measures operative during the various time periods. In 1999, water levels exceeded the previous maximum in 1983 (Figure 2-18), likely due to several wet years during the 1990s and the influence of management actions taken, and water conservation facilities constructed, in the 1980s and 1990s (see Section 2.3.1, above). In the late 1990s, artesian conditions were documented in the western Oxnard Subbasin (UWCD 1999).

The patterns of water level decline and recovery observed in well 01N22W26K04S are observed in Fox Canyon Aquifer wells throughout the Oxnard Subbasin, although absolute changes in water level vary geographically within the Oxnard Subbasin (Figure 2-18). Well 01N22W26K04S is located south of Hueneme Road. Other wells in this area experienced similar water level declines and recoveries to those observed in well 01N22W26K04S (Figure 2-18). Water levels in wells farther inland tend to have larger intra-annual variations in water level (e.g., wells 01N21W06J05S and 01N21W09C04S; Figure 2-18). The groundwater elevation in these wells declines by 40 to 50 feet each year between the spring high and fall low water levels. In contrast, well 01N23W01C02S, adjacent to the coast, declines approximately 5 feet between the spring high and fall low water level (Figures 2-16, 2-17, and 2-18). Water level changes at the coast may be smaller due to the fact that seawater may be intruding and occupying volume within the aquifer as freshwater recedes.

Although groundwater elevations in the Oxnard Subbasin recover after each drought period, groundwater elevations in coastal Fox-specific wells in the southern Subbasin typically remain below mean sea level.

2.3.1.5 Grimes Canyon Aquifer

Spring and Fall 2015 Groundwater Elevations

The Grimes Canyon Aquifer is only found underlying the southern and eastern parts of the Oxnard Subbasin (Turner 1975). Only six wells in the Oxnard Subbasin are screened solely within the Grimes Canyon Aquifer. These wells are located in the southern part of the subbasin, all located west of Revolon Slough (Figure 2-19). In the spring of 2015, recorded groundwater elevations in the Grimes Canyon Aquifer ranged from -31.3 to -75.6 feet amsl (Figure 2-19). In the fall of 2015, groundwater elevations ranged from -38.6 feet amsl to -114.2 feet amsl (Figure 2-20).

Where measured, groundwater in the Grimes Canyon Aquifer flows to the east–northeast from the coast toward the Revolon Slough (Figures 2-19 and 2-20). In the spring of 2015, the hydraulic gradient in the vicinity of Point Mugu was approximately 0.003 feet/feet (Figure 2-19). In the fall of 2015, the hydraulic gradient was approximately 0.008 feet/feet (Figure 2-20).

There is a large degree of uncertainty associated with the groundwater elevation contours, hydraulic gradient, and groundwater flow direction in the Grimes Canyon Aquifer in the spring and fall of 2015 because so few wells are screened solely within the Grimes Canyon Aquifer. The direction of flow, as contoured by the wells that are screened within the Grimes Canyon aquifer likely reflects the LAS groundwater production south of Hueneme Rd (Figure 2-6). However, no wells are screened solely within the Grimes Canyon Aquifer north of Hueneme Road; therefore, the groundwater elevation, hydraulic gradient, and direction of flow in the Grimes Canyon Aquifer is unknown for much of the Oxnard Subbasin. Coastal groundwater elevations were measured below or near sea level in both spring and fall of 2015, and consequently the hydraulic gradient was landward at the coast (Figures 2-19 and 2-20).

Vertical Gradients

Groundwater elevations in the Grimes Canyon Aquifer are, generally, lower than those in the overlying Fox Canyon Aquifer, except adjacent to Port Hueneme in wells 01N22W28G04S and 01N22W28G05S (Table 2-2). The downward vertical hydraulic gradient in the spring of 2015 ranged from 0.047 feet/feet downward at wells 01N21W32Q04S and 01N21W32Q05S to 0.01 feet/feet upward wells 01N22W28G04S and 01N22W28G05S (Table 2-2). Vertical hydraulic gradients were similar in the fall of 2015, ranging from 0.044 feet/feet downward to 0.019 feet/feet upward, in the same wells.

Only well cluster 01N21W32Q has two wells screened within the Grimes Canyon Aquifer (Figure 2-19). Within the Grimes Canyon Aquifer, the vertical hydraulic gradient was 0.084 feet/feet upward in both the spring and fall of 2015 (Table 2-2).

Historical Groundwater Elevation Trends

Groundwater elevations in the Grimes Canyon Aquifer have been measured since 1989. Similar to the water levels in the overlying Fox Canyon Aquifer, the water levels in the Grimes Canyon Aquifer recovered between 1990 and 1996 (Figure 2-21). Between 1996 and 2010, groundwater elevations were relatively stable, with intra-annual variation of up to 80 feet per year, but with inter-annual variation of 10 feet or less. Between 2011 and 2015 groundwater elevations in the Grimes Canyon aquifer declined, coincident with a period of drought. Groundwater elevations in wells 01N22W28G01S and 01N22W35E01S vary less than groundwater elevations in other Grimes Canyon aquifer wells, potentially because they are relatively far from major centers of groundwater extraction or because they are adjacent to the coast, and the intrusion of seawater may moderate freshwater elevation changes (Figures 2-19 and 2-21).

Although groundwater elevations in the Oxnard Subbasin recover to some degree after each drought period, elevations in coastal Grimes Canyon Aquifer-specific wells in the southern Subbasin remain below mean sea level.

2.3.2 Estimated Change in Storage

Estimated monthly change in storage values for the Oxnard Subbasin were generated by the numerical groundwater flow model prepared by UWCD (Sun, pers. comm. 2017). Monthly data reported from the model was summed to get the annual change in storage for the period from water year 1986 to water year 2015. The average annual change in storage in the Oxnard Subbasin was a decrease in storage of approximately 2,000 acre-feet per year. The maximum annual increase in storage was 91,390 acre-feet in water year 1993, and the maximum annual decrease in storage was 47,178 acre-feet in water year 1987 (Figure 2-22). The cumulative change in storage calculated by the model over the period of record was a loss of 59,808 acre-feet (Figure 2-23). Pumping in FCGMA is reported on a calendar year basis, so pumping and spreading in figures is per calendar year, while change in storage is per water year. Annual change in storage does not appear to be strongly correlated to groundwater pumping in the Oxnard Plain. Artificial groundwater recharge at the UWCD spreading grounds appears to have a much larger effect on change in storage (Figures 2-24 and 2-25).

The model results illustrated in Figures 2-22 to 2-25 represent the net change in groundwater storage, including seawater intrusion. The volume of seawater that is included in the model change in storage was calculated for the primary aquifers. The volume of seawater calculated does not include flows of seawater into, or of freshwater out of, the Semi-Perched zone, as water is rarely extracted from it for beneficial use. The average annual change in storage without seawater intrusion in the Oxnard Subbasin was a decrease in storage of approximately 13,500 acre-feet per year. The maximum annual increase in storage without seawater intrusion is 78,000 acre-feet in water year 2005, and the maximum annual decrease in storage minus seawater intrusion is 77,000 acre-feet in water year 1990. The cumulative change in storage without seawater intrusion calculated by the model over the period of record was a loss of 404,000 acre-feet.

Modeled change in storage is dependent on several input parameters to the model, which include groundwater pumping, artificial aquifer recharge, interbasin flows, recharge from precipitation and irrigation returns, stream leakage and groundwater discharge to streams, and inflows from the ocean. Numbers may also initially be biased due to assumptions about the head of water in the aquifer at the start of the model. These inputs were estimated using the best available data and calibrated to water levels in the model to the greatest extent possible. Changes in calculations for these input values, along with continued model calibration, will result in changes in the modeled estimate of change in storage in the future.

2.3.3 Seawater Intrusion

Evidence of seawater intrusion (SWI) in the Oxnard Subbasin was first documented in the 1930s in the vicinity of Port Hueneme and Point Mugu (DWR 1965). Since that time, the landward extent of the seawater intrusion front has been monitored and the causes and sources of increasing chloride concentrations have been studied. Table 2-3 lists historical seawater intrusion reports and studies on the Oxnard Subbasin.

Table 2-3
Seawater/Saline Water Historical Reports and Studies

Title	Author/Agency	Date
Sea Water Intrusion, Oxnard Plain Ventura County	California Department of Water Resources	October 1965
Sea-Water Intrusion: Aquitards in the Coastal Ground Water Basin of Oxnard Plain, Ventura County	California Department of Water Resources, Bulletin No. 63-4	September 1971
Oxnard Plain Groundwater Study	State Water Resources Control Board	March 1979
Chloride Sources in a California Aquifer	John A. Izbicki, USGS	July 1991
A Study of Seawater Intrusion Using Direct-Current Soundings in the Southeastern Part of the Oxnard Plain, California	USGS, Open File Report 93-524	1993
Use of δ18O and δD to Define Seawater Intrusion	John A. Izbicki, USGS	1996

Table 2-3
Seawater/Saline Water Historical Reports and Studies

Title	Author/Agency	Date
Simulation of Ground-Water/Surface-Water Flow in the Santa Clara-Calleguas Ground-Water Basin, Ventura County, California	Hanson et al., USGS; WRIR 02-4136	2003
Mugu Seawater/Saline Water Intrusion Monitoring Program, AB303 Grant, Agreement No. 4600004100	UWCD	April 2007
2007 Update to the Fox Canyon Groundwater Management Agency Management Plan	FCGMA	2007
Oxnard Plain Time Domain Electromagnetic Study for Saline Intrusion	UWCD, Open-File Report 2010-003	2010
Saline Intrusion Update, Oxnard Plain and Pleasant Valley Basins	UWCD	October 2016

An elevated risk of SWI has been found to exist near Port Hueneme and Point Mugu due to the near shore presence of the groundwater-seawater contact in deeply incised submarine canyons (UWCD 2016a).

SWI has been documented in both aquifer systems, and in each primary aquifer, in the Oxnard Subbasin. Seawater preferentially intrudes the aquifers in permeable sand and gravel beds (USGS 2016a). As a result, the eastward extent of the seawater intrusion front varies from north to south along the coastline, and varies within each aquifer (USGS 2016a). In the Oxnard Subbasin, seawater that has intruded the aquifers in the vicinity of Port Hueneme tends to flow southward towards Point Mugu even after groundwater elevations rise, and the landward hydraulic gradient is reversed. As a result higher groundwater elevations in the aquifer do not tend to flush the seawater back out of the aquifer via the original intrusion pathway (UWCD 2016a). Consequently impacts associated with SWI have not been eliminated during wetter than average climatic periods.

2.3.3.1 Causes of Saline Impacts in the Oxnard Subbasin

Under seaward groundwater gradients, groundwater in the Oxnard Subbasin generally flows south and west from the Oxnard Forebay area toward the Pacific Ocean and out to sea. When groundwater heads near the coast fall below sea level or, in confined aquifers, the sea levelequivalent elevation according to the depth of the aquifer outcrop[2], the gradient reverses. In areas of higher transmissivity, seawater is drawn into freshwater aquifers.

In addition to SWI, low groundwater heads in confined zones in the Oxnard Subbasin can create conditions under which high-salinity waters from non-marine sources impact freshwater aquifers. These sources include connate brines released during compaction of aquitards and older, higher-salinity groundwater upwelling from geologic formations deeper than the lower extent of the fresh water aquifers (UWCD 2016a; Izbicki et al. 2005).

Thirdly, although the major aquifer units in the Oxnard Subbasin are commonly separated by low-permeability units, vertical gradients, long-screened wells, and areas of mergence between aquifers can result in vertical groundwater movement between major aquifers (UWCD 2016a). In particular, because water elevations are typically higher in the Semi-Perched Aquifer than in the deeper confined aquifers, higher-salinity water from the Semi-Perched Aquifer may reach confined aquifers via one or more of these mechanisms.

Because zones of low groundwater head cause both SWI and non-marine brine migration into freshwater aquifers, distinguishing the source of salts in any given well is not always possible, particularly at chloride concentrations less than 500 mg/L (Izbicki 1996). In the southern Subbasin, near Mugu submarine canyon, upward migration of brines can cause chloride concentrations to increase before the seawater front reaches a well (Izbicki 1996). Thus, the chloride concentration measured in wells near the Mugu submarine canyon reflect the combined effects of brine migration and seawater intrusion, making it difficult to define the leading edge of the seawater front in this area (Izbicki 1996).

2.3.3.2 Current Extent of Sea Water Intrusion

Known seawater and saline intrusion in the UAS and LAS in 2015 has generally occurred near and southeast of Port Hueneme and in the area surrounding Mugu Lagoon. As of 2015, although SWI had been reduced in some areas due to management actions and wet climatic conditions in the 1990s and 2000s, TDS and chloride concentrations as high as 49,600 and 20,700 mg/L, respectively, were found in wells inland of the southern Oxnard coast (both measured in 01N22W07R05S; see Appendix B and recent water quality data in Section 2.3.4). The extent of saline water intrusion in the Oxnard Subbasin in 2015 is shown in cross-section on Figure 2-28,

2 Because seawater is approximately 1.025 times denser than freshwater (using the Ghyben-Herzberg theory [De Wiest 1965]), the elevation of confined freshwater necessary to counterbalance the pressure of the water in the sea can be several feet above sea level, and depends on the depth at which an aquifer outcrops in the ocean (i.e., the deeper the outcrop, the higher the freshwater elevation necessary to counterbalance the pressure of seawater).

and in Figures 2-29 through 2-34. As discussed above the precise extent of current SWI impacts is difficult to identify, due to the fact that other, non-marine sources of saline water are known to have contributed to elevated chloride concentrations in the southern Oxnard Subbasin.

Seawater intrusion varies by aquifer (see Figure 2-28). Between 1985 and 2015, the UWCD groundwater model indicates that in the Semi-Perched aquifer, water flows consistently from the aquifer to the ocean. In the Oxnard and Mugu Aquifers, in years characterized by relatively high rainfall, groundwater flows from the aquifers to the ocean in the spring, and the flow reverses in the fall; conversely, in dry years ocean water flows into the aquifers in all seasons. In the Hueneme Aquifer, the direction of flow is primarily from the ocean to the aquifers, though there are some months in which the flow direction is oceanward. In the Fox and Grimes Canyon Aquifers, ocean water flows into the aquifers in every month in the period of record.

2.3.3.3 Historical Progression of Seawater Intrusion

Chloride concentrations were first measured in the Oxnard Subbasin in the 1920's. Between 1920 and 1929, the chloride concentration in three wells in the UAS ranged from 40 to 81 mg/L with the lowest chloride concentration detected at the coast near Port Hueneme (FCGMA 2007). Groundwater elevations at this time ranged from 2 to 22 feet amsl (FCGMA 2007). By 1934, when groundwater elevations in the UAS declined to -2 to 9 feet amsl, the chloride concentration at a coastal well near Port Hueneme was 1,346 mg/L (FCGMA 2007). This was the first evidence of a potential seawater intrusion front in the vicinity of Port Hueneme. Between 1935 and 1940, chloride concentrations at the coast declined again and remained below 50 mg/L from 1934 to 1949 (FCGMA 2007). By 1954, however, as groundwater elevations in the UAS had declined to as much as -35 feet amsl, seawater intrusion is interpreted to have affected an approximately 1 square mile area near Port Hueneme, where two UAS wells had chloride concentrations of 1,070 and 1,925 mg/L.

This area of seawater intrusion expanded to the north and east between 1954 and 1959, and by 1959 an additional area of seawater intrusion was identified in the UAS north and east of Point Mugu (FCGMA 2007). Chloride concentrations near Port Hueneme reached 27,350 mg/L and those near Point Mugu reached 11,475 mg/L (FCGMA 2007). As groundwater elevations remained below sea level, the two areas of seawater intrusion continued to expand through the 1960s and 1970s, with the sweater intrusion front eventually reaching as much as 3 miles inland near Port Hueneme by the early 1980s (Izbicki 1996; FCGMA 2007).

The implementation of management strategies and pumping allocations by the FCGMA, along with increased rainfall in the late 1970s and early 1980s reduced the area of the UAS affected by seawater intrusion, even as groundwater elevations remained below sea level throughout much of the Subbasin (FCGMA 2007). With the completion of the Freeman diversion, which allowed for increased aquifer recharge at the spreading basins operated by UWCD, and additional above average rainfall years groundwater elevations in much of the UAS rose above sea level and the area of the UAS affected by seawater intrusion decreased in the 1990s (FCGMA 2007).

At the same time that seawater intrusion in the UAS was being managed and mitigated in the 1980s and 1990s, seawater intrusion began to affect the LAS (FCGMA 2007). By 1989, chloride was detected at a concentration of 6,700 mg/L at a well near Port Hueneme (FCGMA 2007). By 1994, chloride concentrations between 1,000 and 7,000 mg/L were detected near both Port Huenme and Point Mugu (FCGMA 2007). The area impacted by seawater intrusion remained smaller in the LAS than in the UAS throughout the 1980s and 1990s.

Between 2000 and 2013, groundwater elevations in the UAS remained above sea level and there was little change in the extent of seawater intrusion near Port Hueneme (UWCD 2016). As groundwater elevations dropped below sea level during the recent drought, however, chloride concentrations in UAS monitoring wells near the coast began to increase and the seawater intrusion front expanded eastward again (UWCD 2016). Near Mugu submarine canyon, the groundwater elevations in the UAS has remained below sea level and chloride concentrations in wells near the coast are close to those of seawater (UWCD 2016). The current extent of saline water intrusion in both the UAS and LAS is shown in Figures 2-29 through 2-34.

2.3.3.4 Relationships Between Water Elevation and SWI

The relationship between groundwater elevations and SWI, as measured by changes in chloride concentration, is complex. In a some wells, including wells 01N22W20M05S 01N22W29D03S located near Port Hueneme and screened in the Oxnard and Hueneme Aquifers, respectively, chloride concentrations rise as groundwater elevations decline, and chloride concentrations decline as groundwater elevations rise (Figures 2-35A and 2-35B and Figure 2-36). This response suggests that maintaining higher groundwater elevations will limit the eastward extent of seawater intrusion in this area. However, in well 01N22W29D02S, which is located in the same well cluster as well 01N22W29D03S and is screened deeper in the Hueneme Aquifer, the concentration of chloride increased from 1995 through 2015, independent of groundwater elevation (Figure 2-35C and Figure 2-36). The long-term increase in chloride concentration observed in this well suggests that groundwater elevations, even when above sea level, are not limiting the eastward migration of seawater in the aquifer. A similar trend is observed in well 01S21W08L03S, which screened in the Grimes Aquifer, and located near Point Mugu, although in this well, groundwater elevations have remained below sea level since 1990 (Figure 2-35D and Figure 2-36). A complete set of hydrographs for all wells from which both chloride and groundwater elevation data have been collected, showing the relationship between chloride concentration and groundwater elevation, is provided in Appendix B, and locations of selected coastal wells with a long overlap in chloride and groundwater elevation records are shown on

Figure 2-36. A summary of the relationship between chloride concentration and groundwater elevation by region within the Oxnard Subbasin is provided below.

North Coast

In the north coastal Oxnard Plains, groundwater elevations in one nested well cluster (01N23W01C02S-05S) screened in the Oxnard, the Hueneme, and the Fox Canyon Aquifers, were below sea level in the early 1990s, generally remained above or near sea level between the mid-1990s and early 2010s, and dropped below sea level between 2013 and 2015 (Appendix B). In spite of the low groundwater elevations in the historical record, the chloride concentration in the four nested wells 01N23W01C02S-05S (Figure 2-36) has not exceeded 55 mg/L since the wells were completed in 1990 (Appendix B). Additionally, recent chloride concentrations in both the UAS and the LAS are typically below 100 mg/L (see Section 2.3.4).

Port Hueneme

In the vicinity of Port Hueneme, water elevations in confined aquifers were below sea level in the early 1990s, recovered to elevations above sea level, remained there for two decades, and dropped below sea level between 2011 and 2014, after the onset of the recent drought. Records from nested wells 01N22W20M01 through -06 (which are screened in the Semi-Perched, the Oxnard, the Mugu, two zones in the Hueneme, and the Fox; Figure 2-36 and Appendix B) underscore the variability in the relationships between water elevation and SWI in different water-bearing units. Despite the similarity in the five profiles of water elevation over time, seawater preferentially intruded the Oxnard Aquifer in the past, and rising concentrations of chloride are observed in the Oxnard, Hueneme and Fox Canyon Aquifers, in response to the recent decline in groundwater elevations.

South Coast

In general, groundwater elevations in the Mugu, Fox Canyon and Grimes Canyon Aquifers in the South Coast Region have remained near or below sea level since the early 1990s (Figure 2-36 and Appendix B). Elevations in the Hueneme and Oxnard Aquifers largely remained above sea level between the mid-1990s and early 2010s. Within the upper Oxnard Aquifer, chloride concentrations have been decreasing, while rising chloride concentrations have been measured in the lower Oxnard. In this area, elevated chloride concentrations in the Oxnard Aquifer likely result from southward migration of seawater that intruded the aquifer in the vicinity of Port Hueneme during earlier periods of low groundwater elevations (UWCD 2016).

SWIM Area

In the SWIM Area (Figure 2-36), groundwater elevations in the Oxnard aquifer were generally above sea level between the mid-1990s and 2010, and below sea level before and after that period (Appendix B). Groundwater elevations in wells screened in the Hueneme and Mugu Aquifers remained below or near sea level for the duration of the historical record. Chloride responses to groundwater elevation change are heterogeneous in this area; in some wells chloride remains below 100, while periodic or sustained chloride concentrations greater than 1,000 mg/L are observed in others.

Groundwater elevations in the Fox Canyon and Grimes Canyon Aquifers in the SWIM Area have remained below sea level since the early 1990s.

Point Mugu

In all but one case, groundwater elevations in the vicinity of Mugu Lagoon have remained below sea level since the 1990s. Rising chloride concentrations exceeding 1,000 mg/L are evident in the majority of monitoring wells in this region (Figure 2-36; Appendix B).

2.3.4 Groundwater Quality

FCGMA has adopted Basin Management Objectives for nitrate (milligrams per liter (mg/L) as nitrate, or NO_3), chloride (Cl) and total dissolved solids (TDS) in the Oxnard Subbasin (FCGMA 2007; Table 2-4). Additionally, the Water Quality Control Plan: Los Angeles Region (Basin Plan) specifies Water Quality Objectives (WQOs) for TDS, Cl, NO_3, sulfate (SO_4), boron (B), and nitrogen (mg/L nitrate) (LARWQCB 2013; Table 2-4). The current and historical distribution of these five constituents are discussed below, based on aquifer system, rather than individual aquifer. There are too few measurements of water quality in wells screened solely within a single aquifer to allow for meaningful discussion of water quality by aquifer. Additionally, as discussed in Section 2.3.1, the majority of the groundwater production in the Oxnard Subbasin occurs in wells that are screened across multiple aquifers. This production has the potential to impact water quality in multiple aquifers simultaneously. Therefore, impacts to groundwater quality in the Oxnard Subbasin should be considered based on aquifer system, rather than by individual aquifer.

Table 2-4
Basin Plan and FCGMA Water Quality Thresholds for Groundwater in the Oxnard Subbasin

Threshold Source	Sub-Area / Zone Description	Threshold Concentration (mg/L)				
		TDS	*Chloride*	*Nitrate*	*Sulfate*	*Boron*
LARWQCB Basin Plan WQO	Oxnard Forebay and Confined Aquifers	1200	150	45	600	1
	Unconfined & Perched Aquifers	3000	500	45	1000	-
FCGMA 2007 BMO	Oxnard Forebay	1200	-	22.5	-	-
	Oxnard Plain	-	150	-	-	-

Notes:
WQO Water Quality Objective
BMO Basin Management Objective
TDS Total Dissolved Solids
LARWQCB Basin Plan Los Angeles Regional Water Quality Control Board "Basin Plan," or Water Quality Control Plan. Electronic version, accessed February 20, 2017. <http://www.waterboards.ca.gov/losangeles/water_issues/programs/basin_plan/basin_plan_documentation.shtml>
FCGMA 2007 FCGMA (Fox Canyon Groundwater Management Agency). 2007. "2007 Update to the Fox Canyon Groundwater Management Agency Groundwater Management Plan." Prepared by FCGMA, United Water Conservation District, and Calleguas Municipal Water District. May 2007.

Groundwater quality monitoring within the Oxnard Subbasin occurs at on different schedules for different wells. In order to assess the current groundwater quality conditions within the Oxnard Subbasin, the most recent concentration of each of the five constituents listed above was mapped for samples collected between 2011 and 2015. Historical groundwater quality hydrographs are presented in Appendix C. Statistics on the most recent sample date, the maximum and minimum concentrations measured, the number of times sampled, and the number of samples whose concentration exceeded the relevant water quality threshold are presented in Appendix D.

2.3.4.1 Total Dissolved Solids

The water quality objective for TDS is 1,200 milligrams per liter (mg/L) in the Forebay and confined aquifers, and 3,000 mg/L in the unconfined aquifers (LARWQCB 2013). The basin management objective for TDS is 1,200 mg/L for the Forebay (FCGMA 2007). Sources of high TDS water in the Oxnard Subbasin include seawater and non-marine brines migrating via faults or upwelling from older geologic formations (see Section 2.3.3).

Upper Aquifer System

Concentration of TDS in groundwater in the UAS ranged from 652 mg/L to 49,600 mg/L between 2011 and 2015 (Figures 2-37A and 2-37B). Water with TDS concentrations greater than 35,000 mg/L is considered to be brine. Both the highest and lowest concentrations of TDS were measured adjacent to the coast in wells 01N22W27R05S and 01N22W27C02S, respectively

(Figure 2-33A). The highest concentrations of TDS are found in coastal wells in areas known to be impacted by seawater intrusion (e.g., 01S21W08L04S).. UAS wells with concentrations of TDS greater than 1,200 mg/L are found throughout the Oxnard Subbasin.

Lower Aquifer System

Concentration of TDS in groundwater in the LAS ranged from 392 mg/L to 37,200 mg/L between 2011 and 2015 (Figure 2-38). The highest concentration was measured in well 01N21W32Q03S, which is in the southern Oxnard Subbasin, inland from the coast, and is screened within the Grimes Canyon Aquifer (Figure 2-38). The higher concentration of TDS in this area likely resulted from upward migration of brines in deeper formations, induced by lowered groundwater elevations from groundwater production in the LAS (Izbicki et al. 2005; UWCD 2016a). The lowest concentration was measured in well 01N22W35E03S, screened in the Fox Canyon Aquifer south of Port Hueneme (Figure 2-38). In general, TDS concentrations in the LAS are higher in the southern Oxnard Subbasin than in the northern part of the subbasin (Figure 2-38).

2.3.4.2 Chloride

The water quality objective for chloride is 150 mg/L in the Forebay and confined aquifers, and 500 mg/L in the unconfined aquifers (LARWQCB 2013). The basin management objective for chloride is 150 mg/L for the UAS and LAS. Sources of water high in chloride in the Oxnard Subbasin include seawater and non-marine brines migrating via faults or upwelling from older geologic formations (see Section 2.3.3).

Upper Aquifer System

Concentration of chloride in groundwater in the UAS ranged from 23 mg/L to 20,700 mg/L between 2011 and 2015 (Figures 2-39A and 2-39B). The highest concentration of chloride was measured in well 01N22W27R05S, adjacent to the coast south of Port Hueneme (Figure 2-39A). Groundwater from this well also had the highest concentration of TDS. The lowest concentration of chloride was measured in well 01N22W11C02S in the central Oxnard Subbasin (Figure 2-39A). Chloride concentrations in the UAS are higher near the coast, from Point Hueneme south to Point Mugu, than inland or north of Port Hueneme (Figure 2-39A). In the Forebay, the concentration of chloride is less than 150 mg/L (Figure 2-39B).

The UAS has a long history of seawater intrusion, with groundwater elevations below sea level measured as early as the 1930s (see Section 2.3.3; UWCD 2016a). Flow from the ocean into the aquifer is the cause of the high chloride concentrations in the UAS.

Lower Aquifer System

Concentration of chloride in groundwater in the LAS ranged from 33 mg/L to 14,300 mg/L between 2011 and 2015 (Figure 2-40). The lowest concentration of chloride was measured in well 01N23W01C02S on the coast, north of Port Hueneme (Figure 2-40). The highest concentration of chloride was measured in well 01N21W32Q03S, in the southern Oxnard Subbasin (Figure 2-40). Groundwater quality in this well is likely impacted from upward migration of brines, induced by groundwater production in the LAS (Izbicki et al. 2005).

In general, chloride concentrations in the LAS are higher in the southern Oxnard Subbasin than they are elsewhere in the Oxnard Subbasin (Figure 2-40). In the Forebay, the concentration of chloride in groundwater is less than 100 mg/L, while concentrations of chloride south of Port Hueneme exceed 500 mg/L (Figure 2-40). Seawater intrusion affects a smaller area of the LAS than the UAS, and is more pronounced near Point Mugu than near Port Hueneme (UWCD 2016a).

2.3.4.3 Nitrate

The basin management objective for nitrate is 22.5 mg/L in the Forebay (FCGMA 2007). The water quality objective for nitrate as NO_3 is 45 mg/L for the entire Oxnard Subbasin (LARWQCB 2013). Sources of water high in nitrate in the Oxnard Subbasin include agricultural return flows in the Forebay area.

Upper Aquifer System

Concentrations of nitrate as NO_3 in groundwater in the UAS ranged from below the detection limit (ND) to 240 mg/L between 2011 and 2015 (Figures 2-41A and 2-37B). The highest concentration was measured in well 02N22W26C01S in the Forebay (Figure 2-41B). In general, nitrate as NO_3 concentrations are highest in the southern Forebay and northeastern Oxnard Subbasin. The lowest concentrations are found in the southern Oxnard Subbasin, with the concentration of nitrate below the detection limit in the majority of the wells in the southern Subbasin (Figure 2-41A).

Lower Aquifer System

Concentrations of nitrate as NO_3 in groundwater in the LAS ranged from below the detection limit to a high outlier of 57 mg/L, with the next-highest concentration at 22.1 mg/L, between 2011 and 2015 (Figure 2-42). The highest concentration was measured in well 02N21W19A03S, in the northeastern Oxnard Subbasin. The majority of the wells in the LAS have nitrate as NO_3, concentrations below the detection limit. In the Forebay, the concentration of nitrate as NO_3 is lower in the LAS than it is in the UAS (Figures 2-41B and 2-42).

2.3.4.4 Sulfate

The water quality objective for sulfate is 600 mg/L in the Forebay and confined aquifers, and 1,000 mg/L in the unconfined aquifers (LARWQCB 2013).

Upper Aquifer System

Concentrations of sulfate in the UAS ranged from 100 mg/L to 5,740 mg/L between 2011 and 2015 (Figures 2-43A and 2-43B). The highest concentration was measured in well 01N22W27R05S, which also had the highest concentration of chloride and TDS. The lowest concentration was measured in well 01N22W36K09S in the southern Oxnard Subbasin. The majority of the wells in the Oxnard Subbasin have sulfate concentrations below 600 mg/L. Similar to nitrate, wells in the Forebay tend to have higher concentrations of sulfate than wells farther south, with the notable exception of wells 01N22W27R05S and 01S21W08L04S (Figure 2-43A).

Lower Aquifer System

Concentrations of sulfate in the LAS ranged from below the detection limit to 2,030 mg/L between 2011 and 2015 (Figure 2-44). The highest concentration was measured in well 01N21W32Q03S, which also had the highest concentration of chloride and TDS. Only four wells in the LAS had concentrations of sulfate that exceeded 600 mg/L. These wells are distributed throughout the Oxnard Subbasin and do not follow a clear geographic pattern. Similar to nitrate, LAS wells in the Forebay have lower concentrations of sulfate than UAS wells in the Forebay (Figure 2-44).

2.3.4.5 Boron

The water quality objective for boron in the Oxnard Subbasin is 1 mg/L (LARWQCB 2013).

Upper Aquifer System

Concentrations of boron in the UAS ranged from 0.05 mg/L to 5.9 mg/L between 2011 and 2015 (Figures 2-45A and 2-45B). The highest concentration was measured in well 01N22W27R05S, which also had the highest concentrations of sulfate, chloride, and TDS. The lowest concentration was measured in well 02N22W24A01S, in the northeastern Oxnard Subbasin (Figure 2-45A). Only seven wells in the UAS had boron concentrations greater than 1 mg/L between 2011 and 2015.

Lower Aquifer System

Concentrations of boron in the LAS ranged from 0.3 mg/L to 2.2 mg/L between 2011 and 2015 (Figure 2-46). The highest concentration was measured in well 01N21W32Q03S, which also had the highest concentrations of sulfate, chloride, and TDS. Only five wells in the LAS had boron concentrations greater than 1 mg/L between 2011 and 2015.

2.3.4.6 Map of Oil and Gas Deposits

In the database maintained by the County of Ventura, five oil fields entirely or partially fall within the Oxnard Subbasin: Montalvo, W.; Oxnard; El Rio; Santa Clara Avenue; and Saticoy (Figure 2-47). Petroleum extraction in the FCGMA basins occurs below the deepest freshwater aquifer (Hopkins 2013). While trace amounts of organic compounds have been found in deeper wells in southeastern Pleasant Valley (Izbicki et al. 2005), no impacts of petroleum extraction on beneficial use of groundwater have been observed in the FCGMA basins.

2.3.4.7 Maps of Locations of Impacted Surface Water, Soil, and Groundwater

Impaired surface waters (i.e., 303[d] Listed Reaches) that overlie the Oxnard Subbasin include approximately 3 miles of the Santa Clara River, the Revolon Slough, Calleguas Creek, and a number of lined drains serving agricultural areas south of the City of Oxnard (Figure 2-48; SWRCB 2004). The names of the reaches used by the SWRCB, and the impairments listed for each, are included in tabulated form in Appendix E.

Locations of impacted soil and groundwater were assessed on a basin-wide scale by reviewing information available on the SWRCB Geotracker website and the California Department of Toxic Substances Control EnviroStor website. Cases that were closed by the supervisory agency were not considered.

Of the 290 open cases located within the boundaries of the Oxnard Subbasin and Pleasant Valley, groundwater was impacted in 77. Dudek reviewed and catalogued the Constituents of Concern (COCs) present on site in these 77 cases (Figure 2-49). Case details are included in Appendix F.

Of the 71 open cases in the Oxnard Plain in which groundwater is or is potentially impacted, the following COCs were identified as present at the following number of sites (Figure 2-49, Appendix F):

- Chlorinated volatile organic compounds (VOCs), including COCs marked as “solvents,” “VOCs,” “chlorinated hydrocarbons,” and “chlordane,” were present at 34 sites.
- Gasoline and diesel, including COCs marked “TPH” and “petroleum,” were present at 32 sites.
- Metals were present at 27 sites.
- Polychlorinated biphenyls (PCBs) were present at 23 sites.
- Benzene, toluene, ethylbenzene, and/or xylenes (BTEX) were present at 18 sites.
- Pesticides were present at 12 sites.

- Methyl tert-butyl ethylene (MTBE) and/or tert-butyl alcohol (TBA) were present at seven sites.
- Two sites listed other COCs.

Many of these sites are located on land administered by the U.S. military (Figure 2-49). Outside of military bases, these sites tend to occur within the city limits of the Cities of Oxnard, Port Hueneme, and Camarillo.

The risk that contamination in the shallow groundwater of the Oxnard Subbasin would reach the UAS is somewhat mitigated by the presence of a confining layer that separates the semi-perched zone from the water-bearing units of the UAS throughout much of the Oxnard Plain (Turner and Mukae 1975). However, the vertical gradient is directed downward from the semi-perched aquifer to the underlying Oxnard Aquifer, indicating the potential for groundwater movement from the semi-perched aquifer to the Oxnard Aquifer.

Based on a review of open Geotracker and EnviroStor cases with impacted groundwater, it does not appear that existing groundwater contamination in the Semi-Perched aquifer poses a substantial threat to beneficial use of groundwater in the UAS and LAS. Based on a review of the files available on Geotracker for each of the cases in the Oxnard Subbasin which fell outside the bounds of a military base, it appears that in none of the cases were any liable parties required to investigate deeper than 50 feet below ground surface, indicating that impacts to groundwater in the UAS were not a concern for regulatory agencies. [Discussion of the DDW wells (if any) in which VOCs were detected at > ½ the MCL].

2.3.5 Subsidence

Inelastic, or irrecoverable, land subsidence (subsidence) is a concern in areas of active groundwater extraction, including the Oxnard Subbasin. Active causes of land subsidence in the Oxnard Subbasin include tectonic forces, petroleum reservoir compaction, and aquifer compaction (Hanson et al. 2003). Significant water level declines in the FCGMA groundwater basins since the early 1900s suggest that fluid extraction, rather than tectonic activity, is the major cause of land subsidence (Hanson et al. 2003). Subsidence resulting from any of these sources can cause increased flood risk, well casing collapse, and a permanent reduction in the specific storage of the aquifer (Hanson et al. 2003).

Direct measurement of subsidence within the Oxnard Subbasin is limited. Elevation data from USGS benchmark (BM) E548 in the southern part of the Oxnard Plain indicate subsidence of about 1.6 feet (0.49 meters) during the period from 1939 to 1960, and an additional 1 foot (0.31 meters) of subsidence from 1960 to 1978 (Hanson et al. 2003). The average rate of subsidence for these two time periods was similar, averaging approximately 0.07 feet (0.02 meters) per year from 1939 to 1960, and approximately 0.06 feet (0.02 meters) per year from 1960 to 1978

(Hanson et al. 2003). In contrast, elevation data from USGS BM Z901, located approximately 2.6 miles southeast of BM E548, indicate subsidence of approximately 0.3 feet (0.10 meters) between 1960 and 1978. The average rate of subsidence at BM E548 was 0.02 feet (0.01 meters) per year for this time period. The rate of subsidence at BM Z901 decreased to approximately 0.01 feet per year from 1978 to 1992. Data are not available for BM E548 after 1978. The amount of subsidence measured at both BM E548 and BM Z901is the cumulative subsidence from all possible sources, including groundwater pumping, tectonic activity, and petroleum reservoir compaction.

In addition to direct measurement of subsidence in the southern part of the Oxnard Plain, potential subsidence was modeled for the entire Oxnard Plain for different future water production scenarios (Hanson et al. 2003). The scenarios included consideration of proposed water projects and ordinances for the FCGMA Basins. The model results suggest that areas within the Oxnard Plain may experience an additional 0.1 to 1 feet of subsidence by 2040 (Hanson et al. 2003). DWR classified the Subbasin as an area that has a medium to high potential for future subsidence. The amount of future subsidence will depend on whether future water levels decline below previous low levels and remain there for a considerable amount of time (Hanson et al. 2003). Maintaining water levels above the previous low water levels will limit the risk of future subsidence.

2.3.6 Groundwater–Surface Water Connections

The Santa Clara River, Calleguas Creek, Revolon Slough, Mugu Lagoon, Ormond Beach, and McGrath Lake have all been identified as surface water bodies that may have a connection to the semi-perched aquifer in the Oxnard Subbasin (See section 2.3.7). However, groundwater elevation data for the semi-perched aquifer in the Oxnard Subbasin are extremely limited, with no monitoring sites near enough to surface water bodies to establish the extent of the connection between these surface water bodies and underlying groundwater (Figures 2-50 and 2-51).The spatial extents of gaining, losing and dry reaches in the Santa Clary River are seasonally variable (UWCD 2014).

The best available quantitative data for groundwater–surface water connections comes from the UWCD numerical model, which simulates the leakage from major surface water bodies in the Oxnard Subbasin using data from stream gauges and estimated aquifer properties. The UWCD model reports stream leakage from the Santa Clara River and Calleguas Creek into the underlying Semi-Perched Aquifer. Numbers from the model represent net stream leakage and do not necessarily indicate direct connection between surface water bodies and groundwater in the Semi-Perched Aquifer system.

The UWCD model calculated stream percolation for water years from 1986 to 2015 (Table 2-5). The Santa Clara River had net recharge to groundwater in 25 of 30 water years, with an average net recharge to groundwater of ~13,000 acre-feet per year. Although some reaches of the Santa

Clara River are typically gaining in most years, net groundwater discharge to the Santa Clara River was identified as occurring during 1987, 1999, 2002, 2007, and 2013. Conejo Creek exhibited net recharge to groundwater in all years modeled, with an average net recharge to groundwater of ~4,700 acre-feet per year.

Table 2-5
Modeled Surface Water Percolation from Streams in the Oxnard Subbasin

Water Year	Santa Clara River Percolation* (acre-feet)	Calleguas Creek Percolation (acre-feet)
1986	22,467	4,093
1987	396	2,631
1988	16,071	2,564
1989	0	1,755
1990	329	1,105
1991	11,536	2,738
1992	32,059	6,180
1993	45,589	7,378
1994	11,066	2,338
1995	27,931	7,093
1996	14,130	4,826
1997	8,286	4,218
1998	9,148	7,964
1999	0	4,557
2000	13,518	5,304
2001	14,150	7,299
2002	3,440	5,591
2003	20,632	4,353
2004	18,858	5,511
2005	26,873	7,812
2006	1,589	5,805
2007	0	4,628
2008	18,119	6,590
2009	13,226	4,851
2010	29,042	5,201
2011	18,688	7,488
2012	7,105	4,317
2013	0	1,577
2014	7,425	2,390
2015	0	1,184
AVERAGE	**12,643**	**4,542**

* Negative numbers represent discharge of groundwater to the stream.

2.3.7 Groundwater Dependent Ecosystems

Six potential groundwater dependent ecosystem (GDEs) units, defined by dominant surface hydrologic features, were identified in the Oxnard Subbasin (TNC 2017a; Figure 2-52). The potential GDE units were identified using the statewide potential GDE map (TNC 2017b). Of the six potential GDE units identified, the Lower Santa Clara River, McGrath Lake, Ormond Beach, and Mugu units were validated using groundwater elevations measured in wells within or adjacent to the unit to confirm the potential hydrologic connection to groundwater, as described in the Nature Conservancy's GDE Guidance Framework (Rohde et al. 2017). Insufficient well data are available to confirm the depth to groundwater in the Revolon Slough and Lower Calleguas Creek units. Therefore, in the discussion below, these units remain as potential GDEs. Groundwater elevation in the vicinity of these units will be required in order to confirm whether or not the habitat is supported by groundwater.

Lower Santa Clara River GDE

The lower Santa Clara River GDE (located downstream of Highway 101 and upstream of the estuary) comprises approximately 1,300 acres of aquatic habitat, in-channel wetland, and a range of willow-cottonwood riparian forest (City of Ventura 2016). The GDE is located in the floodplain of the lower Santa Clara River, which undergoes substantial transformations in vegetation composition and distribution due to the dynamic nature of the river flows during winter. The lower Santa Clara River GDE supports habitat for several state and federally listed species (Table 2-6).

Flow in the lower Santa Clara River downstream of Highway 101 has historically been perennial (Beller et al., 2011; City of Ventura 2016). Groundwater provides the dry summer baseflow, if it exists, and a quarter of the winter flow (City of Ventura 2011). Groundwater flow direction between the semi-perched aquifer and the lower Santa Clara River, its estuary and nearby McGrath Lake, depends on tidal conditions, river stage, and recharge rates due to agricultural irrigation (City of Ventura 2016). Groundwater levels from wells in the vicinity of the lower Santa Clara River GDE generally range between 7 and 11 feet below ground surface (bgs) (Figure 2-53). The groundwater depths are within the range considered necessary for juvenile establishment (<10 feet) and mature vegetation growth (<20 feet) (City of Ventura 2016).

McGrath Lake GDE

The McGrath Lake GDE includes a coastal freshwater back-dune lake, arroyo willow riparian forest, freshwater emergent marsh, and saline emergent marsh. The McGrath Lake GDE supports critical habitat for several state and federally listed endangered species as well as many special-status bird species (Table 2-6). The GDE is partially protected as McGrath and Mandalay State

Beaches (85 acres) and 197 acres of the GDE are delineated as wetlands in the national wetlands inventory (NWI; USFWS 2016).

McGrath Lake is formed by shallow groundwater that remains perched above a clay layer in the semi-perched aquifer (ESA 2003). McGrath Lake operational water surface elevations are maintained between 2.7 and 3.6 feet amsl (City of Ventura 2011). Groundwater flows toward the Santa Clara River during open-mouth conditions and towards McGrath Lake when the Santa Clara River Estuary fills following mouth closure (City of Ventura 2011). As measured since 2009, depths to groundwater around the McGrath Lake GDE range from ground surface to 10 feet bgs, depending on the well (Figure 2-54).

Ormond Beach GDE

The Ormond Beach GDE, which includes isolated patches of southern coastal salt marsh and coastal freshwater/brackish marsh that have been drained, filled, and degraded by past industrial and agricultural use, is part of a larger 1,500-acre coastal dune–marsh system of dunes, lakes, lagoons, and saltwater and freshwater marshes (WRA 2007; CCC 2017a). Restoration of this coastal dune-marsh system is considered to be the most important wetlands restoration project in southern California (CCC 2017a). The Ormond Beach GDE supports habitat for state and federally listed species as well as 27 special-status plant species and 42 special-status wildlife species (Table 2-6).

The Ormond Beach GDE is hydrologically connected to the semi-perched aquifer. Shallow groundwater elevations are influenced by rainfall, tidal events, and the surface water elevations of the agricultural drains and flood control channels. Depth to groundwater ranges from ground surface to 15 feet bgs (Figure 2-55).

Mugu Lagoon GDE

Mugu Lagoon GDE is the largest salt marsh estuary in Southern California (USFWS 2016). The GDE provides habitat for several state and federally listed species (Table 2-6).

The estimated groundwater depth in the Mugu Lagoon GDE varies between ground surface and 6 feet bgs (Figure 2-56). Estimated depths to groundwater in the GDE, are based on interpolation of water elevation data from representative wells at Naval Base Ventura County Point Mugu to reference point locations within the Mugu Lagoon GDE. Mugu Lagoon receives groundwater discharge from the semi-perched aquifer along with freshwater from Calleguas Creek, the drainage ditches, primarily Oxnard Drainage Ditch No. 2, and salt water from tidal fluctuations.

Lower Calleguas Creek potential GDE

The lower Calleguas Creek potential GDE includes aquatic habitat and mulefat and willow riparian forest. This potential GDE may support native special-status species (Table 2-6).

The Lower Calleguas Creek potential GDE overlies the semi-perched aquifer. The channel has been separated from the adjacent floodplain since the 1960s by a riprap and earthen levee countersunk about 3 feet below the surrounding grade. Thus, Calleguas Creek is a losing reach in the Oxnard Plain. Lower Calleguas Creek maintains a perennial streamflow due to a combination of wastewater effluent and pumped tile drain discharge from adjacent agricultural fields, with the addition of natural precipitation and stormwater runoff during winter months. The degree of groundwater recharge and/or discharge has not been studied and groundwater elevation data are not available for this area. Groundwater elevations at semi-perched aquifer monitoring wells (located approximately 1 mile to the southwest at Naval Base Ventura County Point Mugu) indicate typical groundwater elevations range from -1 to 6 feet amsl. Extrapolated depths to groundwater at the downstream end of the Calleguas Creek GDE, at approximately 12 feet amsl, are between 6 to 13 feet bgs. The extrapolated groundwater depths indicate the potential for the riparian vegetation to access shallow groundwater. Additional data need to be collected within the boundaries of the Calleguas Creek potential GDE in order to determine whether or not the riparian vegetation is accessing shallow groundwater.

Revolon Slough potential GDE

The Revolon Slough potential GDE comprises aquatic habitat and willow riparian forest. This potential GDE may support native special-status species (Table 2-6). The riparian habitat within this potential GDE is considered “de minimis” because of its poor quality and limited extent adjacent to the waterway. Streamflow in lower Revolon Slough is considered to be a combination of agricultural return flow and precipitation and stormwater runoff. The degree of groundwater recharge and/or discharge has not been studied and groundwater elevation data are not available for this area. Groundwater elevations at semi-perched aquifer monitoring wells located approximately 1 mile to the southwest at Naval Base Ventura County Point Mugu indicate typical groundwater elevations range from -1 to 6 feet amsl. Extrapolated depths to groundwater at the downstream end of the Revolon Slough potential GDE would be between 9 and 16 feet bgs. The extrapolated groundwater depths indicate the potential for the riparian vegetation to access shallow groundwater. Additional data need to be collected within the boundaries of the Revolon Slough potential GDE in order to determine whether or not the riparian vegetation is accessing shallow groundwater.

Table 2-6
Ecological Assets

Ecological Assets	Lower Santa Clara River	McGrath Lake	Ormond Beach Wetlands	Mugu Lagoon and Wetlands	Lower Calleguas Creek	Revolon Slough
Locally important, special status, rare, threatened, or endangered plants or animals supported by the GDE.	Santa Ana sucker; western pond turtle; tidewater goby; coast horned lizard; white rabbit-tobacco; Southern Riparian Scrub; least Bell's vireo (CDFW 2016); steelhead	Belding's savannah sparrow; burrowing owl; California least tern; least Bell's vireo; salt marsh bird's-beak; sandy beach tiger beetle; silvery legless lizard; Ventura Marsh milk-vetch (CDFW 2016). Sandy beach tiger beetle, brown pelican, western least bittern, white-faced ibis, osprey, white-tailed kite, northern harrier, sharp-shinned hawk, Cooper's hawk, light-footed clapper rail, western snowy plover, long-billed curlew, California least tern, western yellow-billed cuckoo, burrowing owl, southwestern willow flycatcher, loggerhead shrike, least Bell's vireo, yellow warbler, yellow-breasted chat, Belding's savannah sparrow, California red-legged frog, southwestern pond turtle, silvery legless lizard, San Diego horned lizard, two-striped garter snake, South coast garter snake, Townsend's big-eared bat (Table 3-2, ESA 2003)	Belding's savannah sparrow; California least tern; Coulter's goldfields; California brackish water snail; salt marsh bird's-beak; tidewater goby; western snowy plover (CDFW 2016). western snowy plover, California least tern, California brown pelican, light-footed clapper rail, least Bell's vireo. Southern California saltmarsh shrew, San Diego black-tailed jackrabbit, double-crested cormorant, American bittern, great blue heron, great egret, snowy egret, black-crowned night heron, white-faced ibis, white-tailed kite, northern harrier, Cooper's hawk, sharp-shinned hawk, merlin, mountain plover, long-billed curlew, western burrowing owl, loggerhead shrike, yellow warbler, California horned lark, tricolored blackbird, south coast garter snake, tiger beetle, sandy beach tiger beetle, wandering skipper, globose dune beetle, red sand-verbena, spiny rush, and woolly seablite. (WRA 2007)	arroyo chub, Belding's savannah sparrow, burrowing owl, California brown pelican, California least tern, Coulter's goldfields, estuary seablite, ferruginous hawk, globose dune beetle, least Bell's vireo, light-footed clapper rail, salt marsh bird's-beak, sandy beach tiger beetle, senile tiger beetle, Southern Coastal Salt Marsh, tidewater goby, wandering (=saltmarsh) skipper, western snowy plover (CDFW 2016); peregrine falcon	arroyo chub, two-striped gartersnake, least Bell's vireo (CDFW 2016).	Arroyo chub (CDFW 2016), least Bell's vireo (Dellith 2017)

Table 2-6
Ecological Assets

Ecological Assets	Lower Santa Clara River	McGrath Lake	Ormond Beach Wetlands	Mugu Lagoon and Wetlands	Lower Calleguas Creek	Revolon Slough
Important or critical habitat provided for native species (CH 2016)	southwestern willow flycatcher critical habitat (569 acres), tidewater goby critical habitat (22 acres), western snowy plover critical habitat (35 acres), steelhead critical habitat; Audubon California Important Bird Area	southwestern willow flycatcher critical habitat (32 acres), tidewater goby critical habitat (18 acres), Ventura marsh milk-vetch critical habitat (78 acres); Audubon California Important Bird Area	tidewater goby critical habitat (88 acres), western snowy plover critical habitat (26 acres); Audubon California Important Bird Area	western snowy plover critical habitat (51 acres); Wetland of Regional Importance in the Western Hemisphere Shorebird Reserve Network; Essential Fish Habitat (EFH) and Habitat Areas of Particular Concern (HAPC) are designated for Pacific Coast groundfish and coastal pelagic species in the nearshore marine and estuarine habitats; Laguna Point to Latigo Point Area of Special Biological Significance. Audubon California Important Bird Area	No	No
Portion of GDE that is a recognized wetland (USFWS 2016a; TNC 2017b)	1,180 acres (93%)	197 acres (71%)	207 acres (96%)	5,943 acres (93%)	6 acres (4%)	2 acres (8%)
Protected area, locally important conservation or wildlife corridor plan areas within the GDE	The Nature Conservancy (160 acres), City of Ventura (1.2 acres)	McGrath State Beach (56 acres), Mandalay State Beach (29 acres), Mandalay County Park (0.7 acres)	The Nature Conservancy (129 acres), Port Hueneme Beach Park (1.3 acres)	Point Mugu State Park (0.1 acres)	No	No

Table 2-6
Ecological Assets

Ecological Assets	Lower Santa Clara River	McGrath Lake	Ormond Beach Wetlands	Mugu Lagoon and Wetlands	Lower Calleguas Creek	Revolon Slough
List any environmental beneficial uses designated in the RWQCB Basin Plan for the surface water found in the groundwater basin	• Wildlife Habitat (WILD) • Rare, Threatened, or Endangered Species (RARE) • Migration of Aquatic Organisms (MIGR) • Spawning, Reproduction, and/or Early Development (SPWN) • Wetlands (WET) Also, REC1, REC2	• Estuarine Habitat (EST) • Wildlife Habitat (WILD) • Rare, Threatened, or Endangered Species (RARE) • Wetlands (WET) Also, REC1, REC2	• Estuarine Habitat (EST) • Wildlife Habitat (WILD) • Rare, Threatened, or Endangered Species (RARE) • Wetlands (WET) Also, REC1, REC2	• Estuarine Habitat (EST) • Marine Habitat (MAR) • Wildlife Habitat (WILD) • Preservation of Biological Habitats of Special Significance (BIOL) • Rare, Threatened, or Endangered Species (RARE) • Migration of Aquatic Organisms (MIGR) • Spawning, Reproduction, and/or Early Development (SPWN) • Shellfish Harvesting (SHELL) • Wetlands (WET) Also, REC1 (potential), REC2	Reach 2: • WARM • COLD • Wildlife Habitat (WILD) • Rare, Threatened, or Endangered Species (RARE) • Wetlands (WET) Also, REC1, REC2	Reach 4 (Revolon Slough): • WARM • Wildlife Habitat (WILD) • Wetlands (WET) Also, REC1, REC2
Is the GDE area comprised of > 30% native vegetation? (TNC 2017b)	Yes	Yes	Yes	Yes	Yes	Yes

Sources: CDFW 2016; GreenInfo Network 2016; USFWS 2016a, 2016b; TNC 2017b; WRA 2007; ESA 2003; Dellith, pers. comm. 2017.

2.4 WATER BUDGET

2.4.1 Current Water Budget

(most recent as of January 2015)

- Surface water flows
  - Map of surface water/groundwater interactions (RFP Task 7)
- Inflow to groundwater system by source type (see RFP Task 7 for list of sources)
- Outflows from groundwater system by use sector (see RFP Task 7 for list of sources)
- Change in annual volume of groundwater in storage
- Overdraft
- Water year type
- Sustainable yield estimate
- Identify uncertainties in the groundwater budget (RFP Task 7) and recommend studies to reduce uncertainties (RFP Task 13)

2.4.2 Historical Water Budget

(minimum of 10 years base period, likely to extend through 2014)

- Quantify, and display in graphics, maps and tables (RFP Task 7)
  - Surface water flows
  - Inflow to groundwater system by source type
  - Outflows from groundwater system by use sector
  - Change in annual volume of groundwater in storage
  - Overdraft
  - Water year type
  - Sustainable yield estimate
- Historical water source reliability
- Impact of historical reliability on Agency operations
- Magnitude of diurnal/seasonal/inter-annual fluctuations in water budget components (RFP Task 7)

2.4.3 Projected Water Budget

(using minimum of 50 years of precip, ET, streamflow; see additional details in RFP Task 7)

Quantify and display in graphics, maps and tables (RFP Task 7)

- Surface water flows
- Inflow to groundwater system by source type
- Outflows from groundwater system by use sector
- Change in annual volume of groundwater in storage
- Overdraft
- Water year type
- Sustainable yield estimate

Future scenarios: climate change and sea level rise

Future scenarios: local land use planning, population growth, climate change

2.5 MANAGEMENT AREAS

[Number of Management Areas to be filled in based on future discussions] For each management area:

- Reason for management area
- Minimum thresholds and measurable objectives
- Monitoring and analysis
- Avoiding undesirable results outside the management area

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