EXTRACTION BARRIER AND BRACKISH WATER TREATMENT PROJECT FEASIBILITY STUDY: GROUNDWATER MODELING

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1 INTRODUCTION

United Water Conservation District (United or UWCD) was awarded a Proposition 1 Grant from the California State Water Resources Control Board (Water Board) to evaluate the feasibility of a proposed large-scale extraction barrier well field and brackish water treatment plant located near the southern boundary of the Oxnard groundwater basin (Figure 1). Degraded water quality (chloride, TDS, sulfate, etc.) is present in approximately ten square miles of the Upper Aquifer System (UAS) in the area between Port Hueneme and Point Mugu, the result of both recent and historic episodes of seawater intrusion and the subsequent dispersal of seawater across the southern Oxnard basin by southeasterly groundwater flow in wet periods. Saline water is also dispersed by vertical flow between aquifers, predominantly in areas where vertical head gradients are significant and aquitards between the major aquifers are thin or absent. United is proposing construction of a groundwater extraction well field to intercept the intrusion of seawater near the Mugu submarine canyon and treat the extracted blend of seawater and brackish water at a desalinization facility. A brine line and ocean outfall currently exist in the project area, and the brine line has available capacity to accept brine from United's proposed Extraction Barrier and Brackish Water Treatment Project (Extraction Barrier or Project).

The proposed Project wells would extract poor-quality groundwater for desalinization and advanced treatment, and the treated water will be available for artificial recharge and direct delivery to water users. The wells providing saline water to the treatment facility will be continuously operated as an extraction barrier, maintaining seaward groundwater gradients in the main portion of the basin landward of the extraction barrier wells. Seawater will approach the wells from seaward side of the barrier, where the confined aquifers of the UAS are exposed in the Mugu submarine canyon located just offshore. The California Coastal Commission encourages the use of onshore wells to supply coastal desalter facilities, thus avoiding the need for open-ocean intakes. This Technical Memorandum presents the results of model simulations for various Project pumping scales over a 50-year forward modeling period.

In 2018 UWCD published documentation of a regional groundwater flow model (referred as the Coastal Plain Model) covering the Oxnard coastal plain in southern Ventura County (UWCD, 2018) that was based on MODFLOW-NWT groundwater modeling software (Niswonger, et al., 2011). The Coastal Plain Model was reviewed by an expert panel comprised of nationally recognized expert groundwater modelers since 2016. The expert panel concluded that the Coastal Plain Model is well-designed and well-calibrated (Porcello et al., 2018). United elected to convert the Coastal Plain Model to the modeling software MODFLOW-USG-Transport (Panday, et al., 2017) in order to refine the model to a denser grid along the southern coastal area of the Oxnard basin, simulate solute (chloride) transport over time, and account for the density effect of seawater on the groundwater flow compared to freshwater native to the basin. To calibrate the chloride transport component, the interpreted 2015 (UWCD, 2016) inland extent of seawater intrusion (100 mg/L chloride) was compared to seawater intrusion as simulated from 1985 to 2015 by the MODFLOW-USG-Transport model. The 2015 seawater intrusion extent simulated by the MODFLOW-USG-Transport model is close to the interpreted 2015 seawater intrusion extent. Thus, the calibration of the MODFLOW-USG-Transport model is deemed satisfactory in both the flow and transport components and the MODFLOW-USG-Transport model is appropriate for simulation of the extraction barrier. The conversion and recalibration of the Coastal Plain model to MODFLOW-USG-Transport was part of the Prop 1 Grant work and detailed in a separate technical memorandum (UWCD, 2021b).

This report details the results of modeled simulations for various extraction rates and water delivery options. The benefits of the Project are primarily represented by mapping the inland extent of chloride impacts over time, and changes in chloride concentrations within the impacted areas over time. Changing groundwater conditions within the Oxnard and Mugu aquifers are the focus of this report, but the model also simulates groundwater conditions in shallower and deeper aquifers. Project impacts to surrounding areas are primarily represented by mapping groundwater elevation changes associated with the Project, compared to simulations of a future no-Project baseline condition. The vertical movement of groundwater between the major aquifers in the Project area is also characterized.

Simulations for Project extraction rates ranging from 5,000 to 20,000 acre-feet per year (AFY) were conducted and evaluated. Pumping as little as 5,000 AFY is shown to control the inland advance of saline water in the Mugu area over the 50-year simulation period. Larger pumping volumes promote a more rapid retreat of brackish water from inland areas. One larger Project extraction scenario (15,000 AFY) results in a wider area of drawdown outside the boundaries of Naval Base Ventura County Point Mugu, on the order of 10-20 feet in surrounding areas. Pumping 10,000 AFY resulted in modest drawdown of groundwater elevation in surrounding areas. When the extracted brackish water is treated, UWCD engineering staff estimates an initial recovery rate of 50% based on water quality data from the Project area and the proposed treatment methods, leading to an estimated 5,000 AFY of product water for use by the U.S Navy and other water users in the basin with extraction barrier pumping of 10,000 AFY, for example.

The Oxnard and Mugu aquifers are relatively thin in the area of the proposed well fields, with thickness ranging from approximately 70-150 feet and 50-160 feet, respectively. The calibrated groundwater flow model was used to estimate the number of wells and distribution required to produce groundwater at the various hypothetical Project scales. A large number of simulated extraction wells was required to pump more than 10,000 AFY in the Project area, suggesting large Project scales may not be practical. Smaller Project scales are assessed to be beneficial, feasible and practical. United will continue to work with basin water managers, regulators and stakeholders to determine the appropriate Project scale for the proposed extraction barrier.

2 BASIN SETTING AND PROJECT AREA

The Oxnard basin is located adjacent the Pacific Ocean in southern Ventura County, California, and has a long history of groundwater overdraft and saline intrusion. Much of the land area of the basin was developed by the 1930s, with agriculture being the dominant land use at that time. Urban land uses have grown steadily over time, but agricultural land uses still occupy approximately 45 percent of the basin land area. Major investments in infrastructure for groundwater recharge and surface water distribution, along with State Water Project imports and regulatory programs to manage groundwater extraction, have been only partly successful in mitigating groundwater overdraft in the Oxnard basin and the adjoining Pleasant Valley basin.

United and its predecessor agency have diverted water from the Santa Clara River near Saticoy since the late 1920s for managed aquifer recharge operations, and since the 1950s for the direct delivery of surface water to irrigators, offsetting the need to pump groundwater from the basin. In 1954 United constructed the Oxnard-Hueneme pipeline, along with a well field and recharge facilities at El Rio to move pumping away from coastal areas vulnerable to seawater intrusion. United completed construction of the Freeman Diversion facility in 1990, allowing for diversions soon after major storm events, preventing further downcutting of the river channel, and allow for fish passage around the diversion facility. Efforts related to the conjunctive use of surface water and groundwater continue. In 2002 the Conejo Creek Diversion was completed by Camrosa Water District, bringing additional surface water to the approximately 11,000 acres served by the Pleasant Valley County Water District. The Cities of Oxnard and Camarillo have made major investments in recent years to treat and distribute their wastewater to agricultural areas, and to purchase imported water supplies from the State Water Project. The City of Ventura is working on a pipeline to import State Water and is making additional investments to recycle and use their wastewater. Since the 1990s the FCGMA has implemented a major regulatory program requiring reduced pumping of groundwater and the efficient use of water for irrigation. Despite major local investments in water supply projects, water imports, basin optimization, and the storage and distribution of water, serious overdraft conditions still exist in the Oxnard and Pleasant Valley basins.

Regional aquifer systems extend below the Oxnard coastal plain and into offshore areas where the aquifers are in contact with the ocean. Figure 2-1 shows surface geology, selected structural features, and the Hueneme and Mugu submarine canyons. The aquifers of the Upper Aquifer System (UAS) are recharged by natural recharge mechanisms and by United's artificial recharge activities in the Oxnard Forebay area, which rely on diversions of surface water from the large watershed of the Santa Clara River. Figure 2-2 shows United's delineation of the major aquifers of the Oxnard coastal plain, in a section extending from the Forebay area (at the right of the figure) to the Project area near Mugu canyon. The Oxnard and Mugu aquifers of the UAS are continuous across the basins, as shown in pink and green. A coastal section for these same aquifers is shown in Figure 2-3 (the extraction barrier wells would be located at the right side of this diagram). The aquifers of the Lower Aquifer System (LAS) are uplifted in the Project area and the Hueneme aquifer is absent.

The production aquifers of the Oxnard coastal plain can be classified as being part of either the regional Upper Aquifer System or the Lower Aquifer System (Mukae and Turner, 1975). The UAS consists of the Oxnard and Mugu aquifers. The LAS consists of the Hueneme, Fox Canyon and Grimes Canyon aquifers. The aquifers consist of gravel and sand deposited along the ancestral Santa Clara River, alluvial fan deposits along the flanks of the mountains, a coastal plain/delta complex at the terminus of the Santa Clara River, and marine deposits from transgressional seas. The aquifers are recharged by the natural infiltration of stream flow (primarily from the Santa Clara River in the Oxnard Forebay area, but also along Arroyo Las Posas in the northern portion of the Pleasant Valley basin), artificial recharge of diverted stream flow, mountain-front recharge along the exterior boundaries of the basins, direct infiltration of precipitation on the valley floors of the basins and on bedrock outcrops in adjacent mountain fronts, the percolation of reclaimed water from septic systems and sanitary sewers, and irrigation return flow in agricultural areas.

Prolonged drought conditions since 2012 have caused diminished flows in the Santa Clara River and other local water bodies, and recharge totals to the coastal groundwater basins have been meager. New regulatory restrictions for environmental flows have further curtailed United's surface water diversions and basin recharge activities in recent years. Although healthy groundwater conditions were sometimes achieved in the shallowest confined aquifer of the Oxnard basin (the Oxnard aquifer) following a series of wet years, groundwater elevations in many portions of the deeper confined aquifers of the Oxnard and Pleasant Valley basins remain well below sea level during both wet and dry climatic periods. In fall 2020 broad areas of the Oxnard basin recorded UAS groundwater elevations more than 10 feet below sea level (Figure 2-4). In the Pleasant Valley basin and in the eastern portion of the Oxnard basin, groundwater elevations in the aquifers of the Lower Aquifer System (LAS) commonly ranged from 50 to 100 feet below sea level (Figure 2-5). Water levels above sea level were only recorded in recharge areas in the northernmost portions of the basins in fall 2020. Groundwater elevations below sea level allow the intrusion of saline water into fresh-water aquifers by various mechanisms. The direct lateral intrusion of seawater occurs where aquifers are exposed to the sea in near-shore submarine canyons. Additionally, the compaction of aquitards in response to water level declines can expel connate brines, and low-pressure conditions deep in the aquifer systems can promote the migration of brine along faults and brine upwelling from deeper formations. Regional pumping stresses also result in the vertical flow of both fresh and saline water between aquifers. By these mechanisms, saline water intrusion may degrade water quality further inland of the coastal areas where direct lateral seawater intrusion is known to occur. United continues to monitor the network of coastal monitoring wells and report on basin conditions (UWCD, 2021c).

In the area surrounding Mugu Lagoon, a number of the monitoring wells in the UAS have recorded elevated chloride concentrations since they were installed in 1990 (Figures 2-6 and 2-7). Wells near Port Hueneme show evidence of a new episode of seawater advancing into the basin following the onset of drought conditions in 2012. Other UAS wells located southeast of Port Hueneme record elevated chloride concentrations associated with past episodes of seawater intrusion, as prevailing groundwater flow directions tend to sweep saline water from the Port Hueneme area down the coast towards Mugu Lagoon during periods of higher water levels. The current network of coastal monitoring wells is somewhat limited, making it difficult to determine with certainty the extent of saline impacts in the various confined aquifers of the southern Oxnard basin. To help improve understanding of groundwater flow and solute transport, United has developed a density-dependent solute transport model to simulate the groundwater flow processes of freshwater and saline water that occur near the coast.

The Fox Canyon Groundwater Management Agency (FCGMA) is charged with the preservation and management of groundwater resources within the areas or lands overlying the Fox Canyon aquifer (which includes the Oxnard and Pleasant Valley basins). In 2015, the FCGMA accepted the authority to be the Groundwater Sustainability Agency (GSA) for these basins. In January 2020 the FCGMA submitted draft GSPs for the Oxnard and Pleasant Valley basins to the CA Department of Water Resources (DWR) for review and approval (FCGMA, 2019a, b). The GSP for the Oxnard basin states that seawater intrusion is the primary sustainability indicator in the Oxnard basin. In November 2021 DWR notified FCGMA that the GSPs for the Oxnard and Pleasant Valley basins had been approved. The DWR reviewers noted that new water supply projects are likely required to manage seawater intrusion in the basin.

SGMA requires that GSPs include plans to achieve sustainable groundwater management to avoid undesirable results, such as chronic depletion of groundwater, reduction of groundwater storage, water quality degradation, seawater intrusion, surface water depletions, or land subsidence. GSPs must also include long-term planning goals and measurable objectives with interim milestones in increments of five years that are designed to achieve the basin's sustainability goals within twenty years of GSP implementation. Combinations of projects and pumping reductions were considered to prevent future expansion of the saline water impact front. The Extraction Barrier Project detailed in this report was not sufficiently developed to be included on the project list for the GPS when it was submitted. FCGMA recognizes that an extraction barrier near the Mugu canyon would significantly modify groundwater gradients in this area of chronic seawater intrusion and control the inland advance of seawater intrusion in the greater Project area. United is coordinating Project development with FCGMA staff, who participated as members of the Technical Advisory Committee (TAC) for the Prop 1 grant that sponsored the modeling work detailed in this report.

SEMI-PERCHED AQUIFER

The Semi-perched aquifer is the shallowest regional aquifer present in the study area, and the sole hydrostratigraphic unit of the Shallow Aquifer System. This unconfined aquifer is regionally extensive and covers much of the Oxnard basin (though not present in the Oxnard Forebay area) and much of the Pleasant Valley basin, and is not utilized for groundwater production. In the Project area, this aquifer extends from land surface to approximately 80 feet below ground surface (bgs) in the north and to approximately 140 feet bgs in the south near Laguna Point. The thickness varies across the study area, and the unit is interpreted to be thinnest in areas northwest of the Naval Base Ventura County (NBVC) Point Mugu (Figure 2-8). The aquifer is hydraulically connected with surface waters on base, most notably Mugu Lagoon and the lowest reach Calleguas Creek, but also with the adjacent complex of tidal wetlands, where there is a recognized exchange of water and tidal influences are observed in measured groundwater elevations from wells screened within the upper portions of Semi-perched aquifer (TT EM Inc., 2003). Other notable nearby surface water features, the Ventura County Game Preserve and Point Mugu Game Preserve, also referred to as the “duck ponds,” located northwest of the base, can act as recharge sources to the Semi-perched aquifer and may influence horizontal gradients (OHM, 1998). Some surface water features on base, primarily Mugu Lagoon, are understood to be a discharge area for the shallow groundwater from the Semi-perched aquifer. However, water level responses from tidal cycles are observed in shallow monitoring wells and high tides can provide short-term recharge, particularly near the inlet from the lagoon to the ocean (TT EM Inc., 2003). The interaction of shallow groundwater and surface waters of the lagoon creates zones of alternating recharge and discharge in the shallow groundwater system.

In the vicinity of the NBVC Point Mugu, the Semi-perched aquifer is characterized as consisting of interbedded sands, silts, clays, and a few thin gravel beds (UWCD, 2021a). There is significant variation in sediments, even over relatively short distances, and sediments appear to be laterally discontinuous. Near the surface, test boring data indicate that discontinuous clay and silt beds are fairly common, and range in thickness from a few feet to up to 20 ft. thick. These sediments overlie coarser, more permeable units, which are more common in the middle depth range of the aquifer, before sediments become finer-grained sediments near the base of the aquifer.

A Confining Unit of fine-grained sediments serves to confine the underlying Oxnard aquifer and perch the overlying Semi-perched aquifer. In the Project area, interpretations of lateral continuity of the Confining Unit, thicknesses of the Semi-perched aquifer and the Confining Unit, and elevations of both units relied on the cross-sections created using available borehole data from the study area (UWCD, 2021a). There is significant variation in both the lithology and thickness of the Confining Unit in the study area, however, previous investigations at the base have found that there is little or no evidence of mixing or hydraulic connection between the Semi-perched and the deeper Oxnard aquifer at the time of investigation (TT EM Inc., 2003). Similar observations were documented at the nearby Halaco Superfund site, located four miles northwest of the Project area, where there were concerns regarding contamination in the Semi-perched aquifer migrating to deeper aquifers (CH2M Hill, 2012). The geologic setting and hydrogeologic conditions at the Halaco site are similar to those on base. United's mapping of the Confining Unit thickness in the Project area is shown in Figure 2-9.

The shallow unconfined aquifer of the Oxnard basin is commonly called the Semi-perched aquifer because some areas exist where the Confining Unit is thin or discontinuous, allowing some water exchange with the Oxnard aquifer. Water exchange between the Oxnard aquifer and the Semi-perched aquifer can also be facilitated by corroded or improperly constructed wells, which provide a conduit for the vertical flow of water between aquifers. Abandoned or improperly destroyed wells are not known to exist in the Project area.

UPPER AQUIFER SYSTEM

The Upper Aquifer System is comprised of two aquifers: the Oxnard and Mugu aquifers. These aquifers are important regional aquifers that are widely used for municipal and agricultural water supply in the Oxnard basin, particularly the Oxnard aquifer. These regional aquifers are recognized as being continuous across the Oxnard and Pleasant Valley basins, though the character of the UAS changes in Pleasant Valley to more fine-grained and interbedded. In the Oxnard Forebay area, the coarse alluvial shallow sediments are mapped as Oxnard Aquifer to land surface, and the aquifer is unconfined. The Oxnard Forebay is the primary recharge area for the Oxnard and Mugu aquifers, and where groundwater elevations are commonly the highest in the basin. During wet periods, groundwater commonly flows from the Forebay to all coastal portions of the Oxnard basin, providing hydrostatic pressure to the aquifer areas near the coastline, which prevents the intrusion of seawater when heads are above sea level. Seawater intrusion in these two aquifers is a recognized long-term problem in coastal areas and as a regional concern; the Project is designed to mitigate past seawater intrusion and prevent future intrusion in the UAS in the southern portion of the Oxnard basin.

Within the NBVC Point Mugu boundaries, lithology of the Oxnard aquifer is variable but consists primarily of fine-to-coarse sand, with interbeds of clay, silt, and gravel (Densmore, 1996). This aquifer historically discharged to the Pacific Ocean, where submarine outcrops allow direct interaction with seawater. However, when inland pumping of the aquifer exceeds recharge, depressed groundwater elevations can result and lead to a flow reversal in coastal areas and subsequent seawater migration to the aquifer from the Pacific Ocean. Thickness of the Oxnard aquifer ranges from approximately 70 to 140 ft in the Project area (Figure 2-10).

The Mugu aquifer is also composed of variable sediments in the study area, consisting primarily of sands and gravels with silt and clay interbeds (Densmore, 1996). The Mugu aquifer is generally finer-grained than the Oxnard aquifer, though there are some notable sequences of permeable sands and gravels, particularly near the base of the aquifer. The clays and finer-grained sediments that occur in the Mugu aquifer inhibit vertical flow within the unit. Thickness of the

Mugu aquifer ranges from approximately 50 to 150 ft in the Project area (Figure 2-11). The Mugu and Oxnard aquifers are generally separated on base by an aquitard, though the aquifers are interpreted to merge near Laguna Point, based on lithologic logs (UWCD, 2021a). The thickness of the aquitard separating these confined aquifers varies and is interpreted to range from 0 to 35 ft. thick in the Project area (Figure 2-12).

Contoured surface elevations of the hydrostratigraphic units of the UAS, created as part of United's recent (2021a) mapping effort, were compared to previously mapped contours included in a DWR seawater intrusion report (DWR, 1965). These surfaces largely are coincident, but United's mapping shows more variation in the aquifer elevations, partly due to greater spatial density of available borehole data now compared to 1965. The surface of the Oxnard aquifer is similar, but units below show some variation between the two mapping efforts. United mapped the base of the Oxnard aquifer up to 70 ft. shallower than DWR. United also mapped the base of Mugu approximately 100 ft. shallower than DWR near Laguna Point; United mapped the material underlying the Mugu aquifer as the Fox Canyon aquifer.

LOWER AQUIFER SYSTEM

The Lower Aquifer System is comprised of three aquifers: the Hueneme, Fox Canyon and Grimes Canyon aquifers. United (2018) mapped the lower portion of the Fox Canyon aquifer as a distinct hydrostratigraphic unit. These regional aquifers are widely used for municipal and agricultural water supply on the Oxnard coastal plain. The aquifers of the LAS tend to be finer-grained and less permeable than those of the UAS and have been subjected to extensive faulting and folding. The Hueneme aquifer is absent in the Project area, having been uplifted and eroded away (Figures 2-2 and 2-3).

Refinements to the geologic conceptual model and the inclusion of recently incorporated deeper borehole data has improved mapping of the areas of aquifer mergence between the UAS and LAS. Measured groundwater elevations in the Mugu aquifer are significantly lower than those in the overlying Oxnard aquifer in the greater Project area. The downward head gradient between the two aquifers, as well as within the Mugu aquifer, is interpreted to be a result of connectivity between the Mugu aquifer and the underlying Fox Canyon aquifer of the LAS. Heads in the LAS are consistently lower than in the UAS in this vicinity, and groundwater flows down into areas of lower pressure in the Fox Canyon aquifer. Groundwater elevation measurements from wells screened in the UAS also show downward vertical head gradients from the Oxnard aquifer to the Mugu aquifer.

The Extraction Barrier Project scenarios detailed in this Technical Memorandum do not include or propose production wells screened in the aquifers of the LAS. The larger Project scenarios do however serve to mitigate the migration of saline water down from the Mugu aquifer to the underlying Fox Canyon aquifer in the Project area by lessening the head differentials or reversing gradients between the two aquifers, thereby reducing the flow of saline groundwater down into the Fox Canyon aquifer. United is exploring additional Project scenarios with limited extraction from LAS wells to intercept saline water moving landward and downward in areas north of the Project area, but those preliminary evaluations are not detailed in this report.

SEAWATER INTRUSION

Seawater intrusion is associated with periods of drought and groundwater overdraft when groundwater elevations tend to fall below sea level. Historic Ventura County precipitation records indicate that the region has experienced several extended drought periods over the past century. The period 1923-1934 was relatively dry, experiencing only two years with rainfall totals greater than average. Although relatively few water level records exist for water wells on the Oxnard basin during that time, water levels in parts of the coastal plain were measured as much as five feet below sea level in the early 1930s (DWR, 1965). The period 1935-1944 was relatively wet, but the summer of 1945 marked the start of another extended dry period. By the early 1950s water levels had declined to 30 feet below sea level in some portions of the Oxnard basin (DWR, 1965). Water levels recovered somewhat in the late 1950s, but overdrafted basin conditions persisted in the early 1960s before the onset of wetter conditions in the late 1960s. Broad areas of the Oxnard basin recorded water levels below sea level again during droughts in the mid-1970s and late 1980s, before an extended wet period beginning in 1991 resulted in substantial water level recovery of the aquifers of the UAS in particular, following construction of the Freeman Diversion when diversions and artificial recharge volumes increased. Operation of the Freeman Diversion also resulted in increased surface water deliveries to growers in the Oxnard and Pleasant Valley basins. The aquifers of the UAS and LAS are now again critically overdrafted following persistent drought conditions that began in 2012. Each of the drought periods mentioned above witnessed water levels below sea level near the coast, resulting in episodes of seawater intrusion from the near-shore Hueneme and Mugu submarine canyons, most notably in the aquifers of the UAS.

High chloride concentrations were first detected in groundwater in the Oxnard basin in the vicinity of the Hueneme and Mugu submarine canyons in the early 1930s (DWR, 1965) and became a serious concern in the 1950s. Early monitoring programs used only existing production wells and older abandoned wells as monitoring points; sampling of these wells indicated that there was a widespread area of elevated chloride concentrations in the coastal areas between Port Hueneme and Mugu Lagoon. In some cases this reliance on old production wells led to misinterpretations regarding the extent of saline intrusion in the aquifers of the UAS, as high chloride concentrations in some of the samples was caused by poor-quality water leaking from the Semi-perched aquifer (rather than seawater, as presumed). Interpretations of the historical extent of saline intrusion have been previously characterized by the USGS (1996, Figure 2-13), in the FCGMA's 2007 Update to their Groundwater Management Plan, and more recently by United (2010, 2016, 2021). The current network of nested monitoring wells in the southern Oxnard basin is somewhat limited but allows a more reliable determination of conditions (water quality and head) in the various aquifers than was available prior to the 1990s.

As part of ongoing basin monitoring and data collection programs, United has been collecting and analyzing groundwater elevation data and water quality samples from aquifer-specific coastal monitoring wells since the early 1990s. Chloride data from these wells has been used to interpret the inland extent of chloride impacts over time. A coastal monitoring well located near Laguna Point and screened in the Oxnard aquifer has shown consistently high chloride concentrations. Water quality data from recent years (2016 – 2020) show increasing chloride concentrations in other monitoring wells located north and northwest of Laguna Point.

Seawater intrusion is also recognized in the Mugu aquifer, which, like the Oxnard aquifer, is in direct hydraulic communication with the Pacific Ocean where the aquifer outcrops offshore (Izbicki, 1996, Hanson, et al., 2003). Chloride time series plots show chloride concentrations have increased in recent years in the Mugu aquifer in the Mugu area, as they have in the Oxnard aquifer. As described above, strong downward head gradients are recognized in the Mugu area where the low heads in the Fox Canyon aquifer draws water down from the Mugu aquifer, and likewise the lower heads in the Mugu aquifer draws water down from the Oxnard aquifer where lateral seawater intrusion predominates. It should be noted that there are other potential sources of chloride in the coastal zone in addition to lateral seawater intrusion, including the migration of brines from older, uplifted formations, the dewatering of marine clays, and cross-contamination from corroded or poorly-constructed wells. See UWCD OFR 2021-03 (United, 2021c) for a more detailed characterization of basin conditions, a brief history of management actions to address overdraft and seawater intrusion, and chloride concentrations recorded in coastal monitoring wells over the past 30 years.

3 EXTRACTION BARRIER DESCRIPTION AND GOALS

When overdraft and seawater intrusion persist in coastal basins, engineered solutions can be employed to block seawater intrusion pathways and protect water quality in the interior of the basin. Injection barriers have been used in heavily urbanized basins in southern California since the 1960s. Successful injection barriers require a thorough understanding of the inland extent of saline water, a dense spacing of injection wells to maintain an effective pressure mound to prevent the break-through of seawater, and a reliable supply of feed water for the barrier. Some barriers have been constructed within the extent of saline water impacts, protecting the basin from further seawater intrusion, but stranding brackish water behind the barrier. Recycled wastewater from inland urban communities is commonly used as a component of the barrier feed water. In the Oxnard basin, the coastal cities of Oxnard and Ventura have plans to use their treated wastewater for purposes other than an injection barrier to control seawater intrusion. Alternative sources of water to supply an injection barrier have not been identified. Many investments have already been made by various agencies in southern Ventura County to deliver water directly to agricultural users, thereby reducing groundwater extractions that create landward groundwater gradients in coastal areas.

Extraction barriers are an alternative method to control coastal groundwater gradients and prevent the intrusion of seawater in overdrafted basins. Wells located near the coast serve to lower groundwater elevations, inducing groundwater flow from all directions towards the pumping depression created by the continuous operation of the extraction barrier wells. Brackish water associated with prior episodes of seawater intrusion flows towards the barrier wells from inland areas. The onshore flow of seawater in the production aquifers increases from that previously induced by inland basin pumping stresses, but the seawater does not advance beyond the extraction barrier well field. Produced water can either be treated and put to beneficial use or disposed of as waste. Given the large surface area where seawater enters the production aquifers the capture of marine organisms with the seawater is not a concern, as it is with open-water intakes at some coastal desalination facilities.

In the Oxnard basin, where seawater intrusion is interpreted to occur primarily at the near-shore Hueneme and Mugu submarine canyons, extraction well fields can be strategically located in the areas where seawater intrusion is concentrated. An additional advantage of extraction barriers over injection barriers is that the inland extent of chloride impacts need not be precisely known. The area of influence of the pumping depression of the extraction barrier wells can be determined with more confidence than the inland extent of chloride impacts in a basin with a long history of overdraft and seawater intrusion.

Coastal seawater extraction barriers are comparable to the common “pump and treat” systems used to contain contaminant plumes in inland areas. Extraction barrier well fields are designed to intercept the flow of seawater advancing inland from the Pacific Ocean, and to gradually pull the older leading edges of the inland brackish water plumes back towards the coastal extraction barrier wells.

In 1966, CA DWR constructed an experimental extraction barrier using five wells in the Oxnard aquifer (DWR, 1970). The wells were located northeast of the Port of Hueneme along Pleasant Valley Road and were constructed in a linear array that spanned approximately one-half of a mile in length. Background investigations regarding the area's geology, hydrology, and water quality were conducted by DWR earlier in the 1960s to determine the lateral and vertical extent of sea water in the southern Oxnard basin (DWR, 1965). The purpose of the experimental extraction-type barrier was to investigate the feasibility of using extraction wells to create a hydraulic pressure trough in the confined Oxnard aquifer near Port Hueneme, and to assess the effectiveness of the extraction barrier pressure trough to prevent seawater intrusion. United was a project partner with DWR and operated the extraction barrier well field.

Pumping of the barrier wells occurred from spring 1967 to spring 1968, with some interruptions and testing performed within that period. Pumping capacity of the well field was approximately 8,900 acre-feet per year (five extraction wells, each producing 1,100 gallons per minute). The produced water was discharged through a pipeline to a ditch located at Naval Construction Battalion Center Port Hueneme, and the water drained to the Pacific Ocean. From November 1967 to January 1968, heavy rainstorms caused natural recharge to increase across the Oxnard Plain and decreased the pumping from nearby supply wells. With the extraction wells operating simultaneously, and the wet period increasing the water levels in the basin, away from the pressure-trough, the areal extent of the seawater intrusion in the Port Hueneme vicinity was decreased in the Oxnard aquifer. From this experiment DWR concluded that "an extraction-type barrier [was] technically feasible to protect the Oxnard aquifer in the vicinity of Port Hueneme from further seawater intrusion." It was determined that seawater intrusion did continue during operation of the experiment barrier, and DWR estimated that additional extraction wells and approximately 14,200 acre-feet per year of pumping would be required to create a sufficient seaward hydraulic gradient to eliminate sea-water intrusion. The barrier wells and raw water discharge pipelines suffered from extensive corrosion and the demonstration barrier project was abandoned. Figure 3-1 is from the DWR report illustrating the profile of groundwater heads from the coast through the barrier.

United's proposed Extraction Barrier and Brackish Water Treatment Project at NBVC Point Mugu is similar to DWR's experimental barrier that was operated near Port Hueneme 50 years ago, but the proposed Mugu extraction wells are located near the coastline and as close to the offshore Mugu submarine canyon as possible. The coastal well locations for the Mugu project serve to minimize the onshore areas of the basin where seawater flows through the confined Oxnard and Mugu aquifers towards the barrier wells.

A conceptual groundwater flow diagram for the proposed extraction barrier project is shown in Figure 3-2. As described previously, seawater flows as groundwater through the confined Oxnard and Mugu aquifers from offshore areas to the production well(s), and brackish water flows towards the wells from inland areas. It is intended that the existing horizontal flow in the overlying Semi-perched aquifer remains unperturbed, and any downward flow that may be induced by vertical gradients from project pumping is negligible. Modeled vertical flux between aquifers associated with project pumping is detailed in Section 6 of this report. A natural seawater density wedge is thought to exist in the Semi-perched aquifer in the area of the proposed project production wells, but the inland extend of the density wedge remains poorly defined (TT EM Inc., 2003). If vertical leakage down from the Semi-perched aquifer does occur near the extraction barrier wells, it would likely consist of saline water from the base of the seawater density wedge, and not entrain fresh water from shallower zones of the Semi-perched aquifer.

While the project pumping scenarios evaluated in this report do not include any pumping from the Fox Canyon aquifer of the LAS, pumping from the Mugu aquifer provides a water quality benefit to the Fox Canyon aquifer. Vertical gradients in the area inland of the extraction barrier wells are likely to persist for a number of years, given the current heavy reliance on groundwater production from LAS wells in both the Oxnard and Pleasant Valley basins. As brackish water is drawn back towards the extraction barrier wells near the coast, fresh water from the interior of the basin will move south over the area of aquifer mergence. If downward head gradients to the LAS still exist when fresh water moves over this area of aquifer mergence, recharge to the LAS will consist of fresh water as opposed to saline water, as it is today. In areas more proximal to the extraction barrier wells, upward vertical head gradients between the Fox Canyon aquifer and the Mugu aquifer are simulated in all the project scenarios, as detailed in Section 6.

United's objective, in partnership with the U.S. Navy and with support from the Fox Canyon Groundwater Management Agency, is to design and build an extraction barrier project that prevents new episodes of seawater intrusion in the Mugu area and draws saline and brackish water associated with past seawater intrusion events back towards the coast in the southern portions of the Oxnard basin. Water produced by the extraction barrier wells will be treated to potable standards for use by NBVC and potentially other users, and to agricultural standards to offset pumping on the critically overdrafted Oxnard and Pleasant Valley basins. The Extraction Barrier and Brackish Water Treatment Project is being advanced as an effective way to control saline water intrusion, identified as the most critical sustainability indicator for the Oxnard basin. The manipulation of groundwater gradients in the southern portion of the Oxnard basin will help increase the sustainable yield of the Oxnard basin, but groundwater recharge in the Oxnard Forebay area remains a critical activity to bring the basin out of a condition of overdraft and sustain groundwater production from the basin.

4 NUMERICAL GROUNDWATER FLOW MODEL

To simulate the effectiveness of proposed extraction wells operated to prevent new episodes of seawater intrusion in the aquifers of the UAS, and to limit the inland extent of brackish groundwater, a numerical groundwater flow model capable of simulating density-dependent solute transport is needed to simulate water flow and solute transport. Originally United proposed to use SEAWAT (Langevin, et. al., 2008). Because SEAWAT is no longer supported by USGS, United modified their original proposal to Water Boards to use newer modeling software, MODFLOW-USG-Transport (Panday, et al., 2017). MODFLOW-USG-Transport uses a NWT scheme similar to MODFLOW-NWT and SEAWAT used an old wet/dry scheme. With the approval from grant managers at Water Boards, UWCD adopted MODFLOW-USG-Transport for the Extraction Barrier Project assessments.

In 2018 United published a regional groundwater flow model (referred as the Coastal Plain Model), which included the extraction barrier project area located at the southern boundary of the Oxnard basin (UWCD, 2018; Figure 4-1). Since 2016 the Coastal Plain Model had been reviewed by an expert panel comprising three nationally recognized groundwater modelers (Dr. Sorab Panday, Mr. Jim Rumbaugh, and Mr. John Porcello). The expert panel concluded that the regional groundwater model is well-designed and well-calibrated (Porcello, et al., 2018). The Coastal Plain Model was constructed using the popular USGS groundwater model software MODFLOW-NWT (Niswonger, et al., 2011), but is not capable of simulating solute transport or the higher density of seawater compared to fresh groundwater native to the basin. The Coastal Plain Model was well-calibrated and only a transport component is needed to become a fully functional transport model. Therefore, the Coastal Plain Model provided a solid starting point for building a saline water transport model. The following sections detail the conversion of the MODFLOW-NWT model to the MODFLOW-USG-Transport model, the model grid refinement in the coastal area between the Mugu and Hueneme submarine canyons, the recalibration of the groundwater flow component, and the calibration of the density-dependent saline water transport components.

4.1 MODEL CONVERSION

Both MODFLOW-NWT and MODFLOW-USG-Transport share some commonly used functionalities (or “packages”). In converting the Coastal Plain Model into a MODFLOW-USG-Transport based model, the packages retained are listed in Table 4-1, below. The packages with the same names share the same input format, the same data or parameters, the one exception being that the model grid number designations are different between the structured grid used in MODFLOW-NWT and the denser unstructured grid used in MODFLOW-USG-Transport.

Table 4-1: The common packages used in both MODFLOW-NWT and MODFLOW-USG-Transport

MODFLOW-NWT & MODFLOW-USG Common Package		Input Data
BAS6	Basic	Basic input data including the initial head, active cell data
RCH	Recharge	Surface water recharge from artificial recharge, agricultural/M&I return flow
EVT	Evapotranspiration	Evapotranspiration by wetlands and plants
DRN	Drain	Tile drain
STR	Stream Routing	Santa Clara River, Conejo Creek, Arroyo Las Posas, Calleguas Creek
GHB	General Head Boundary	Interaction with seawater at the submarine outcrop
HFB6	Horizontal Flow Barrier	Faults
WEL	Well	Mountain front recharge and underflow along Arroyo Las Posas
OC	Output Control	Model output control

The General Head Boundary (GHB) conditions used to simulate the interaction with seawater at the submarine outcrop in Layers 1, 3, 5, 7, 9, and 11 were retained and were modified to use mean sea level (2.73 ft) as the hydraulic head, and the chloride concentration of 19,400 mg/l (seawater) for MODFLOW-USG-Transport relative to the equivalent freshwater head in MODFLOW-NWT.

The packages that differ between MODFLOW-NWT and MODFLOW-USG are listed in Table 4-2. The different packages carry different names and have different input formats between MODFLOW-NWT and MODFLOW-USG; however, the input data or parameters remain the same.

Table 4-2: The different packages used in MODFLOW-NWT and MODFLOW-USG-Transport

MODFLOW-USG Package		MODFLOW-NWT Package		Input Data
DISU	Unstructured Discretization	**DIS**	Discretization	Model grid data
LPF	Layer-Property Flow	**UPW**	Upstream Weighting	Aquifer properties
CLN/WEL	Connected Linear Network and Well	**MNW2**	Multi-Node Well Package, version 2	Extraction wells
SMS	Sparse Matrix Solver	**NWT**	Newton Solver	Numerical Solver
BCT	Block-Centered Transport	**-**	-	Transport input data
DDF	Density Dependent Flow	**-**	-	Density dependent data

The simulation period for the converted MODFLOW-USG-Transport model is the same as for the Coastal Plain Model: January 1985 to December 2015, with monthly time steps.

4.2 MODEL REFINEMENT

As shown in Figures 2.6 and 2.7, seawater intrusion has been a problem in both the Mugu and Port Hueneme areas for decades. To perform a comprehensive simulation of past seawater intrusion and movements of saline water in the Oxnard basin, the Port Hueneme area was included in the area for model refinements and solute transport modeling.

Recognizing that there is an important geological feature located east of Port Hueneme, namely a thick fine-grained canyon-fill deposit separating the Mugu and Hueneme aquifers, additional available well completion reports and geophysical logs were reviewed and interpreted, resulting in a revised geological model in that area surrounding the canyon-fill feature. As detailed in Section 2, the conceptual model around the NBVC Point Mugu was further refined to detail the local variation of the aquifers and aquitards. These refinements are detailed in United Technical Memorandum "Geological Model Refinements Near Naval Base Ventura County Point Mugu, CA" (UWCD, 2021a). The revised mapped thickness of the aquifers and aquitards in the southern Oxnard basin was incorporated in the thickness of model cells for the aquifers and aquitards near Point Mugu and Port Hueneme in the MODFLOW-USG-Transport model. United's recent work related to the mapping and interpretation of geologic features near Mugu and Hueneme canyons was funded by the Prop 1 grant.

The Coastal Plain Model was based on a uniform model grid of 2,000 ft. by 2,000 ft., as shown in Figure 4-2. To better simulate the brackish water in the southern Oxnard basin and better incorporate the boring log data in shallow layers, local model grid refinements were applied along the coastal area from Port Hueneme to Point Mugu including the Project area for the extraction barrier wells, as shown in Figure 4-3. The local model grid refinements transitions from 2,000 ft to 1,000 ft to 500 ft on a side. Thickness of the model cells varies based on the geologic mapping of the individual layers.

4.3 MODEL CALIBRATION

When a well-calibrated numerical flow model is converted from one model software to another, the calibration performance in the converted model may change. In addition, when the hydrogeological conceptual model is refined, the numerical model may need recalibration after the refined geologic conceptual model is implemented into the numerical model. In this extraction barrier feasibility study, both the model software conversion and the refined hydrogeological conceptual model were implemented. The model software for this study was converted from MODFLOW-NWT to MODFLOW-USG-Transport. Also, the revised aquifer and aquitard layering near the Mugu and Hueneme submarine canyons was incorporated in the numerical model. As a due diligence check United staff reviewed the model calibration of the converted MODFLOW-USG-Transport model and made necessary adjustments to recalibrate and improve the converted MODFLOW-USG-Transport model.

The resulting model calibration was evaluated with scatter plots and well hydrographs. The scatter plot compares measured groundwater elevation from all or many wells around the area of interest with the simulated values from the corresponding wells. The well hydrograph compares measured groundwater elevation over time from individual wells with the simulated values over time. Figures 4-4 and 4-5 show the scatter plots from all wells within the Oxnard basin, including the area where the brackish water extraction wells will be located, and the geologic model refinement was implemented. Figure 4-4 is based on the MODFLOW-NWT model before the model conversion and geologic model refinements. Figure 4-5 is based on the MODFLOW-USG-Transport model after the model conversion, layering refinements, and recalibration. By comparing the result between the MODFLOW-NWT and MODFLOW-USG-Transport models in Figures 4-4 and 4-5, it is noted that the scatter plots are similar before and after the model conversion. Further, the blue data points from the UAS (shallow confined aquifers) and the green data points from the wells screened in both UAS and LAS (deep confined aquifers) cluster closer along the 45-degree solid red line in the MODFLOW-USG-Transport model (Figure 4-5), showing an improvement in model calibration with the MODFLOW-USG-Transport model.

In addition to evaluating all groundwater elevation measurements from confined aquifer wells located within the Oxnard basin using scatter plots, local wells near Point Mugu were also evaluated by comparing groundwater elevation hydrographs. Additional wells outside of the Project area were inspected. It is found that there is little difference between MODFLOW-NWT and MODFLOW-USG-Transport models because there is no change in input parameters, model grid sizes, and boundary conditions. Five multi-level wells were selected near the project area (see Figure 4-6). Figures 4-7 through 4-11 show groundwater elevation hydrographs from five multi-level well systems:

1) 01N22W35E01S, 01N22W35E02S, 01N22W35E03S, 01N22W35E04S, and 01N22W35E05S
2) 01N22W36K05S, 01N22W36K06S, 01N22W36K07S, and 01N22W36K08S
3) 01S22W01H01S, 01S22W01H03S, and 01S22W01H04S
4) 01S21W18L03S, and 01S21W18L04S
5) 01N21W32Q03S, 01N21W32Q04S, 01N21W32Q05S, and 01N21W32Q06S

By comparing Figures 4-7 through 4-11 it is observed that most of the groundwater elevation hydrographs are similar, but wells 01N22W35E04S, 01N22W36K08S, 01S22W01H03S and 01N21W32Q05S, which are screened in Mugu aquifer, show a better fit between simulated groundwater elevation (in orange lines) and the measured groundwater elevations (in blue dots) for MODFLOW-USG-Transport model compared to the MODFLOW-NWT model. The comparison shows that the converted MODFLOW-USG-Transport model improves the calibration in the UAS wells, particularly in the Mugu aquifer, while the model calibration for groundwater elevations in other aquifers remain well-calibrated.

Considering both the scatter plots and well hydrographs, it is concluded that the converted MODFLOW-USG-Transport model is well-calibrated. Further, because of the geologic conceptual model refinement in the UAS mentioned earlier, the MODFLOW-USG-Transport model is improved in the UAS relative to the older Coastal Plain Model based on MODFLOW-NWT. The MODFLOW-USG-Transport model improvements in the UAS benefit the coastal extraction barrier analysis, as the primary brackish water extraction wells will operate in the UAS.

As mentioned above, the converted MODFLOW-USG-Transport model is able to simulate the density-dependent element of saline water transport. The Block Centered Transport (BCT) package is used to simulate the solute transport component. To account for the density of saline water, the DDF (Density Dependent Flow) component is used in the MODFLOW-USG-Transport model. The density and chloride concentration of seawater used in the MODFLOW-USG-Transport model are 63.9262 lb/ft^3 and 19,400 mg/l. The density for freshwater is 62.4 lb/ft^3. The MODFLOW-USG-Transport model simulates chloride transport and incorporates the density differences of varying chloride concentrations in calculating groundwater pressure heads in the groundwater flow simulations.

To account for the dispersion in the solute transport, the horizontal longitudinal dispersivities were assumed to be 100 ft, and 100 ft in the X and Y directions. The vertical longitudinal dispersivity was assumed to be 1 ft to account for vertical anisotropy. For sensitivity analysis, the dispersivities were assumed to be 1 ft, 1 ft and 0.01 ft, respectfully. From the sensitivity analysis of dispersity parameters, the difference in chloride concentrations and hydraulic heads were negligible. The insensitivity of the flow and transport to the dispersivity parameters was expected as the significant advective mixing of brackish and fresh water during wet and dry years is a more dominant process than solute transport by dispersion.

To start the simulation for solute transport, the initial brackish water extent at the beginning of the modeling period is required. An initial saline and brackish water extent in 1985 was first manually estimated based on two studies:

- 1985-1989 Seawater Intrusion Inland Extent in Upper Aquifer System by FCGMA (FCGMA et al., 2007)
- 1989 Oxnard Aquifer Seawater Intrusion Inland Extent by USGS (Izbicki, 1996)

The manually estimated concentration was used as the initial concentration in a one-stress simulation with stress period 30,000 days (82 years), with assumed pre-1985 pumping rates so that the simulated output concentration is better equilibrated. The simulated output concentration shown in Figure 4-12 is used as the initial (1985) chloride concentration (mg/L).

To calibrate the transport component of MODFLOW-USG-Transport, the inland extent of brackish water at the end of the modeling period is also required. The 2015 brackish water inland extent was delineated by chloride concentrations of 100 mg/L from an United investigation that relied on water quality data from coastal monitoring wells and geophysical studies (UWCD, 2016). The simulated chloride concentration at end of 2015 from the MODFLOW-USG model was compared with the 2015 brackish water inland extent, as interpreted by United. Figure 4-13 shows the simulated chloride concentration in Oxnard aquifer and the 2015 delineated brackish water inland extent (in black line) in Oxnard aquifer, as interpreted by United. From Figure 4-13, it is noted that the simulated brackish water inland extent (100 mg/L) closely approximates the delineated brackish water inland extent. To evaluate the onshore trend of the chloride concentration in Oxnard aquifer, the contour lines of simulated chloride concentrations in Oxnard aquifer in 100, 500, 1,000, 5,000, 10,000, and 15,000 mg/L were plotted against the 2015 chloride concentrations as measured in the coastal monitoring wells (Figure 4-14). Figure 4-14 also shows measured chloride concentrations from the Oxnard aquifer monitoring wells and demonstrates that the simulated chloride concentration captures the spatially varied chloride concentration as measured.

Figure 4-15 shows the simulated chloride concentration in Mugu aquifer and the 2015 interpreted inland extent of brackish water in the Mugu aquifer (UWCD, 2016). From Figure 4-15, it is noted that the simulated brackish water inland extent (100 mg/L) is close to the 2015 delineated brackish water inland extent (in red line) except for an isolated area north of the runway of the NBVC Point Mugu, where the simulated inland extent is more extensive than United's 2015 estimation. The expanded area of brackish water simulated by the model is caused by an area of mergence between the Oxnard and Mugu aquifers where the aquitard that commonly separates these aquifers is absent. Saline water in the Oxnard aquifer leaks down to the Mugu aquifer because heads are lower in the Mugu aquifer. To evaluate the inland trends of chloride concentrations in the Mugu aquifer, simulated chloride concentration contour lines of 100, 500, 1,000, 5,000, 10,000, and 15,000 mg/L were plotted against the measured 2015 chloride concentrations from Mugu aquifer monitoring wells in Figure 4-16. Figure 4-14 shows that the simulated chloride concentration captures the observed and spatially varied chloride concentrations in Mugu aquifer.

Because the MODFLOW-USG-Transport model can simulate the interpreted inland extent of saline and brackish water in both Oxnard and Mugu aquifers, it is concluded that the re-calibrated MODFLOW-USG-Transport as converted from the MODFLOW-NWT Coastal Plain Model is appropriate for simulating the movement of saline and brackish water in response to the operation of a coastal extraction barrier well field.

5 PROJECT ALTERNATIVES

The MODFLOW-USG-Transport model was used to evaluate six project alternatives, including a no action base case and five extraction barrier designs with different extraction rates. When the extracted water is treated the product water recovery rate is assumed to be 50% based on preliminary engineering estimates provided by United's Engineering Department. Product water quality is being designed to meet drinking water standards as well as irrigation standards for local crops, which require low sodium and chloride concentrations. It is assumed that 1,500 AFY of the available treated water will be used by the U.S. Navy, and the remainder will be distributed to United Pumping Trough Pipeline (PTP) service area and the Pleasant Valley County Water District service area, in equal proportion.

United staff in collaboration with the U.S. Navy visited the Naval Base Ventura County installation at Point Mugu to identify potential well sites for the extraction barrier wells. The preliminary list of potential well locations is shown on Figure 5-1.

The six project alternatives are described below and listed in Table 5-1.

- No Action: Base-case condition with no extraction barrier wells.
- 5K W: The extraction barrier wells extract a total of 5,000 AFY from the Oxnard aquifer (3,000 AFY) and the Mugu aquifer (2,000 AFY). The extracted brackish water is pumped to waste, without treatment. The well locations are shown in Figure 5-2.
- 5K T: The extraction barrier wells extract a total of 5,000 AFY from the Oxnard aquifer (3,000 AFY) and the Mugu aquifer (2,000 AFY). The extracted brackish water is assumed to be treated with a 50% water recovery rate, generating 2,500 AFY for local users. The well locations are shown in Figure 5-2.
- 10K: The extraction barrier wells extract a total of 10,000 AFY from the Oxnard aquifer (6,000 AFY) and the Mugu aquifer (4,000 AFY). The extracted brackish water is assumed to be treated with 50% water recovery rate, generating 5,000 AFY for water users in the basin. The well locations are shown in Figure 5-3.
- 15K: The extraction barrier wells extract a total of 15,000 AFY from the Oxnard aquifer (10,000 AFY) and the Mugu aquifer (5,000 AFY). The extracted brackish water is assumed to be treated with a 50% water recovery rate, generating 7,500 AFY for water users in the basin. The well locations are shown in Figure 5-4.
- 20K: The extraction barriers extract a total of 20,000 AFY from the Oxnard aquifer (14,000 AFY) and the Mugu aquifer (6,000 AFY). The extracted brackish water is assumed to be treated with a 50% water recovery rate, generating 10,000 AFY for water users in the basin. The well locations are shown in Figure 5-5.

Table 5-1. Brackish Barrier Project Alternatives.

Scenario	Extraction rate (AFY)	Treated water for usage (AFY)	Treated water usage (AFY)			Oxnard well number	Mugu well number	Oxnard Extraction (AFY)	Mugu Extraction (AFY)
			Navy	PTP	PV				
No Action	0	0	0	0	0	0	0	0	0
5K W	5000	0	0	0	0	6	4	3000	2000
5K T	5000	2500	1500	500	500	6	4	3000	2000
10K	10000	5000	1500	1750	1750	12	10	6000	4000
15K	15000	7500	1500	3000	3000	16	12	10000	5000
20K	20000	10000	1500	4250	4250	20	20	14000	6000

To evaluate the effectiveness of the proposed extraction barrier, a model simulation of future hydrology and basin conditions is needed to simulate operation of the extraction barrier at various project scales and assess project impacts and benefits. In 2018 and 2019 the Fox Canyon Groundwater Management Agency, along with their consultants and cooperators, worked to developed various future groundwater model simulations in preparing their Groundwater Sustainability Plans (GSPs) in compliance with the Sustainable Groundwater Management Act (SGMA). The assumed future conditions selected by FCGMA for evaluating basin sustainability in their GSPs are ideal scenarios for simulating the brackish water extraction barriers, as the GSPs were developed based on FCGMA's best understanding of and assumptions for the future basin conditions. The FCGMA GSP model runs were based on two historic 50-year hydrologic conditions: 1930 to 1979 and 1940 to 1989 with two climate factors: 2030 CF and 2070 CF, resulting in four future groundwater simulation conditions for the GSP sustainability analysis (FCGMA, 2019a). To analyze the proposed coastal extraction barrier scenarios, only one future condition (i.e., one GSP run instead of all four) is required, as the project assessment is focused on the effectiveness of the extraction barriers in controlling seawater intrusion and removing brackish water from the aquifers of the UAS, not what seawater intrusion might occur under various future climate conditions. After informally consulting with FCGMA staff, UWCD staff selected the GSP run based on no cutbacks of future pumping as the scenario for simulating the extraction barriers. The 1930-1979 with 2070 climate factor was selected, as it was considered the most conservative hydrologic condition in the GSPs.

To simulate the extraction barrier operations at various scales, the simulated groundwater elevations and chloride concentrations in December 2015 (from the calibration model simulation from January 1985 to December 2015) were selected as the initial groundwater conditions and the initial chloride concentrations for the future 50-year simulation. The initial chloride concentrations in Oxnard and Mugu aquifers for future simulations are shown in Figures 4-13 and 4-15.

6 PROJECT FEASIBILITY DISCUSSION

Modeled simulations of groundwater conditions resulting from the operation of the proposed extraction barrier project at various scales were used to assess project impacts and benefits. Feasibility of the extraction barrier at varied Project scales was evaluated in the following ways:

- The extraction rates and the potential limitations of the local geology on extraction rates.
- Containment of the inland extent of brackish water and prevention of seawater intrusion in the future.
- Flow of water from shallower or deeper aquifers not targeted for groundwater production, resulting from changes in vertical groundwater head gradients.
- Changes in groundwater elevation in the production aquifers in the areas surrounding NBVC Point Mugu, which could impact existing wells and water users.

When modeling brackish water extraction rates, it was desirable to use as few extraction wells as possible to minimize well construction costs and the related pipeline costs. However, when higher extraction rates were modeled with fewer wells, the simulations indicated that the higher extraction rates with fewer wells were sustainable during normal rainfall and wet years but were not sustainable during drought periods when groundwater elevations across the basin are lower. To ensure the full project extraction rates were simulated for model comparison purposes, more wells were added as necessary. From Table 5-1 it is noted that the number of required extraction wells increases as the magnitude of the pumping increases. Aquifer thickness and aquifer properties in the project area become limiting factors with the larger projects. This report does not include a feasibility assessment based on the costs of constructing a large number of wells or land availability for well sites, which likely will be limiting factors.

The effectiveness of the extraction barrier was evaluated by comparing modeled chloride concentrations in groundwater and the inland extent of chloride impacts at the end of the 50-year simulations under different extraction barrier scenarios. Figures 6-1 and 6-2 show chloride concentrations in the Oxnard and Mugu aquifers at the end of 50 years of operating the extraction barriers with different extraction rates, and for the no barrier base case. From Figure 6-1 it is noted that the inland extent of chloride (based on 100 mg/L chloride concentration) in the Oxnard aquifer retreats toward the coast under all extraction rates from 5,000 to 20,000 AFY, indicating the extraction barrier pumping schemes are effective in remediating the impacts associated with past seawater intrusion in the Oxnard aquifer. From Figure 6-2 it is noted that the inland extent of chloride based on 100 mg/L chloride concentration in the Mugu aquifer is stabilized with extraction rate at 5,000 AFY, and the SWI extent retreats toward the coast under extraction rates from 10,000 to 20,000 AFY, indicating the extraction barrier pumping schemes are effective in stabilizing/remediating saline water intrusion in the Mugu aquifer.

In addition to the effects of extraction barriers on the inland extent of chloride, the potential to impact the aquifers located above and below the Oxnard and Mugu production aquifers was also investigated. Simulated vertical flow between Semi-perched, Oxnard, Mugu, and Fox Canyon aquifers are listed in Table 6-1. It is noted that vertical flow from Semi-Perched aquifer to Oxnard aquifer increases as the extraction rate for brackish water extraction barriers increases. In the Mugu aquifer, downward vertical flow to the Fox Canyon aquifer reverses when an upward vertical gradient is created by the extraction barriers pumping. To better evaluate vertical flow down from the Semi-perched aquifer to Oxnard aquifer, the average seepage velocity (the groundwater flow seeping from the Semi-perched to the Oxnard aquifer) was calculated to be in the range of 1.0E-4 ft/day (see Table 6-1). The areal (spatially varied) seepage velocity is also calculated and shown in Figure 6-3 using the end of multi-year drought (November 1965) when groundwater elevations for the simulation period are lowest in the production aquifers. The areal average seepage velocity is small, in the range of 1.0 E-6 to 1.0E-3 ft/day, depending upon the extraction rates.

Table 6-1. Vertical Flow Between Aquifers.

Average Annual Vertical Flow (AFY)							
From Aquifer	to Aquifer	No Action	5K W	5K T	10K	15K	20K
Semi-Perched	Oxnard	63	116	110	154	204	271
Oxnard	Mugu	439	573	563	876	921	872
Mugu	Fox Canyon	848	-117	-136	-720	-1097	-1892
Average Vertical Leakage (FT/DAY)							
From Aquifer	to Aquifer	No Action	5K W	5K T	10K	15K	20K
Semi-Perched	Oxnard	5E-05	1E-04	1E-04	1E-04	2E-04	2E-04
Oxnard	Mugu	4E-04	5E-04	5E-04	8E-04	8E-04	8E-04
Mugu	Fox Canyon	7E-04	-1E-04	-1E-04	-6E-04	-1E-03	-2E-03

1. The average vertical (AFY) is calculated based on an area (3,149 acres) covering most of NBVC installation at Point Mugu
2. The average vertical leakage (ft/day) is an average over the the same area (3,149 acres) covering most of the NBVC installation at Point Mugu
3. Negative values indicate the flows are reversed in direction

Given the low seepage velocity from Semi-Perched aquifer to the Oxnard aquifer listed in Table 6-1 and shown in Figure 6-3, groundwater flow in Semi-Perched aquifer is further evaluated using particle tracking simulation. The USGS particle tracking software, MODPATH Version 7 (Pollock, 2016) was used to simulate the movement of particles released in the middle of Semi-perched aquifer. Figure 6-4 shows the simulated particle movement over 50 years of simulated extraction barrier pumping. Particle tracks in the Semi-perched aquifers for selected No Action, 5K W and 20K scenarios show very similar results. From the particle tracking simulations, all the particles remain within the Semi-Perched aquifer under all six scenarios, and the particle movement between the No Action scenario and the other five extraction barrier scenarios are very similar, indicating the dominant horizonal flow in Semi-Perched aquifer is little affected by the extraction barrier pumping and the vertical gradient created by the pumping.

Lastly, the potential impact of the various extraction barrier pumping schemes on nearby wells was evaluated by calculating the groundwater elevation drawdown in the greater Project area. Figure 6-5 shows the simulated water levels in November 1965 (at the end of multi-year drought) in the Oxnard aquifer for selected scenarios No Action, 5K W and 20K. In order to better visualize the water level drawdown in the Oxnard aquifer associated with the extraction barrier pumping, the difference in the simulated groundwater elevations in November 1965 for the No Action scenario is compared to the other pumping scenarios (Figure 6-6). Simulated groundwater elevations in the Mugu aquifer and the water level drawdowns with extraction barrier pumping are plotted in Figures 6-7 and 6-8.

In order to compare the groundwater drawdown side-by-side between different scenarios, two “hypothetical” monitoring wells were selected (Wells A and B in Figure 6-9). Well A is located north of the Project extraction wells at the NBVC Point Mugu installation boundary. Well B is located about 2 miles from the NBVC Point Mugu, representing the location of an existing production well. Figure 6-10 shows the simulated water levels from the Well A location in Oxnard and Mugu aquifers for all Project pumping scenarios. It is noted in Figure 6-10 that the water level difference (drawdown) in Oxnard aquifer at the Well A location between different extractions rates relative to Scenario No Action ranges from 10 ft (Scenario 5K W) to 30 ft (Scenario 20K) and the water level differences (drawdown) in Mugu aquifer at Well A relative to Scenario No Action ranges from 5 ft (Scenario 5K W) to 20 ft (Scenario 20K). Figure 6-11 shows the simulated water levels at the Well B location in the Oxnard and Mugu aquifers for all Project scenarios. It is noted in Figure 6-11 that the water level drawdowns in Oxnard and Mugu aquifers at Well B relative to Scenario No Action are similar, ranging from 5 ft (Scenario 5K W) to 10 ft (Scenario 20K). As mentioned earlier, Well B may serve as a local user’s production well and the groundwater level drawdown on local user’s production wells caused by the extraction barrier scenarios is relatively small, ranging from 5 to 10 ft.

7 CONCLUSIONS

The MODFLOW-USG-Transport model detailed in this report simulates groundwater flow and saline water transport from 1985 to 2015 in the Oxnard basin, as well as simulations of brackish water extraction barriers for a 50-year simulation period based on an Oxnard basin GSP scenario with no pumping cutbacks, as used by FCGMA (2019a). An extraction barrier near the Mugu submarine canyon is identified as an effective way to control saline water intrusion in the basin.

The MODFLOW-USG-Transport model developed as part of this investigation is considered to be well-calibrated. The model was calibrated by comparing available groundwater elevation measurements from 1985 to 2015 with the simulated groundwater elevations, including the density effect from seawater. By comparing the delineated 2015 inland extent of saline water in Oxnard and Mugu aquifers, and by comparing simulated chloride concentration with data from monitoring wells located within the area of chloride impacts in Oxnard and Mugu aquifers over the past 25 years, the calibration of the MODFLOW-USG-Transport model was confirmed.

Various brackish water extraction barriers were simulated with extraction rates ranging from 5,000 to 20,000 acre-feet per year. A scenario with no extraction barrier (No Action) was also simulated for comparison. From Section 6, it is noted that the simulated extraction barriers effectively draw saline water in the Oxnard aquifer back towards the coast and stabilize or draw back the inland extent of saline water in the Mugu aquifer, depending on Project extraction rates in Mugu aquifer.

Project impacts on the aquifers located above and below the aquifers with extraction barrier wells were evaluated. It is shown that the impact on the Semi-Perched aquifer above the Oxnard aquifer is small and the impact on the Fox Canyon aquifer below the Mugu aquifer is more significant, suggesting the extraction barrier may also improve chloride concentration in the Fox Canyon aquifer over time, especially with simulations involving larger pumping volumes from the Mugu aquifer.

Project impacts on the local production wells were also investigated. It is determined that the drawdown in Oxnard aquifer caused by extraction barriers under the most conservative condition (at the end of multi-year drought) ranges from 5 to 10 ft in both the Oxnard and the Mugu aquifers. The 5 to 10 ft of drawdown is considered acceptable when compared with the thickness of the UAS aquifers in the areas surrounding NBVC Point Mugu. In the surrounding areas the Oxnard aquifer ranges in thickness from approximately 90 to 150 ft, and the thickness of Mugu aquifer ranges from approximately 90 to 170 ft.

The extraction barrier scenarios are considered to be feasible based on the primary set of Project benefits and impacts detailed in this report. A phased approach may be helpful to incrementally increase the number of extraction wells for a larger Project as Project benefits are demonstrated after initial construction.

The Prop 1 grant awarded to United has funded development of a valuable solute transport model that will be used extensively to further investigate Project scenarios designed to control the spread of saline water in the aquifers of the southern Oxnard basin. The model calibration work identified that the vertical flow of saline groundwater between the Oxnard and Mugu aquifers is more significant than previously recognized in an area of aquifer mergence northwest of NBVC Point Mugu and deserves additional study.

United will continue to work with the U.S Navy, the Fox Canyon Groundwater Management Agency, California Water Boards Division of Drinking Water, the Los Angeles Regional Water Quality Control Board and other regulators as necessary to develop and build the Extraction Barrier and Brackish Water Treatment Project at Naval Base Ventura County Point Mugu. United’s objective is to develop and advance an extraction barrier project that helps to preserve and optimize the sustainable yield of the Oxnard and Pleasant Valley basins, satisfies the U.S. Navy’s need for a resilient and independent supply of potable water, minimizes impacts to surrounding pumpers and Disadvantaged Communities, and minimizes the environmental risks associated with the project.

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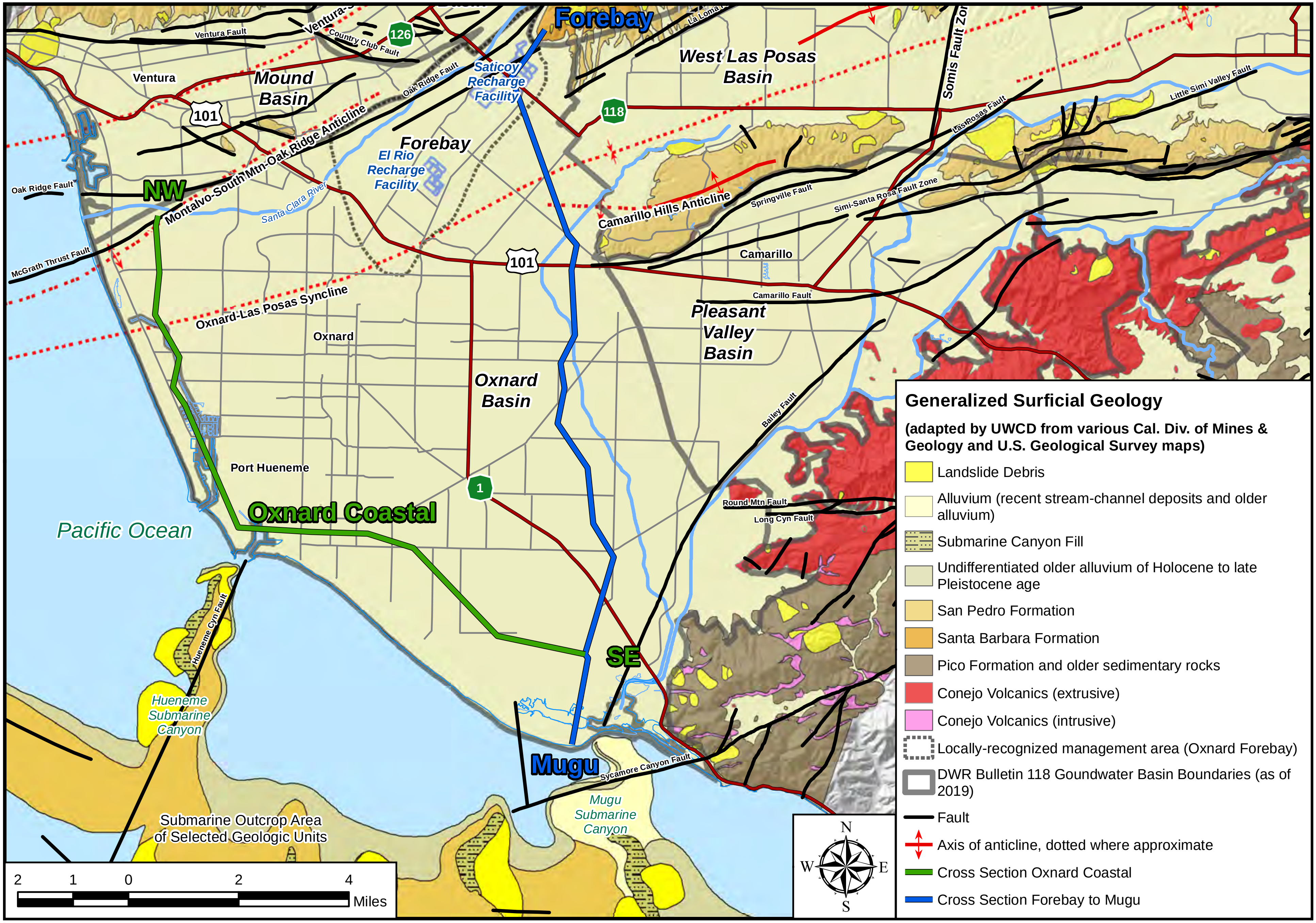

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Cross Section Forebay to Mugu (7x Vertical Exaggeration)

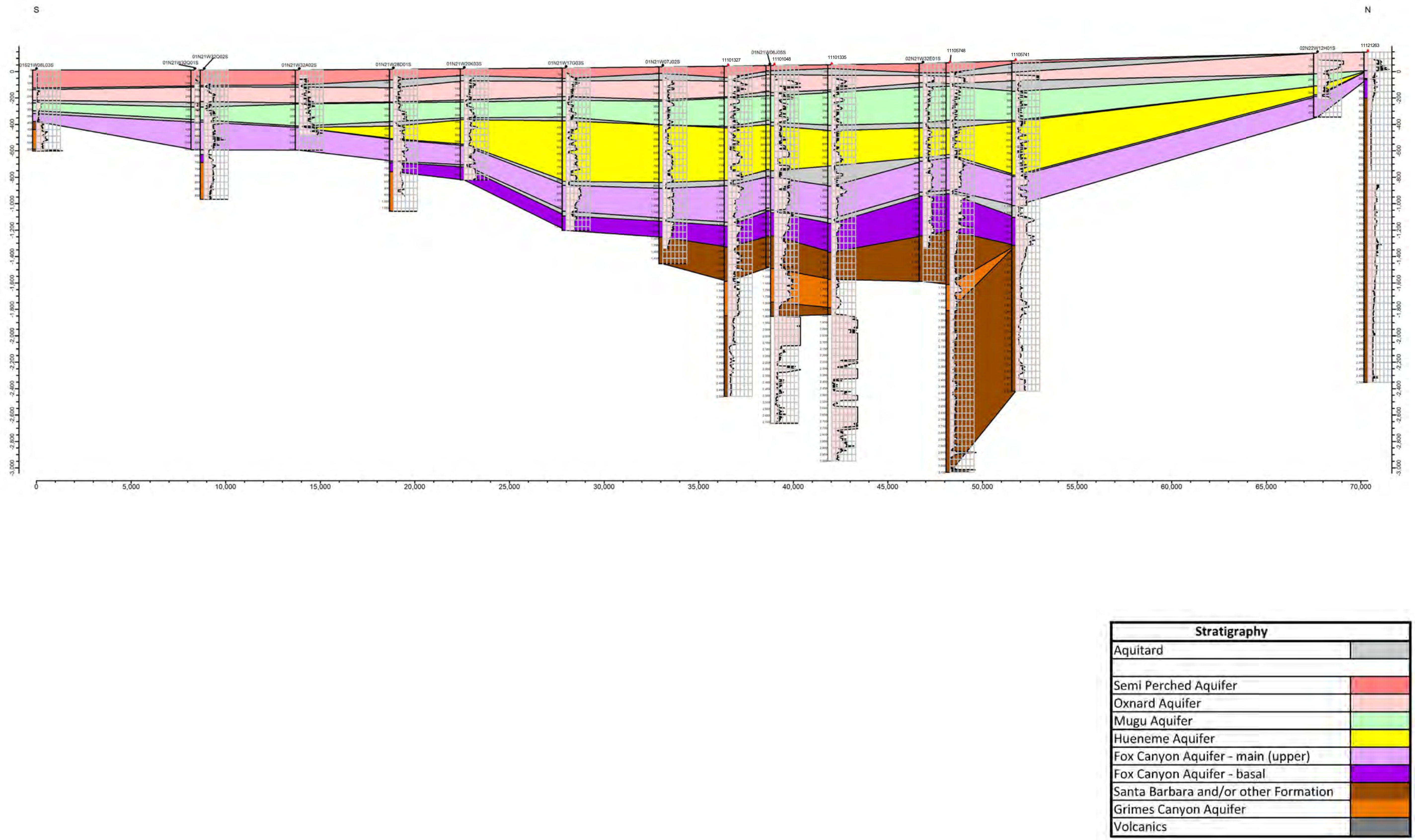
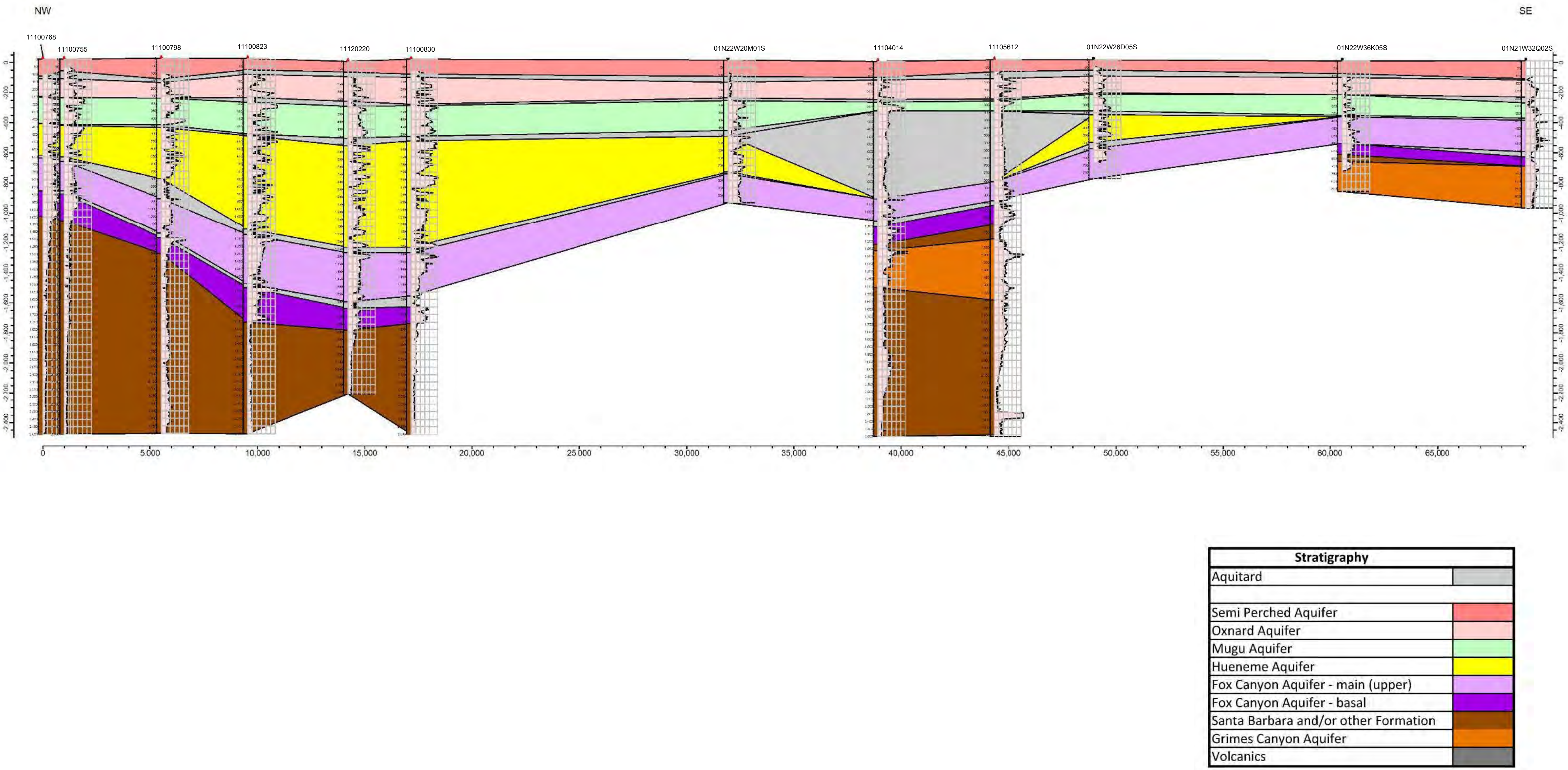


Figure 2-2. Cross Section Forebay to Mugu.

Cross Section Oxnard Coastal (7x Vertical Exaggeration)



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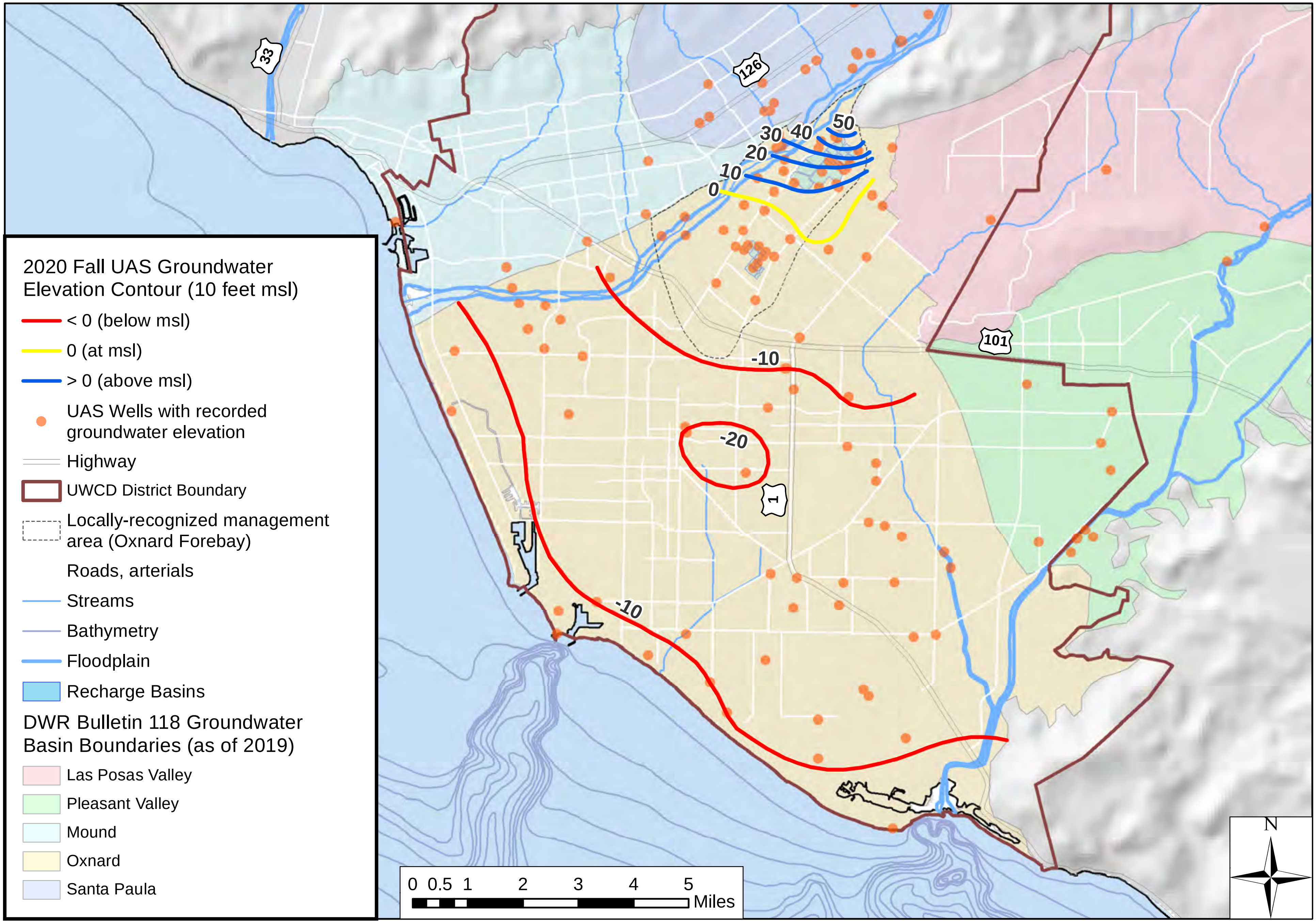

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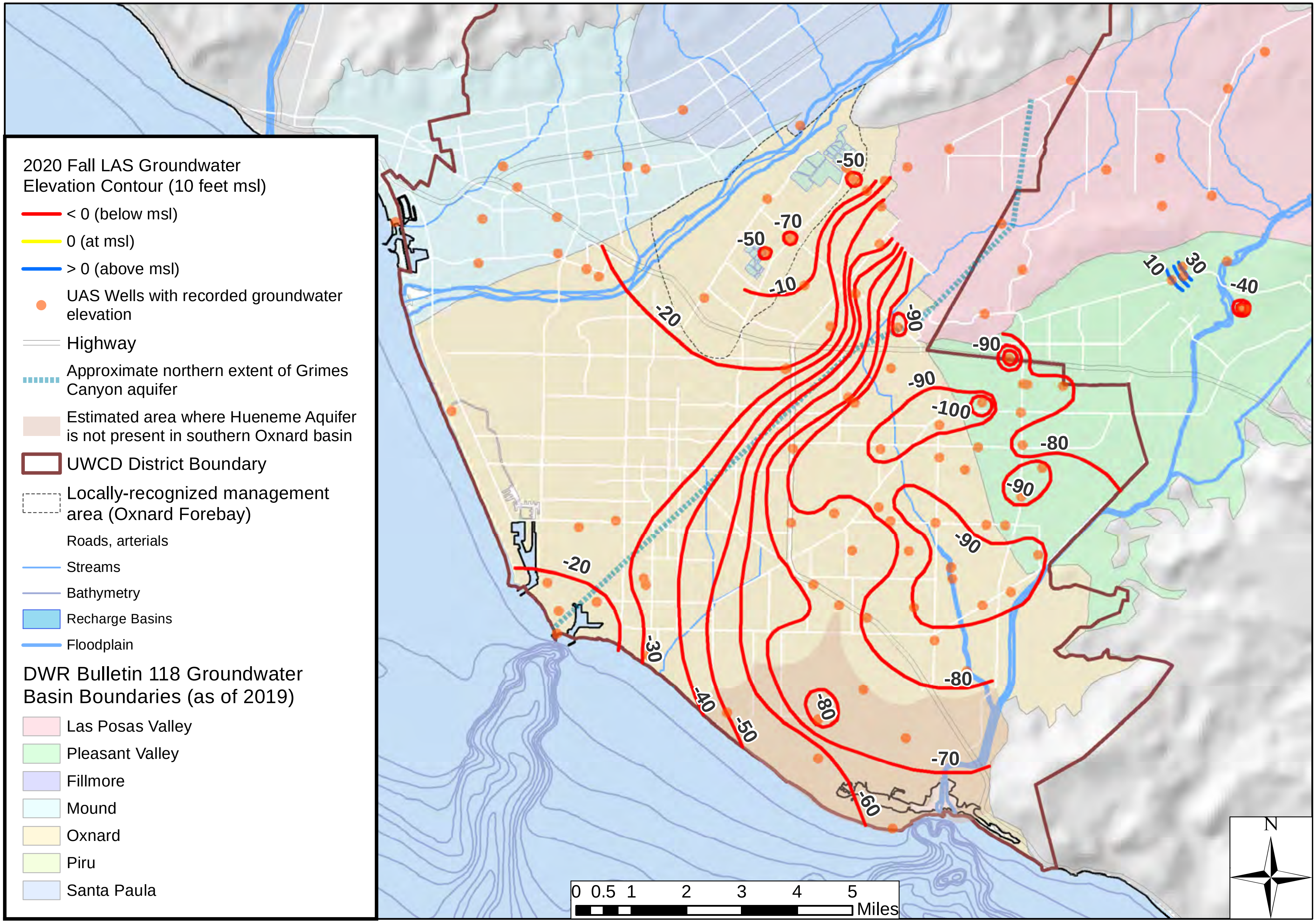

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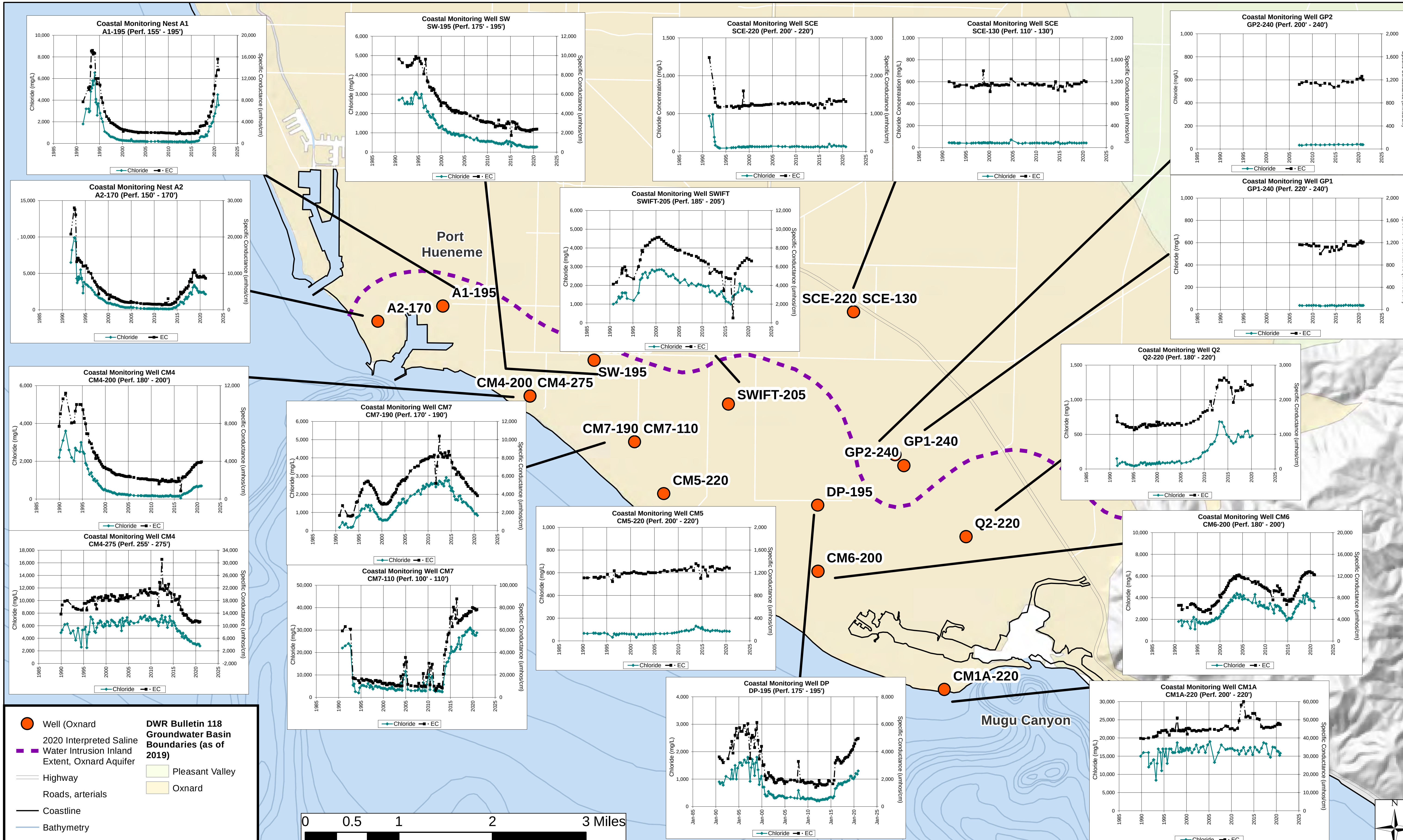

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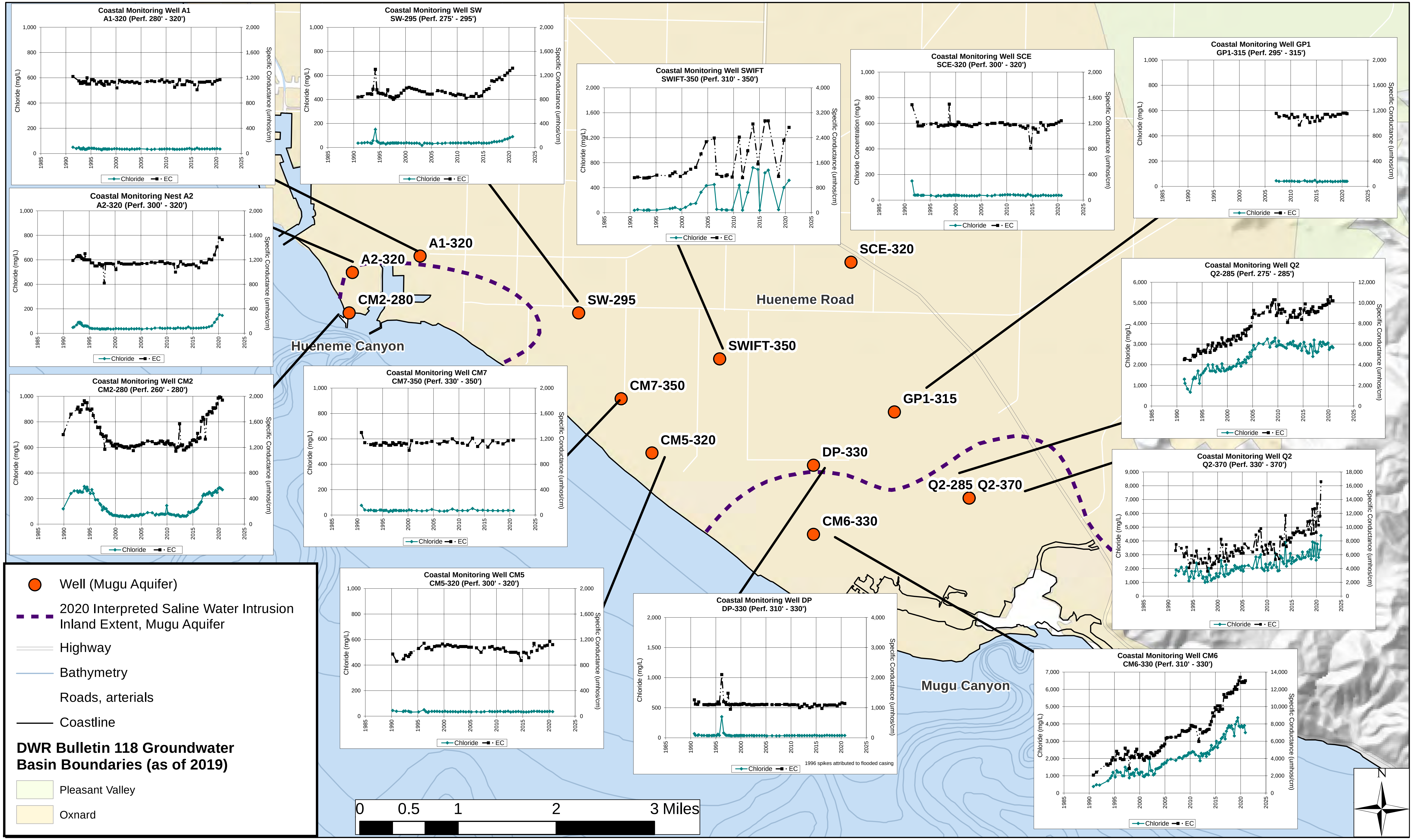

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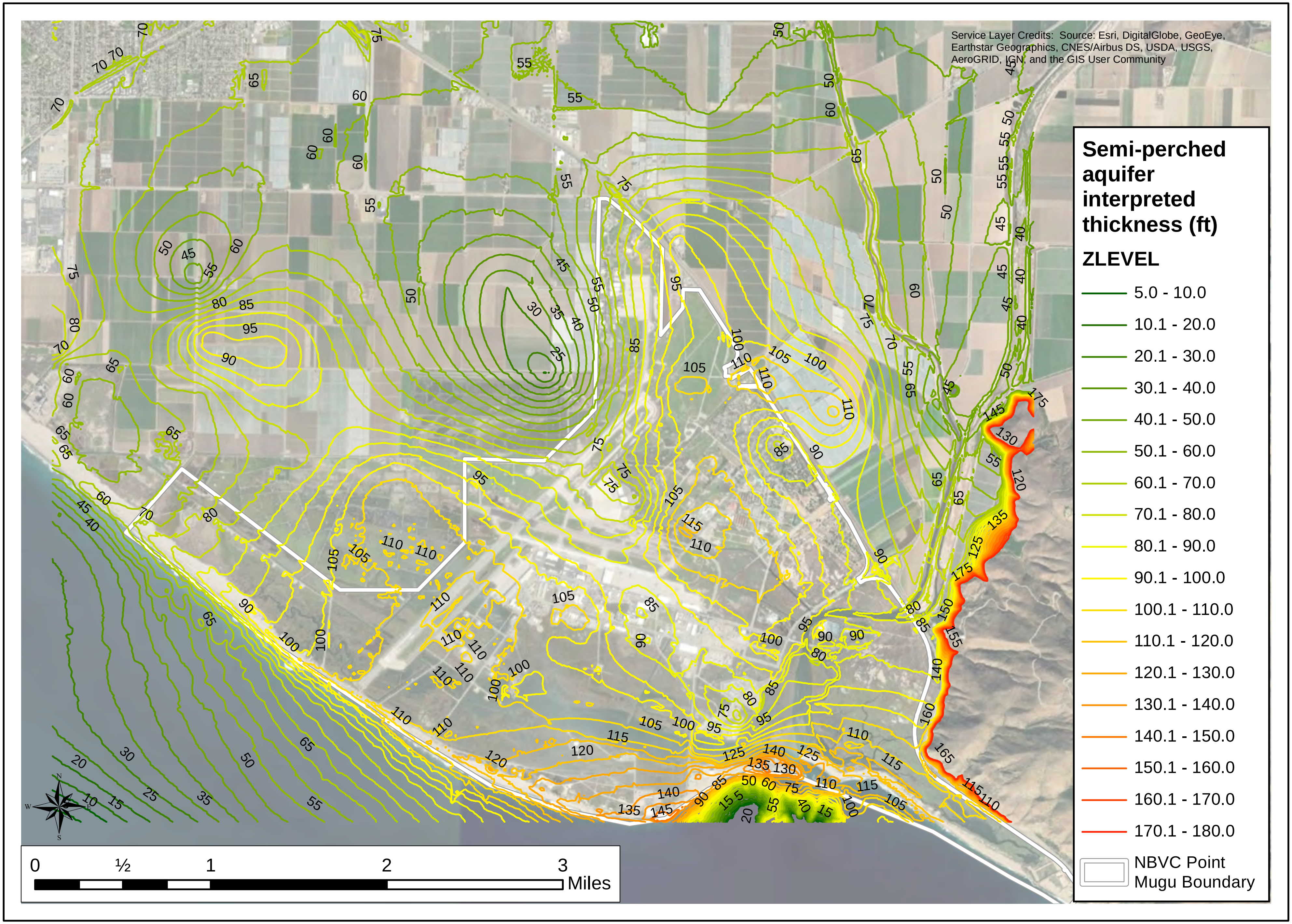

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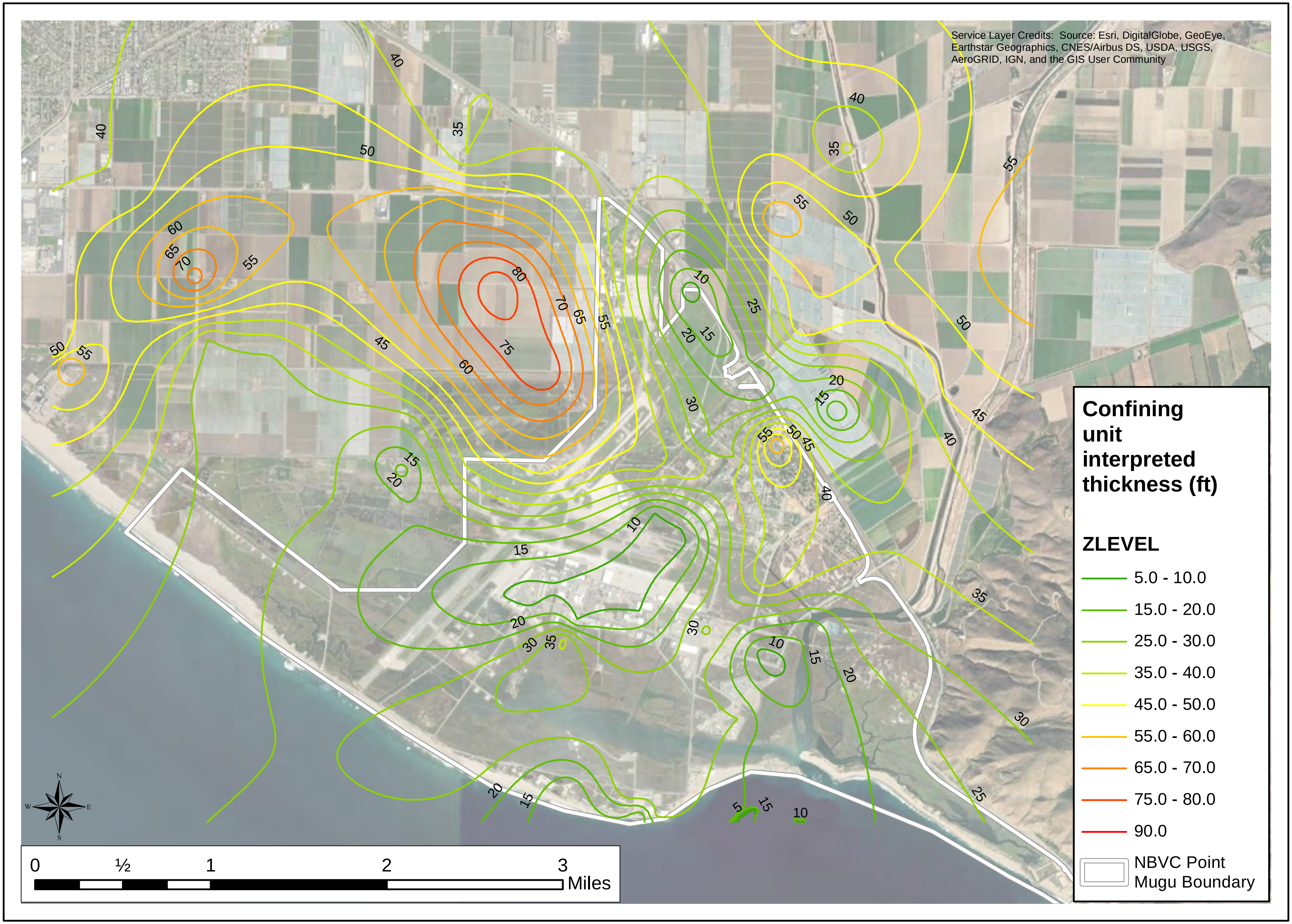

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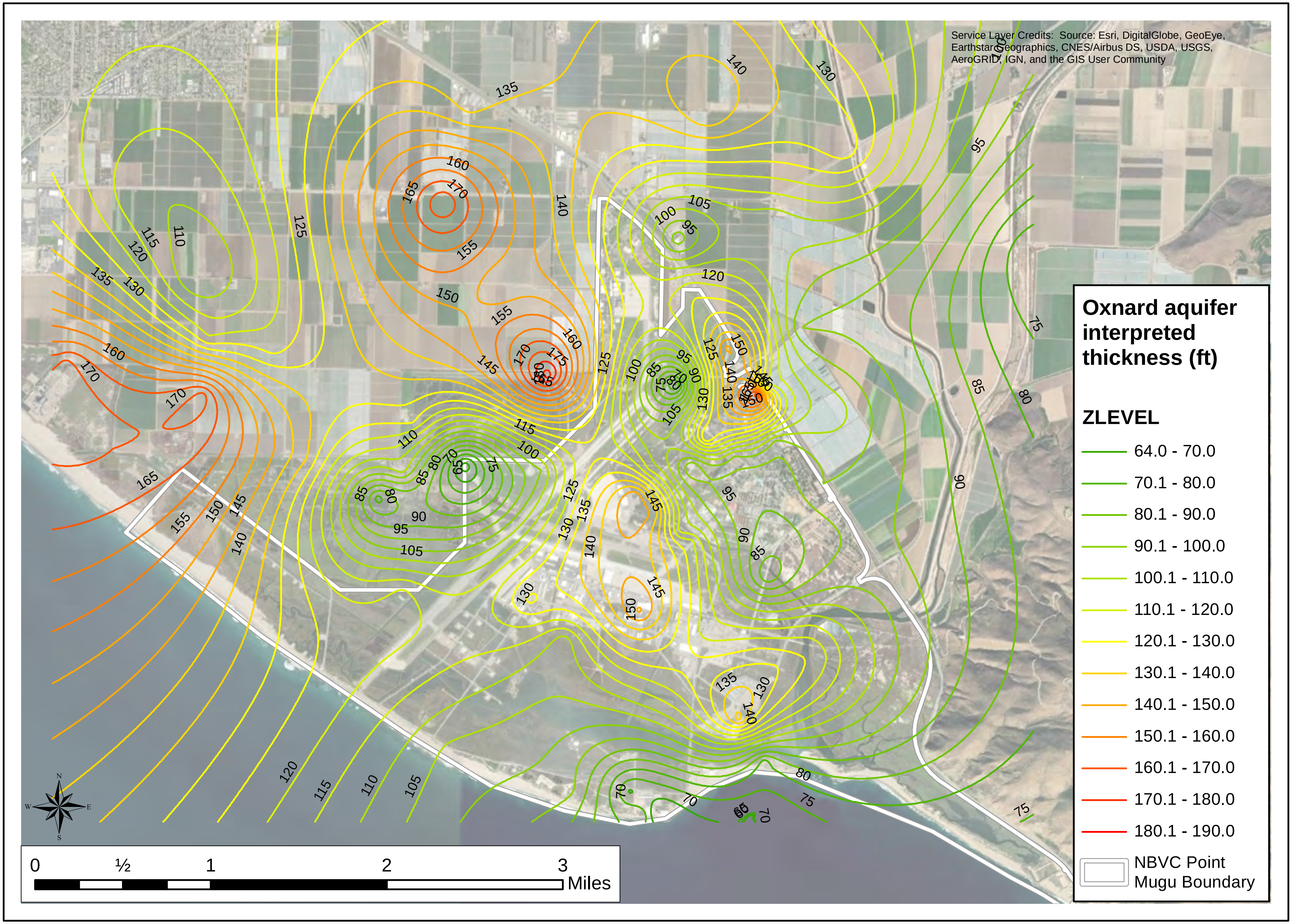

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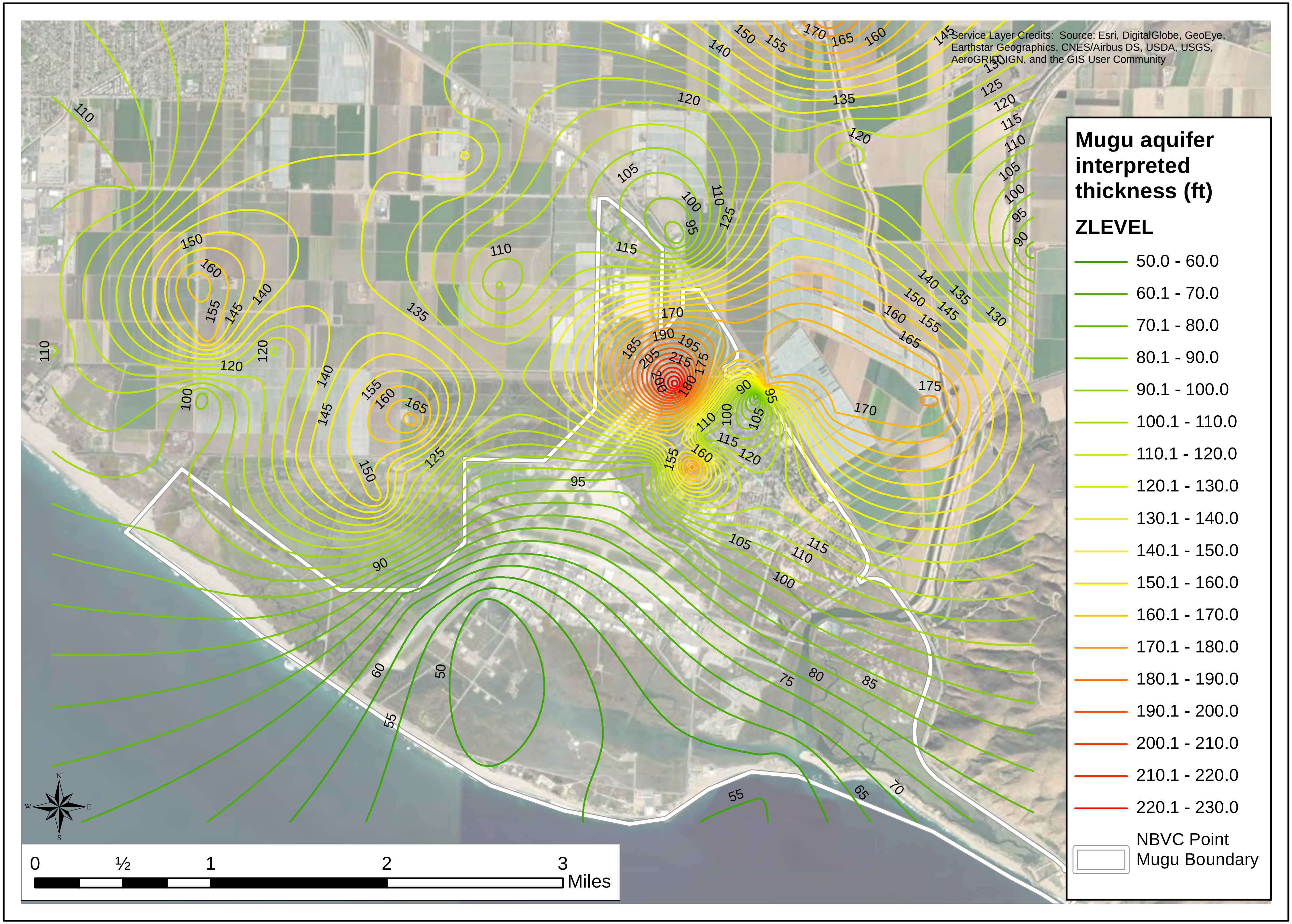

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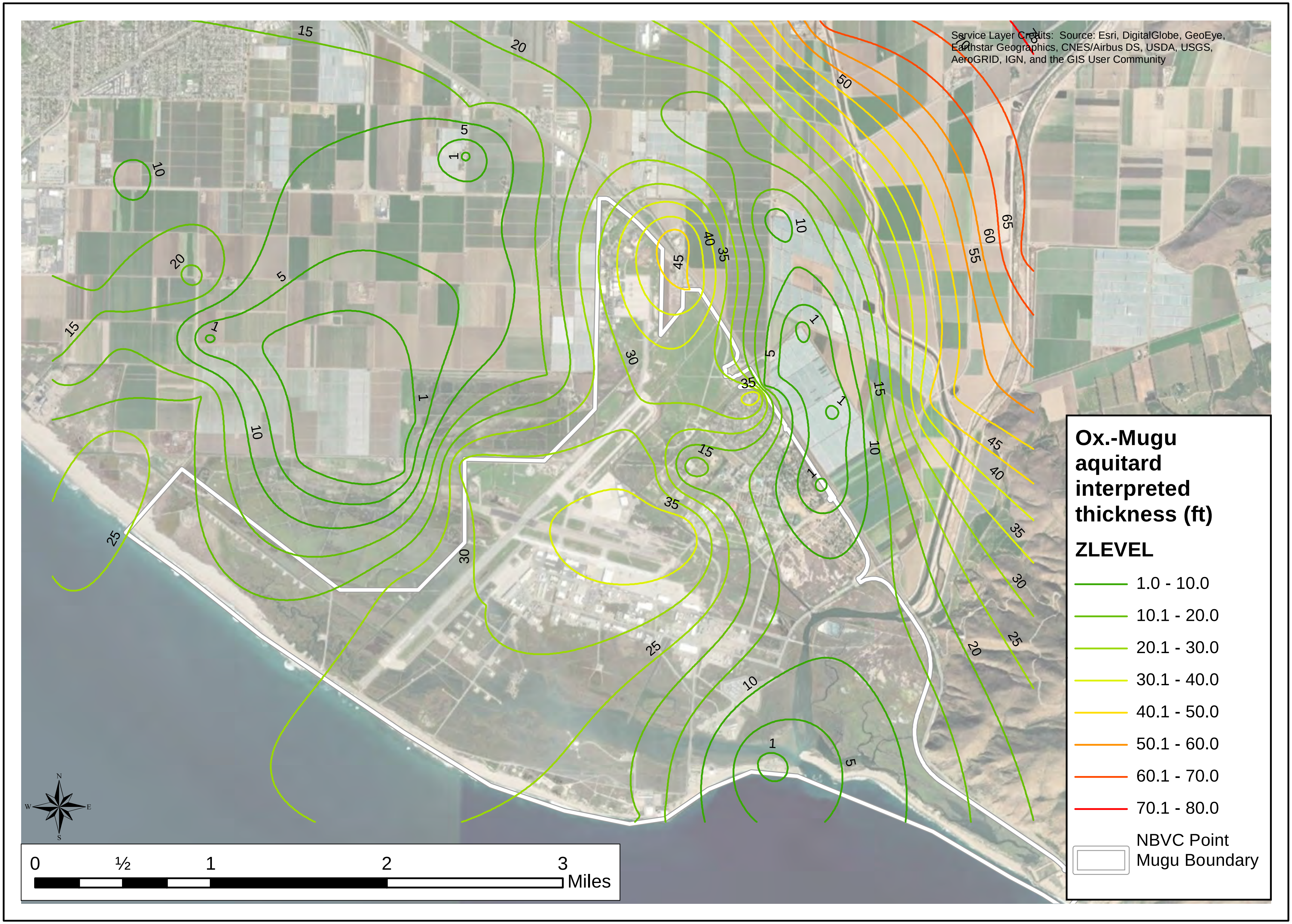
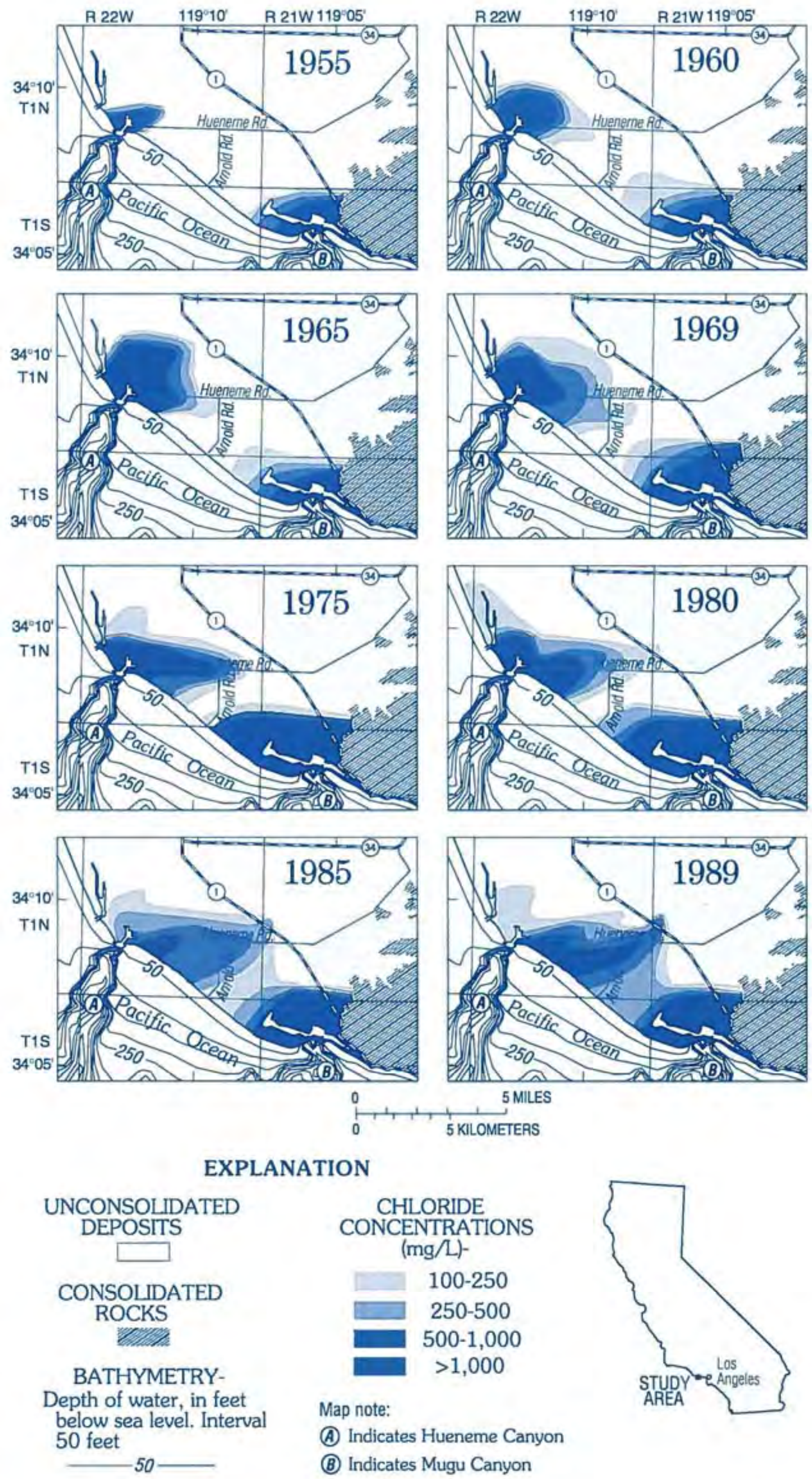


Figure 2-12. Oxnard – Mugu aquitard interpreted thickness.



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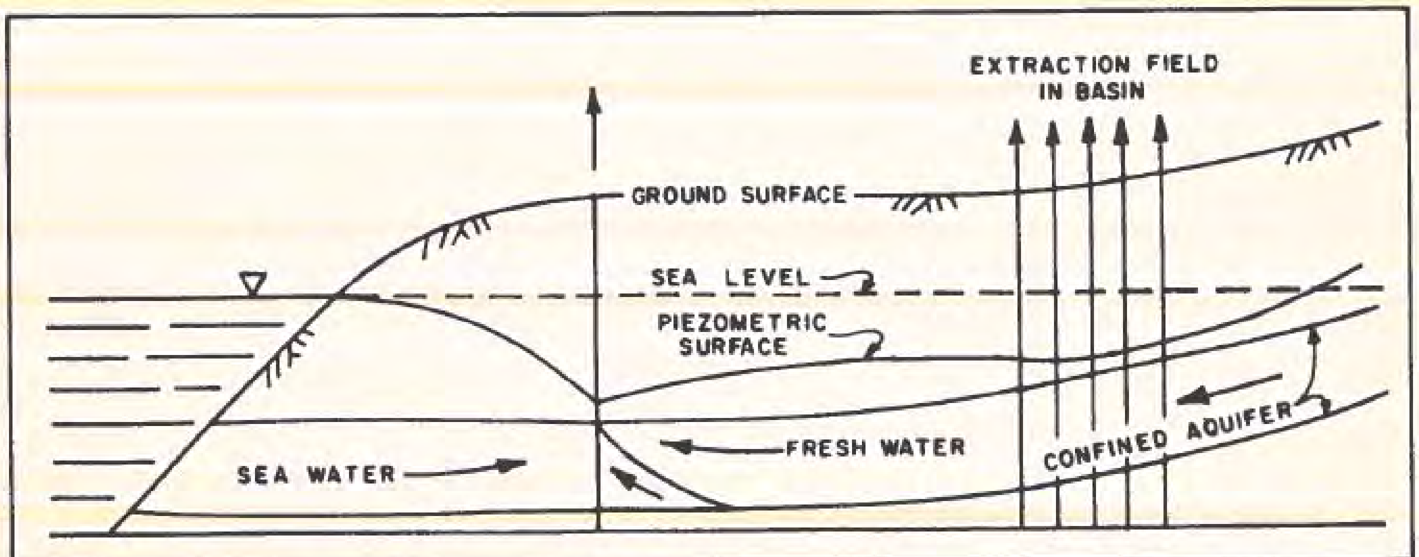


Figure 15 – HYDRAULIC CONDITIONS IN A CONFINED AQUIFER WITH AN EXTRACTION TYPE SEA–WATER INTRUSION BARRIER

Figure 3-1. Oxnard extraction barrier concept, section of hydraulic conditions in confined aquifer (figure from DWR, 1970).

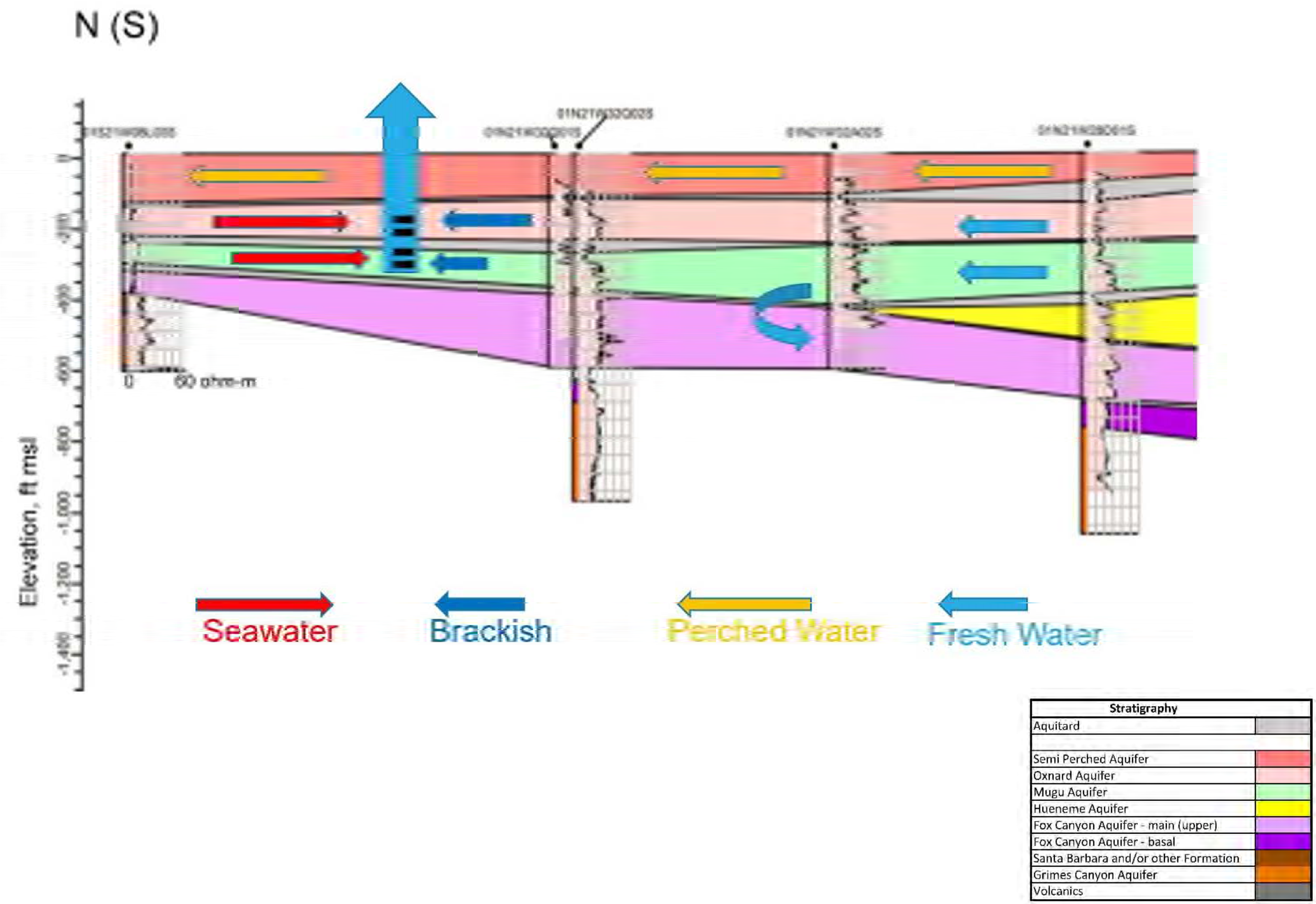


Figure 3-2. Conceptual groundwater flow diagram for the proposed extraction barrier project.

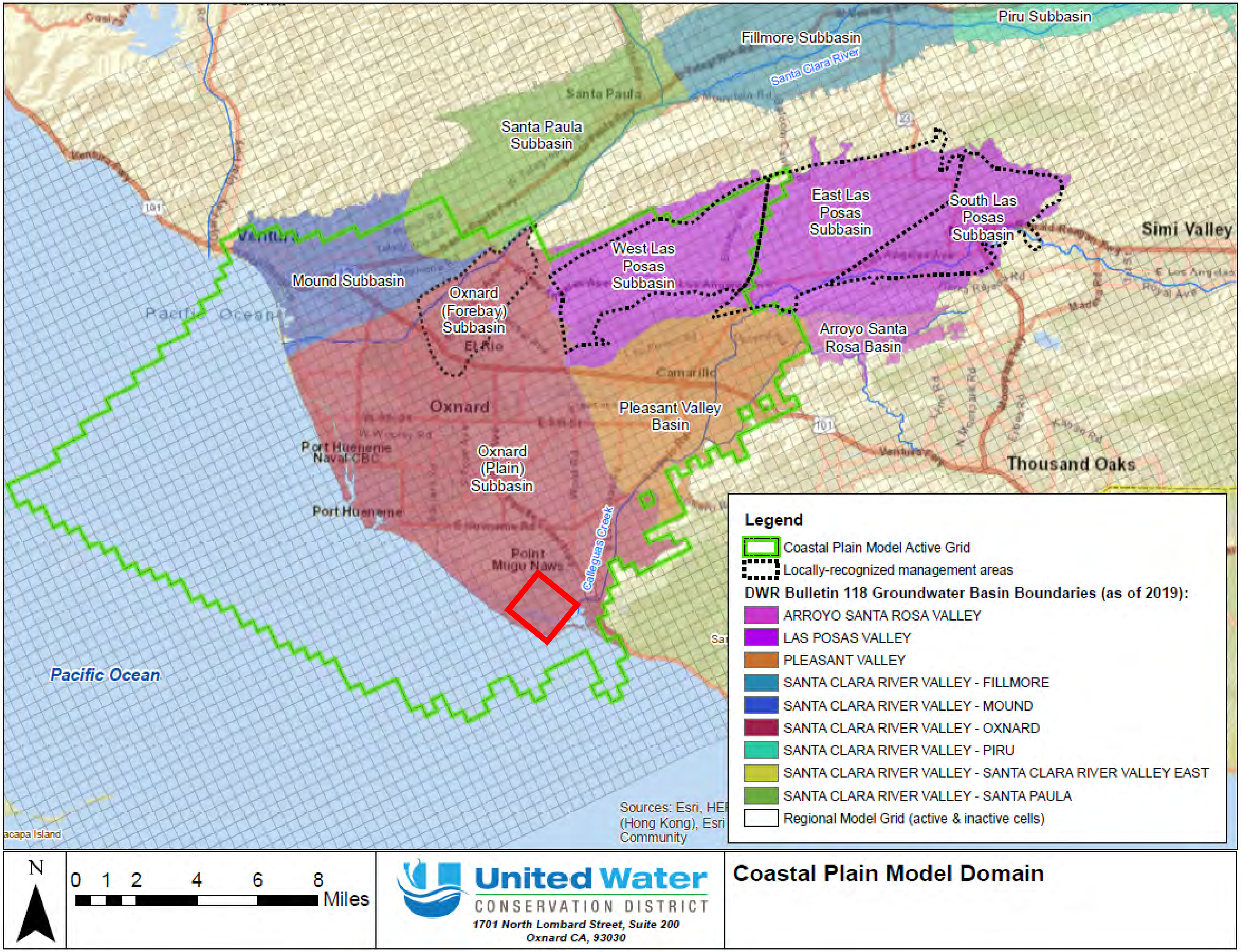
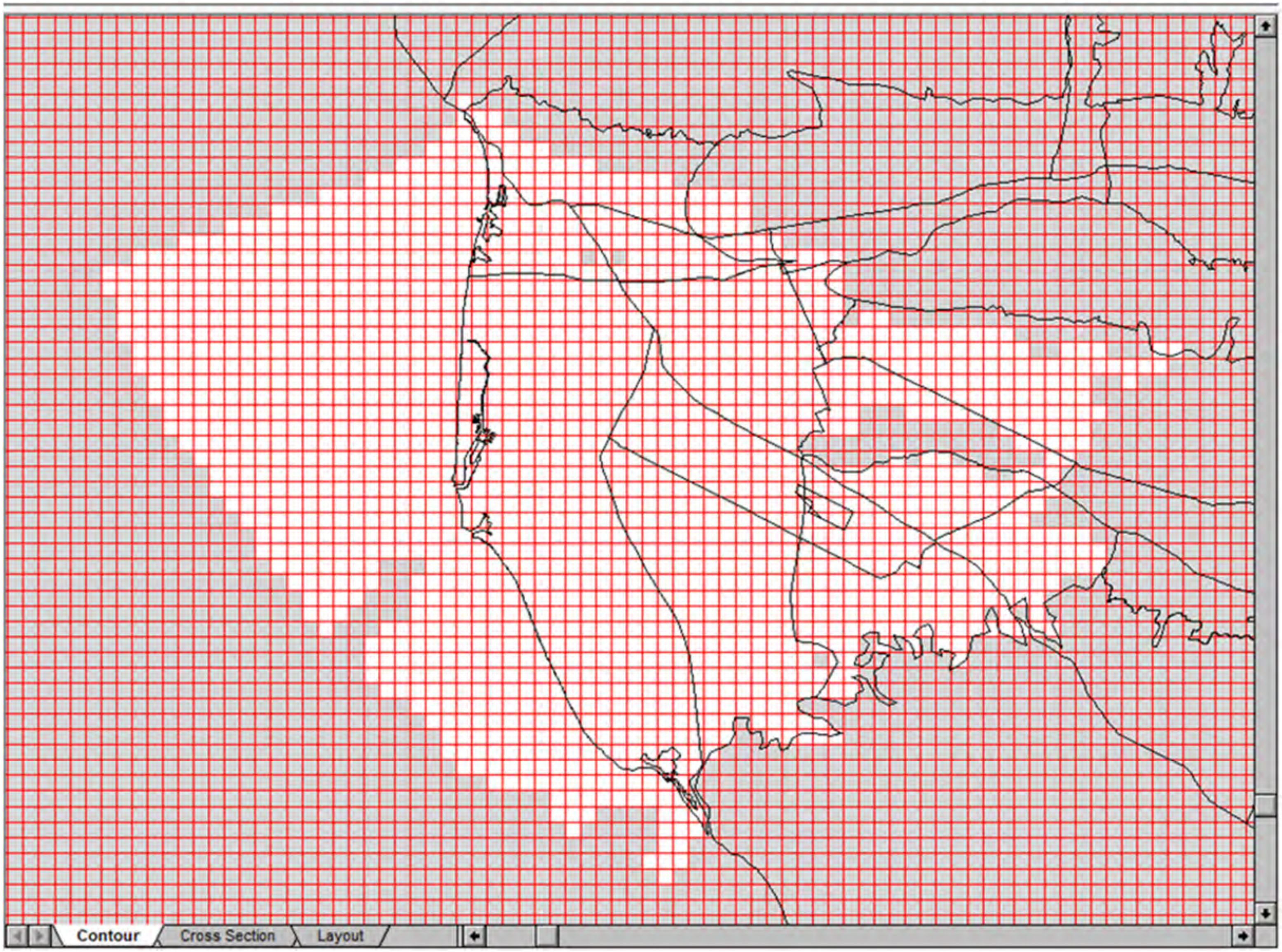


Figure 4-1. Coastal Plain Model domain, with extraction barrier Project location outlined in red.



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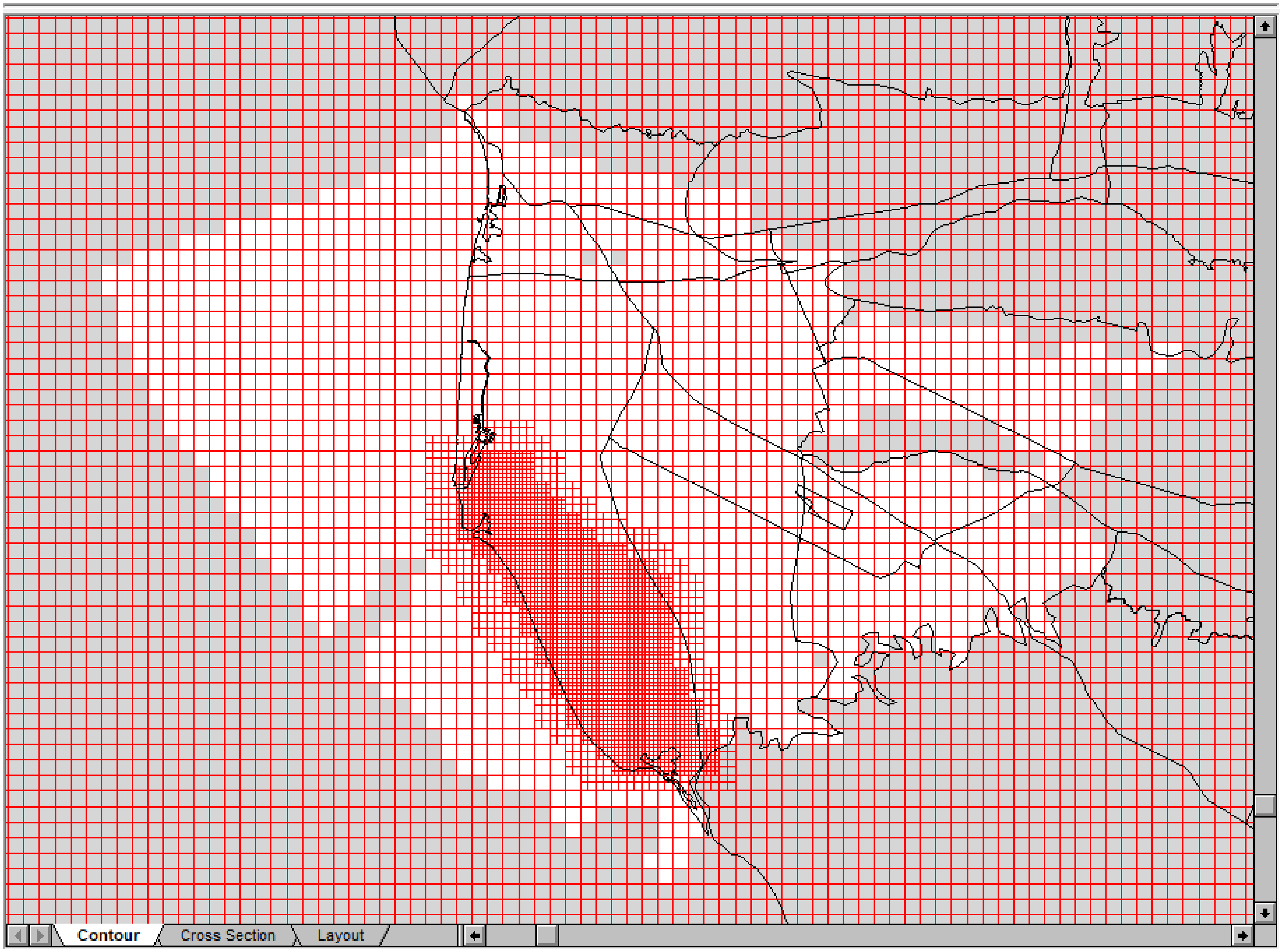

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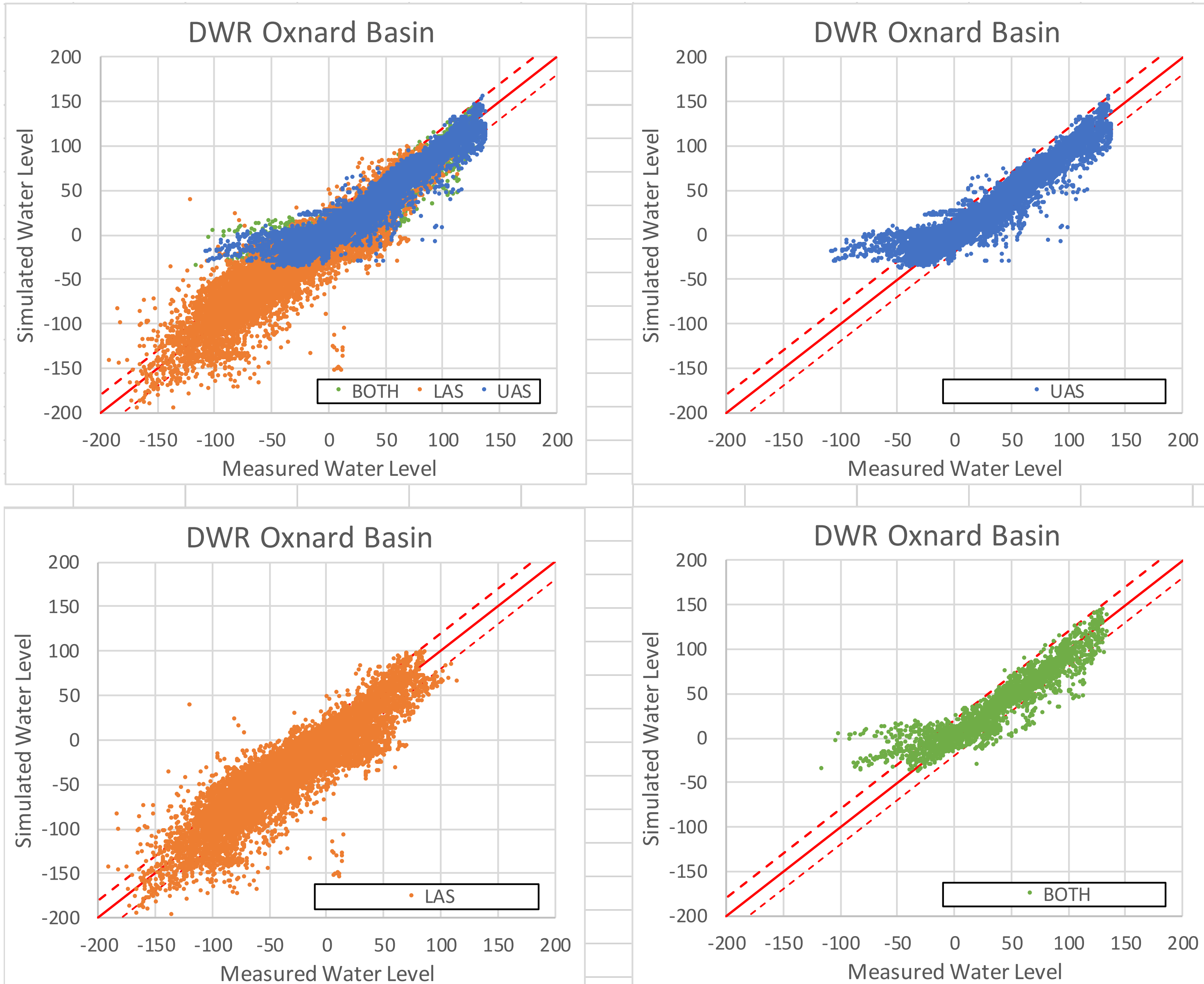

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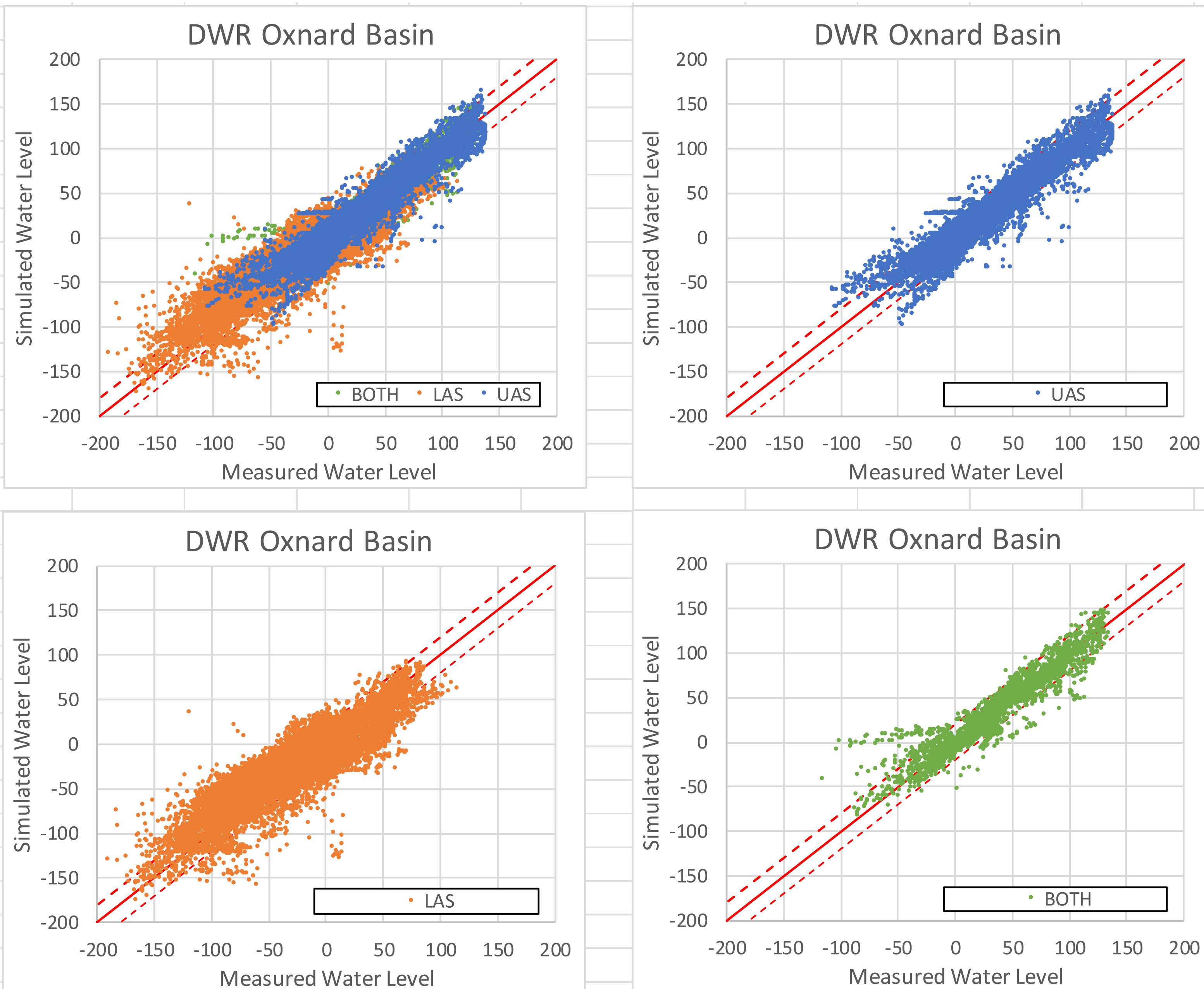

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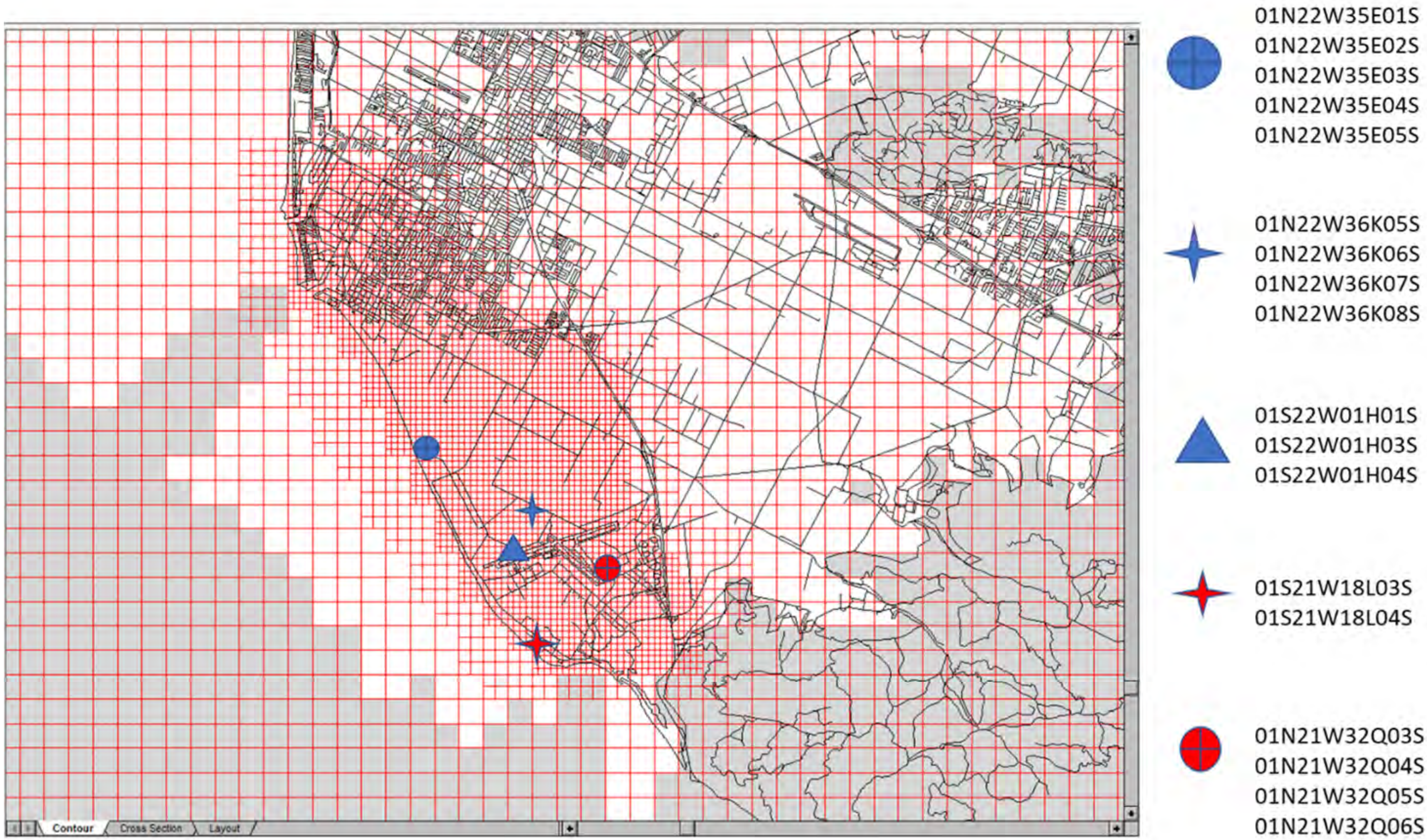

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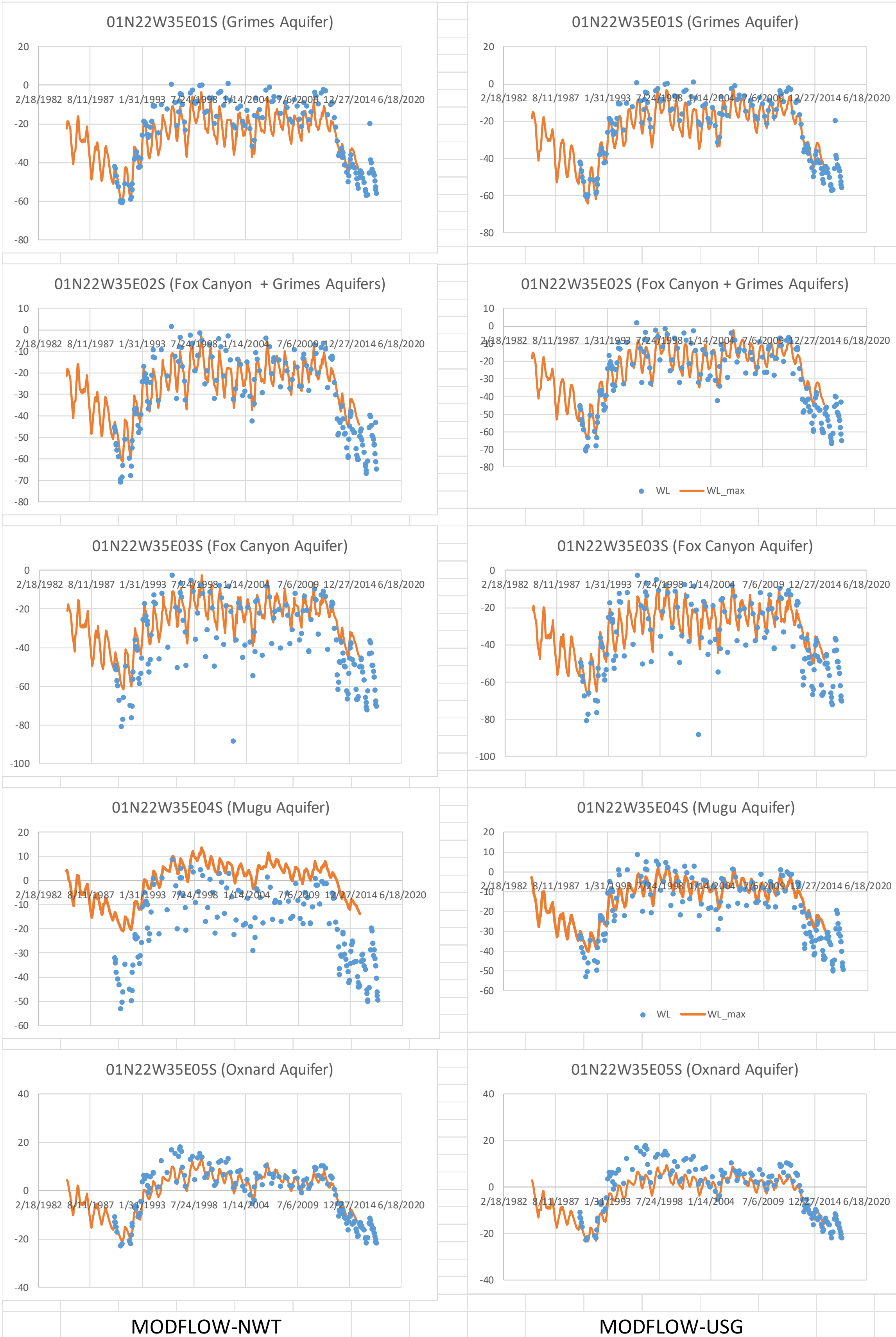

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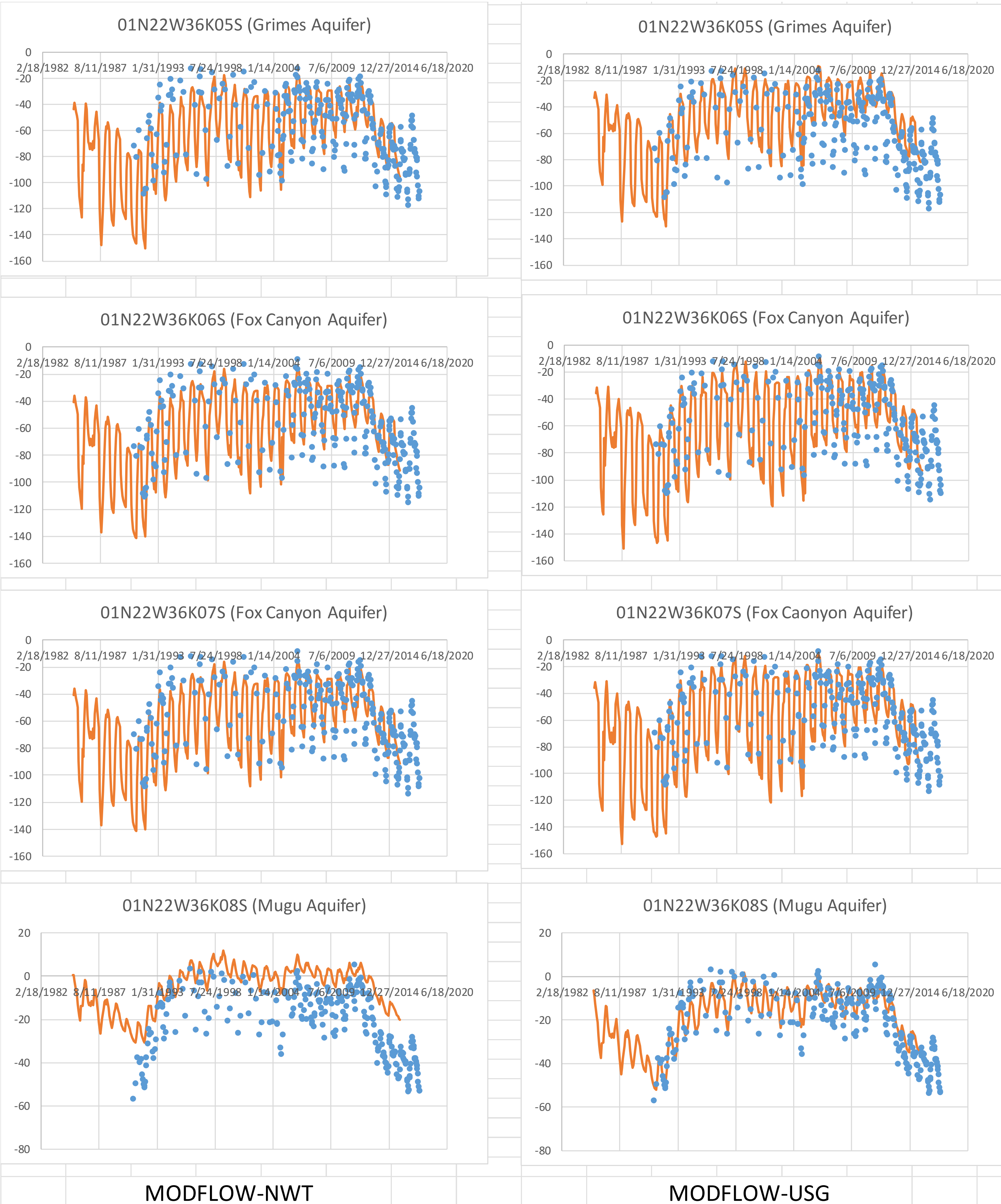

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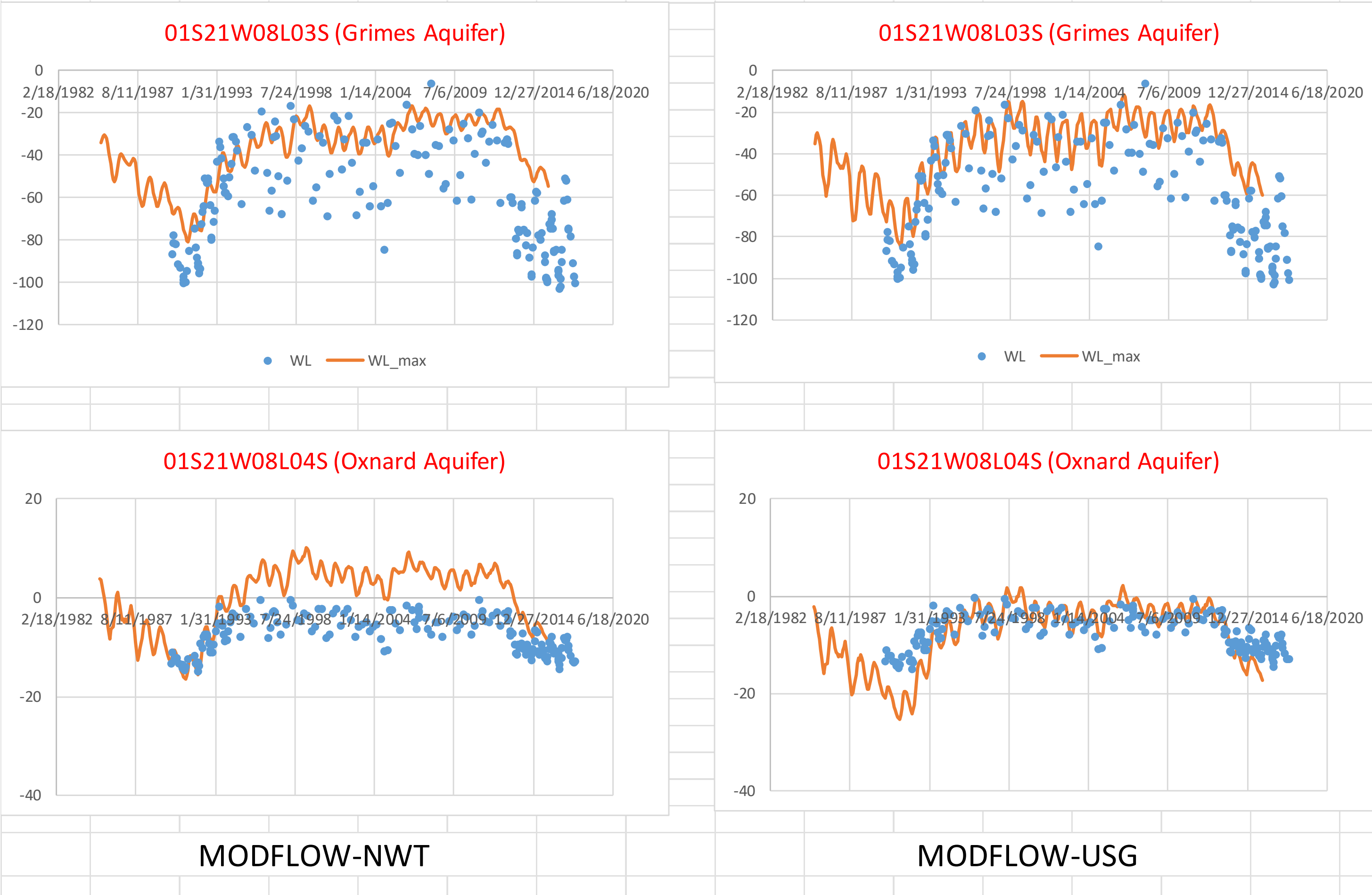

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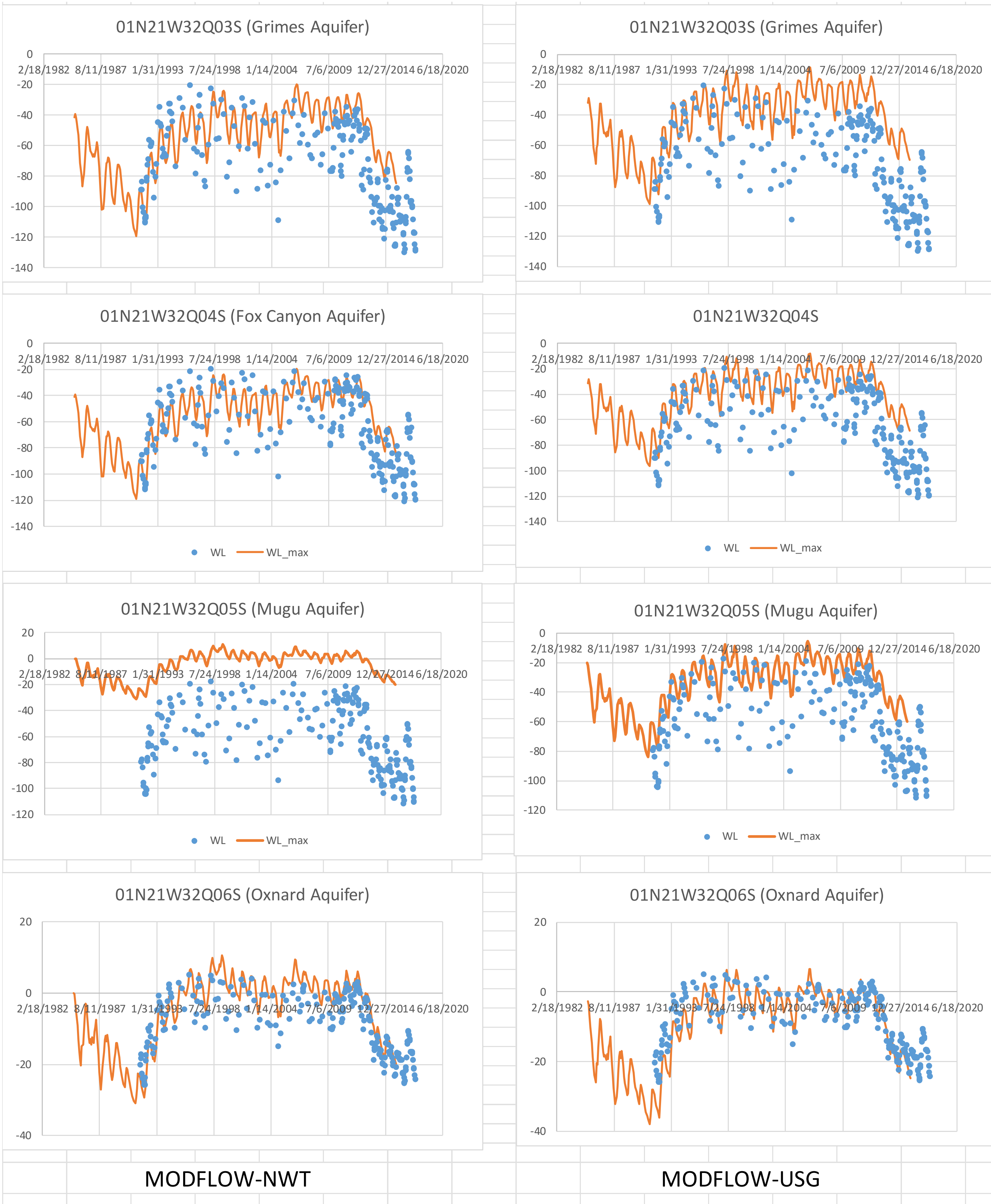

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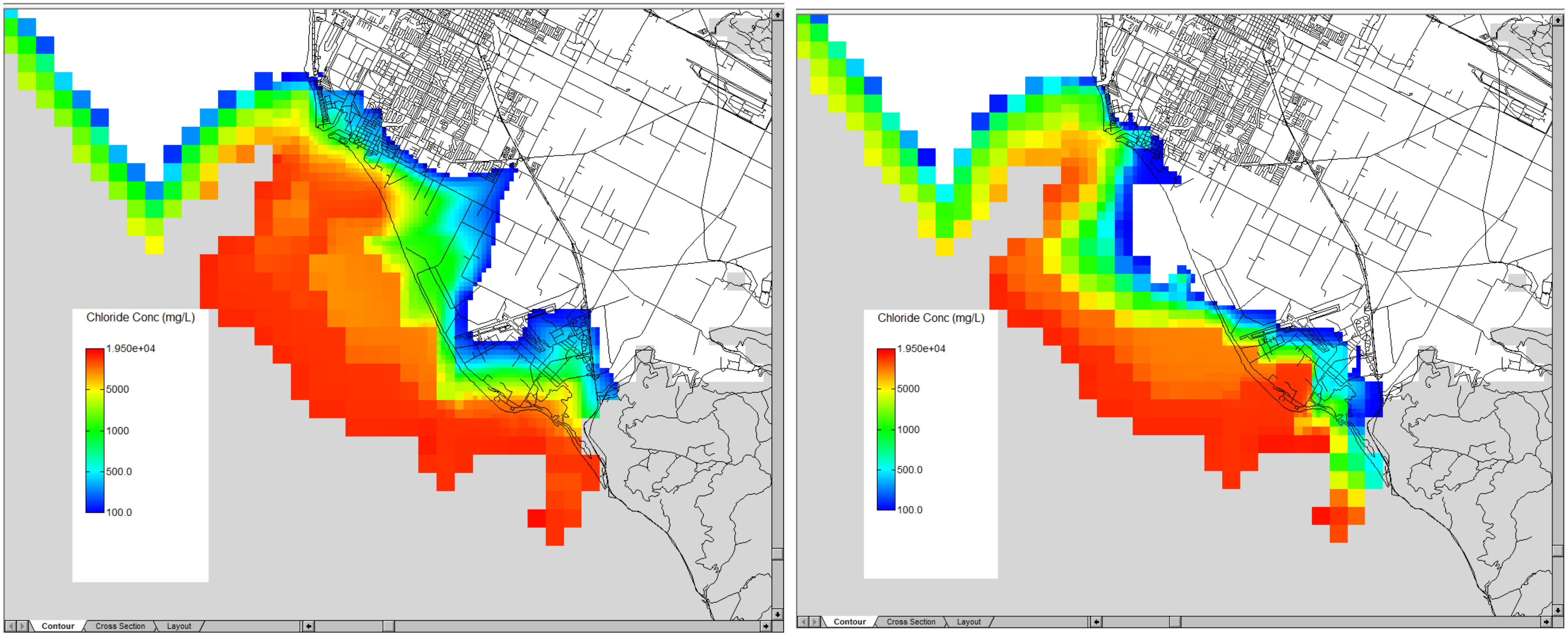


A. Initial chloride concentrations in the Oxnard aquifer.

B. Initial chloride concentrations in the Mugu aquifer.

Figure 4-12. Simulated initial (1985) chloride concentrations in the Oxnard and Mugu aquifers.

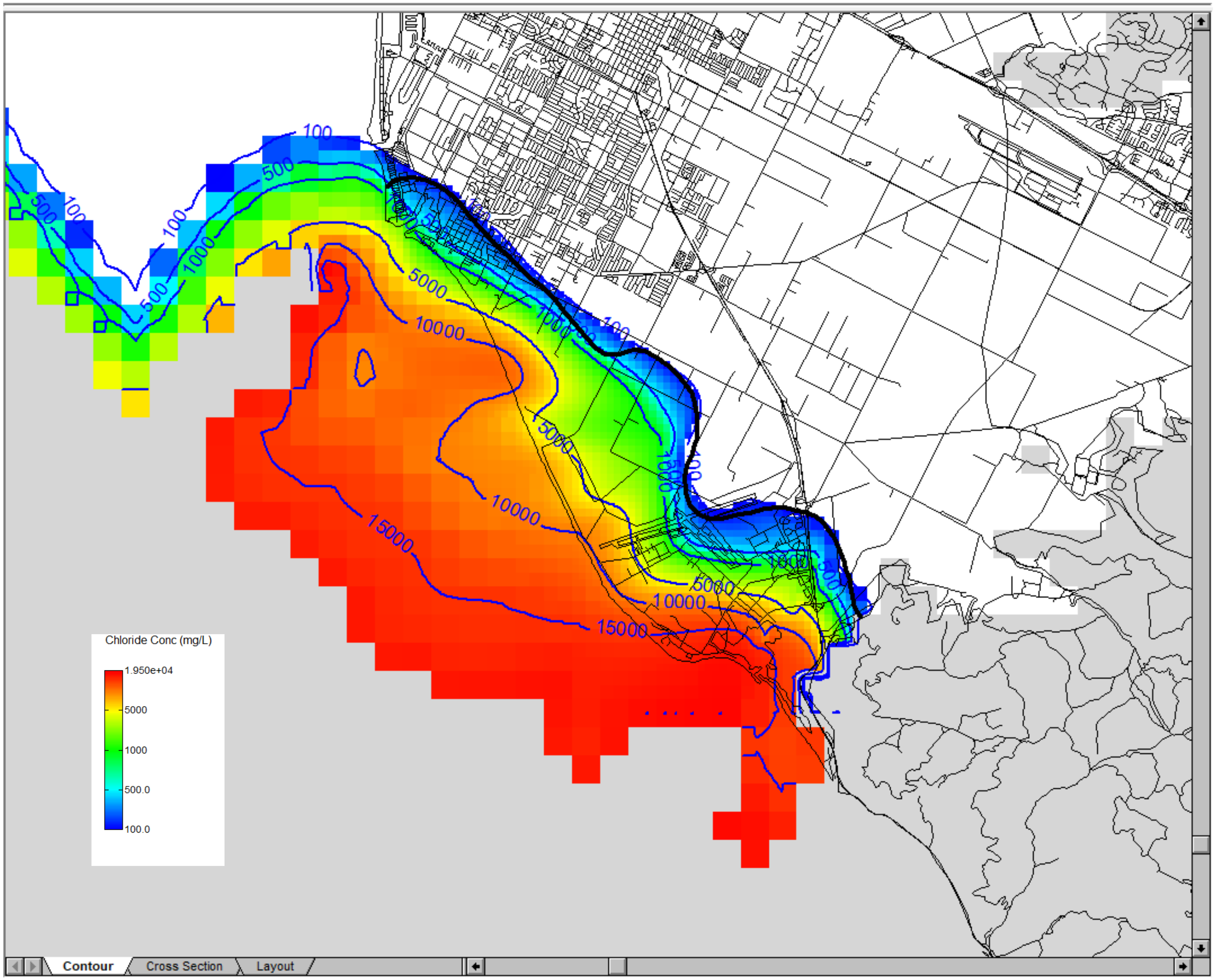


Figure 4-13. Simulated chloride concentrations in the Oxnard aquifer at the end of 2015, and the 2015 interpreted inland extent of brackish water (in thick black line).

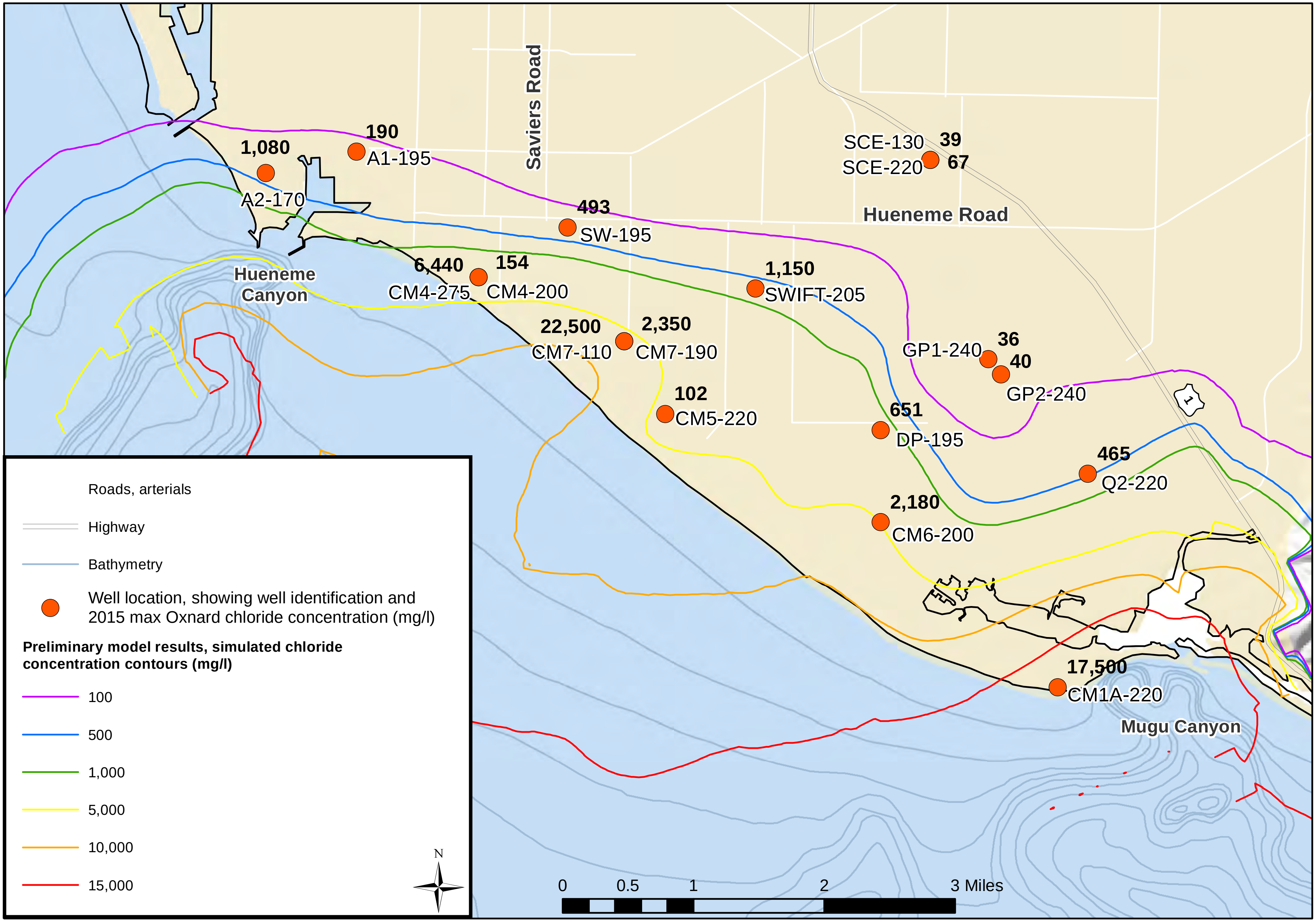


Figure 4-14. Simulated chloride concentration in the Oxnard aquifer at the end of 2015, and measured chloride concentrations from 2015.

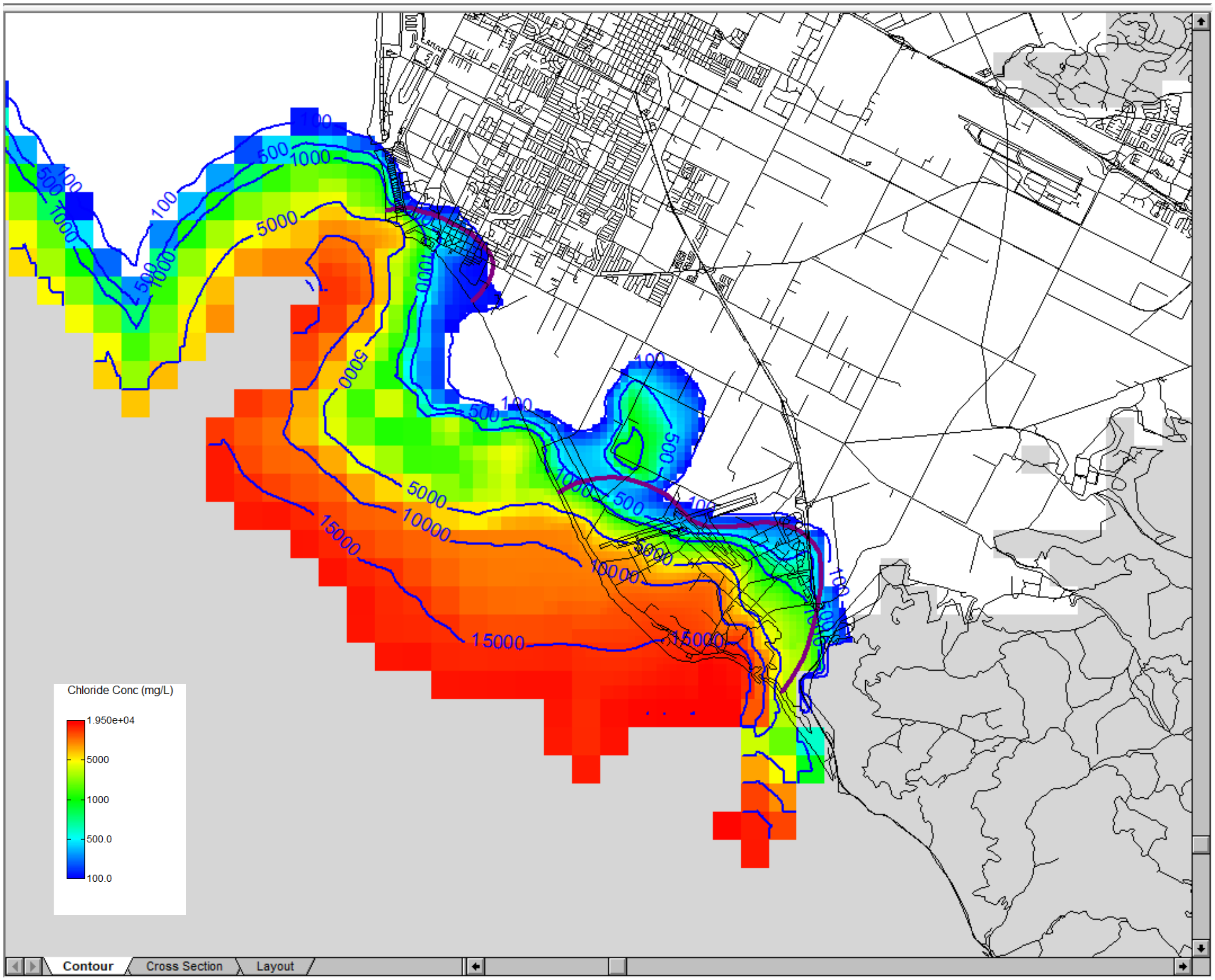


Figure 4-15. The simulated chloride concentration in Mugu aquifer at the end of 2015, and the 2015 interpreted inland extent of brackish water (in pink line).

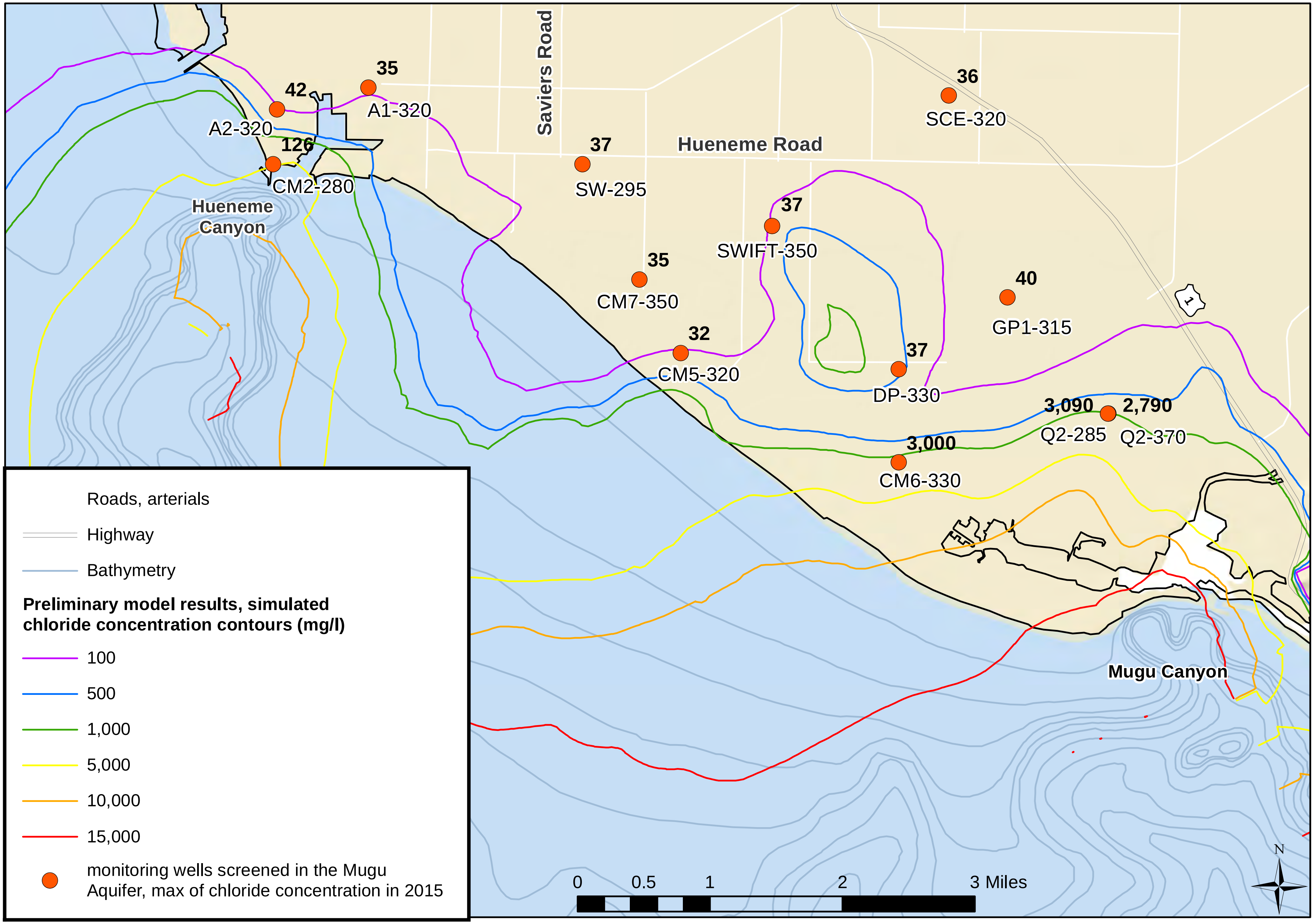


Figure 4-16. Simulated chloride concentrations in the Mugu aquifer at the end of 2015, and measured chloride concentrations from 2015.

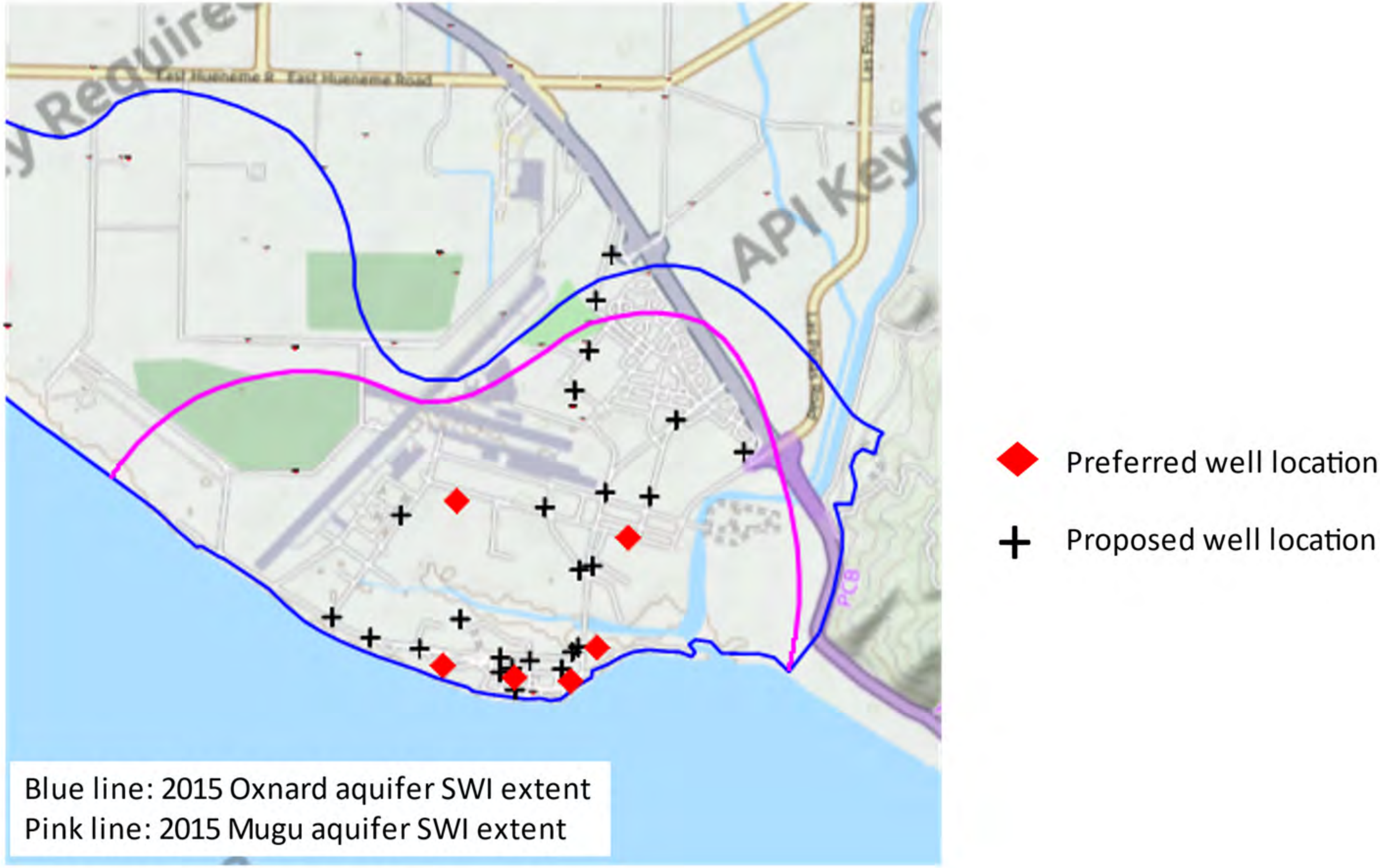


Figure 5-1. Proposed well locations for extraction barriers.

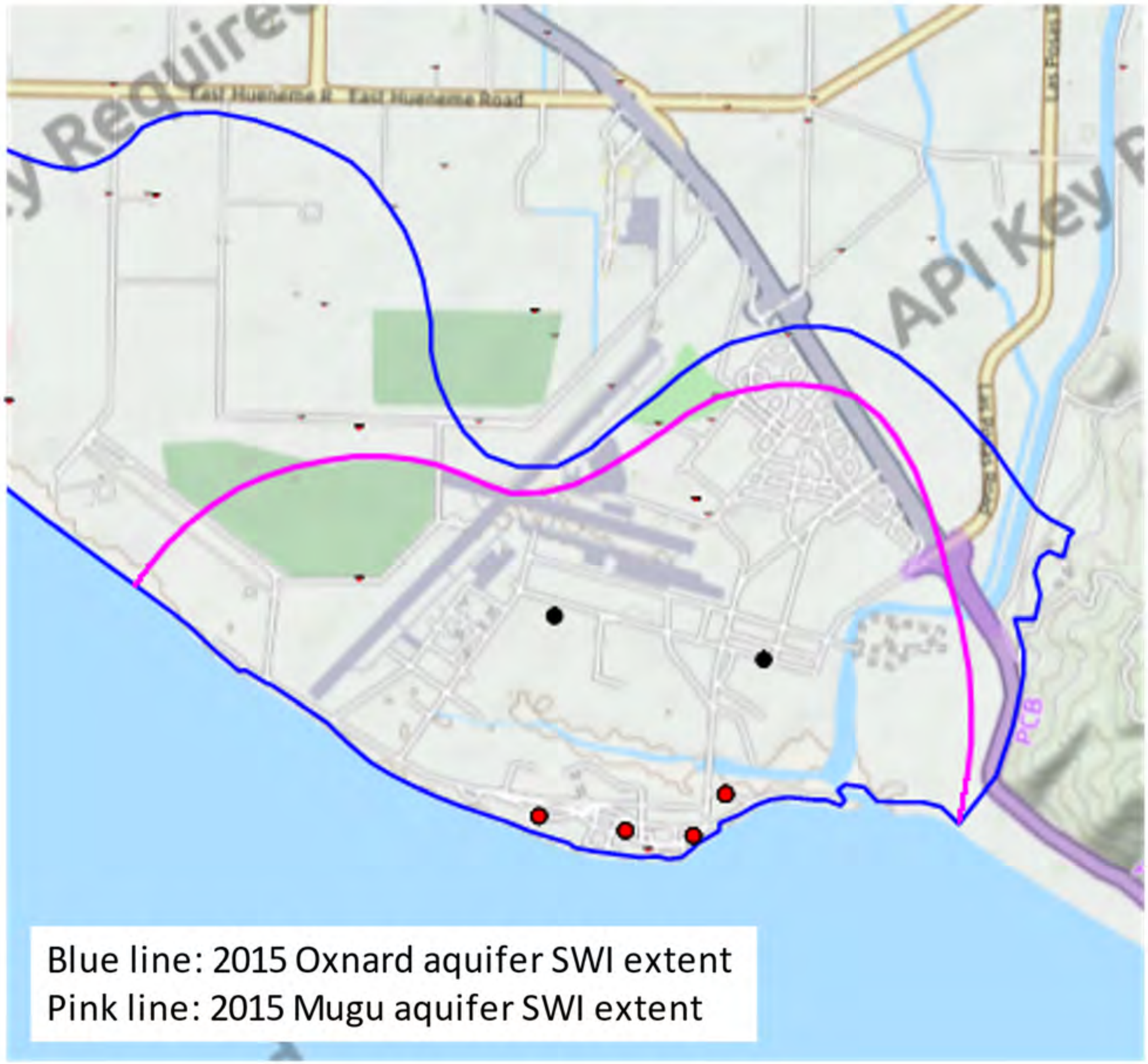


Figure 5-2. Proposed well locations for total extraction rate at 5,000 AFY (scenarios 5K W and 5K T).

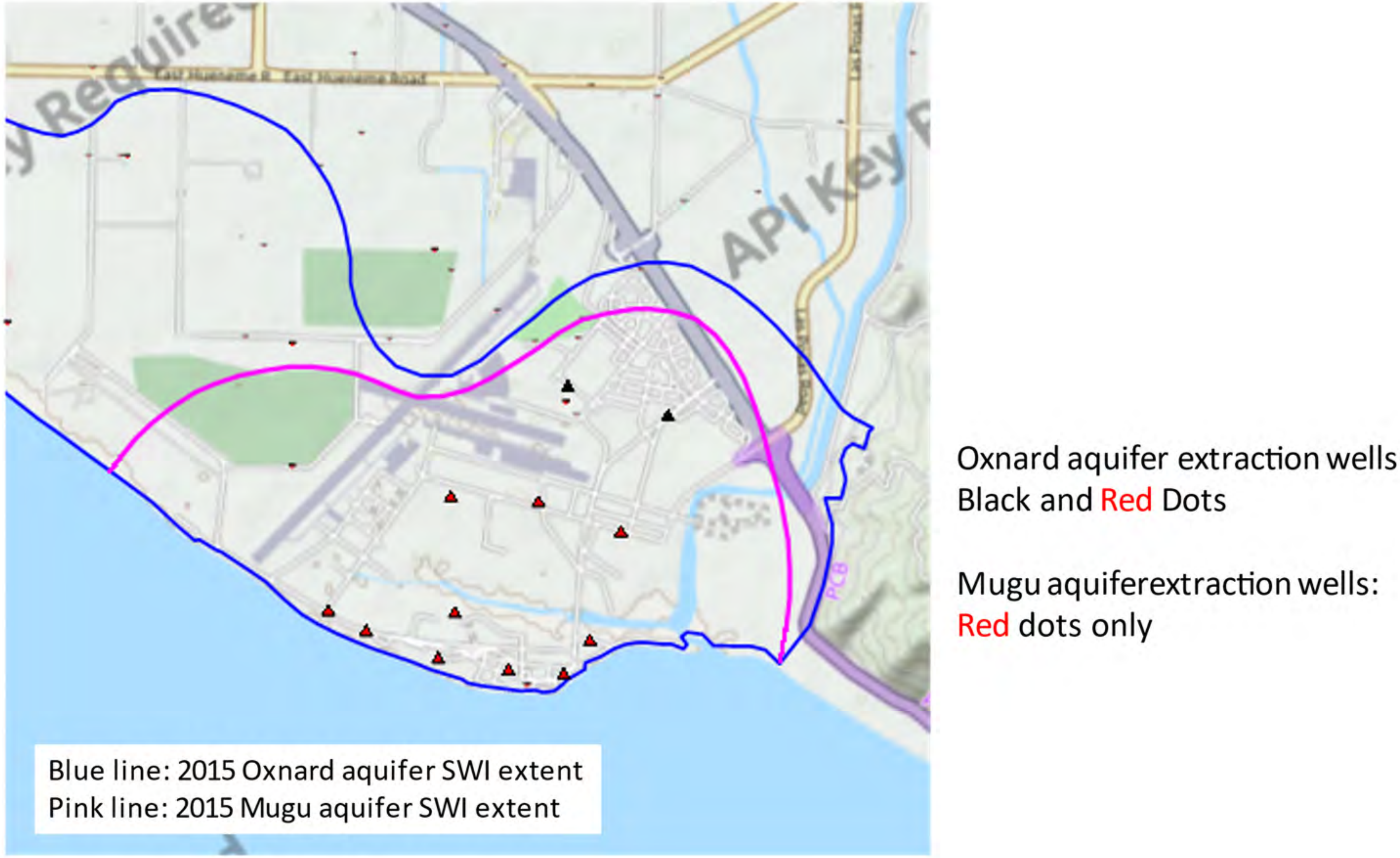


Figure 5-3. The proposed well locations for total extraction rate at 10,000 AFY (scenario 10K).

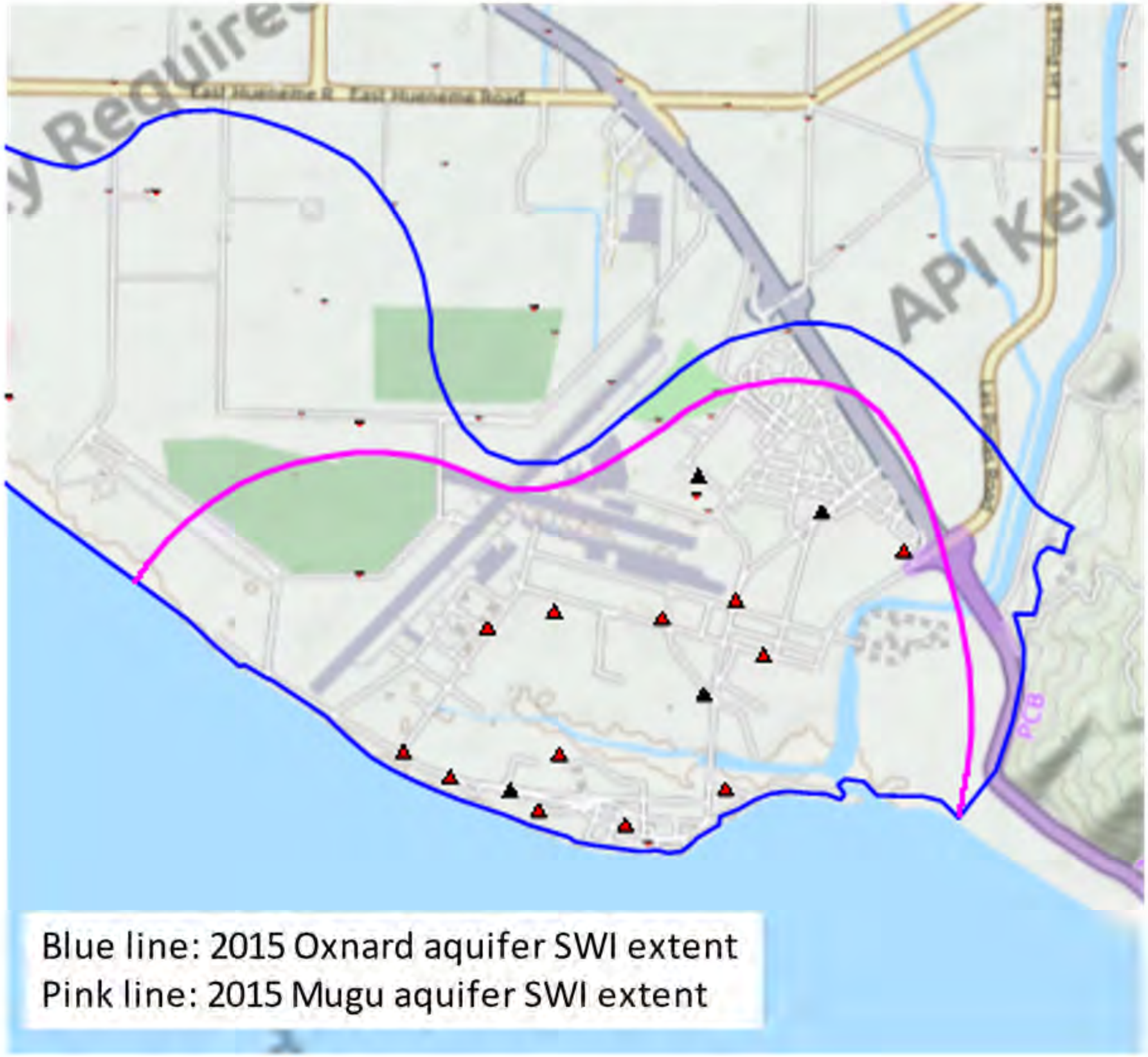
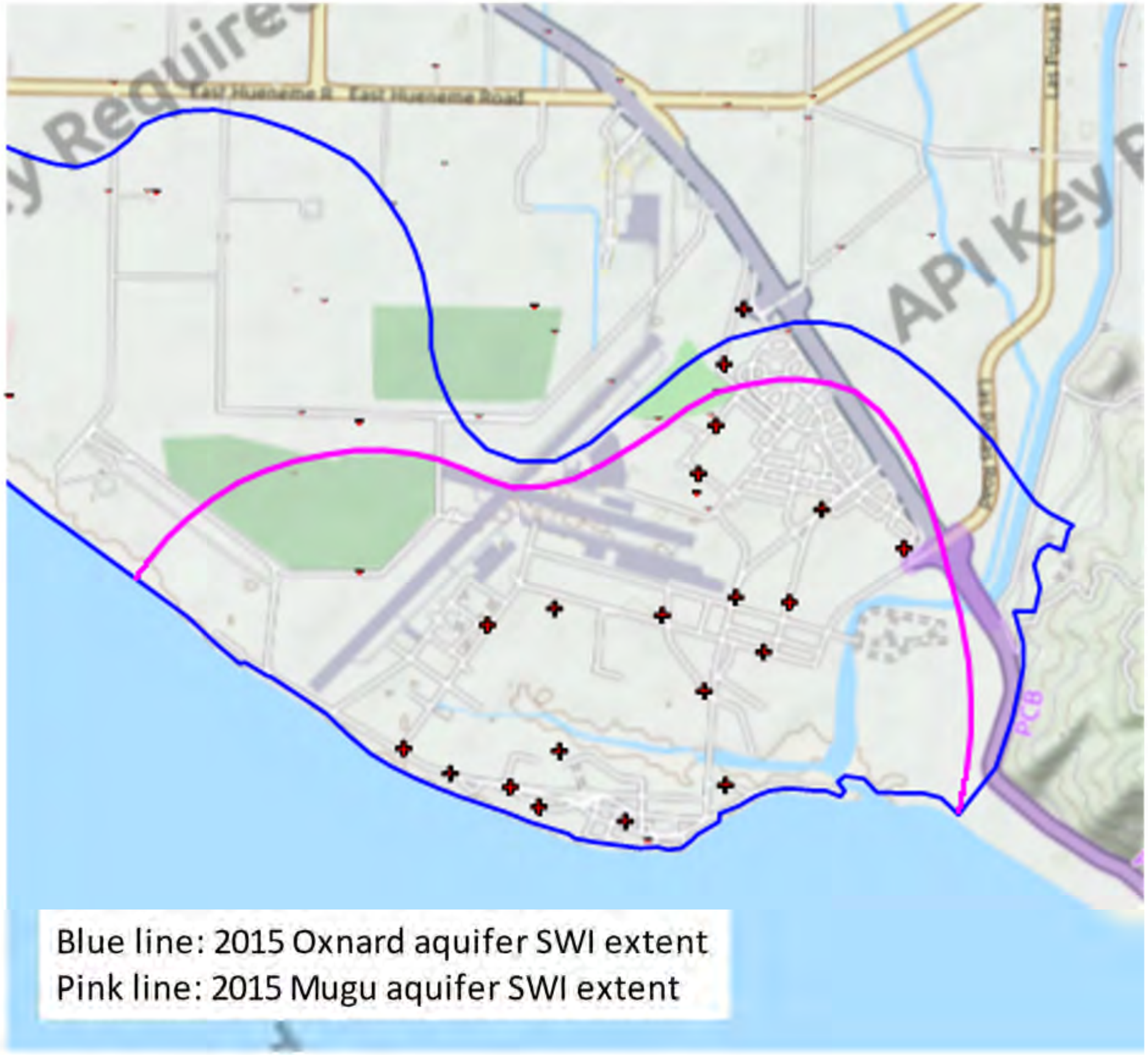


Figure 5-4. The proposed well locations for total extraction rate at 15,000 AFY (scenario 15K).



The extraction wells in Oxnard and Mugu aquifers share the same well locations shown in red cross symbol

Figure 5-5. The proposed well locations for total extraction rate at 20,000 AFY (scenario 20K).

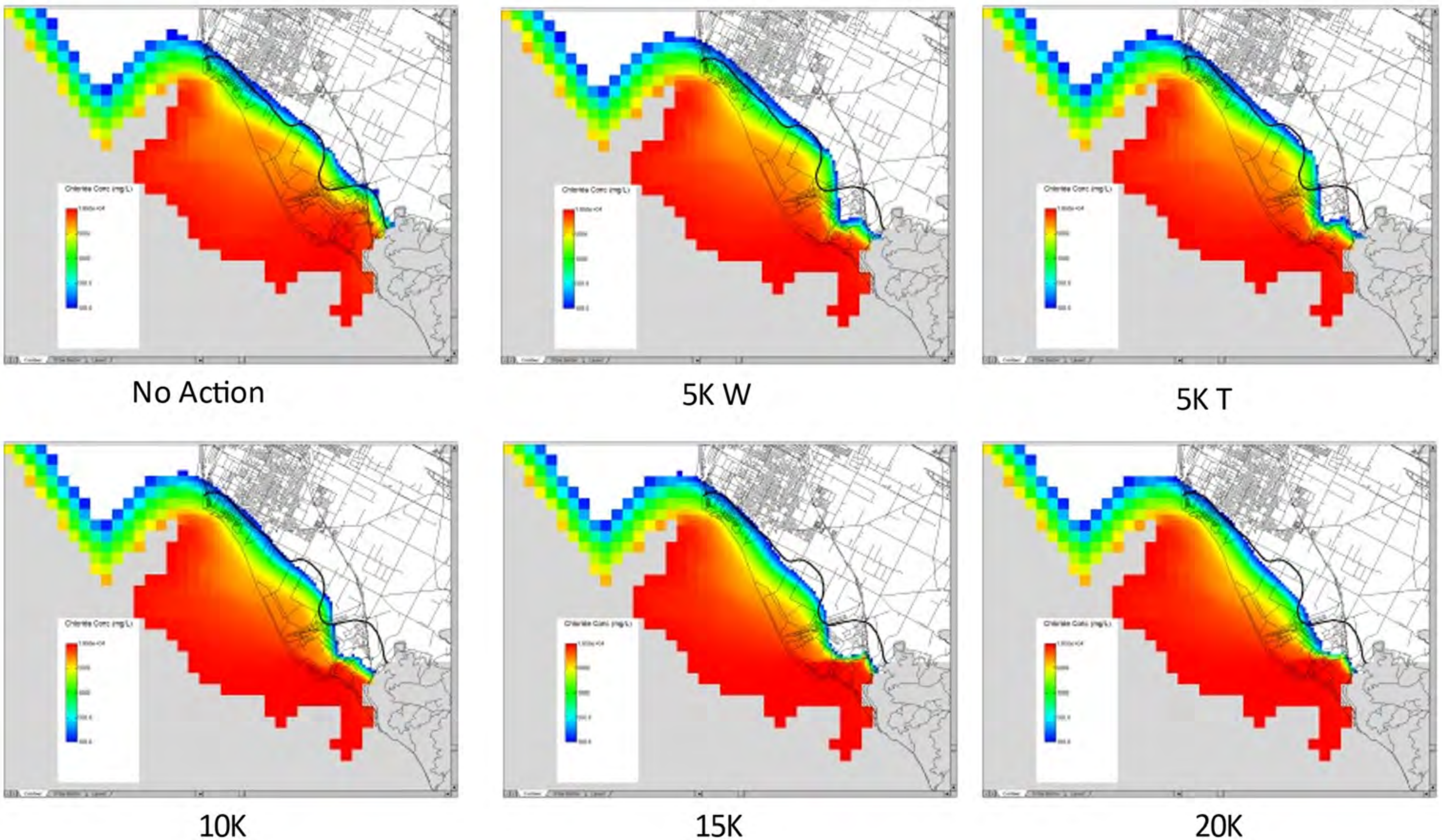


Figure 6-1. Simulated chloride concentration in the Oxnard aquifer after 50 years of Project operation, all Project scenarios including No Action (no extraction barriers).

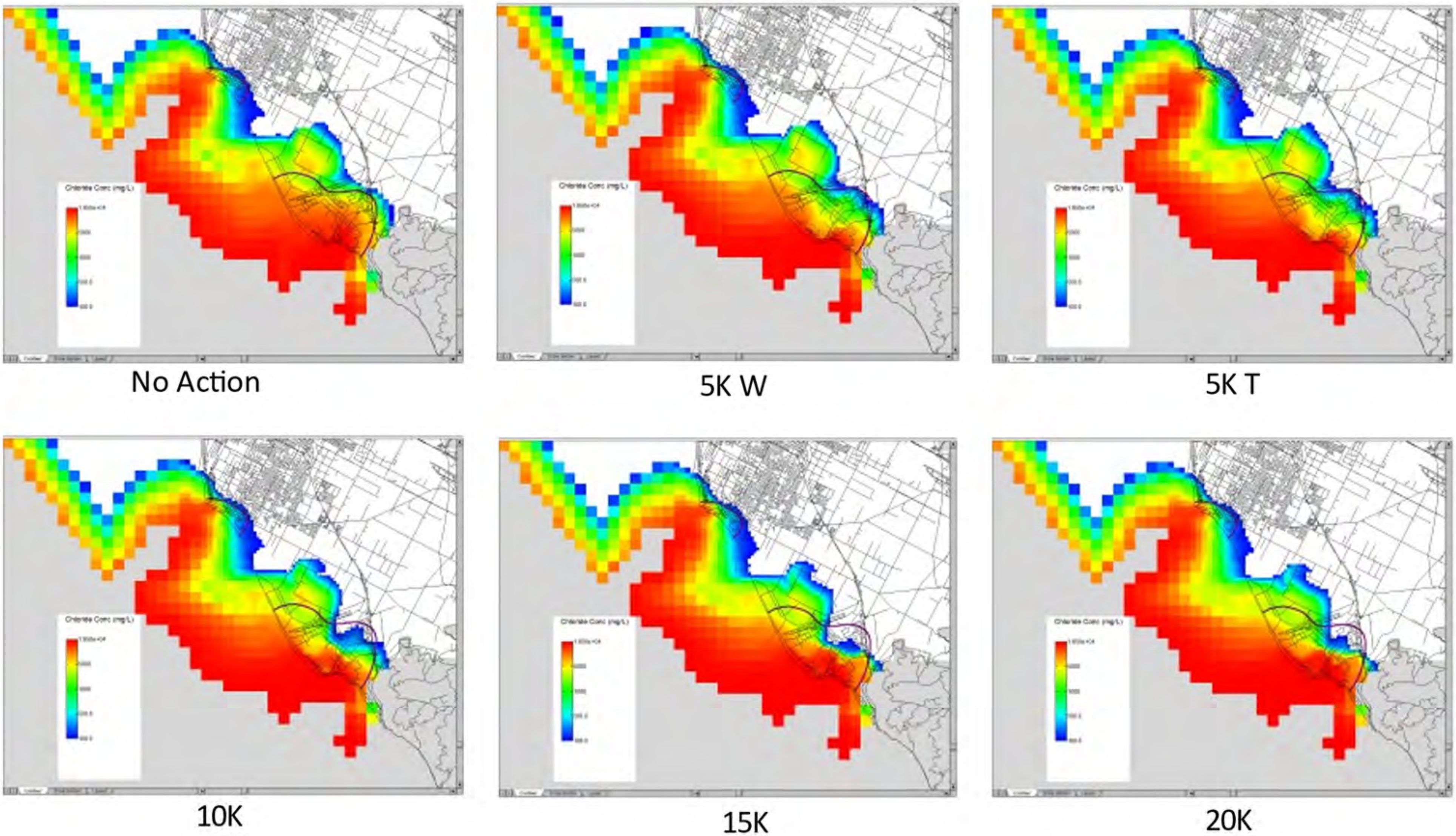


Figure 6-2. Simulated chloride concentration in the Mugu aquifer after 50 years of Project operation, all Project scenarios including No Action (no extraction barriers).

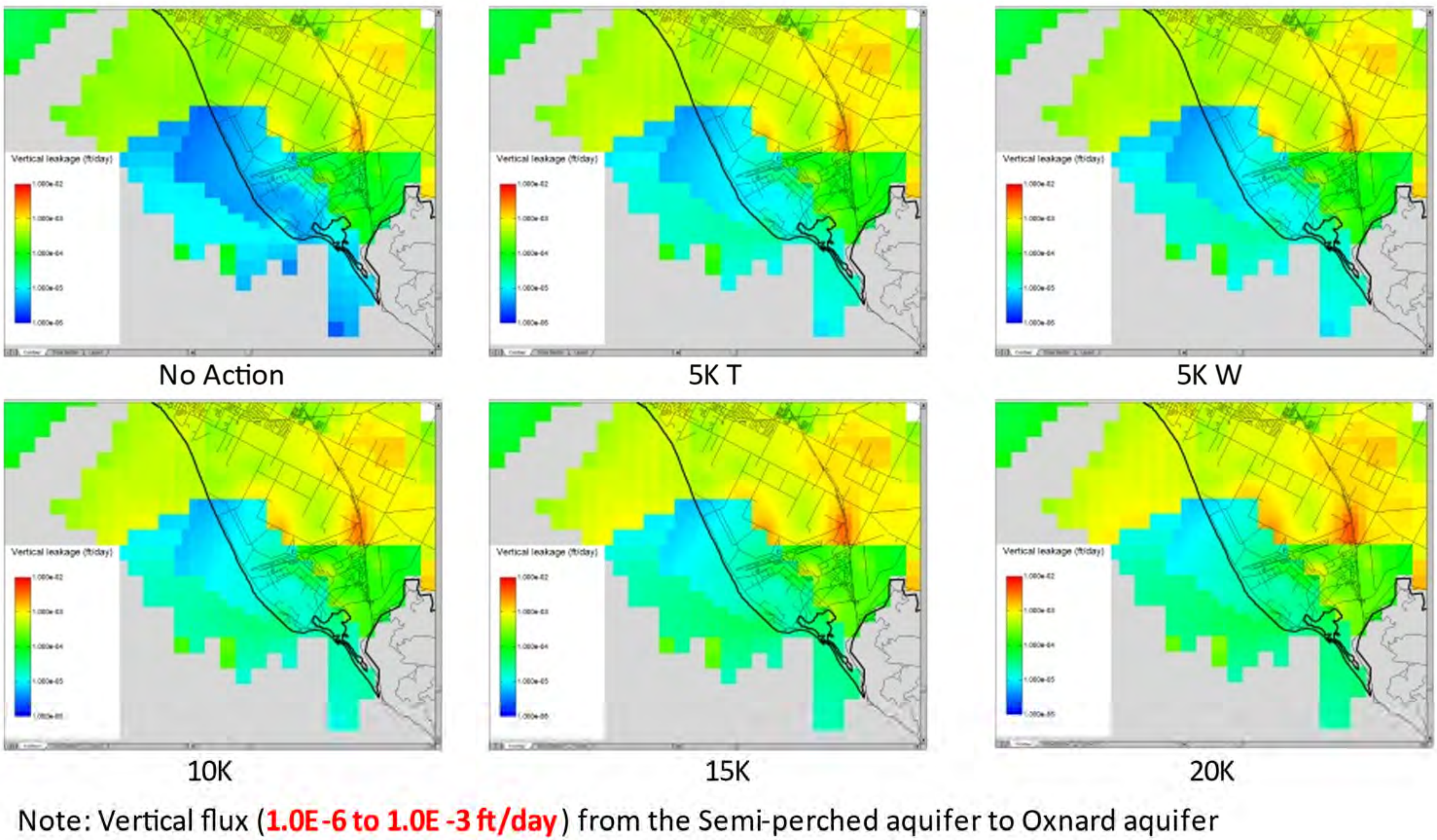
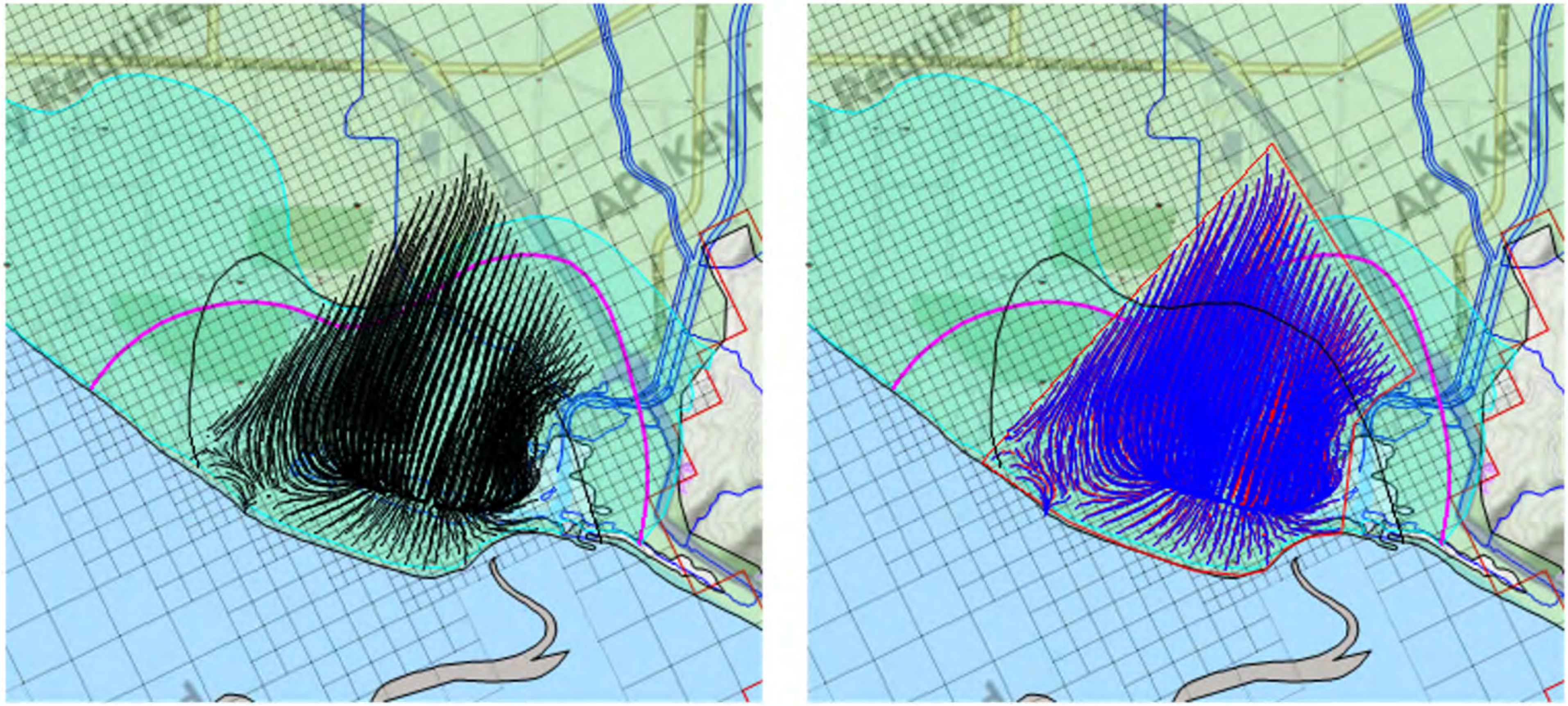


Figure 6-3. Simulated vertical groundwater flow velocity from Semi-Perched aquifer to Oxnard aquifer in November 1965 (end of multi-year drought).



No Action (in black lines)

5K W (in red lines)
20K (in blue lines)

Figure 6-4. The movement of particles released in the middle of Semi-Perched aquifer. No particles escape into Oxnard aquifer over the 50-year simulation period. The particle movements are similar among the six scenarios including no action. Only Scenarios No Action, 5K W and 20K are shown. Scenario 20K includes the particle paths from Scenario 5K W (in red lines) indicating there is little difference between scenarios.

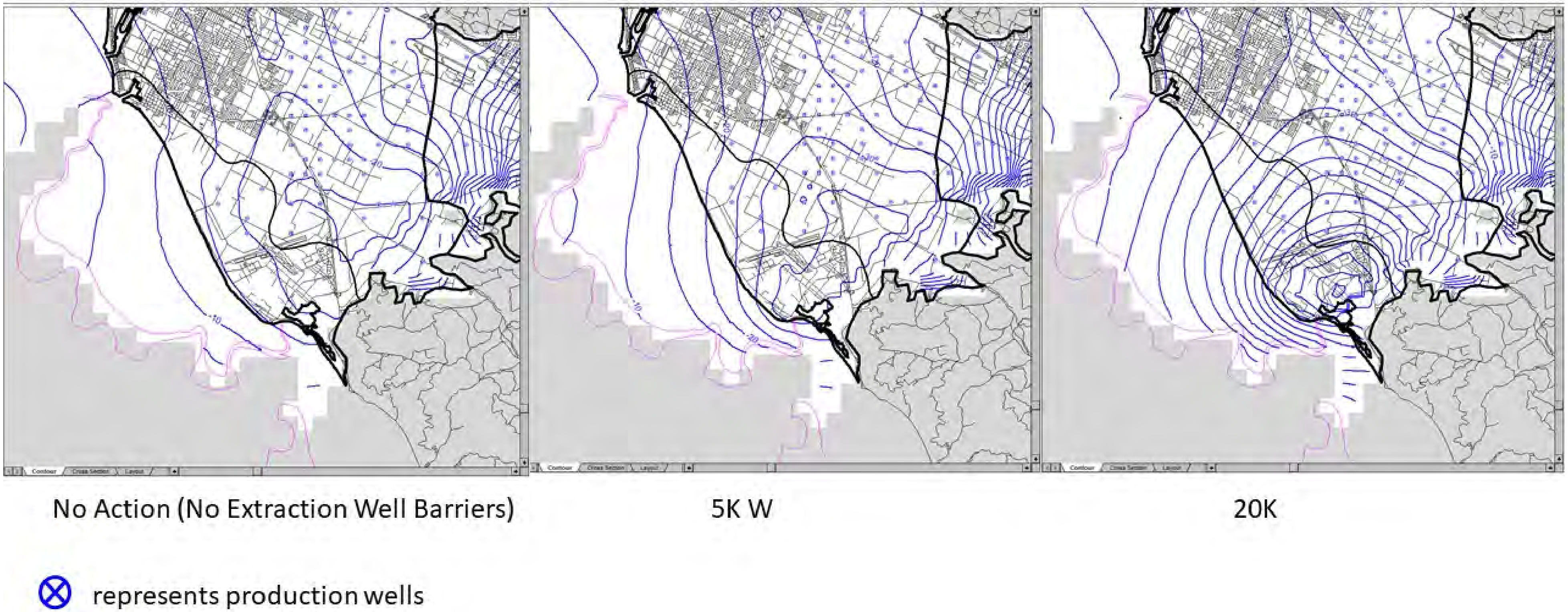


Figure 6-5. Simulated groundwater elevations in the Oxnard aquifer in November 1965 (end of multiple year drought) for scenarios No Action, 5K W and 20K.

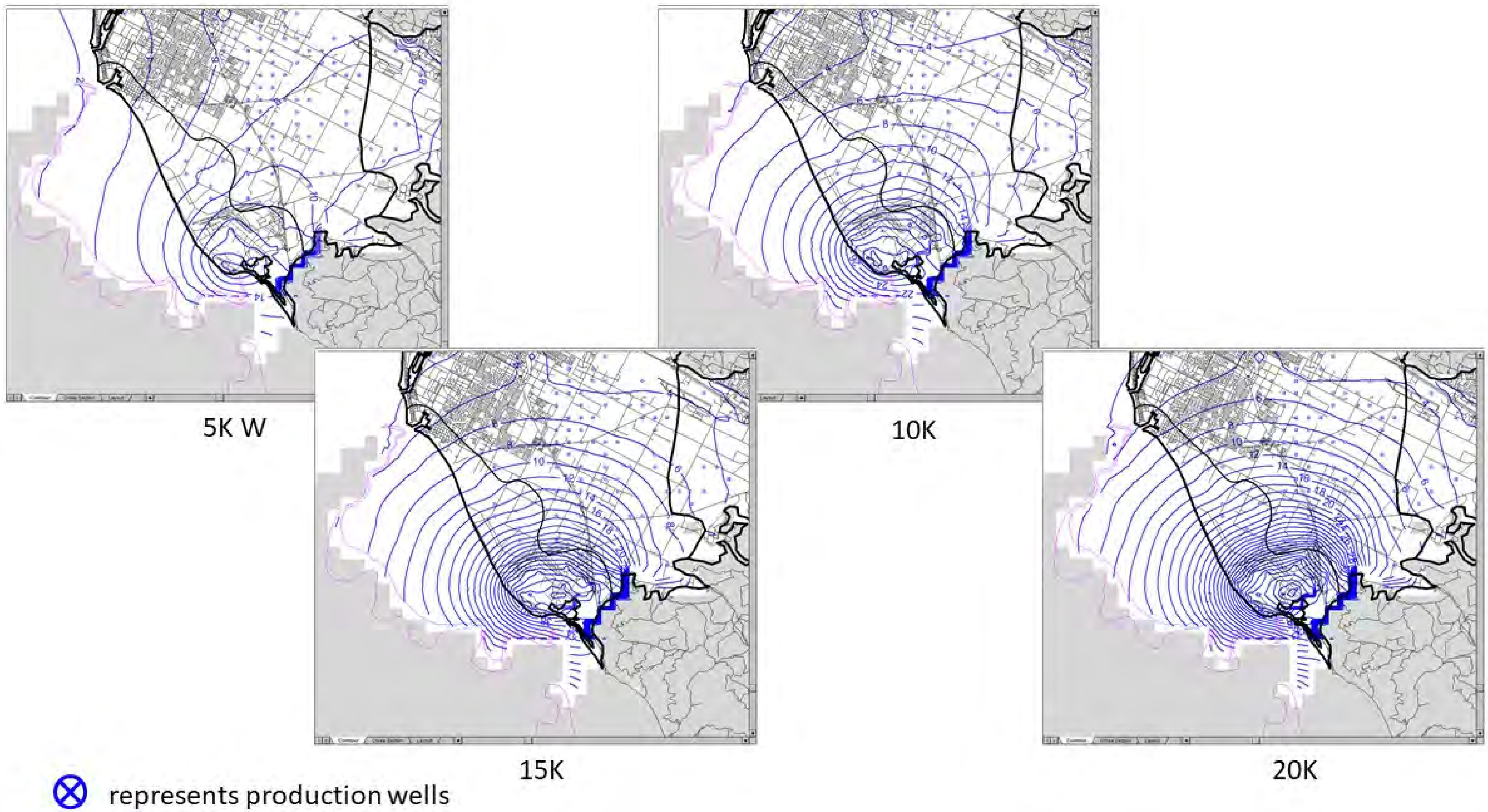
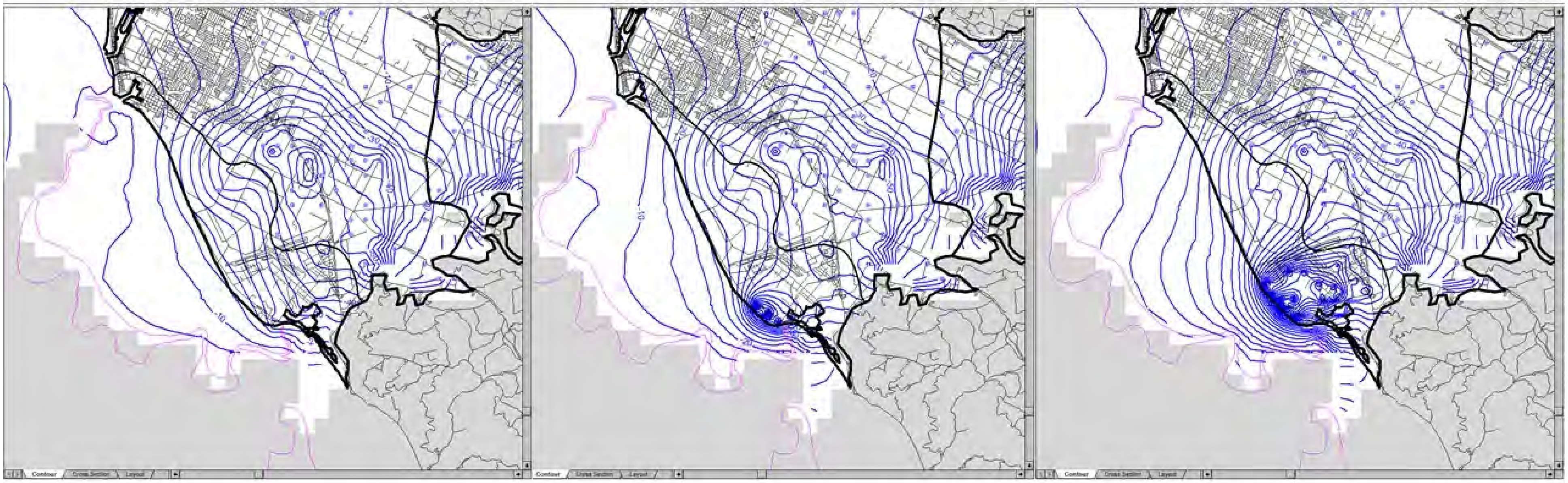


Figure 6-6. Oxnard aquifer drawdown caused by extraction barrier pumping (difference in the simulated groundwater level) relative to the No Action scenario in November 1965 (end of multiple year drought).



No Action (No Extraction Well Barriers)

5K W

20K

⊗ represents production wells

Figure 6-7. Simulated groundwater elevations in the Mugu aquifer in November 1965 (end of multiple year drought) for scenarios No Action, 5K W and 20K.

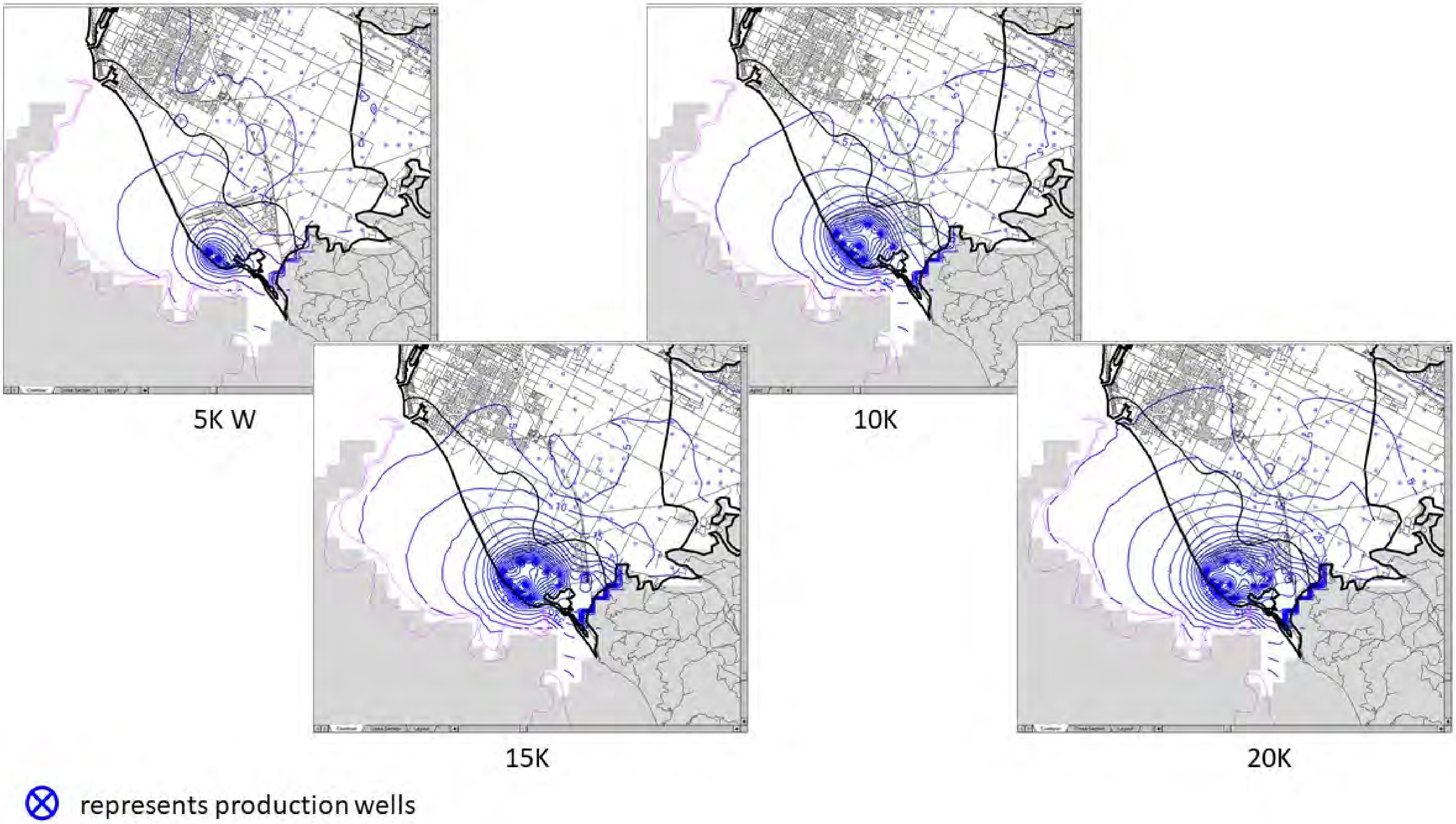
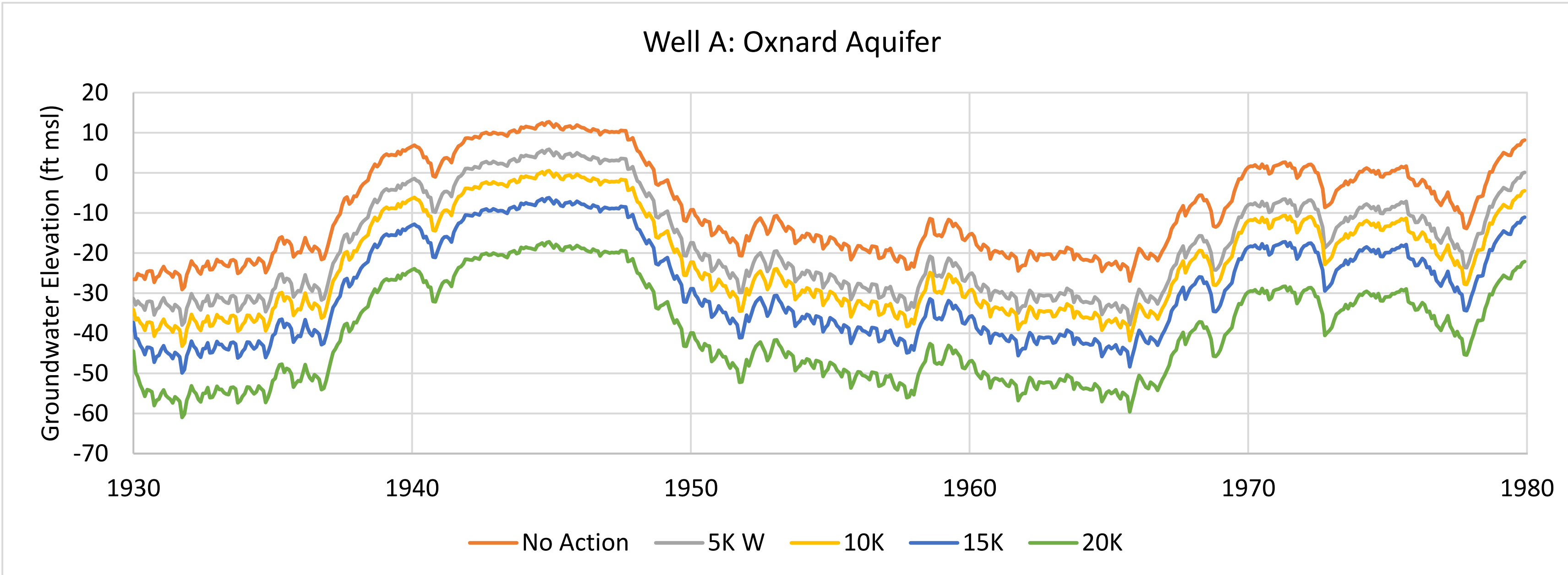


Figure 6-8. Mugu aquifer drawdown caused by extraction barrier pumping (difference in the simulated groundwater level) relative to the No Action scenario in November 1965 (end of multiple year drought).

Figure 6-9. Example well locations A and B, southern Oxnard basin.



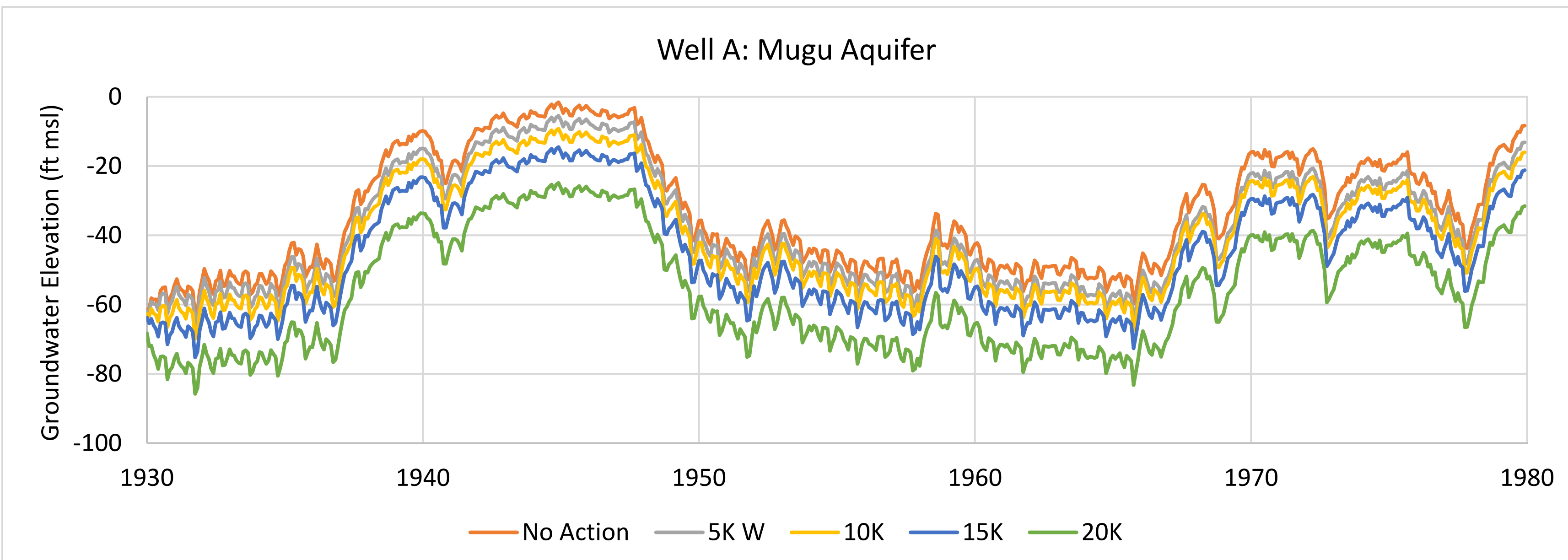
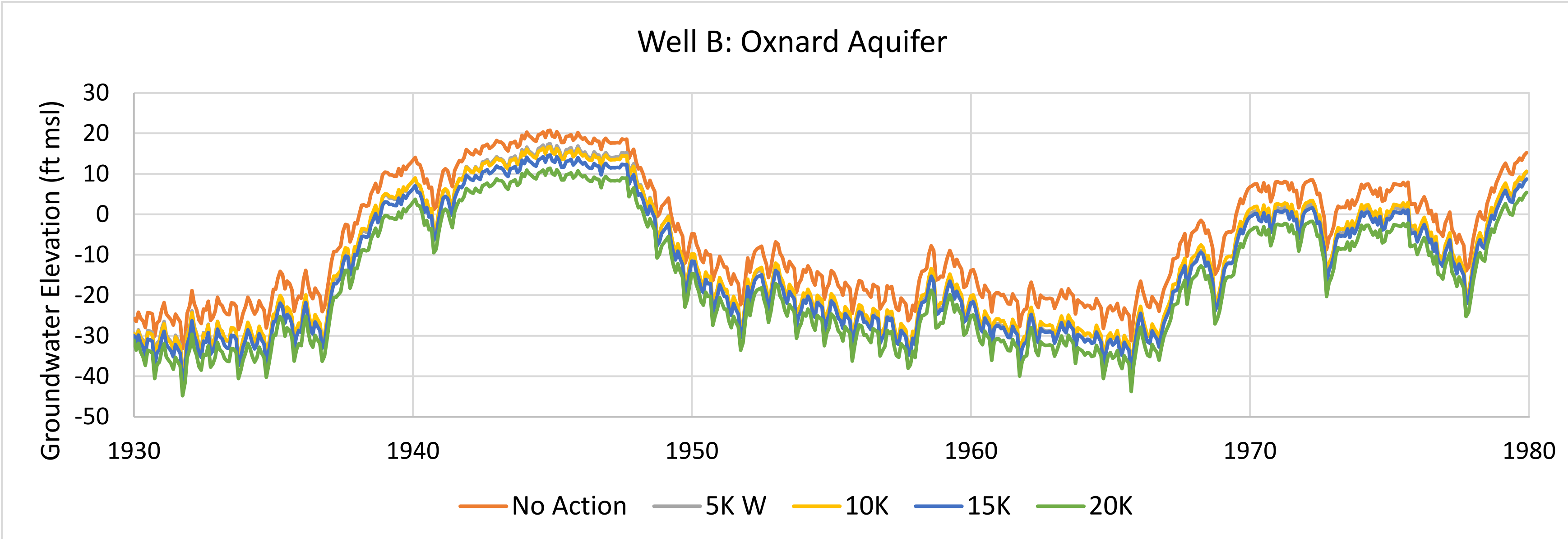


Figure 6-10. Simulated water levels in the Oxnard and Mugu aquifers at the Well A location next to NBVC Point Mugu.



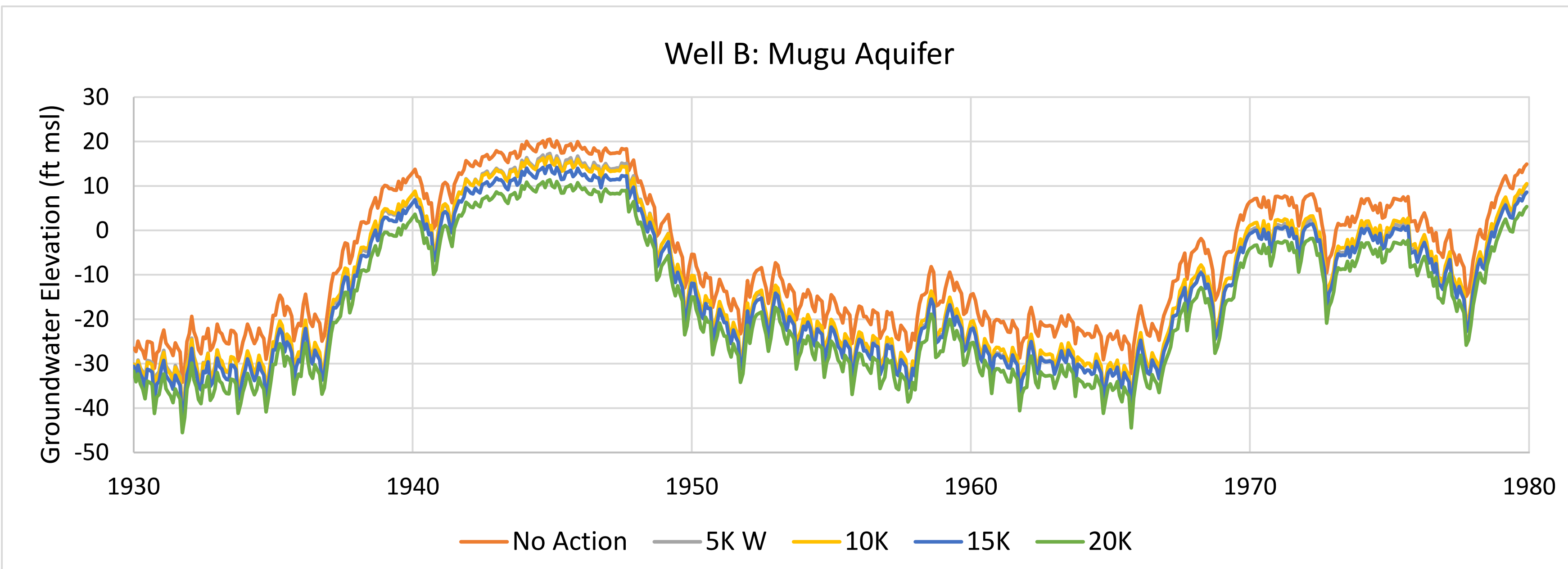


Figure 6-11. Simulated water levels in the Oxnard and Mugu aquifers for the Well B location representing location of an active production well.