
Stratigraphic controls on seawater intrusion and implications for groundwater management, Dominguez Gap area of Los Angeles, California, USA

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Abstract Groundwater pumping has led to extensive water-level declines and seawater intrusion in coastal Los Angeles, California (USA). A SUTRA-based solute-transport model was developed to test the hydraulic implications of a sequence-stratigraphic model of the Dominguez Gap area and to assess the effects of water-management scenarios. The model is two-dimensional, vertical and follows an approximate flow line extending from the Pacific Ocean through the Dominguez Gap area. Results indicate that a newly identified fault system can provide a pathway for transport of seawater and that a stratigraphic boundary located between the Bent Spring and Upper Wilmington sequences may control the vertical movement of seawater. Three 50-year water-management scenarios were considered: (1) no change in water-management practices; (2) installation of a slurry wall; and (3) raising inland water levels to 7.6m above sea level. Scenario 3 was the most effective by reversing seawater intrusion. The effects of an instantaneous 1-m sea-level rise were also tested using water-management scenarios 1 and 3. Results from two 100-year simulations indicate that a 1-m sea-level rise may accelerate seawater intrusion for scenario 1; however, scenario 3 remains effective for controlling seawater intrusion.

Keywords Coastal aquifers · Conceptual models · Numerical modeling · Salt-water/fresh-water relations · USA

Introduction

Development of groundwater in coastal Los Angeles (USA) in the twentieth century led to extensive water-level declines, and associated seawater intrusion (Poland et al. 1959; Land et al. 2004). Since the 1950s, numerous steps have been taken to address these issues, including basin adjudication and formation of the Water Replenishment District of Southern California (WRDSC), which is charged with protecting and managing the groundwater in the region. Specific actions taken include reduced pumping and increased artificial recharge. Of particular relevance to seawater intrusion, three sets of barrier wells (West Coast Basin, Dominguez Gap (Fig. 1), and Alamitos Gap) were constructed to inject water along the coast to create hydraulic barriers to seawater intrusion (Reichard et al. 2003). Currently, approximately $3.7 \times 10^7 \text{ m}^3/\text{year}$ of water are injected into the three sets of barrier wells. While the barrier wells have had a significant impact on reducing seawater intrusion, it is still occurring in the Dominguez Gap (Land et al. 2004).

The US Geological Survey (USGS), in cooperation with WRDSC, has conducted analyses of the regional groundwater system of coastal Los Angeles (Land et al. 2002; Reichard et al. 2003; Land et al. 2004; Reichard and Johnson 2005). In recent years the USGS, WRDSC, and the Los Angeles County Department of Public Works (LACDPW), have conducted an extensive research-drilling program in the Dominguez Gap area of coastal Los Angeles (Hillhouse et al. 2002, Fig. 1). A primary goal of this program has been to develop a detailed representation of the sequence stratigraphy of the area, in order to improve the strategies for seawater-intrusion control. The sequence-stratigraphic model resulting from this work was based on data collected from five continuously cored wells constructed by the USGS, supplemented by data from existing wells in the area (Ponti et al. 2007; Edwards et al. 2009).

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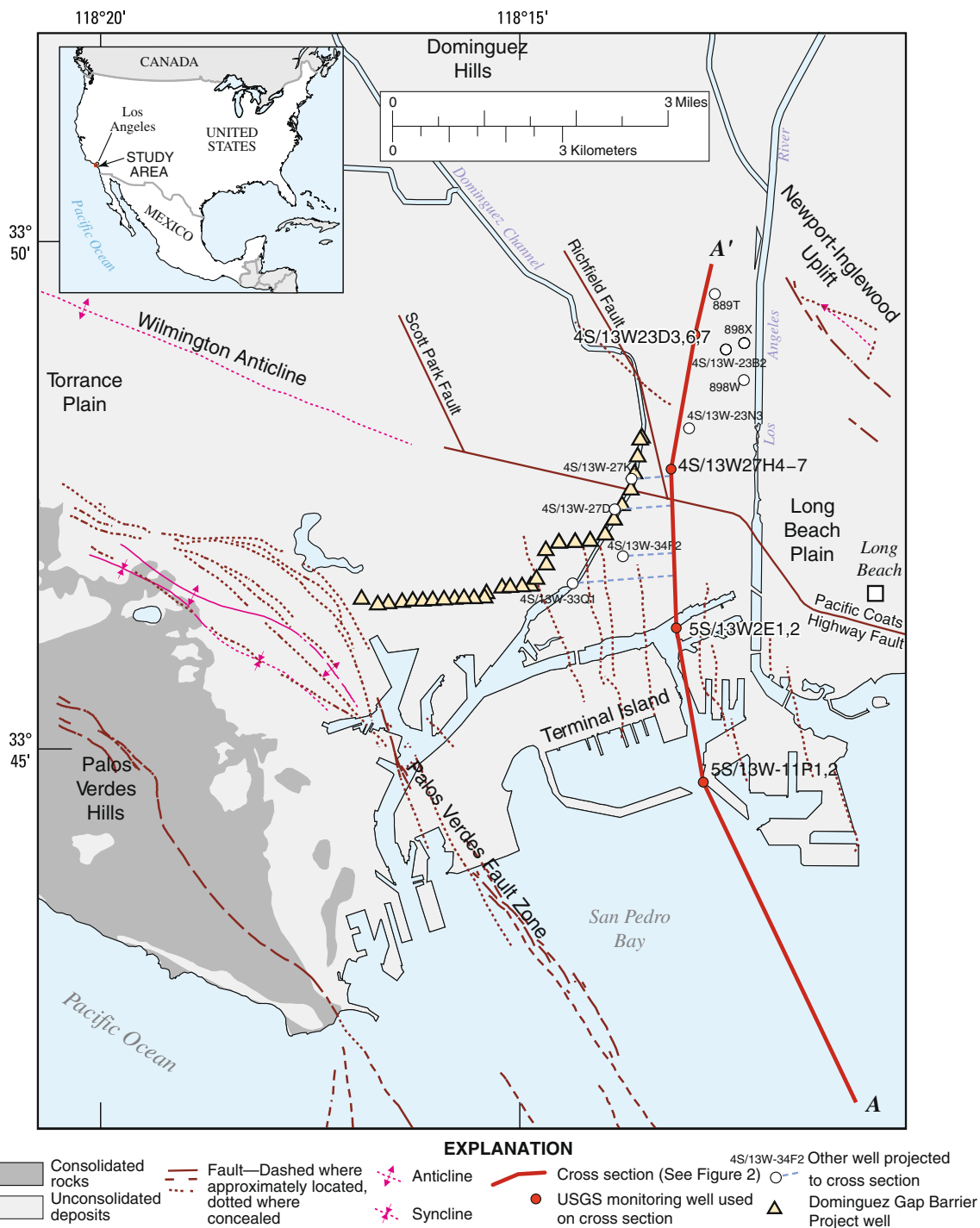


Fig. 1 Location of study area, Dominguez Gap area, California

Geologic setting and hydrogeology

The Dominguez Gap region of the southwest Los Angeles basin comprises the portion of the coastal plain of Los Angeles County adjacent to San Pedro Bay, within the cities of Long Beach and Torrance (located northwest of the city of Long Beach; not shown in Fig. 1). The term “Dominguez Gap” comes from the water gap that occurs just south of Dominguez Hills, where the Los Angeles River flows southward across the Newport-Inglewood uplift (Fig. 1). Structurally, the Dominguez Gap region

generally lies above the buried Wilmington anticline and is bounded on the northeast by the Newport-Inglewood Fault system and on the southwest by the Palos Verdes Fault. Late Pleistocene alluvial, colluvial, and paralic deposits are exposed at the land surface over much of the region, with the exception of the area near the Los Angeles River where up to ~30 m of Holocene-age fluvial and estuarine sediment fill an incised channel that was cut by the river during the last glacial period (~18 ka ago) when sea level was approximately 120 m below present.

Table 1 Correlation table relating sequence geology to aquifer nomenclature in the Dominguez Gap area, California (modified from Ponti et al. (2007))

Formation (DWR 1961)	Sequence (Ponti et al. 2007)	Aquifer north of Pacific Coast Highway Fault		Aquifer south of Pacific Coast Highway Fault	
		DWR (1961)	Reichard et al. (2003)	DWR (1961)	Reichard et al. (2003)
Holocene	Dominguez	Gaspur	Recent	Gaspur	Recent
Lakewood	Mesa Pacific	Gage	Lakewood	Gage	Lakewood
San Pedro	Harbor	Lynwood	Upper San Pedro	Lynwood	Upper San Pedro
	Bent Spring	Silverado			
	Upper Wilmington				
	Lower Wilmington	Sunnyside	Lower San Pedro	Silverado	
	Pliocene A	Pico			
	Pliocene B		Pico		Lower San Pedro
	Pliocene C	Not penetrated by water wells	Not penetrated by water wells	Pico	
	Tertiary undifferentiated	Not penetrated by water wells	Not penetrated by water wells	Not penetrated by water wells	Not penetrated by water wells

DWR California Department of Water Resources

The stratigraphy of water-bearing deposits in the Dominguez Gap region has been extensively described in a number of studies, the most significant of which are Poland and Piper (1956), Poland et al. (1959), California Department of Water Resources (1961), and Zielbauer et al. (1962). Following the work of Woodring et al. (1946), all of these studies classify the Holocene and Pleistocene deposits of the region into three primary series. Using the terminology defined in California Department of Water Resources (1961), the lower Pleistocene series comprises San Pedro Formation, a marine unit that is folded over the Wilmington anticline and exposed along the Palos Verdes and Newport-Inglewood uplifts. The San Pedro Formation is composed of three principal water-bearing units; from

oldest to youngest, they are: (1) the Sunnyside aquifer, (2) the Silverado aquifer, which is the principal producing aquifer in the region and locally can reach a thickness of 200 m, and (3) the overlying Lynwood aquifer. All aquifers primarily consist of marine sand with lenses of fine gravel. Reichard et al. (2003) recently reclassified these aquifers into the Lower San Pedro (Sunnyside) and Upper San Pedro (Silverado and Lynwood) aquifer systems. The upper Pleistocene Lakewood Formation is thought to unconformably overlie the San Pedro Formation. It is less deformed than the San Pedro Formation and consists of a mix of shallow marine, estuarine, fluvial, and colluvial deposits. It crops out at the surface in the Torrance and Long Beach plains. One principal water-

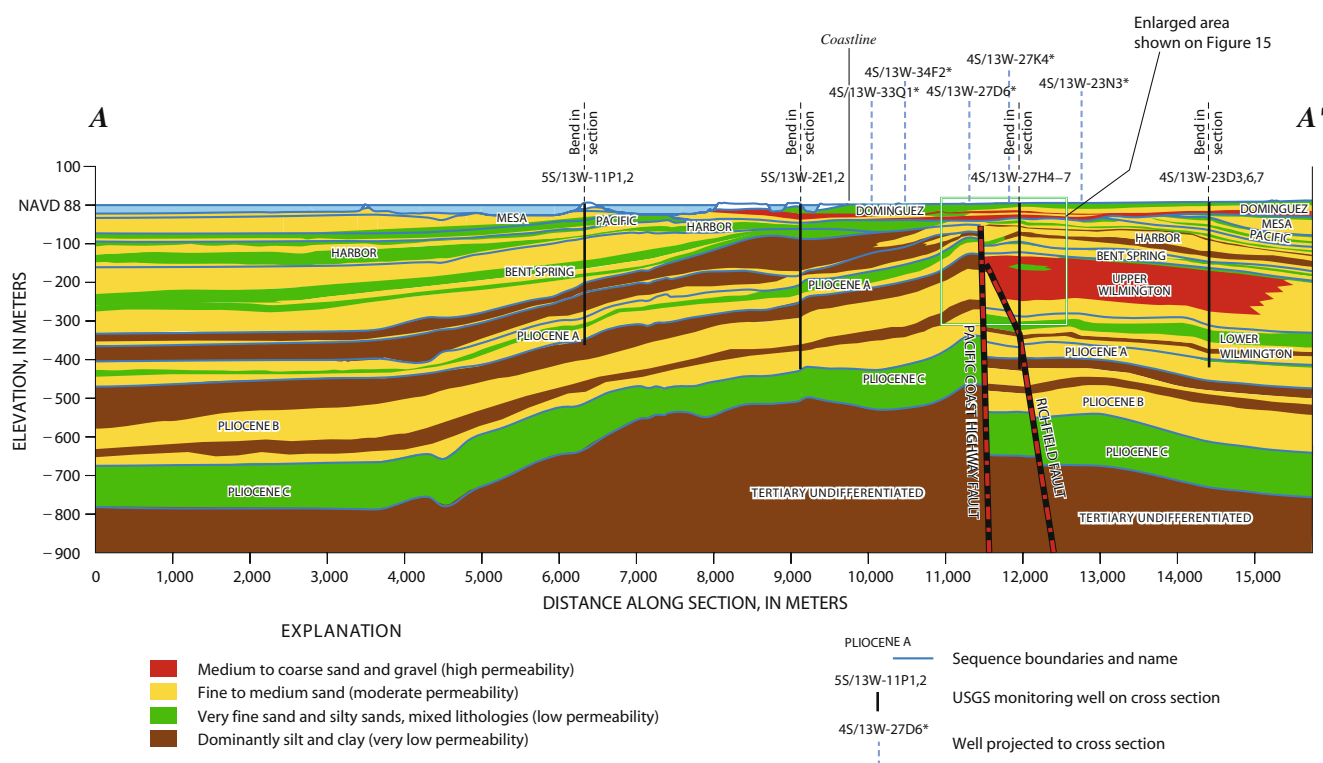


Fig. 2 Hydrostratigraphic cross section

bearing unit, the Gage aquifer (Lakewood aquifer system of Reichard et al. 2003), is identified within the Lakewood Formation. The Gage consists primarily of interbedded fine-to-medium sands with local coarse lenses and is in general thinner and lithologically more heterogeneous than the aquifers of the San Pedro Formation. Overlying the Lakewood Formation is the Holocene series, which consists dominantly of fluvial deposits of the Los Angeles River, intercalated with fine-grained estuarine mud. The

basal portion of this series is composed of fluvial channel gravels of the Gaspar aquifer (Recent aquifer system of Reichard et al. 2003).

The lithostratigraphic-based units above are defined and correlated in the subsurface based upon similar gross lithology and stratigraphic position. While this approach is useful for defining zones in the subsurface where aquifer materials exist, it does not explicitly account for lateral variations in lithology due to facies changes within a

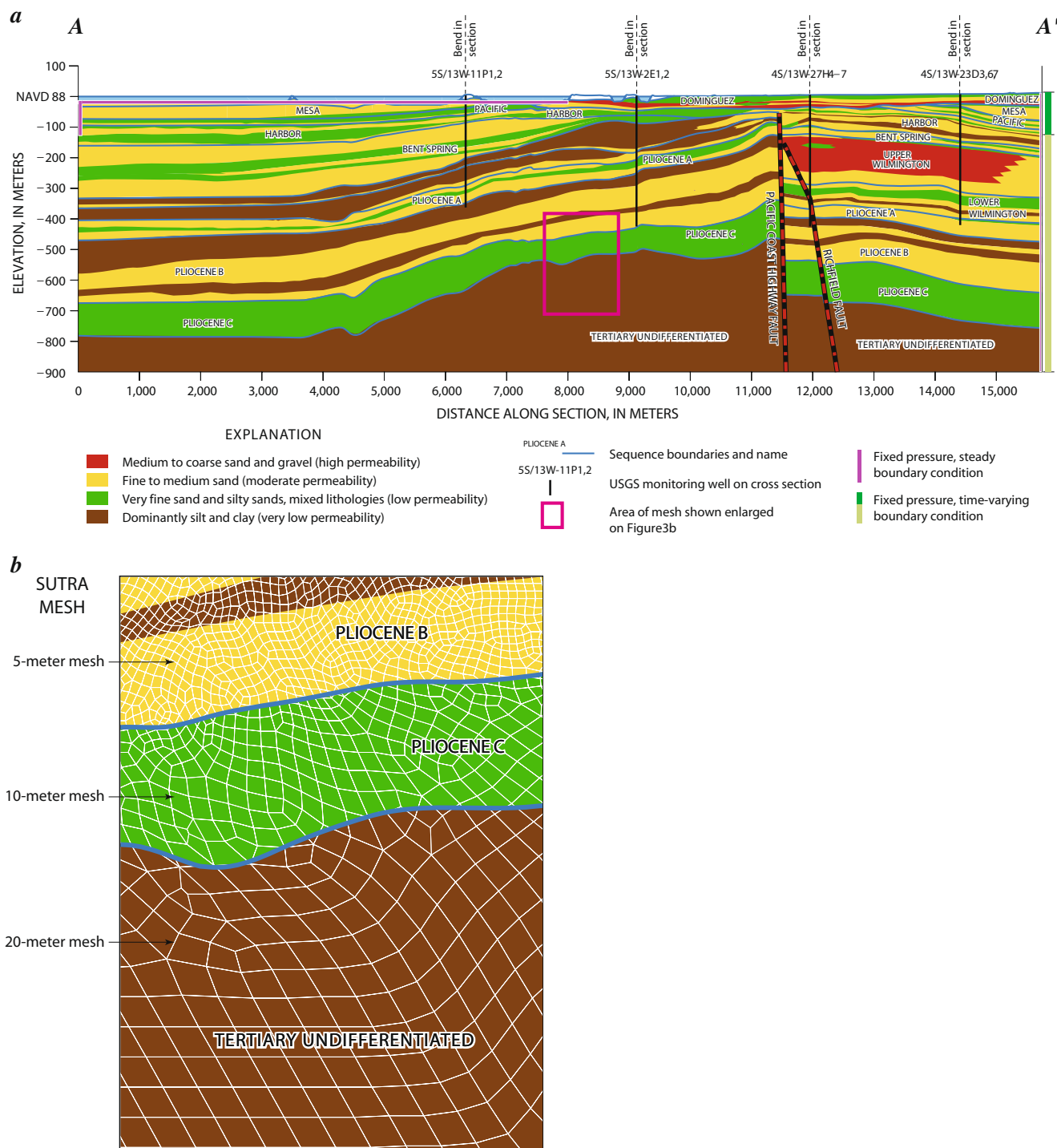


Fig. 3 a Model boundary conditions and b enlarged view of finite-element mesh

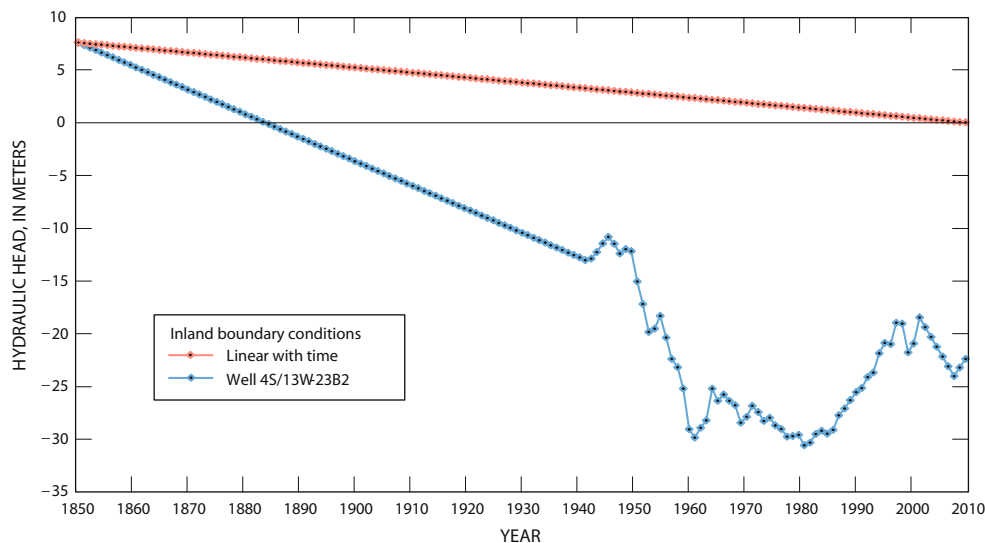


Fig. 4 Plot showing the two time-varying boundary conditions on the inland boundary (linear trend for top 124 m and lower based on data from 4S/13W-23B2)

depositional unit and may not accurately represent the true continuity of coarse-grained water-bearing facies, or the interconnection of aquifer facies among the various units. In contrast, recent work by Ponti et al. (2007) incorporates the concept of sequence stratigraphy, an approach that ties together packages of sediment that are genetically related and deposited within a specified interval of time, even though their lithologies may vary both laterally and vertically. Sequences and their vertical stacking are controlled by base level (sea level) change, sediment supply, and available accommodation space. Within these depositional systems, the various facies have lateral relationships that are mappable and predictable, thus allowing for the lateral distribution of aquifers and their confining fine-grained aquitards to be better defined.

Ponti et al.'s (2007) approach identifies seven stratigraphic sequences within the Holocene and Pleistocene deposits of the Dominguez Gap area, three Pliocene sequences, and a Tertiary sequence, all of which comprise some portions of the groundwater flow system. The association among the sequences defined by Ponti et al. (2007) and the aquifer systems defined by California Department of Water Resources (1961) and Reichard et al. (2003) is shown in Table 1. Associated with each sequence is a lithologic representation of the system where the lithologies are assigned to four texture categories: medium to coarse sand and gravel; fine to

medium sand; very fine sand and silty sands; and dominantly silt and clay (Fig. 2).

Ponti et al.'s (2007) study also identified the presence of young folding and a fault system (Pacific Coast Highway or PCH Fault) that affects aquifer correlation and continuity (Fig. 1). Ponti et al. (2007) hypothesized that the folding and faulting created potential pathways for seawater in shallow deposits to migrate into the deep aquifers. An example of how the PCH Fault affects aquifer correlation and continuity are the sands of the Upper Wilmington sequence north of the PCH Fault, which have been assigned to the Silverado aquifer (see Table 1), that are juxtaposed against sands contained within Ponti et al.'s Pliocene A and B sequences south of the fault (Fig. 2).

Study approach

The goals of the work presented in this paper are to: (1) quantitatively test the hydraulic implications of the sequence stratigraphy presented in Ponti et al. (2007) and Edwards et al. (2009) using a solute-transport model, (2) utilize the calibrated transport model to assess the possible effects of alternative management strategies, and (3) utilize the calibrated transport model to assess the possible effects of a potential 1-m sea-level rise resulting from climate change.

Table 2 Initial and final hydraulic and transport parameters, Dominguez Gap area, California

Texture description	Color in Fig. 2	Horizontal permeability (m ²)		Vertical permeability (m ²)		Porosity (1)		Longitudinal dispersivity (m)		Transverse dispersivity (m)	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Medium-to-coarse sand and gravel	Red	1.00E-10	3.80E-10	1.00E-12	3.80E-11	0.25	0.30	300	600	30	5
Fine-to-medium sand	Yellow	1.00E-11	4.10E-12	1.00E-13	4.10E-13	0.30	0.30	300	600	30	5
Very fine sand and silty sands	Green	1.00E-12	1.10E-13	1.00E-14	1.10E-14	0.35	0.40	300	600	30	5
Dominantly silt and clay	Brown	3.60E-14	3.60E-14	3.60E-16	3.60E-17	0.45	0.50	300	600	30	5

The solute transport is simulated using SUTRA (Voss and Provost 2002), a two or three-dimensional, finite-element, density-dependent, groundwater flow and solute-transport model. The simulated results are representative estimates of groundwater flow and chloride (Cl) transport from the Pacific Ocean (San Pedro Bay) to the Dominguez Gap area since groundwater development was initiated in coastal Los Angeles in the mid-1800s. The approach taken is to simulate quasi steady-state conditions, assumed to be representative of those in 1849; then simulate transient flow and transport from 1850 through 2004. The modeling considers flow and transport along an approximate flow line; however, the true groundwater flow and transport system is three-dimensional. A somewhat similar approach was taken by Nishikawa (1997) to test the validity of alternative assumptions regarding the offshore hydrogeology in Ventura County, California. The faults in the region are not considered explicitly in the model, i.e., the effects of

faulting on pressures and chloride concentrations are assumed to be captured by the juxtaposition of the stratigraphic layering caused by faulting.

Groundwater flow and transport model

Spatial and temporal discretization

The finite-element mesh used to discretize the sequence-stratigraphic cross section is shown in Fig. 3. The horizontal and vertical extents of the model domain are about 15,800 m and about 900 m, respectively. The elevation of the top of the domain varies from about 20 m below sea level (bsl) to about 13 m above sea level (asl). The bottom elevation of the domain is 900 m bsl. For this study, sea level is referenced to the North American Vertical Datum 88 (NAVD88). The mesh consists of 87,191 nodes and 86,643 elements with horizontal and vertical variable gridding. The modeled section has an arbitrary width of 1 m.

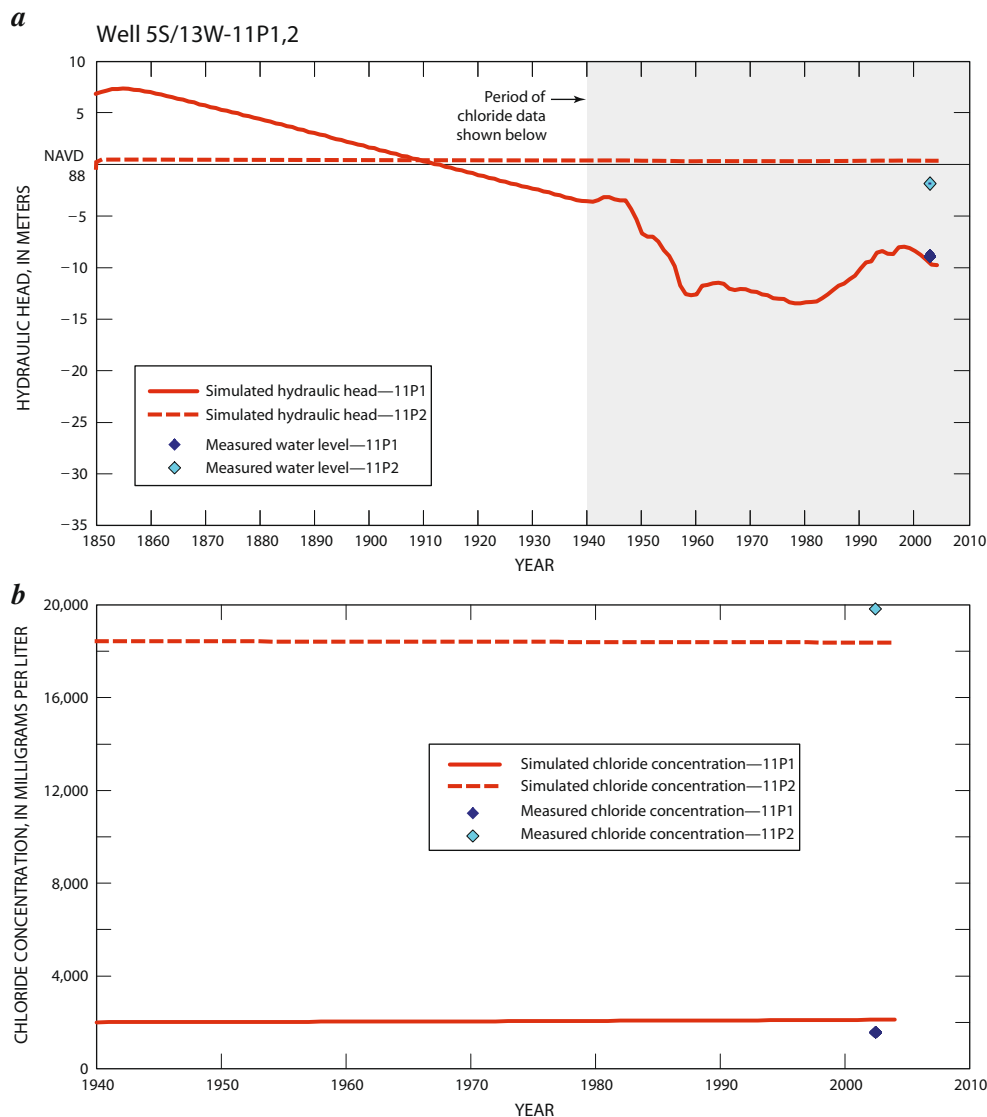


Fig. 5 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 5S/13W-11P1,2

Irregularly shaped quadrilateral finite elements were used in these simulations. The gridding varies from fine (5 m × 25 m) at shallow depths to coarse (20 m × 100 m) near the bottom of the domain (Fig. 3b). The finer mesh allows for better characterization of thin layers of low permeability and provides accurate calculations of sharp spatial changes in pressure and concentration. The simulation period used to estimate initial conditions is 10,000 years using 10-year time steps. The transient-state simulation of 155 years uses 2-week time steps for numerical stability.

Initial and boundary conditions

The steady-state condition is reached by performing a long-term (10,000 years) transient simulation from an arbitrary initial condition. The resulting pressure and Cl distributions are used as initial conditions (1849) for the historical, transient simulations. In general, no-flow or fixed-pressure (FP), with specified concentration of Cl in

the water entering the domain, boundaries are used in this model (Fig. 3a). The FP-vertical offshore boundary extends from the top of the domain to 120 m bsl, reflecting that the sediments below this elevation extend far offshore. The FP-horizontal offshore boundary corresponds to the approximate location of the ocean bottom from 0 to 8,020 m (in x-direction). The FP-inland boundary extends from land surface (about 13 m asl) to the bottom of the domain, and is steady for the steady-state simulation and time varying for the transient simulation. The FP-inland boundary is a simplification reflecting the general effects of stresses on water levels at this location; however, specific local pumping and injection effects may not be reflected in the simulated results because stresses within the cross section are not explicitly addressed. A no-flow boundary occurs along the bottom boundary and along the offshore boundary from 120 to 900 m bsl.

For the steady-state simulation, the FP-offshore boundaries are hydrostatic using the density of seawater

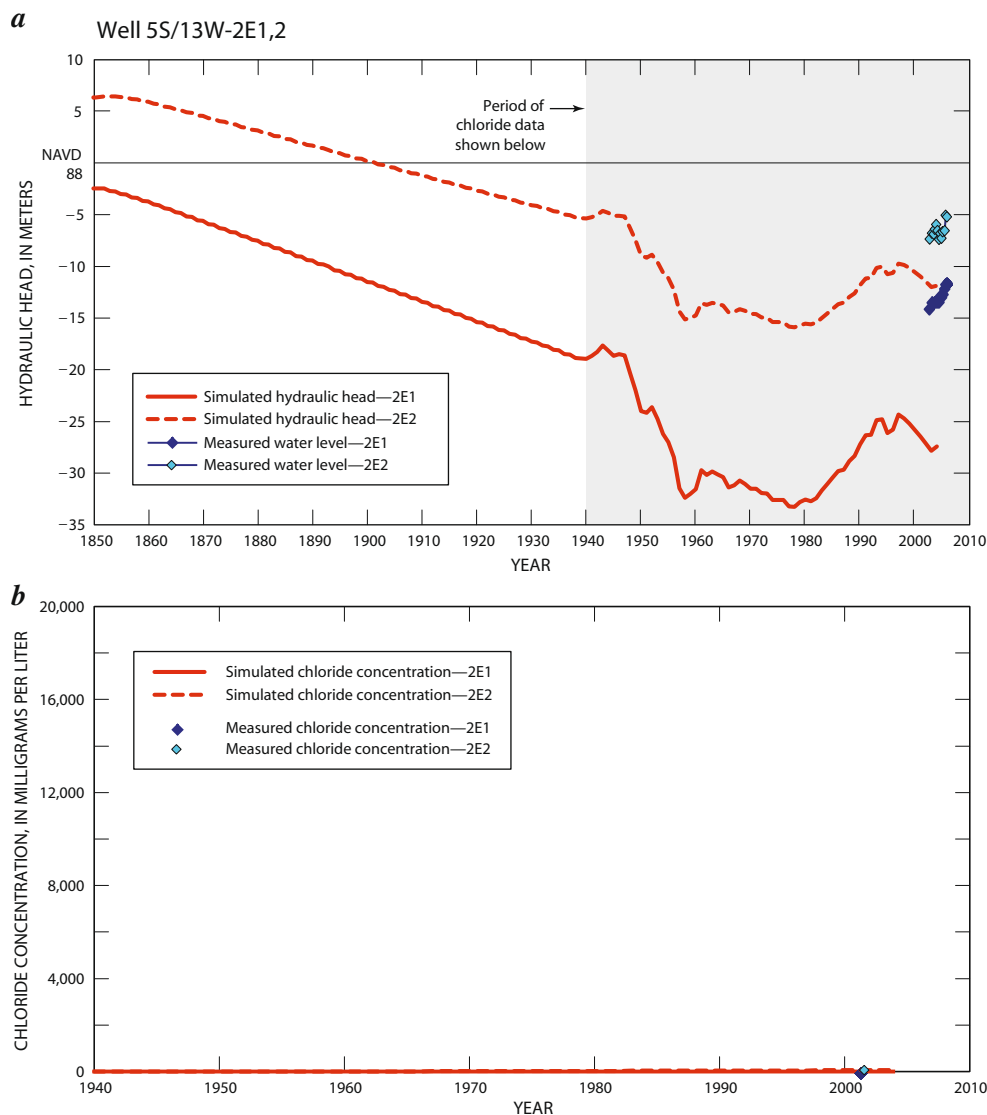


Fig. 6 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 5S/13W-2E1,2

(1,024 kg/m³) and assuming sea level is equivalent to 0 m. The Cl concentration associated with these boundaries is 19 parts per thousand or 0.019 (unitless) or 19,000 mg/L. The FP-inland boundary is also hydrostatic but uses the density of freshwater (1,000 kg/m³) and assumes a head of 7.6 m asl. Mendenhall (1905) shows water levels near the inland location of the cross section to be about 6 m. It is assumed that water levels somewhat higher than this were present 50 years earlier in 1849. The Cl concentration associated with this boundary is set at 0 mg/L.

For the transient simulation, the FP-offshore boundaries are unchanged from the steady-state simulation. The FP-inland boundary is also hydrostatic; however, it is divided into two time-varying boundaries (Fig. 3a). The upper part of the inland boundary extends from land surface to 124 m bsl and varies linearly from an initial water level of 7.6 m asl, in 1849 (steady state), to 0 m in 2004. The use of 0 m in 2004 is reasonable because water-level data collected from three shallow wells, located about 1,500 m seaward of the inland model boundary, had

observations of about 2 m bsl. These wells (889 T, 898 W and 898X) are operated by the LACDPW and have top and bottom perforations ranging between 8 and 31 m bsl. The time-varying pressure of the lower part of the inland boundary is estimated from water levels observed at a nearby well (4S/13W-23B2 shown in Fig. 1) with data collected since 1938. Well 23B2 is 325 m deep and is perforated between 195 to 270 m bsl. The missing water-level data between 1850 and 1938, and any other missing data, are linearly interpolated (Fig. 4). The inland boundary is divided at 124 m bsl corresponding to the shallowest, low-permeability layer (Fig. 3a).

System parameters

Model properties—permeability (k), fluid compressibility, fluid density, fluid viscosity, porosity (n), solid matrix compressibility, solid-grain density, dispersivity (α), and diffusion coefficient—affect the rate and extent to which

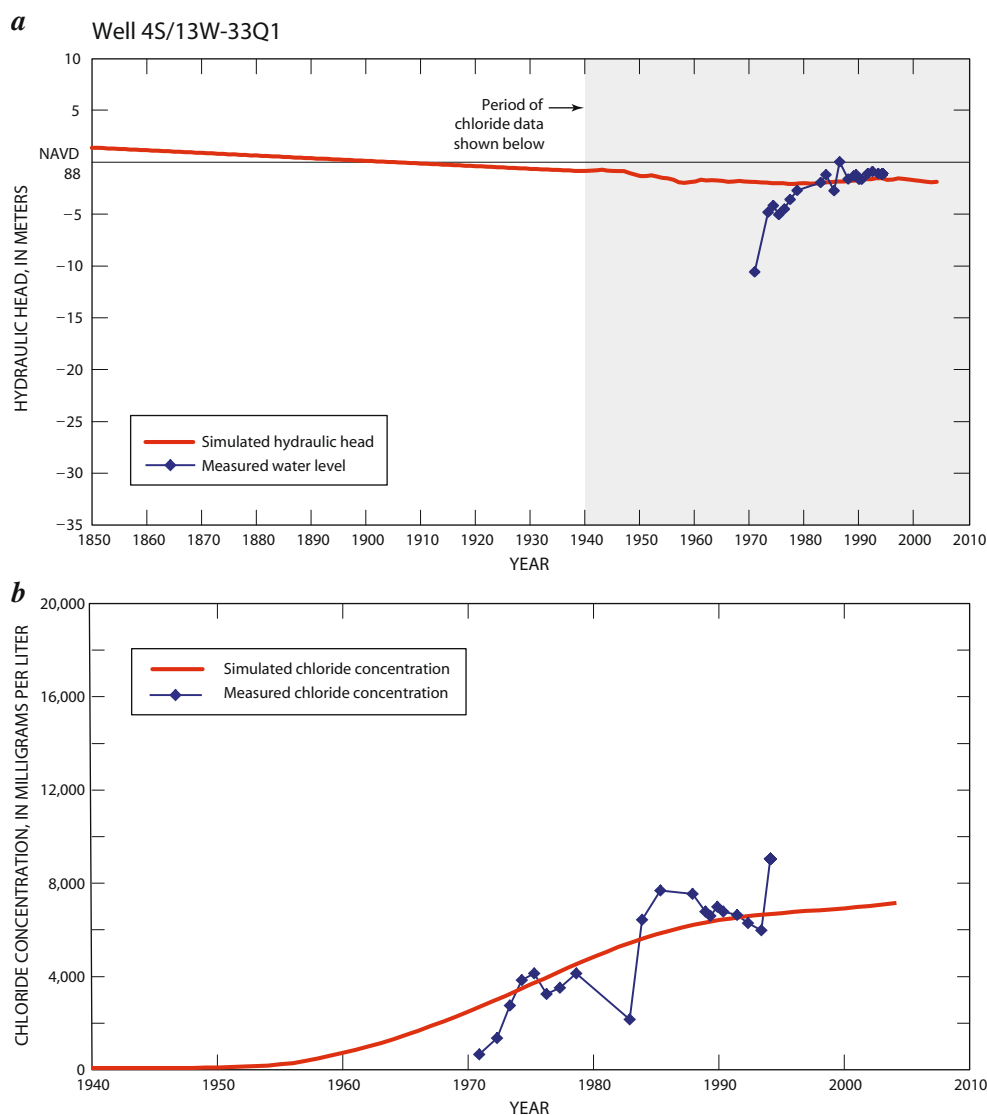


Fig. 7 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-33Q1

simulated water moves through an aquifer, the volume of water in storage changes, groundwater-levels change as a result of stresses, and dissolved salts are transported. Fluid compressibility, diffusion coefficient, seawater density, freshwater density, fluid viscosity, solid matrix compressibility, and solid-grain density were based on published data and assigned values of $4.47 \times 10^{-7} \text{ m}^2/\text{N}$, $1.0 \times 10^{-9} \text{ m}^2/\text{s}$, $1,024 \text{ kg/m}^3$, $1,000 \text{ kg/m}^3$, 0.001 kg/ms , $1.0 \times 10^{-9} \text{ m}^2/\text{N}$, and $2,600 \text{ kg/m}^3$, respectively (Freeze and Cherry 1979). The other parameters (k , n , α) were assigned via trial-and-error parameter estimation. Initial and final parameter values are shown in Table 2.

The primary data used for calibration were measured water levels and Cl concentration at 16 wells; calibration results for 16 selected wells are presented in geographic order starting from the coast moving inland in Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13. The construction information for the selected wells is presented in Table 3. As noted earlier, local

pumping and injection was not explicitly included in the numerical model; therefore, the results do not reflect their potential impacts.

There were two primary goals of the model calibration. The first was to match the large difference in Cl concentrations in the shallow versus deeper zones at the coast, as seen at wells 5S/13W-11P1,2 (Fig. 5b). The second was to simulate the downward movement of high-Cl water in the area of the PCH Fault (Figs. 1 and 2), as observed in well 4S/13W-27H7 (Fig. 11b). Additional goals of the calibration were to match measured water levels and Cl concentrations at the other 13 wells. The main modifications to aquifer parameter values required to achieve these calibration goals were anisotropy ratio for permeability, porosity, and dispersivity.

Permeability was assumed to be heterogeneous and anisotropic. The initial permeability values were assigned to the four texture categories delineated in Fig. 2. The initial

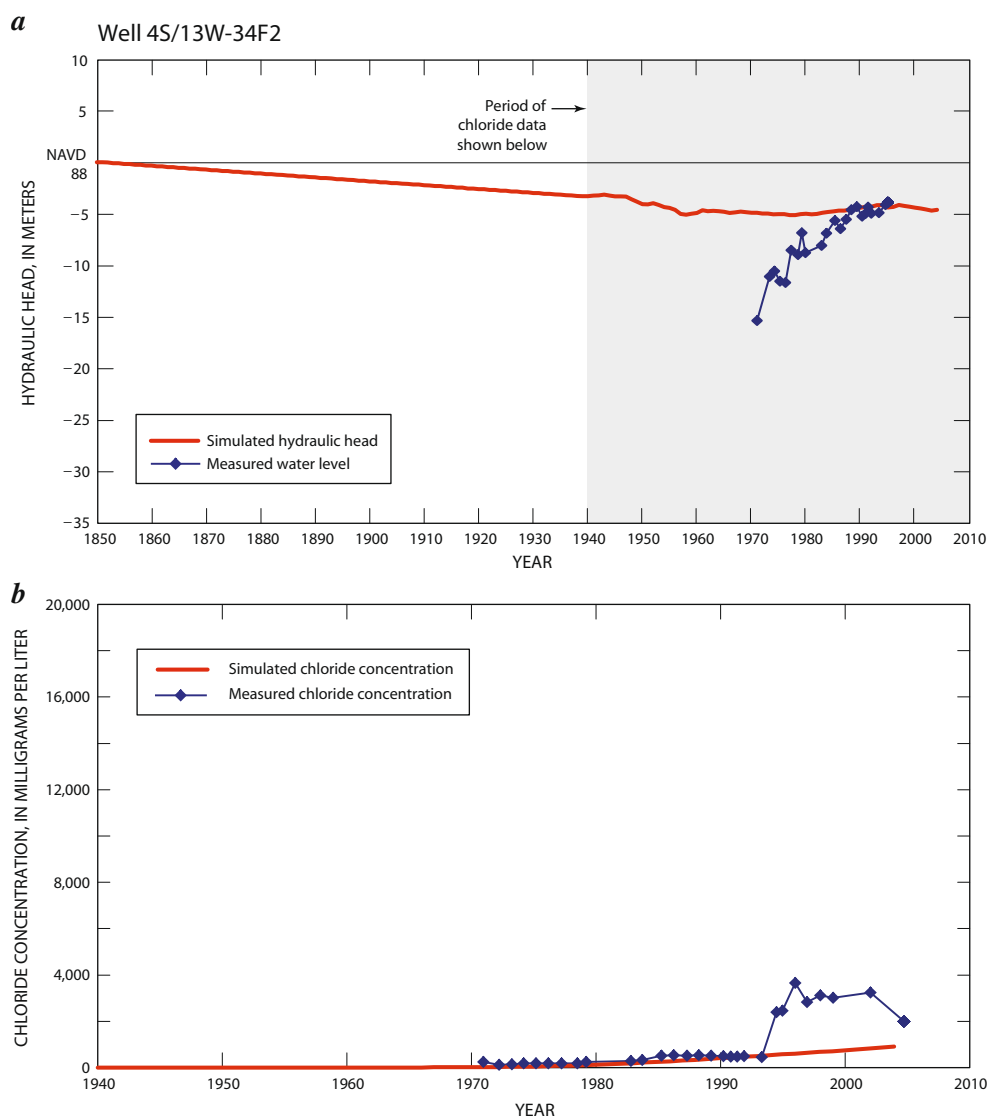


Fig. 8 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-34F2

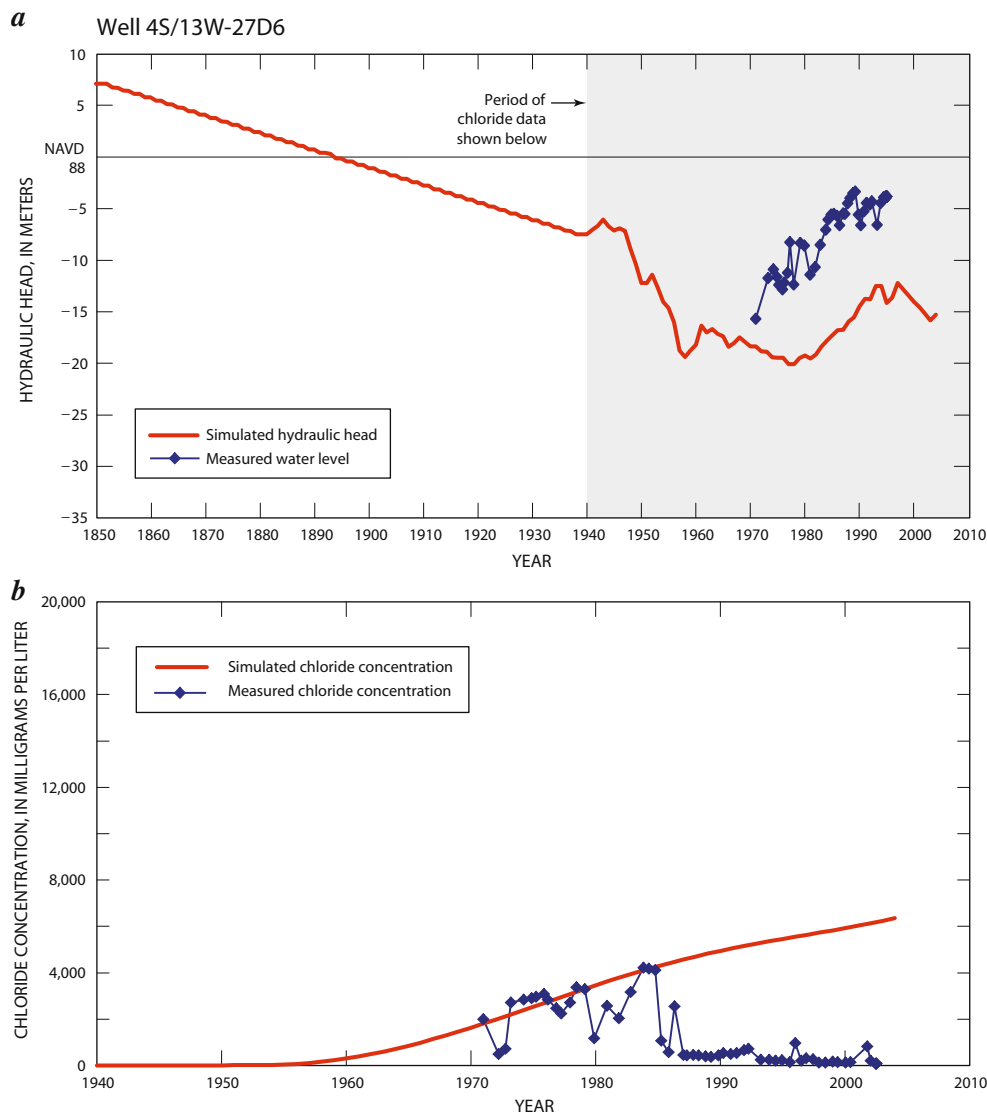


Fig. 9 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-27D6

and final k values are listed in Table 2. The anisotropy ratio of k was initially assumed to equal 100:1 (i.e., $k_{\text{horiz}}/k_{\text{vert}} = 100$) for all texture categories; however, during the parameter-estimation process the ratios were changed to 10:1 for all textures except the very-low-permeability silt and clay (brown in Fig. 2). The permeability anisotropy ratio for this texture category was assigned a value of 1,000:1 in order to match the measured data which show relatively small Cl concentrations at depth near the coast (Fig. 5b).

Porosity was assumed to be heterogeneous and values were assigned to each of the four texture categories. The initial and final n values are listed in Table 2. The porosity values were adjusted to better match the timing of the Cl front in the model with that of the observed data. The porosity value of each texture, except the fine-to-medium sand (yellow in Fig. 2), was increased from initial values by 5% to slow simulated Cl migration inland to better match the measured data.

Dispersivity was assumed to be homogeneous and anisotropic. The initial and final values of α are listed in

Table 2. Note that the initial longitudinal (α_L) to transverse (α_T) ratio of 10:1 was increased to 120:1 (i.e., $\alpha_L/\alpha_T = 120$). Although the ratio was increased by an order of magnitude, the final, individual values of α_L and α_T (600 and 5 m, respectively) are reasonable based on data reported by Gelhar et al. (1992). However, for any model with a large observation scale such as the model in this study, the calculated dispersivities cannot have a high degree of reliability (Gelhar et al. 1992). In SUTRA, dispersivity aligns with the direction of flow (Voss and Provost 2002). Due to the low vertical permeability of the silt and clay and silt-to-very-fine-sand regions (brown and green, respectively in Fig. 2), the primary direction of flow is inland; thus, these changes in dispersivity allowed for a sharper vertical transition zone and a more diffuse horizontal transition zone.

The estimated parameters were the permeabilities and porosities of the four texture categories and the longitudinal and transverse dispersivities. The hydraulics and the seawater transport were most sensitive to the permeabilities; e.g., the downward migration of seawater was

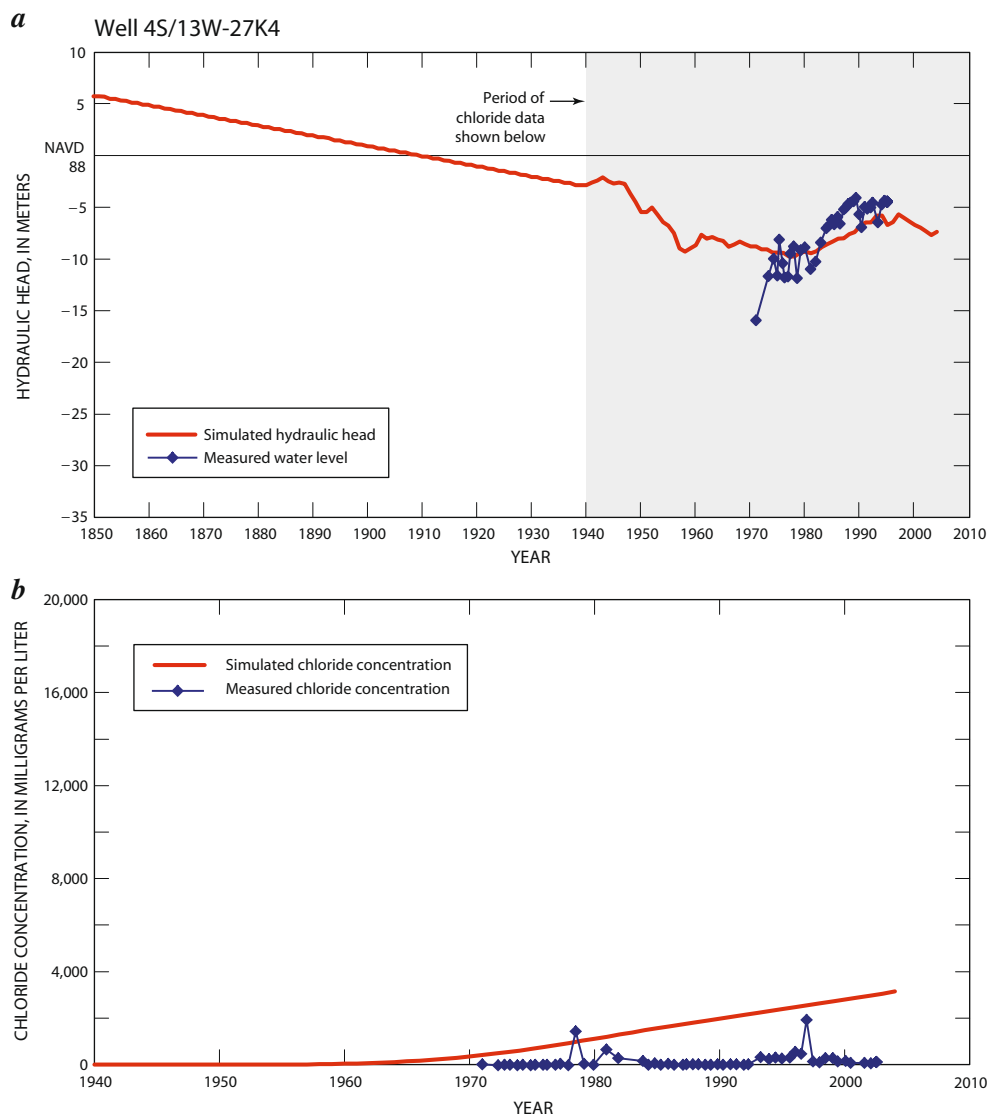


Fig. 10 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-27K4

sensitive to the permeability of the dominantly silt and clay category (brown in Fig. 2). In addition, the horizontal-to-vertical anisotropy of this value must be large (1,000:1) to prevent seawater from migrating downward too far and to allow for horizontal fronts to move inland. However, once the appropriate anisotropy ratio for this texture category had been determined and fixed, slight changes in its permeability had a smaller relative impact than that of the other three texture categories. The permeabilities of the remaining three texture categories all had relatively similar effects on the results. One value may have a greater effect than the others given particular values for the other parameters; therefore, the task became finding the best combination of values via trial-and-error. Changes in porosities of the four texture categories and the dispersivities affected primarily the results of seawater transport. Changes in the porosity values for each of the four categories had a similar effect on the results; however, smaller porosities allowed

seawater to migrate too quickly. Therefore, these values were increased, close to maximum values reported in the literature, to obtain good results. Changes in longitudinal and transverse dispersivities had the smallest effect on the overall results of the model; however, these values had significant impacts on two wells: 4S/13W-33Q1 and 5S/13W-11P1 (one of the primary calibration wells). Increasing the longitudinal dispersivity and decreasing the transverse dispersivity was necessary to not only gain significant improvements at the two aforementioned wells but also to gain a slight overall improvement at the remaining wells.

Model-calibration results

The objective criteria used throughout the calibration process is qualitative rather than quantitative, i.e., a mathematically calculated objective such as least-squares, was not used. The data obtained at each of the wells are

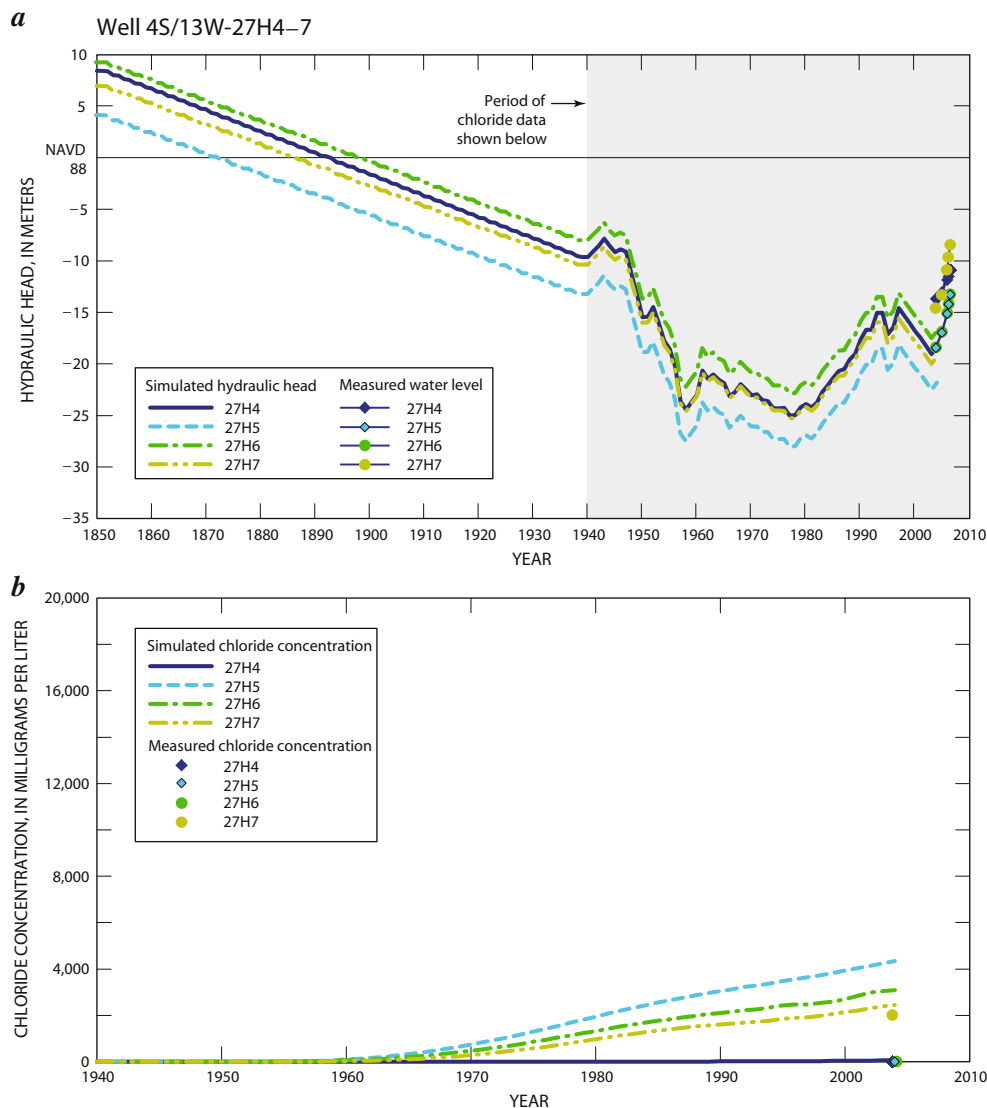


Fig. 11 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-27H4-7

not equally weighted and the determination of an appropriate weighted objective function was not straightforward. In addition, the forward model runtime was approximately 6 h using a workstation with dual 2.66 GHz quad-core Xeon processors; therefore, the application of a formal optimization algorithm such as Gauss-Newton, was infeasible. Moreover, the sensitivity analysis was also qualitative; each parameter was perturbed individually and the effects of each perturbation were observed qualitatively using plots of observed versus predicted values. Based on these results, the direction and step size of the next iteration was evaluated. Due to lengthy runtimes, a quantitative search algorithm and sensitivity analysis for this study was infeasible.

The contours of simulated Cl distributions for initial conditions (1849) and the end of December 2004 are shown in Fig. 14. The initial-condition Cl distribution indicates that the 2,000 mg/L Cl (about 10% seawater) did not reach the coastline (Fig. 14a). As noted above, the low vertical permeability of the uppermost clay layers prevents

the seawater offshore from being transported down into the Pliocene A sequence and below (Figs. 2 and 5b).

The 2004 Cl contours indicate that Cl is drawn inland by below-sea-level water levels (Fig. 14b) through the high- k sands and gravels of the Dominguez sequence (Fig. 2). Seawater is transported down through the underlying Bent Spring and into the Upper Wilmington sequence just inland from the PCH and Richfield Faults (Fig. 2).

Measured and simulated hydrographs and breakthrough curves for 16 selected wells are presented in geographic order starting from the coast moving inland in Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13. The construction information for the selected wells is presented in Table 3.

Wells 5S/13W-11P1,2 are USGS monitoring wells located closest to the coast (Fig. 1) that are perforated between 332 and 338 m and 102 and 108 m bsl (Table 3), respectively. As noted above, a primary calibration goal was to simulate the large difference in Cl concentrations between the shallow and deeper zones. There are limited water-level and Cl data at these wells; however, the

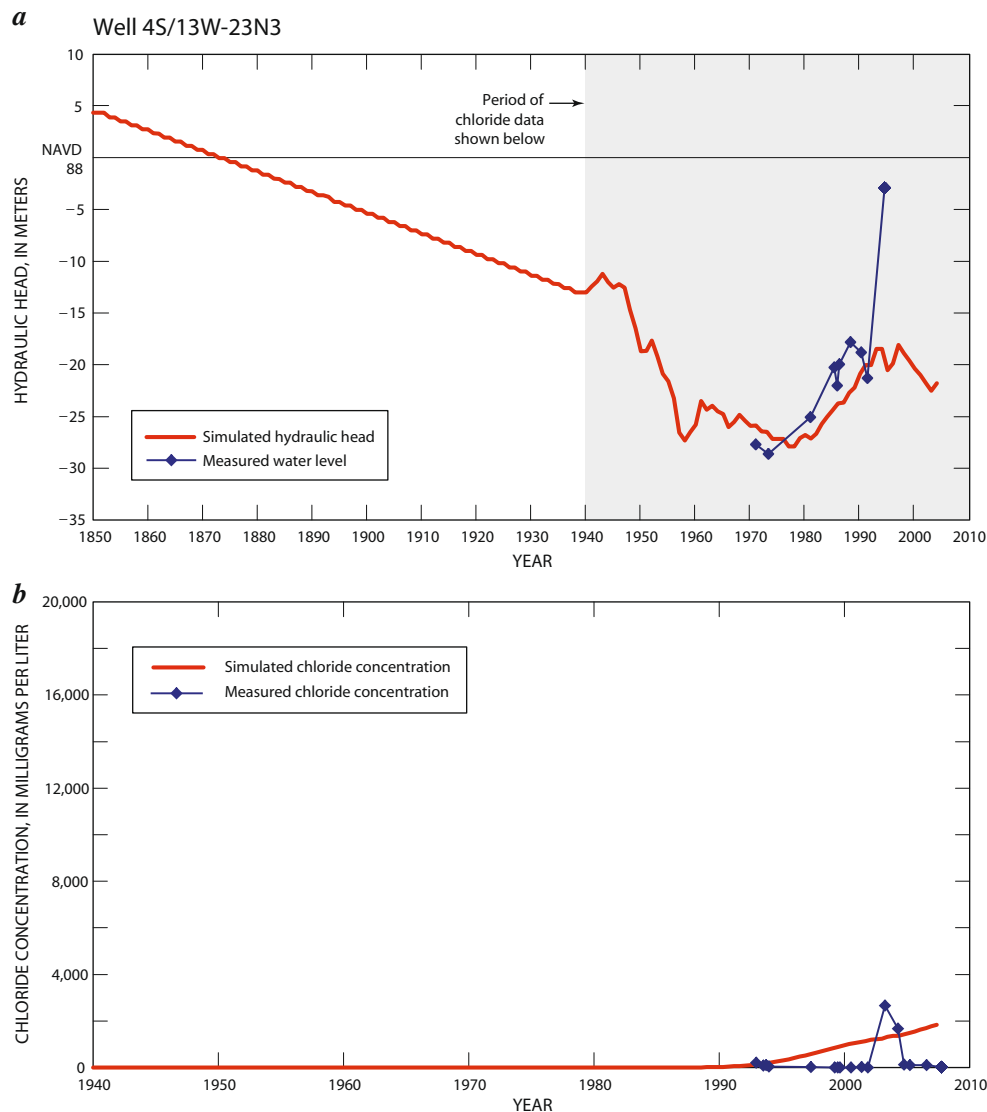


Fig. 12 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-23N3

simulated hydraulic heads and breakthrough curves are in good agreement with the measured data (Fig. 5). In addition, the simulated results maintain the vertical gradient in the measured water levels and Cl concentrations, i.e., higher water levels and Cl concentrations at shallow depths (11P2) and lower water levels and Cl concentrations at deeper depths (11P1, Fig. 5).

Wells 5S/13W-2E1,2 are USGS monitoring wells located inland of wells 11P1,2 (Fig. 1) that are perforated between 366 and 372 m bsl and 244 and 250 m bsl (Table 3), respectively. The simulated hydraulic heads underestimate the measured water-level data at both wells; however, the simulated Cl concentrations are in good agreement with the low measured Cl concentrations (Fig. 6). In addition, the vertical hydraulic gradient is simulated at this well, although the simulated gradient is greater than the measured.

Well 4S/13W-33Q1 is an LACDPW monitoring well located inland of the coastline (Fig. 1) that is perforated between 34 and 55 m bsl (Table 3). The

simulated hydraulic heads match the measured water-level data relatively well; however, the earliest measurements are lower than the simulated values (Fig. 7a). This may be due to local or transient pumping effects. The simulated breakthrough curve is in good agreement with the measured Cl concentrations, although the front arrives earlier than the measured Cl (Fig. 7b). The early arrival of the Cl front may be explained by a too high α value; however, if the α value is decreased then the simulated results at other wells are adversely affected.

Well 4S/13W-34F2 is an LACDPW monitoring well (Fig. 1) that is perforated between 93 and 116 m bsl (Table 3). The simulated hydraulic heads match the measured water-level data relatively well later in time; however, the earliest measurements are lower than the simulated values (Fig. 8a). Like well 33Q1, this may be due to local or transient pumping effects. The simulated breakthrough curve is in good agreement with the observed Cl concentrations early in time; however, the

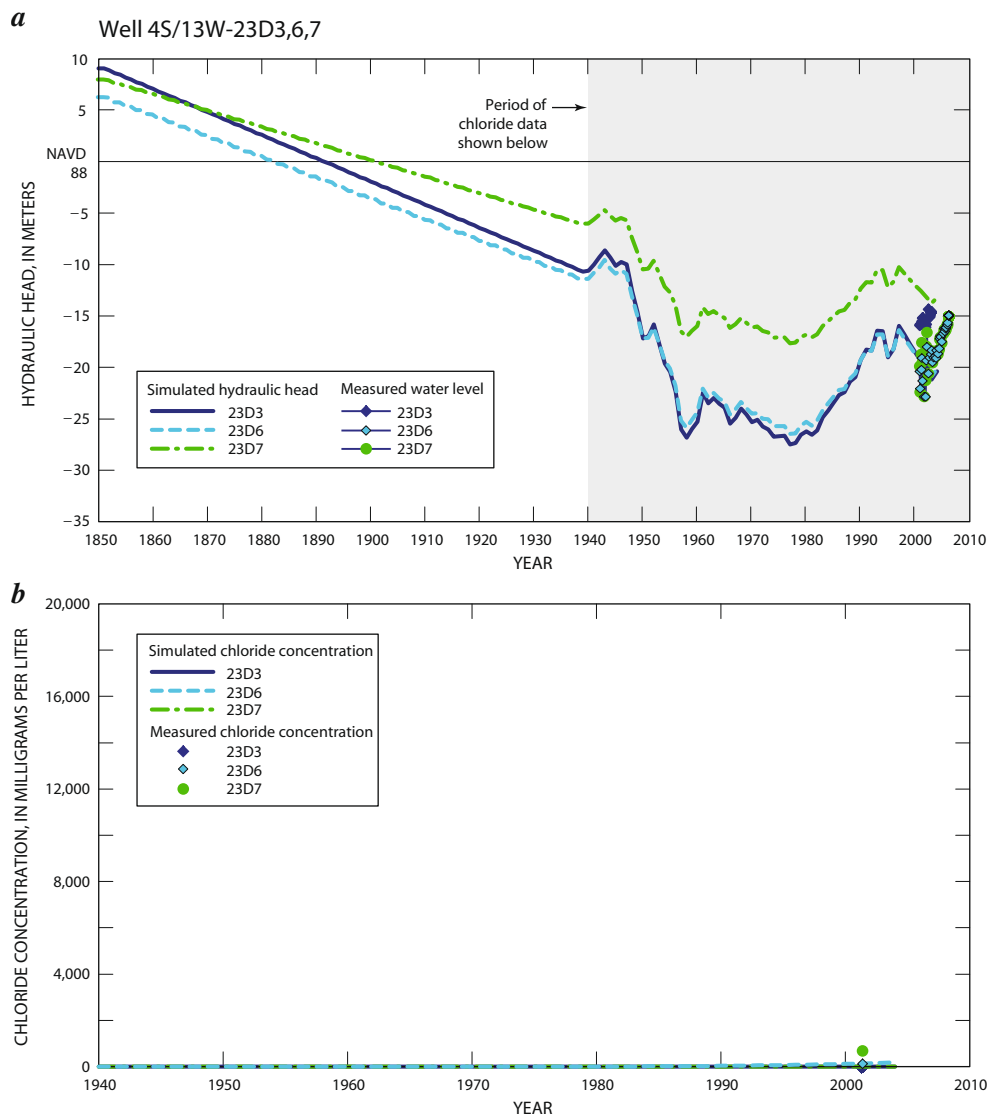


Fig. 13 Simulated and measured **a** hydrographs and **b** chloride breakthrough curves for well 4S/13W-23D3,6,7

measured Cl increase starting around 1995 is not simulated (Fig. 8b).

Well 4S/13W-27D6 is an LACDPW monitoring well on the coastline-side of the PCH Fault (Fig. 1) that is perforated between 82 and 114 m bsl (Table 3). The simulated hydraulic heads are lower than the measured water level data (Fig. 9a). The simulated breakthrough curve is in good agreement with the early observed Cl concentrations; however, the decrease in measured Cl concentrations beginning in the mid-1980s is not simulated (Fig. 9b). These low measured Cl concentrations may be due to local injection effects from the nearby Dominguez Gap Barrier Project that are not explicitly addressed in the model.

Well 4S/13W-27K4 is an LACDPW monitoring well located inland of the PCH Fault (Fig. 1) that is perforated between 66 and 88 m bsl (Table 3). The simulated hydraulic heads match the measured water-level data relatively well (Fig. 10a). The simulated breakthrough curve somewhat overestimates the mea-

sured Cl concentrations; however, the simulated breakthrough curve does match the measured peak Cl concentrations (Fig. 10b).

Wells 4S/13W-27H4-7 are USGS monitoring wells that are perforated between 360 and 372 m bsl; 198 and 204 m bsl; 143 and 149 m bsl; and 110 and 116 m bsl, respectively (Table 3). As noted above, a primary calibration goal was to simulate the downward movement of high-Cl water as observed in well 27H7. In general, the magnitudes of the simulated hydraulic heads are in good agreement with the measured water-level data; however, the simulated hydraulic-head gradient is incorrect (Fig. 11a), i.e., the measured data indicate a downward gradient from 27H7 to 27H5; however, the simulated results indicate that 27H6 has the highest simulated hydraulic heads. The simulated breakthrough curves are in good agreement with the measured Cl data for the shallowest and deepest wells (27H4 and 7, respectively); however, the simulated breakthrough curves overestimate the measured data at the intermediate-depth wells

Table 3 Well construction for wells used for model calibration, Dominguez Gap area, California

Local Name	State well No.	Depth of top perforation	Depth of bottom perforation	Land surface altitude
Long Beach-5 No. 1	5S/13W-11P1	332.32	338.41	3.05
Long Beach-5 No. 2	5S/13W-11P2	102.13	108.23	3.05
Long Beach-4 No. 1	5S/13W-2E1	365.85	371.95	1.52
Long Beach-4 No. 2	5S/13W-2E2	243.90	250.00	1.52
362H	4S/13W-33Q1	33.54	54.88	3.35
361X	4S/13W-34F2	92.99	115.85	1.83
361U	4S/13W-27D6	82.32	114.33	4.27
370U	4S/13W-27K4	65.55	88.41	4.27
Long Beach-7 No. 1	4S/13W-27H4	359.76	365.85	4.88
Long Beach-7 No. 2	4S/13W-27H5	198.17	204.27	4.88
Long Beach-7 No. 3	4S/13W-27H6	143.29	149.39	4.88
Long Beach-7 No. 4	4S/13W-27H7	109.76	115.85	4.88
889P	4S/13W-23N3	140.24	143.29	5.30
Long Beach-3 No. 1	4S/13W-23D3	411.59	423.78	7.01
Long Beach-3 No. 4	4S/13W-23D6	161.59	167.68	7.01
Long Beach-3 No. 5	4S/13W-23D7	125.00	131.10	7.01

Depths in meters below land surface. Land surface altitude in meters above sea level

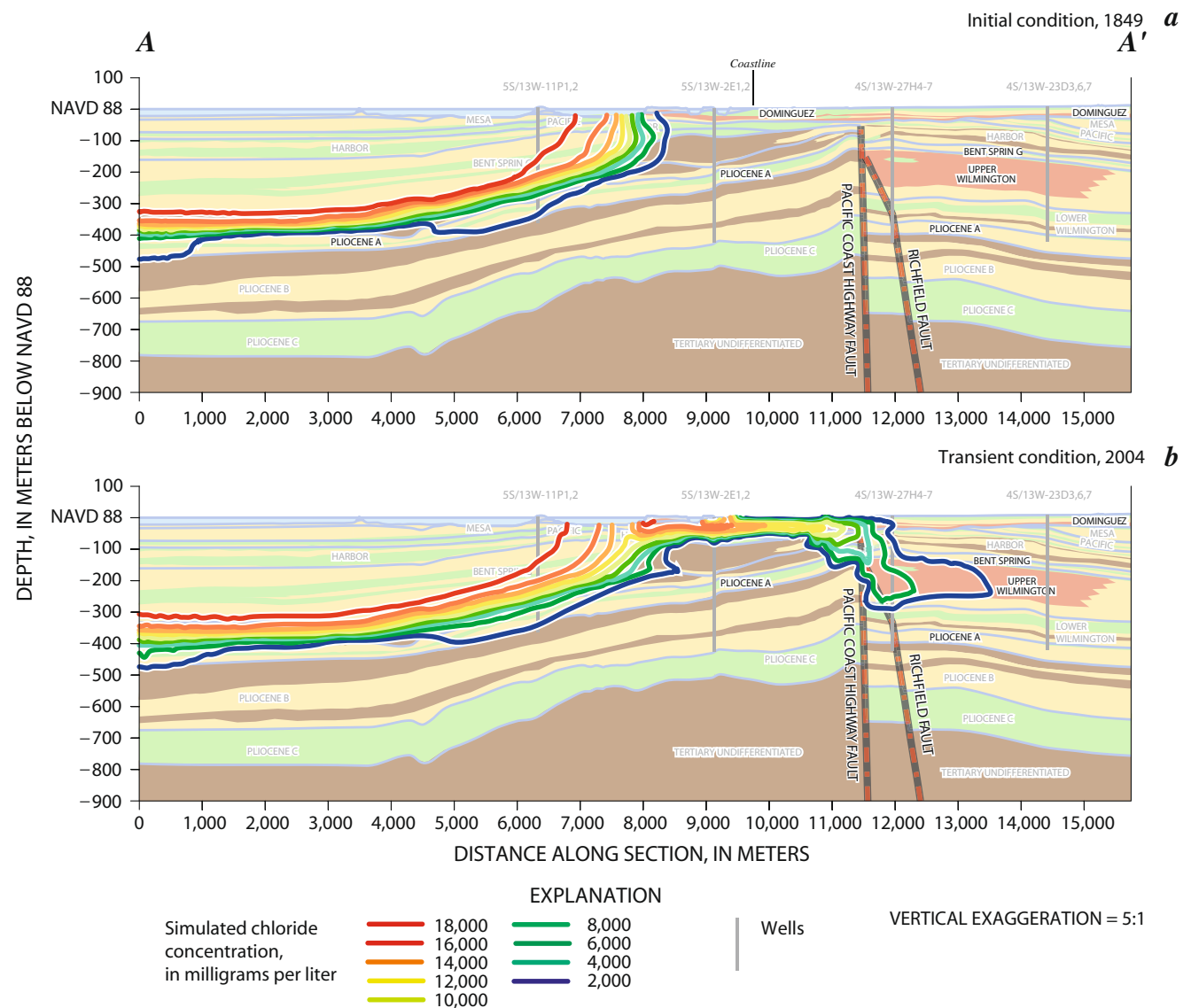


Fig. 14 Contours of simulated chloride concentrations for: **a** 1849 (initial condition) and **b** 2004

(Fig. 11b) indicating that the model is overestimating the vertical transport of Cl.

Well 4S/13W-23N3 is an LACDPW monitoring well inland of wells 27H4-7 (Fig. 1) that is perforated between 140 and 143 m bsl (Table 3). In general, the simulated hydraulic heads are in good agreement with the measured water-level data with exception of the high water-level measurement made in 1994 (Fig. 12a). The simulated breakthrough curve overestimates early and late measured Cl data and underestimates the peak Cl concentration (Fig. 12b).

Wells 4S/13W-23D3,6,7 are USGS monitoring wells near the inland boundary of the model domain (Fig. 1)

that are perforated between 412 and 424 m bsl; 162 and 168 m bsl; and 125 and 131 m bsl, respectively (Table 3). The simulated hydraulic heads are in good agreement with the measured water-level data at well and 23D6; however, the measured water-level data are underestimated and overestimated at wells 23D3 and 23D7, respectively (Fig. 13a). The high, simulated hydraulic heads at 23D7 may be the result of the time-varying FP-inland boundary not accurately representing the water levels at this depth. The simulated breakthrough curves indicate no Cl reaches these wells; however, there are low measured Cl concentrations at

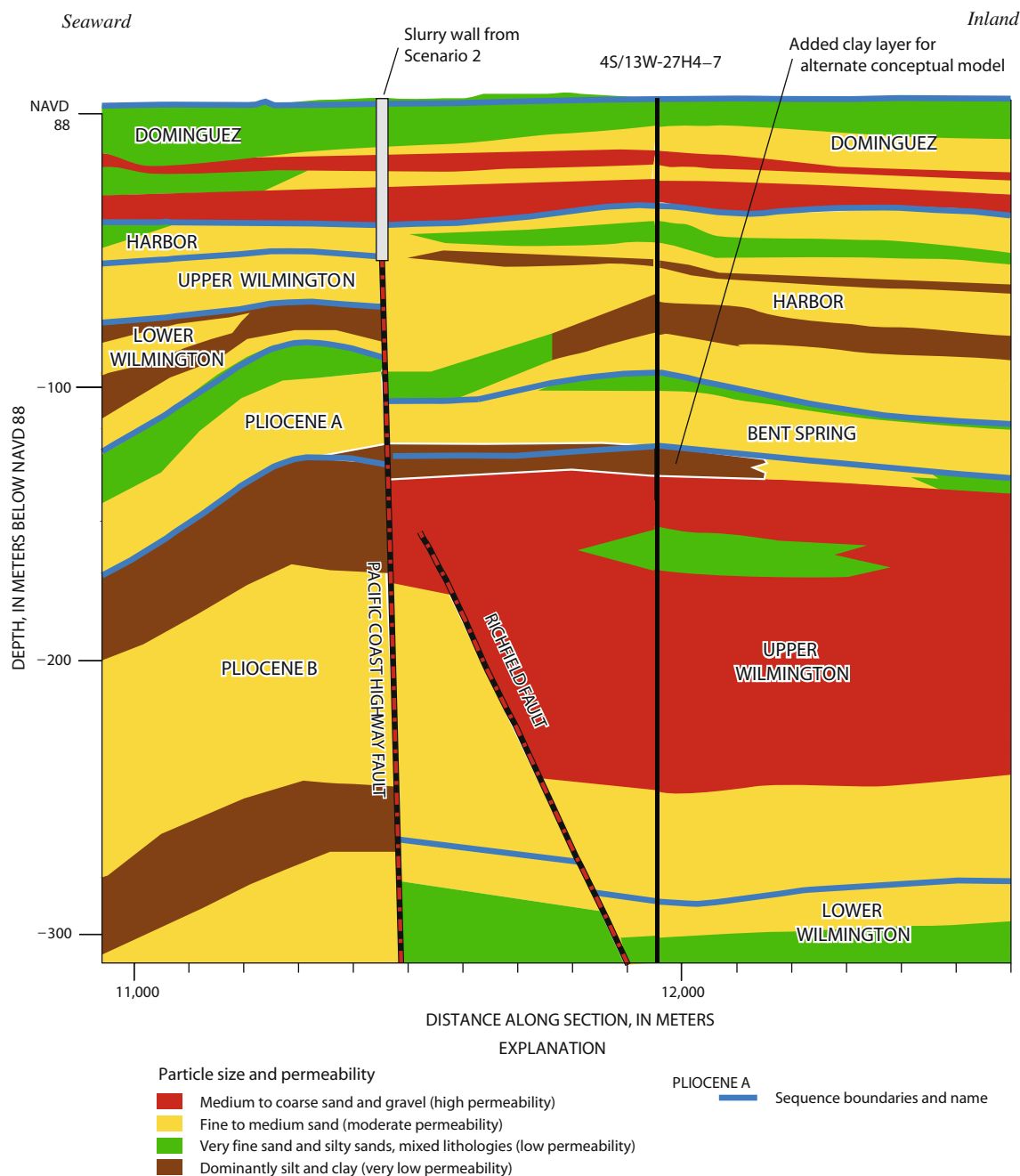


Fig. 15 The modified model layer (highlighted between the Bent Spring and Upper Wilmington sequences; see Fig. 2) for the alternative conceptual model and the location of the slurry wall for model scenario 2

well 23D7 (Fig. 13b). These results are consistent with the overestimation of hydraulic heads at 23D7.

In general, the simulated results are consistent with the overall pattern of seawater intrusion observed in the Dominguez Gap area: higher Cl concentrations in the shallower deposits and relatively freshwater at depth and near the coast (Fig. 5b); some downward movement of Cl near the PCH Fault (Fig. 11b), and with little Cl present farther inland (Fig. 13b).

Alternative conceptual model

While the model results described above reproduce the downward movement of high-Cl water from the shallow system near the PCH Fault as observed at well 4S/13W-27H7, the model simulates higher Cl concentrations extending deeper than the measured data indicate

(Fig. 11b). Specifically, the simulated Cl concentrations for wells 4S/13W-27H5 and 27H6 are higher than the well 27H7 concentrations (Fig. 11b); however, the observed data suggests the Cl concentrations should be near zero. Geochemical data (major-ion composition, tritium and carbon-14 activity, and the stable isotopes of water) for these wells indicate significant differences between 27H6 and 27H7 and significant similarities between wells 27H5 and 27H6 (M. Land, US Geological Survey, personal communication, 2007). In addition to the simulated Cl concentrations, the simulated hydraulic gradient between wells 27H6 and 27H7 is not in agreement with the measured data. Although, the lithologic description of the cores collected when well 4S/13W-27H4-7 was constructed does not indicate the existence of fine-grained sediments between 27H7 and 27H6 (Ponti et al. 2007; Fig. 12), the observed Cl, other geochemical data, and the stratigraphic boundary between the Bent Spring and Upper Wilmington

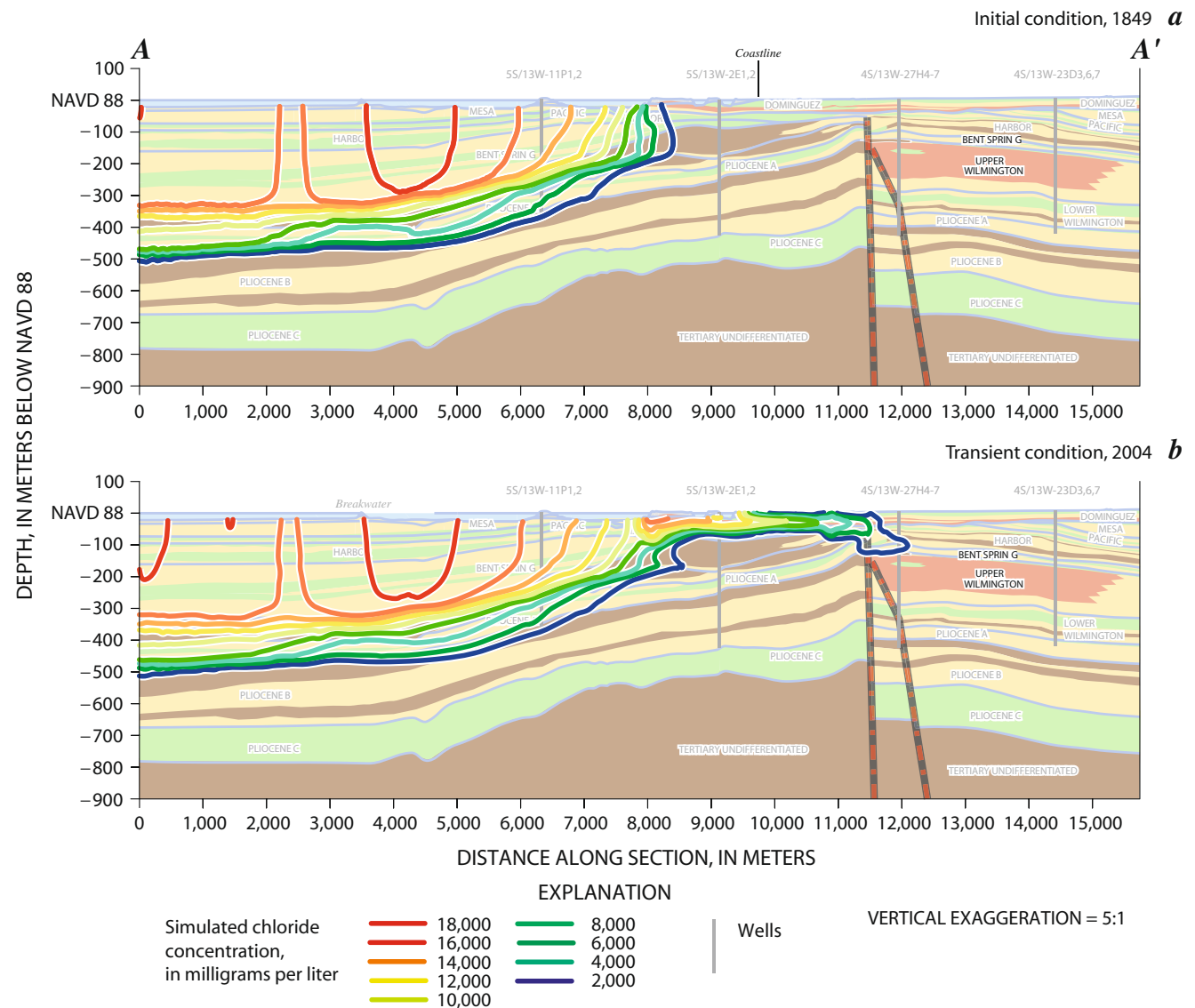


Fig. 16 Contours of simulated chloride concentrations for: **a** 1849 (initial condition) and **b** 2004 using the alternative conceptual model

sequences (Fig. 15) indicate that there may be a geologic control that hinders hydraulic communication between the Harbor and Upper Wilmington sequences.

As a numerical experiment, a low-permeability silt and clay layer was added extending from the PCH Fault, along the top of the high-permeability region of the Upper Wilmington sequence, to approximately 200 m inland of well 4S/13W-27H5 (Fig. 15). The addition of this silt and clay layer required the recalibration of the model that was achieved by increasing both the horizontal and vertical permeability of the very fine sand and silty sand textures (green regions in Fig. 2) by one order of magnitude. The simulated Cl contours for initial conditions (1849) and the end of December 2004 are shown in Fig. 16. The initial-condition Cl contours indicate that the 2,000 mg/L Cl contour moves slightly deeper and slightly farther inland than the original simulation (Fig. 16a).

The simulated 2004 Cl contours indicates that Cl is not drawn as far inland as the original simulation (Fig. 16b). In addition, seawater is transported down into the underlying Bent Spring and does not reach the Upper Wilmington sequence until the front migrates beyond the new silt and clay layer (Fig. 16b). Rising freshwater from the deep formations moving to the ocean bottom causes the pattern of the 16,000 and 18,000 mg/L contours in the shallow, offshore area (Fig. 16). This pattern does not occur if the original k values of the very fine sand and silty sand regions were used to simulate the initial conditions; however, the transient simulations would not converge. This indicates that the offshore k values for the very fine sand and silty sand regions may be lower than the onshore values, perhaps due to consolidation of the sediments. The strategy of this study was to consider only four texture categories; therefore, a separate adjustment of

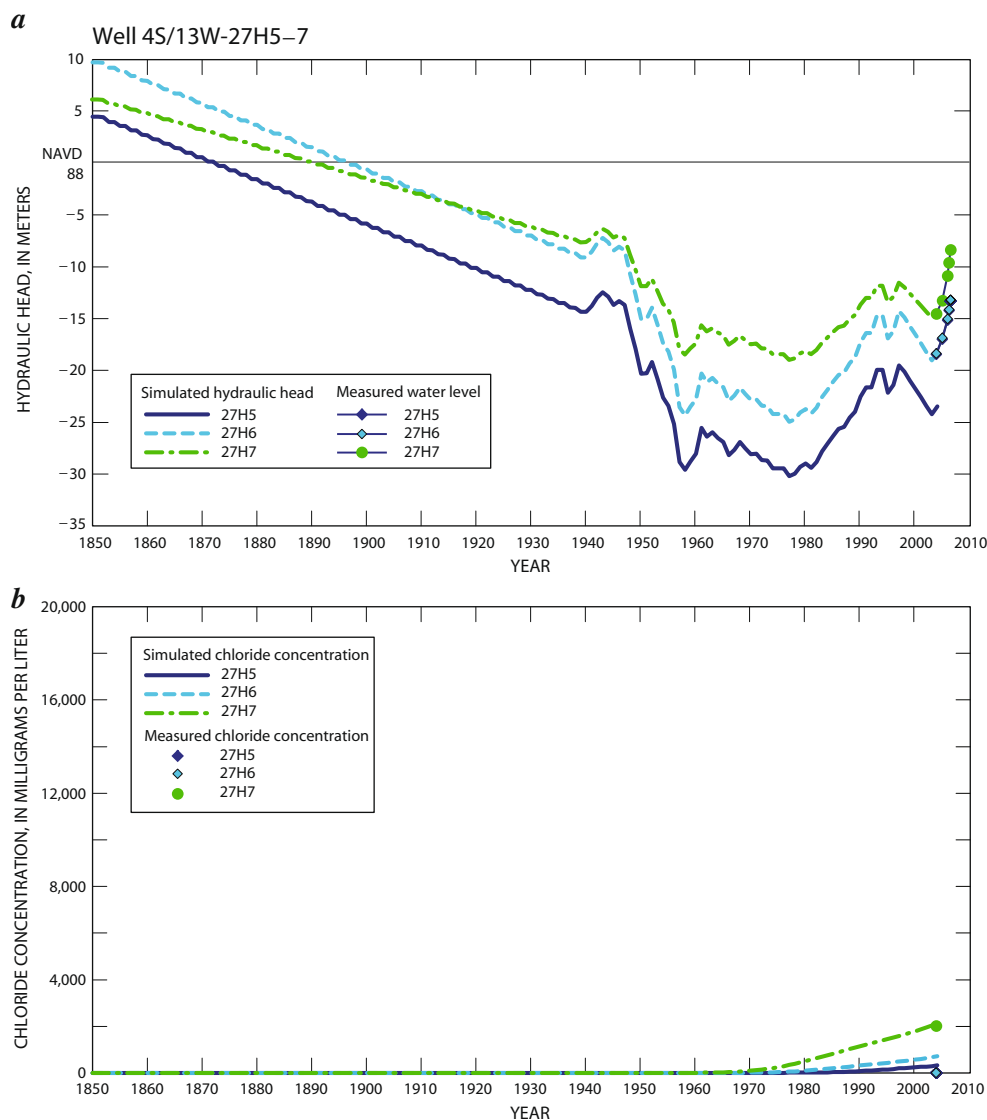


Fig. 17 Simulated and measured **a** hydrographs and **b** breakthrough curves using the alternative conceptual model for wells 4S/13W-27H5-7

the offshore very fine sand and silty sand regions was not implemented. The use of the results based on this conceptual model is reasonable however because the rising freshwater occurs far offshore (about 4,000 m

from 5S/13W-11P1,2 and 10,000 m from 4S/13W-27H4-7); therefore, the rising freshwater probably does not affect the simulated hydraulic heads and Cl concentrations in the area of interest.

Initial condition (2004) *a*

A'

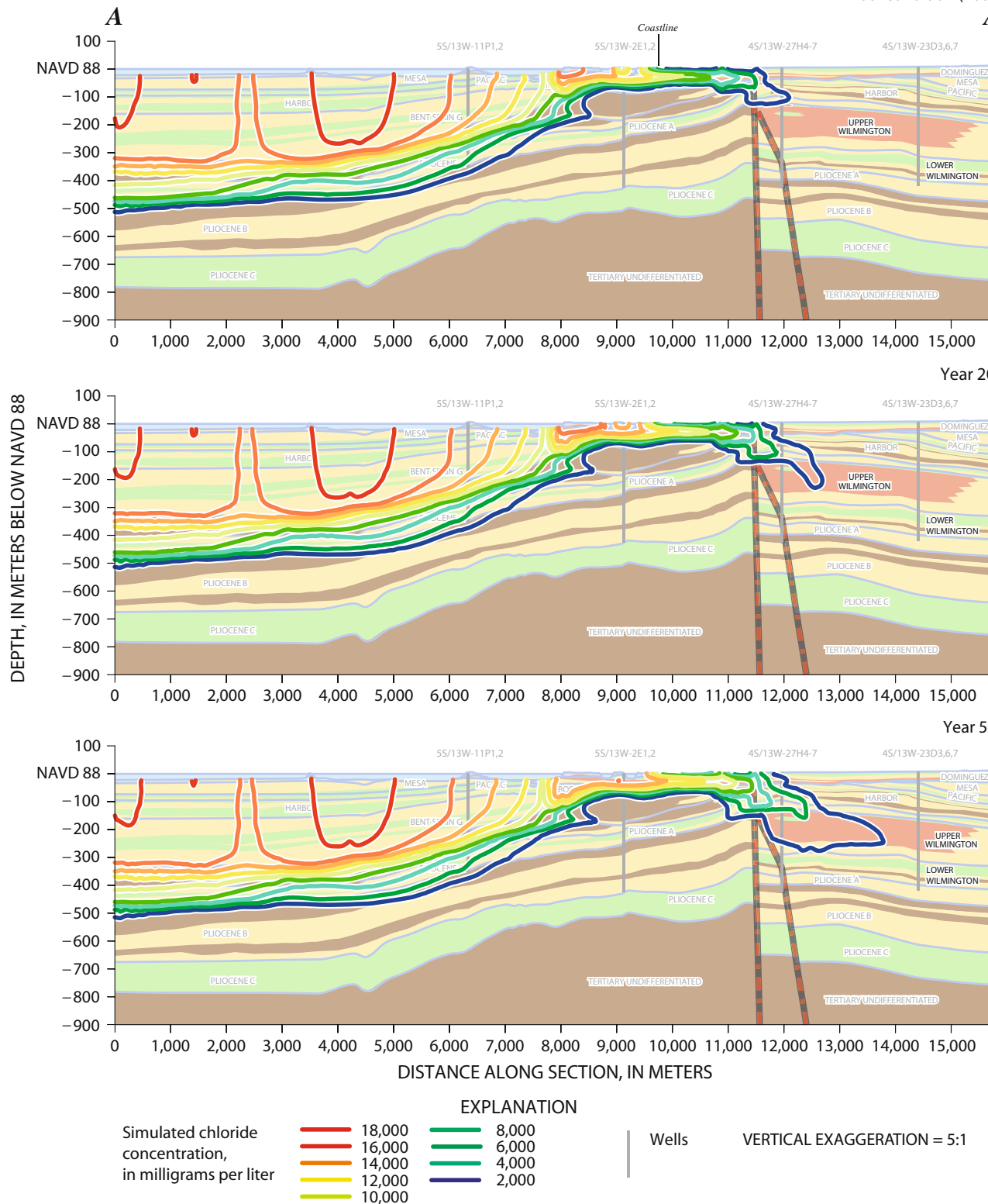


Fig. 18 Contours of simulated chloride concentrations for model scenario 1 (status quo conditions) using the alternative conceptual model for: **a** 2004 (initial condition), **b** year 20, and **c** year 50

The resulting breakthrough curves for wells 4S/13W-27H5-7 indicate the simulated concentrations at 27H7 match the observed Cl data and the significant differences in measured Cl concentrations between wells 27H7 and

27H6 are simulated (Fig. 17b). In addition, the simulated hydraulic heads and gradient between wells 27H6 and 27H7 are in agreement with the measured data at these wells (Fig. 17a). Although these results are based on a

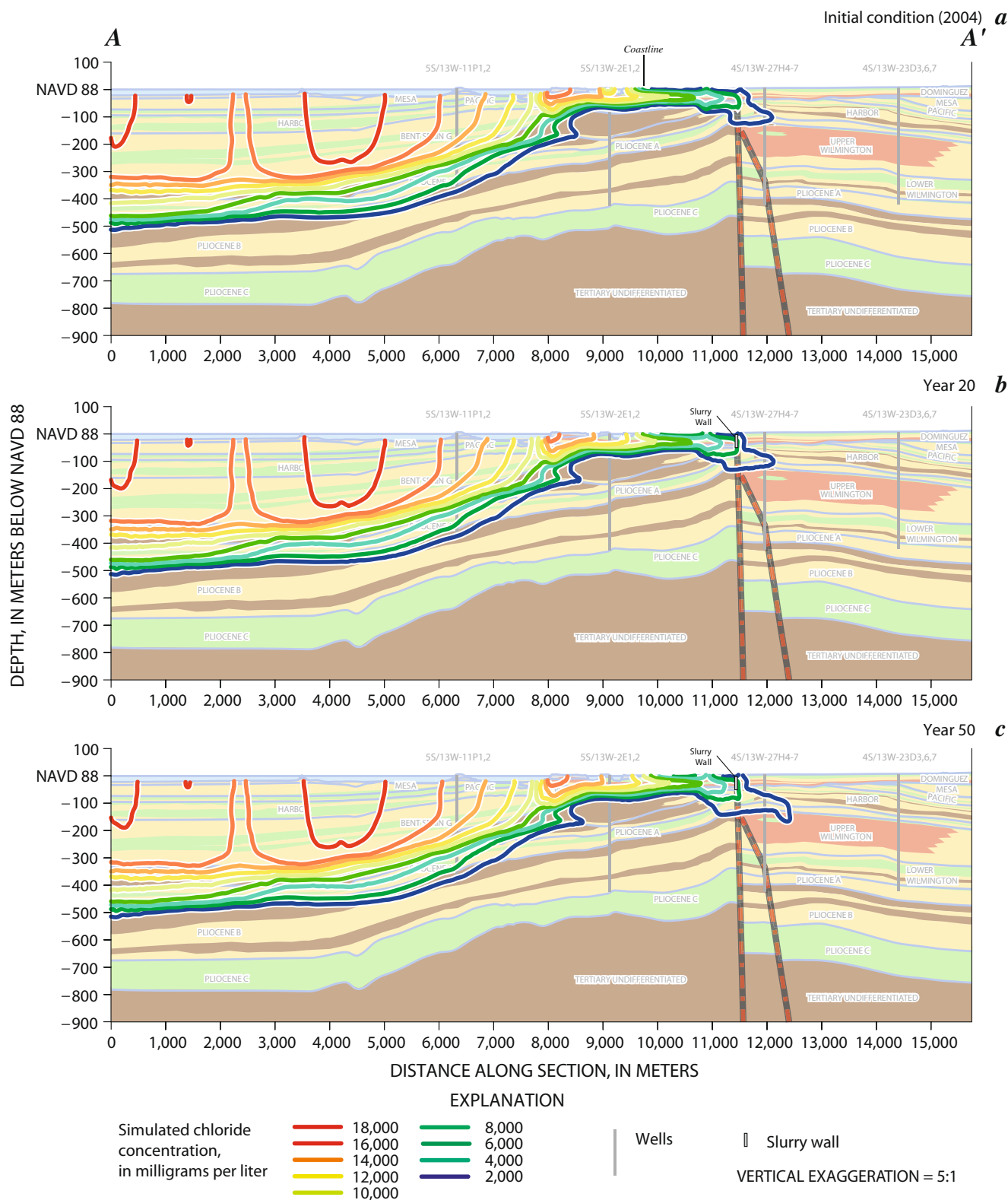


Fig. 19 Contours of simulated chloride concentrations for model scenario 2 (slurry wall) using the alternative conceptual model for: **a** 2004 (initial condition), **b** year 20, and **c** year 50

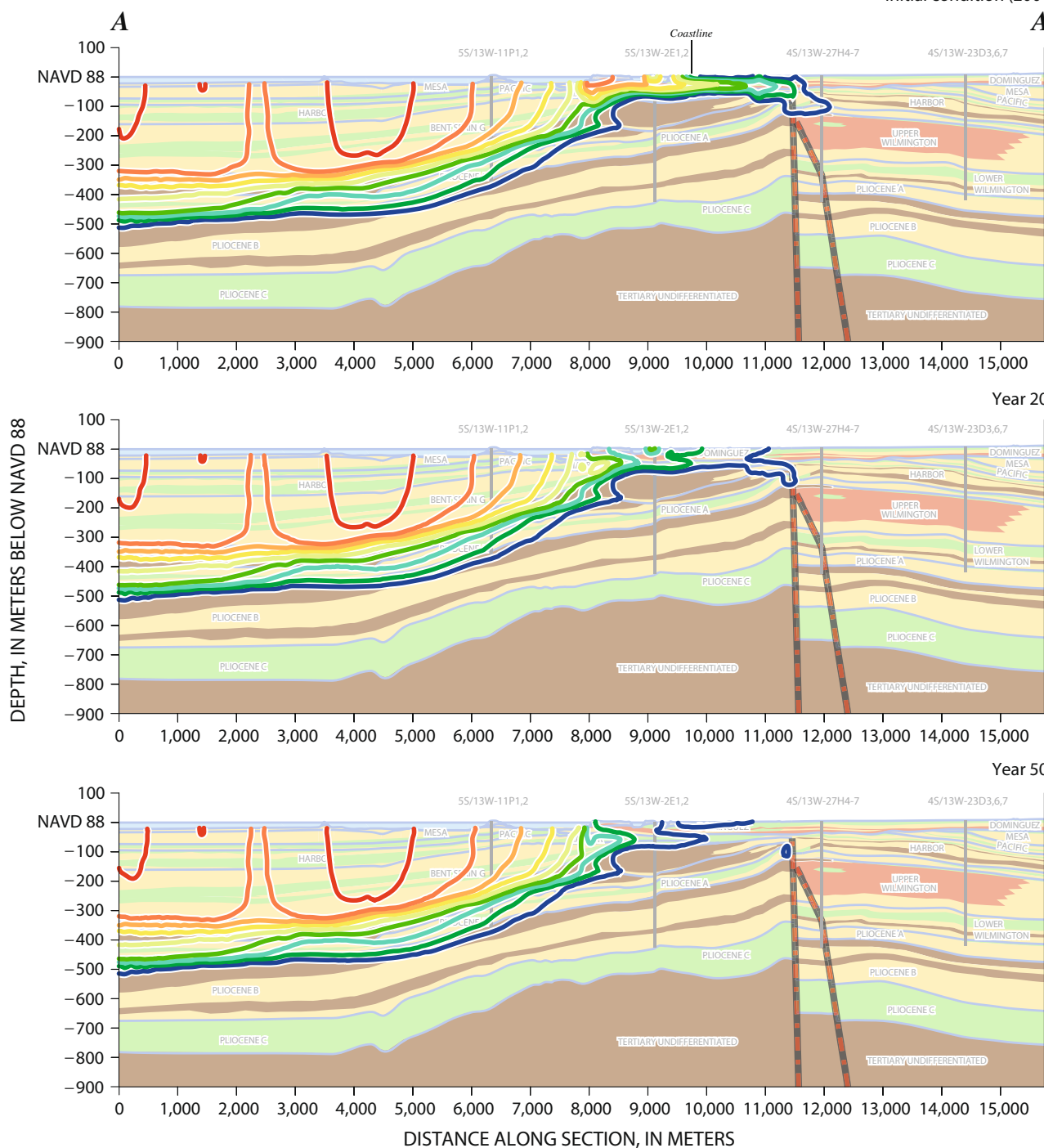
Initial condition (2004) **a****A'**

Fig. 20 Contours of simulated chloride concentrations for model scenario 3 (7.6-m-higher inland-boundary water levels) using the alternative conceptual model for: **a** 2004 (initial condition), **b** year 20, and **c** year 50

numerical experiment, they indicate that some type of hydraulic barrier exists between 27H7 and 27H6 corresponding to the stratigraphic boundary between the Bent Spring and Upper Wilmington sequences.

Simulation of future water-management scenarios

While the cross-sectional transport models presented here are very simplified representations of the three-dimensional hydrogeologic system, they can be used to test the effects of potential future seawater-intrusion management scenarios. Three specific scenarios were tested using the calibrated groundwater flow and transport model that was based on the alternative conceptual model. The alternative conceptual model was used because it better simulated the vertical hydraulic gradient and Cl transport at wells 4S/13W-27H4-7. All three scenarios used a 50-year simulation horizon.

The first scenario (base case) assumed the status quo, that is, the inland boundary conditions are maintained at the same levels as simulated for 2004 (water levels equal to sea level at boundary elevations above 124 m bsl and equal to 22.4 m bsl at boundary elevations below 124 m bsl). The second scenario assumes that a 50-m deep slurry wall is installed near the location of the PCH Fault in order to control further seawater intrusion (Fig. 15). A concrete-bentonite slurry wall was assumed with a permeability of $1.02 \times 10^{-17} \text{ m}^2$ (Portland Cement Association 2007) with an assumed porosity of 0.001. The same inland boundary conditions as those in the first scenario were used. The third scenario assumes that actions are taken (increased injection and/or reduced pumpage) to raise inland water levels to 7.6 m asl; therefore, the pressure is increased over the entire FP-inland boundary.

Figures 18, 19, 20 show the simulated Cl distributions for the initial condition (2004), year 20, and year 50 for

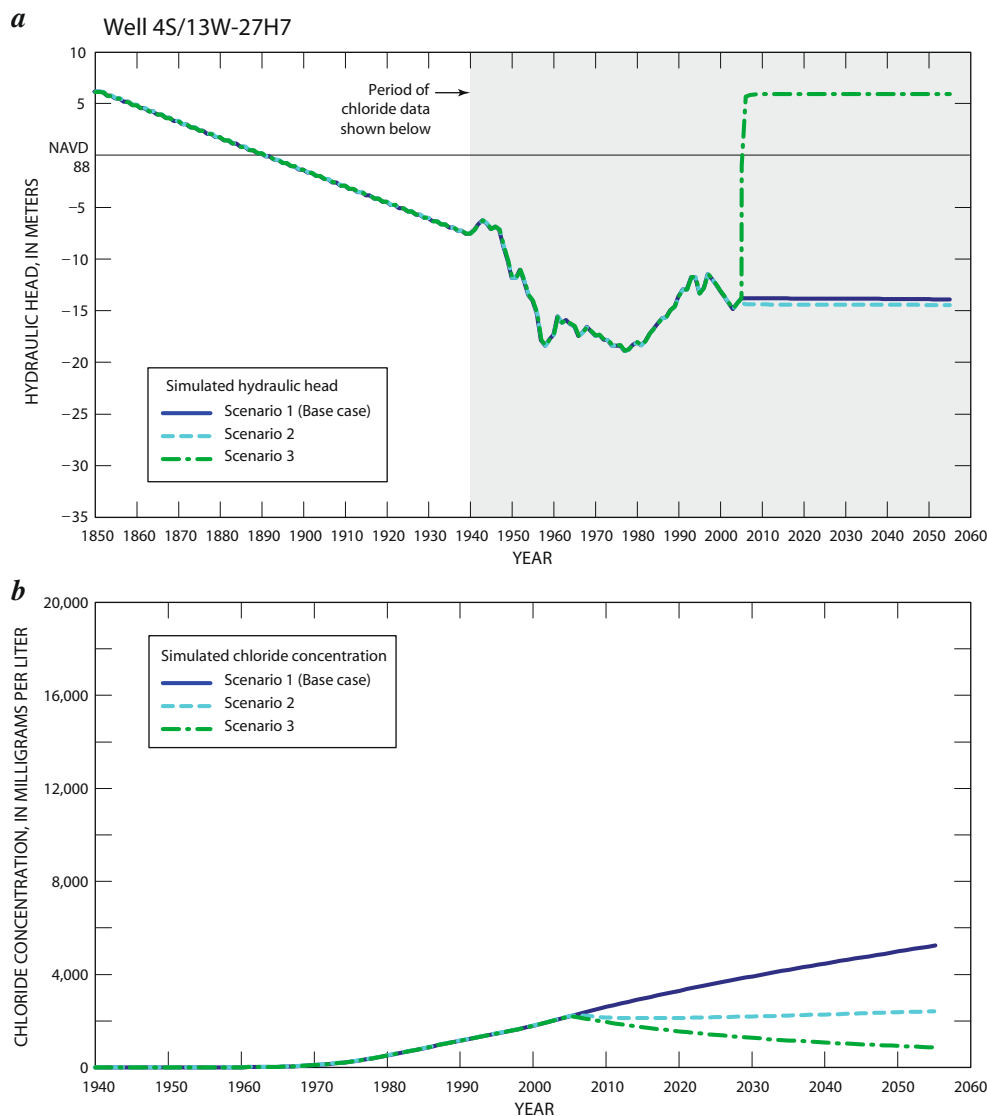


Fig. 21 Simulated **a** hydrographs and **b** breakthrough curves for model scenarios 1–3 using the alternative conceptual model at well 4S/13W-27H7

each scenario using the calibrated groundwater flow and transport based on the alternative conceptual model. The base case (scenario 1) simulated Cl contours indicate the greatest inland extent of the Cl front (Fig. 18). After

50 years under status quo conditions, the 2,000 mg/L Cl contour has moved downward from the Upper Wilmington sequence into the Lower Wilmington sequence (Fig. 18c). After 50 years, the slurry wall (scenario 2) has slowed the

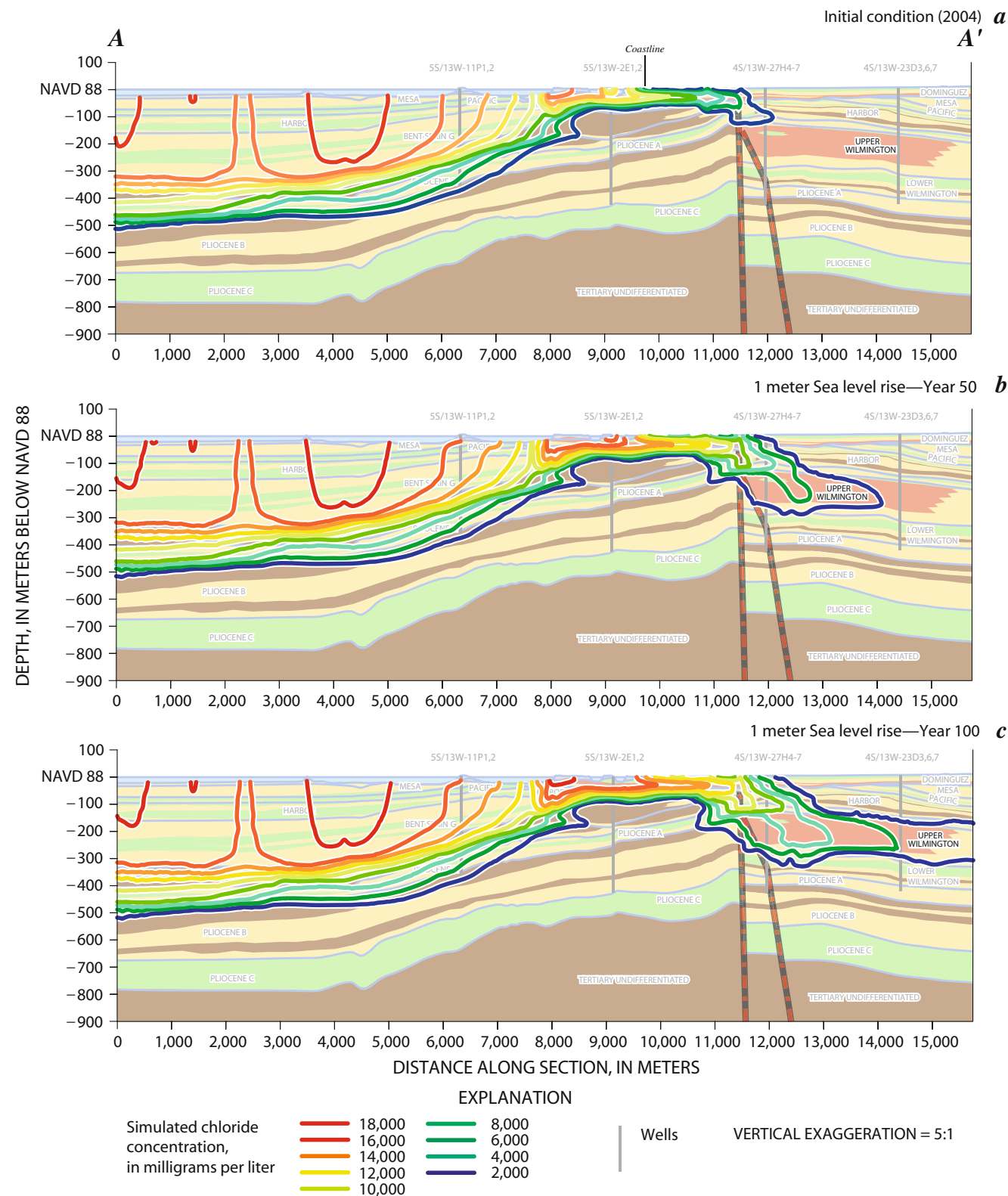


Fig. 22 Contours of simulated chloride concentrations assuming a 1-m sea-level rise for model scenario 1 using the alternative conceptual model for: **a** 2004 (initial condition), **b** year 50, and **c** year 100

transport of seawater compared to status quo conditions; however, the 2,000 mg/L contour has passed wells 4S/13W-27H4-7 and moved into the Upper Wilmington sequence (Fig. 19c). After 50 years of increased inland water levels

(scenario 3), the 2,000 mg/L Cl contour was moved seaward almost reaching wells 5S/13W-2E1,2 and there is a small amount of low-concentration-Cl water trapped behind the PCH Fault (Fig. 20c).

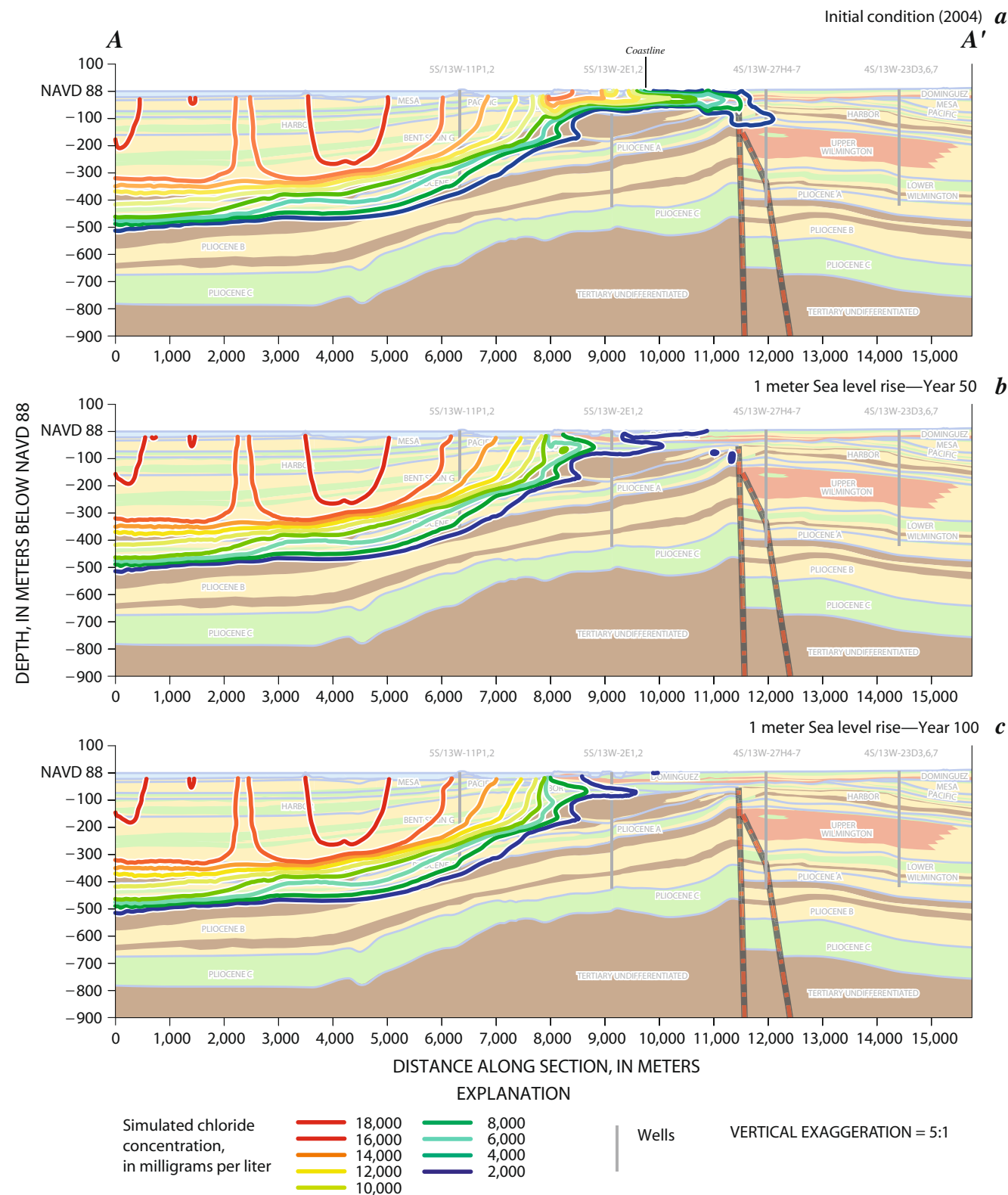


Fig. 23 Contours of simulated chloride concentrations assuming a 1-m sea-level rise for model scenario 3 using the alternative conceptual model for: **a** 2004 (initial condition), **b** year 50, and **c** year 100

The simulated hydrographs and breakthrough curves at well 4S/13W-27H7 for the three scenarios are shown in Fig. 21. Recall this well is located about 3,300 m seaward of the inland boundary and is perforated between 110 and 116 m bsl. Scenario 1 has the greatest simulated Cl concentrations with a maximum concentration of 5,900 mg/L. The breakthrough curve for scenario 2 indicates that the simulated Cl concentrations at well 4S/13W-27H7 remained relatively constant (less than 2,500 mg/L) after 2010 (year 6, Fig. 21b). For scenario 3, the simulated Cl concentrations decreased from an initial condition of 2,200–860 mg/L in 2055 (year 50, Fig. 21b).

Sea-level rise

The Intergovernmental Panel on Climate Change (IPCC) reported that increasing concentrations of greenhouse gases (e.g., carbon dioxide) in the atmosphere might result in a sea-level rise in the next 100 years of 0.6 m or more (Intergovernmental Panel on Climate Change 2007). To test the possible effects on seawater intrusion, the calibrated model based on the alternative conceptual model was run assuming a sea-level rise of this general magnitude, i.e., an instantaneous 1-m increase on the FP-offshore boundaries. The model horizon was 100 years

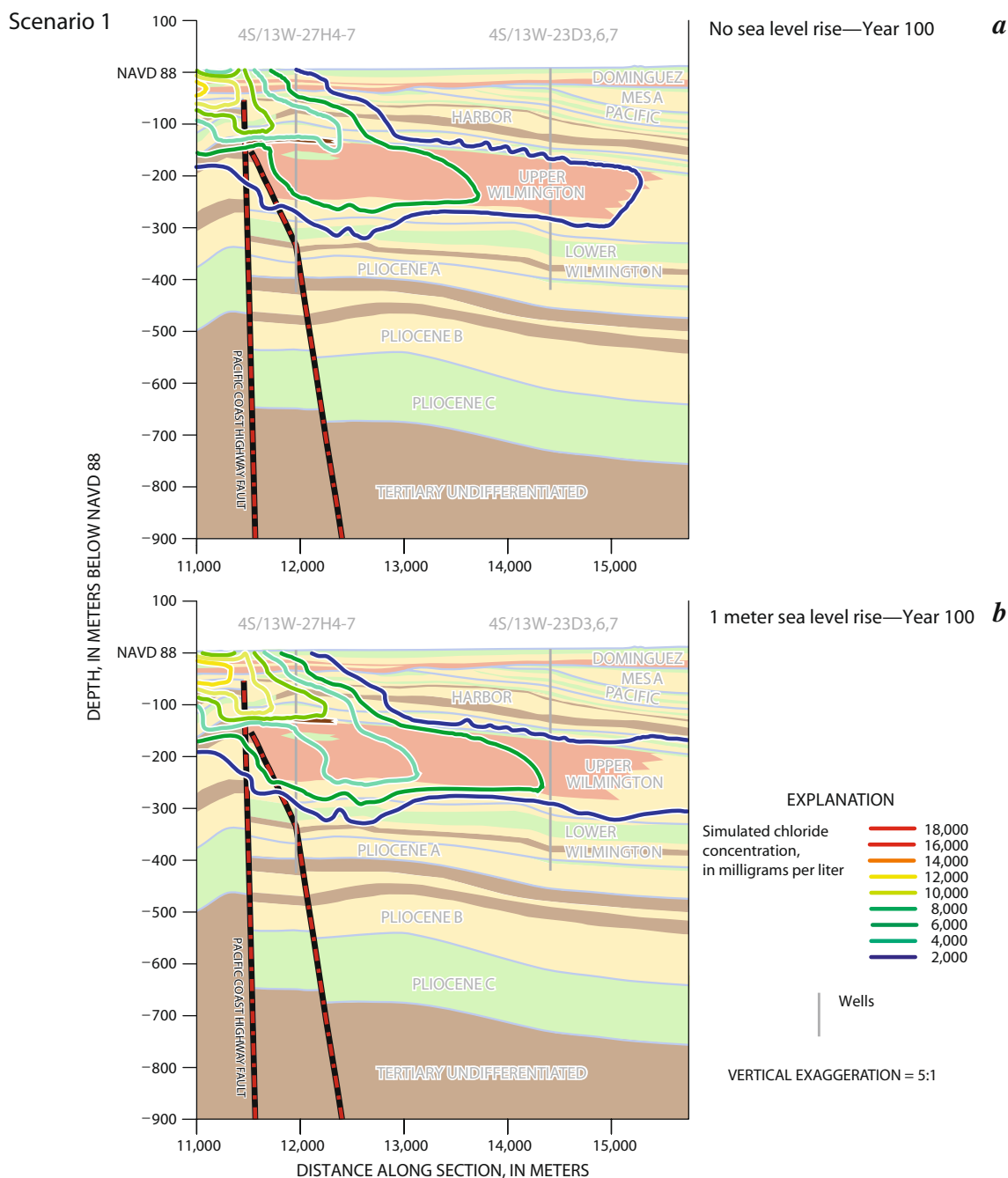


Fig. 24 Year-100 contours of simulated chloride concentrations for model scenario 1 using the alternative conceptual model and assuming: **a** a 0-m sea-level rise and **b** a 1-m sea-level rise

using simulated 2004 conditions as initial conditions and water-management scenarios 1 and 3 were tested.

Simulated Cl contours for initial conditions, 50 years, and 100 years for both scenarios are presented in Figs. 22 and 23. Assuming 2004 water levels are maintained at the inland model boundary (scenario 1) results in the Cl moving landward with the 2,000 mg/L contour moving past the inland model boundary after 100 years (Fig. 22c). Assuming an inland boundary condition rise to 7.6 m asl (scenario 3) results in the Cl front moving seaward and the 2,000 mg/L contour is pushed back to well 5S/13W-2E1,2 by year 100 (Fig. 23c).

A comparison is made between assuming a 0-m and 1-m sea-level rise for scenarios 1 and 3, respectively. Figure 24 shows the simulated 100-year Cl contours inland of the PCH Fault assuming scenario 1 conditions for the 0-m and 1-m sea-level rise. Assuming a 0-m sea-level rise results in the 2,000 mg/L contour almost reaching the inland boundary (Fig. 24a). Assuming a 1-m sea-level rise results in the 2,000 mg/L moving past the inland boundary and the 4,000 mg/L contour moving almost 500 m farther inland than the 0-m sea-level rise (Fig. 24b).

The simulated 100-year Cl contours, assuming scenario 3 conditions for the 0-m and 1-m sea-level rise, are essentially identical. After 100 years, for both the 0-m and 1-m sea-level rise, the Cl front is pushed back to well 5S/13W-2E1,2. These results indicate that raising inland water levels to 7.6 m asl may help mitigate the effects of a 1-m sea-level rise.

Conclusions

The cross-sectional groundwater flow and solute-transport model presented here is quite simplified, and clearly does not fully represent the complexity of the heterogeneous groundwater flow and transport processes in the Dominguez Gap area. However, it provides a useful tool with which to test the hydrogeologic implications of the recently developed sequence stratigraphic model of the Dominguez Gap area (Ponti et al. 2007), to evaluate the potential impacts of three future management scenarios on seawater intrusion, and to evaluate the potential impacts of a 1-m sea-level rise.

The simulated chloride concentration results indicate that the clay layers must have very low permeability values with high horizontal-to-vertical anisotropy ratios, for seawater not to have moved down into deeper formations offshore. This conclusion is verified by measured chloride concentrations.

A major hypothesis of Ponti et al. (2007) is that the recent folding associated with the Pacific Coast Highway Fault has preferentially eroded fine-grained units, thereby providing a pathway for seawater to migrate down from shallow deposits into deeper zones near the fault (such as observed at well 4S/13W-27H7). Results of the simulations show that discontinuity in the shallow clay layers in this area does allow for seawater to move downward. However, the groundwater flow and solute-transport model simulates higher-chloride water extending to greater depths than

observed chloride data indicate (e.g., monitoring wells, 4S/13W-27H5-6) and the vertical hydraulic gradient is incorrect. An alternative conceptual model, which incorporated a low-permeability layer above the Upper Wilmington sequence at this location, provided a better match to the observed data. These results indicate that some type of hydraulic barrier exists between 27H7 and 27H6 that corresponds to the stratigraphic boundary between the Bent Spring and Upper Wilmington sequences.

The flow and transport model, based on the alternative conceptual model, was applied to assess the likely progression of seawater intrusion over the next 50 years for three alternative scenarios: (1) base case, where inland boundary water levels remain at 2004 levels; (2) installation of a 50-m deep slurry wall to act as a physical barrier to seawater intrusion; and (3) the raising of inland water levels to form a hydraulic barrier to seawater intrusion. Results showed that seawater would continue to intrude landward when using scenario 1. Scenarios 2 and 3 resulted in less seawater intrusion, but only scenario 3 showed seawater actually retreating.

The effects of a 1-m sea-level rise on seawater intrusion were estimated using the alternative conceptual model and management scenarios 1 and 3. After 100 years, a 1-m sea-level rise may allow seawater to migrate farther inland than a 0-m sea-level rise assuming 2004 water levels are maintained at the inland boundary. After 100 years, there is little difference between the 0 and 1-m sea-level rise assuming that inland-boundary water levels are increased to 7.6 m above sea level.

In this study, the model calibration and scenario simulations have been deterministic, i.e., uncertainties in model parameters, boundary conditions, sea-level rise, etc. have not been considered due to the lengthy run-time of the numerical model. An avenue of further research would include the exploration of model-reduction techniques used to reduce the computation burden of this model; these include artificial neural networks, nonlinear regression, etc. With this reduction, an uncertainty analysis and a formal search algorithm for parameter estimation would be feasible. In addition, model-reduction would allow for the development of a three-dimensional model for the study region. However, the current model is highly nonlinear which limits the level of attainable model reduction.

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