

Seawater Intrusion in California Coastal Aquifers

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Coastal aquifers sustain critical freshwater resources for California's communities and economies, from public water supplies to irrigation water to support productive agricultural regions where marine-moderated climates support long growing seasons. While these aquifers benefit from their proximity to the coastal mountains (runoff and recharge), this location also makes them inherently vulnerable to seawater intrusion. A relatively small increase in groundwater salinity can compromise drinking water and irrigation uses. Intrusion of just 3% seawater by volume into a fresh groundwater aquifer will exceed California's upper limit of 1,000 milligrams per liter total dissolved solids for drinking water, potentially driving costly water treatment and presenting limitations for irrigation. Because even the dilute leading edge of this zone can affect drinking water and irrigation uses, understanding the location and dynamics of the freshwater-saltwater interface ("SWI interface") is critical to protecting fresh coastal groundwater resources. In this article, we present simple analytical methods to provide first-order estimates of the location and depth of the SWI interface. These methods help screen seawater intrusion risk before advancing to more detailed field investigations or numerical modeling.

Estimating the SWI Interface – Back-of-the-Envelope Analytical Methods

Several analytical methods are available to approximate the position of the SWI interface (Fetter, 2001). These methods are useful for screening-level evaluations, conceptual model development, and communication. The primary simplifying assumptions for these methods include: homogeneity, isotropy, and simplified aquifer and flow geometries (Panthi et al., 2022). The geometric variables relevant to the three analytical methods we present are referenced in Figure 1.

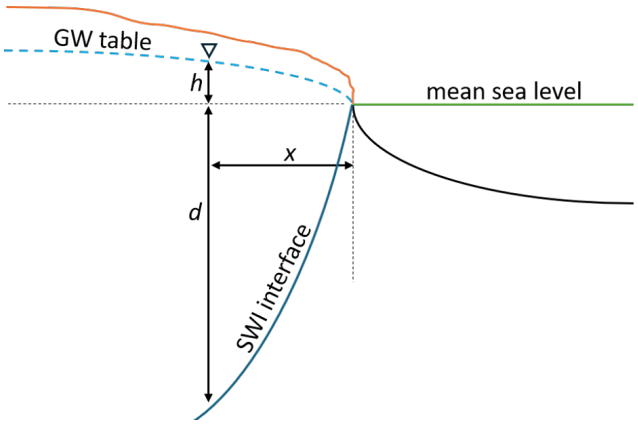


Figure 1: Conceptual diagram of the SWI interface and relevant geometric variables.

The first method is the well-known Ghyben-Herzberg (G-H) relationship (Equation 1) (example units are provided in square brackets):

$$(1) \qquad \frac{d}{h} = \frac{\rho_f}{\rho_s - \rho_f} = G$$

where:

d = depth of the SWI interface below mean sea level, [ft MSL]

h = elevation of the GW table above mean sea level, [ft MSL]

p_f = fresh groundwater density, [≈1000 kg/m3 at 0 mg/L salinity]

p_s = saline groundwater density, [≈1026 kg/m3 at 35,000 mg/L salinity]



The G-H relationship is derived from energy conservation, wherein the SWI interface is conceived to exist at equal pressure as any seaward point at the equipotential height. This approximation invokes several assumptions, including:

(1) SWI interface that meets the groundwater table at the tidal zone;

(2) vertical equipotential lines;

(3) homogenous, unconfined coastal aquifer.

While the G-H relationship provides the simplest method for estimating the SWI interface, it provides only a 1-D solution (depth) and requires observation(s) of the groundwater elevation at the desired distance inland from the coast, *x*.

The Dupuit-G-H model (Equations 1 & 2), however, incorporates the G-H relationship with the equation for unconfined flow to resolve the SWI interface depth at any *x*-location, provided that the shoreline-normalized coastal flow, *q*, is known or can be estimated:

$$(2) \qquad d(x) = \sqrt{\frac{2qxG}{K}}$$

where:

x = inland distance from the shoreline at mean sea level to the point of SWI interface quantification, [ft]

q = volumetric groundwater discharge at the coast, per unit length of coastline, [ft3/d/ft]

K = hydraulic conductivity of the coastal aquifer, [ft/d]

Lastly, the Glover model modifies the Dupuit-G-H model to allow for a coastal groundwater seepage face, eliminating both assumptions (1) and (2) and providing an improved location/depth solution for the SWI interface as:

$$(3) \qquad d(x) = \sqrt{\frac{q^2G^2}{K^2} + \frac{2qxG}{K}}$$

Real World Applications of Analytical Estimates

A practical application of the G-H relationship can be found in the early development of the West Coast Basin Barrier, one of the largest seawater intrusion mitigation projects in California. During the Manhattan Beach pilot study, engineers used the G-H pressure-balance equation (Equation 1) to determine the minimum freshwater head required to prevent seawater intrusion. Using measured specific gravities of 1.027 for seawater and 1.002 for recharge water, together with an aquifer depth of approximately 110 ft below sea level, they calculated that groundwater levels between recharge wells needed to be maintained at about 2.7 ft above sea level to balance seawater pressure at the base of the aquifer. This target hydraulic head became the design criterion for the recharge barrier (California Department of Water Resources, 1955).

Initial analytical estimates based on the Dupuit-G-H and Glover formulations predicted that 3 cfs of recharge was required to maintain the target head along a 4,000-ft reach of coastline; however, pilot testing indicated a larger recharge rate of 4.5 cfs was needed. The difference was attributed to an increase in hydraulic gradient during recharge associated with inland aquifer storage effects, upward leakage through confining layers, and lateral spreading beyond the assumptions of the one-dimensional analytical model. To account for these effects, the investigators introduced an empirical correction term in their analytical methods to represent the recharge-induced increase in hydraulic gradient, bringing the analytical estimate into agreement with field observations (California Department of Water Resources, 1955). The project's evolution illustrates the role of back-of-the-envelope analytical methods as a starting point that can be refined through field data and iteration.

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The "Homogeneous Aquifer" Assumption:

The assumption of a homogeneous coastal groundwater aquifer – employed for all analytical SWI interface equations (1, 2, and 3) – is highly idealized. In truth, coastal groundwater flows often exhibit significant spatial variability due to heterogeneities in the coastal aquifer as well as the benthic sediments (Young & Pradhanang, 2021). And, because the SWI interface is a function of the coastal groundwater flow, its location/depth exhibits similar (though subdued) spatial variabilities. Consequently, employing an average coastal groundwater discharge, q, in Equations (2) and (3) can underestimate the SWI interface depth for areas exhibiting significant coastal groundwater flows, and can overestimate the SWI interface depth for areas without appreciable coastal groundwater flows. Accordingly, zones that exhibit larger coastal groundwater flows can be protective of seawater intrusion, providing a natural barrier against seawater intrusion. However, the converse is also true – if the hydraulic gradient is reduced and flow direction reversed, such as during times of excess pumping, these same locations can behave as preferential seawater intrusion contamination pathways to the aquifer. Practitioners should exercise caution and are advised to explore plausible upper and lower flow values, using these back-of-the-envelope analyses, to account for uncertainties and SWI interface "spreading" factors due to diffusion, longitudinal dispersion, periodic forcings (e.g. pumping, tides, etc.), and aquifer heterogeneities.

Aquifer Heterogeneities and Numerical Modeling of Seawater Intrusion

As the subsurface geology is the static framework that is a principal control on groundwater flow, properly addressing seawater intrusion requires a clear understanding of the hydrostratigraphic framework from which groundwater samples are being collected and to better define the aquifer architecture and groundwater basin characterization. A robust geologic model is therefore a prerequisite to define the hydrostratigraphic unit being sampled. Figure 2 depicts the subsurface geologic framework in the LA Basin from the Whittier Narrows to Long Beach, just north of the Dominguez Gap seawater intrusion barrier project, and shows that groundwaters from a "single" aquifer unit – the Silverado Aquifer – can actually derive from one or more of a series of separate, structurally dipping, hydrostratigraphic units (Ehman & Edwards, 2017).

The preceding analytical methods are valuable tools for conducting first-order estimations of the SWI interface and resultant seawater intrusion risk to coastal aquifers. However, more robust methods are often required to understand the impact of subsurface heterogeneities and variable groundwater conditions on flow dynamics and seawater intrusion risk. Numerical modeling can help close this gap, providing a means to test coastal demand and climate scenarios and resultant seawater intrusion outcomes for heterogeneous subsurface environments.

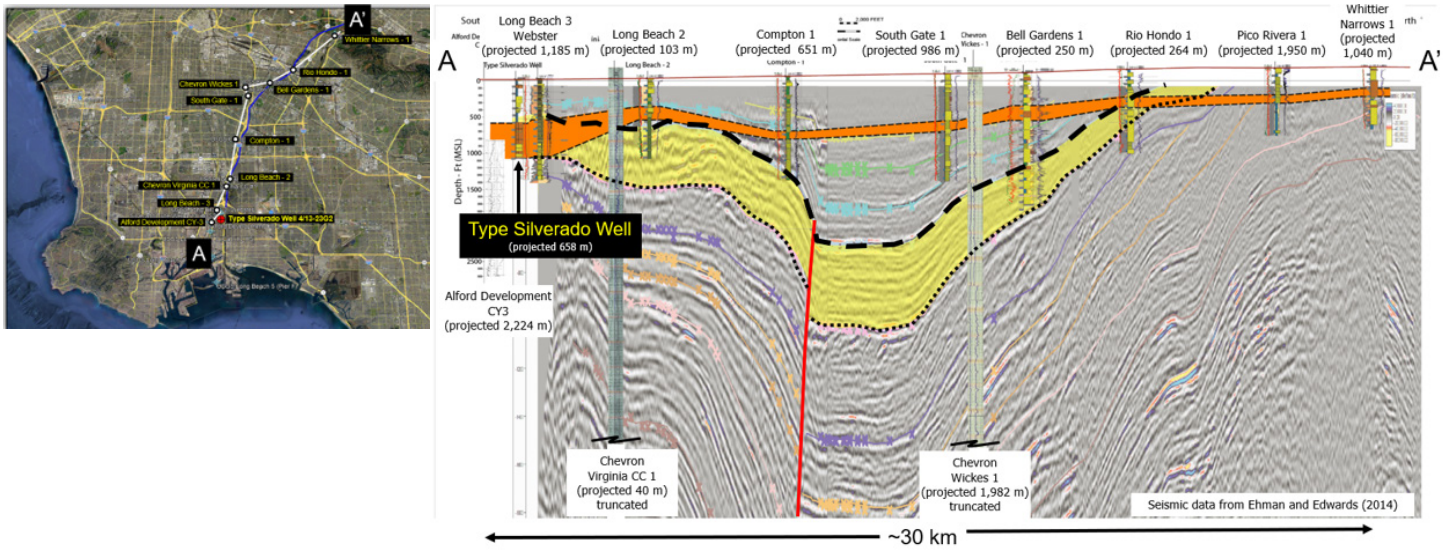


Figure 2: A-A' cross section of seismic profiles from Whittier Narrows-1 to the Silverado type well. In orange is the Silverado Aquifer as defined in DWR Bulletin 104 (California Department of Water Resources, 1961) and in yellow is the type well Silverado unit mapped out based on the seismic data. This indicates that multiple hydrostratigraphic units intersect the "Silverado Aquifer". *Figure revised from Ehman & Edwards (2017).*

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