A New Focus on Groundwater–Seawater Interactions
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Evaluation of the hydraulic gradient at an island for low-level nuclear waste disposal

PREM ATTANAYAKE & MICHAEL SHOLLEY
Bechtel Corporation, San Francisco, California 94119-3965, USA
pmattana@bechtel.com

Abstract The geographic and hydrological isolation of small islands makes them enticing candidates for the subsurface disposal of low-level radioactive waste. Placement of waste deep below the seabed is a scenario under which such repositories have been considered. One of the key hydrogeological factors influencing the suitability of such a repository is the groundwater gradient across the island and beneath the offshore area. The hydraulic gradient affects the direction and velocity of groundwater flow and, hence, the potential transport of radionuclides. In this study, the hydraulic gradient at a small island off the coast of China was evaluated for the performance assessment of a potential low-level nuclear waste repository. A preliminary assessment of the hydrogeology for the proposed offshore disposal chambers indicated that an unfavourable hydraulic gradient might occur under several scenarios.

Key words hydraulic gradient; saltwater–freshwater interface

INTRODUCTION

This paper is intended to provide a conceptual understanding of hydraulic gradients at a small island off the coast of China. For the proposed offshore disposal chambers (shown in Fig. 1), a sustained hydraulic gradient might occur under several circumstances. Possible temporary hydraulic gradients imposed during disposal chamber construction, operation and closure activities are unlikely to have an impact on the long-term performance of the facility, and are not evaluated in this document. This paper evaluates the possibility of sustained hydraulic gradients under the following circumstances of dynamic equilibrium:

– the potential for a confined aquifer to receive recharge at high elevations on the mainland and to extend beneath the sea to the island (located 20 km offshore), resulting in mainland groundwater flow reaching the island;
– the presence of a freshwater lens overlying saline groundwater at the island or extending from a nearby island;
– a hypothetical pumped well inducing flow of saline groundwater toward the island; and
– a low hydraulic gradient in the saline groundwater, with flow toward the freshwater-saline water mixing zone.

POSSIBLE REGIONAL HYDRAULIC GRADIENT

The formations underlying the coast of China in the vicinity of the island, and beneath the island, consist mostly of Jurassic-Cretaceous igneous rocks, mainly granitic

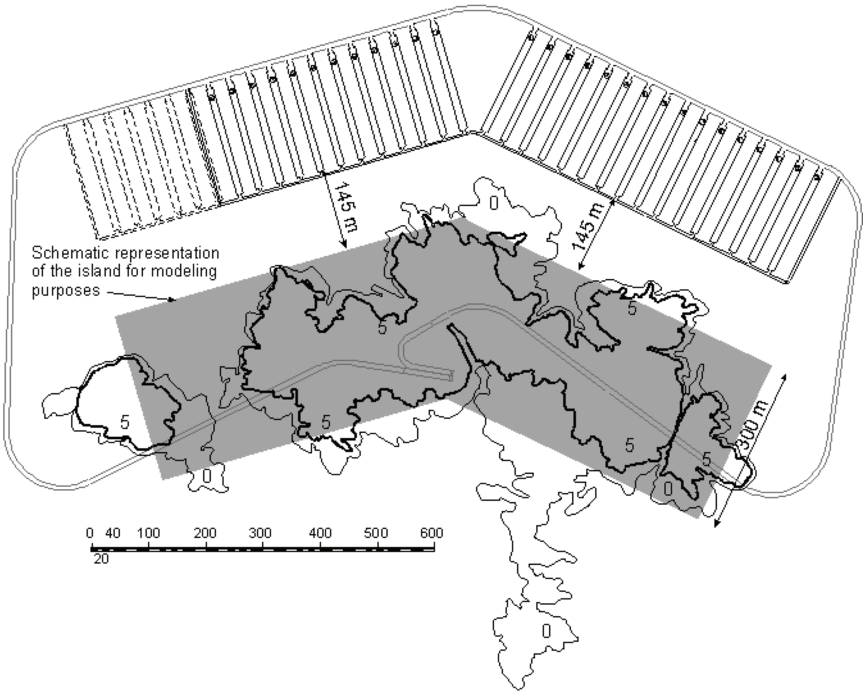


Fig. 1 Proposed offshore disposal chambers.

intrusives with some volcanics. In the study area, the rocks are predominantly granite and gabbro. Groundwater of the mountainous coastal area, approximately 20 km west of the disposal island, is primarily designated as "fissure water in magmatic rocks in mountains and hills" of low yield (Chinese Academy of Geological Sciences, 1988). In the mountainous coastal area the rocks "at shallow depths often abound with unconfined water in weathered fissures" (UNESCAP, 1983). However, the igneous rocks "at depth contain little water or are impermeable". In the coastal terrain, low-flow seasonal springs commonly appear within the weathered bedrock. Small quantities of groundwater also occur in alluvial and marine deposits of limited extent within local coastal plain areas, with low yields and containing brackish water near the coastline. There is no evidence of confined freshwater at the coast to provide the necessary head to drive freshwater offshore toward the island.

Figure 2 shows a cross-sectional conceptual model of mainland hydrogeology and expected conditions extending into the Taiwan Strait. Fine-grained seabed sediments overlie the igneous rocks beneath the Taiwan Strait between the mainland and the island and might provide a confining layer, a barrier to upward groundwater flow from the underlying fractured bedrock. However, the seabed sediments do not extend onshore to the "fissured" bedrock of the mainland or of the island. The absence of seabed sediments near the shore of the island is discussed further in evaluating the "local hydraulic gradient". As discussed previously, there is no evidence of confined water at the coast to sustain groundwater beneath the seabed sediments. Groundwater of the mainland primarily discharges to springs and streams. Any groundwater that might reach the coastline would discharge to the near-shore sea through a freshwater–saline water interface. Flow of mainland freshwater extending offshore 20 km to the island is considered unlikely.

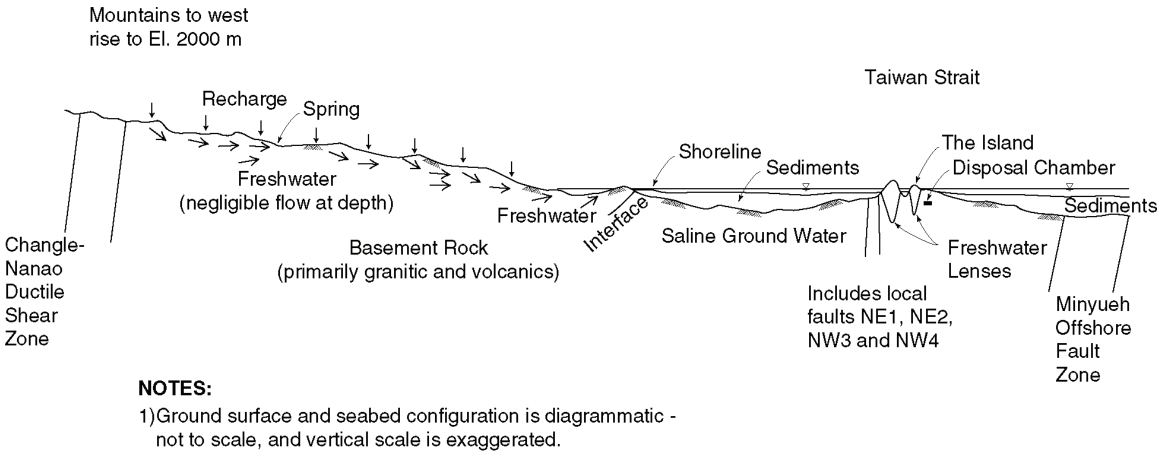


Fig. 2 Regional groundwater flow patterns.

EVALUATION OF LOCAL HYDRAULIC GRADIENT

The bedrock at the island consists of fractured granite intruded by dioritic dikes. The bedrock at a nearby second island consists primarily of fractured gabbro. Potentially confining seabed sediments appear to be absent offshore from the islands where seawater depth is less than 30 m. The disposal chambers underlie this area of shallow seawater. Further offshore from the islands, where seawater depth is >30 m, the sediment thickness ranges from 10 to 140 m.

Water-level measurements are available from shallow and deep open boreholes drilled during the preliminary design investigation. Figure 3 shows approximate average groundwater levels and interpreted water level contours. The highest water levels are shown as El. +9 to +14 m mean sea level (m.s.l.) near the highest hills on the island. Wells at low ground surface elevations show significant response to tidal fluctuations.

The island groundwater consists of a freshwater lens overlying saline groundwater. The interface between the freshwater and denser saline groundwater essentially forms a no-flow boundary for freshwater under conditions of dynamic equilibrium. The recharge rate from precipitation, the hydraulic conductivity, and the island size affect the thickness and offshore extent of the freshwater lens.

The location of the freshwater–saline water interface was estimated analytically with a method described by Cooper *et al.* (1964) and Todd (1980). The estimate shows that the freshwater in an equilibrium condition could extend to El. –194 m beneath the island, with freshwater discharge extending to 48 m offshore. Seabed sediments are absent at this distance, corresponding to a seawater depth of 10 m, so a near-shore confining layer is considered absent. These results indicate freshwater flow might extend within approximately 50 m of the disposal chambers, based on an offshore distance of about 100 m to the chambers.

A cross-sectional analytical Flownet model of the freshwater lens based on the interface location provides an evaluation of the flow pattern and hydraulic gradients within the freshwater lens. Figure 4 shows the Flownet results with groundwater flow lines and head drops. Hydraulic gradients estimated from Fig. 4 are typically 0.01 to 0.02 within the freshwater lens.

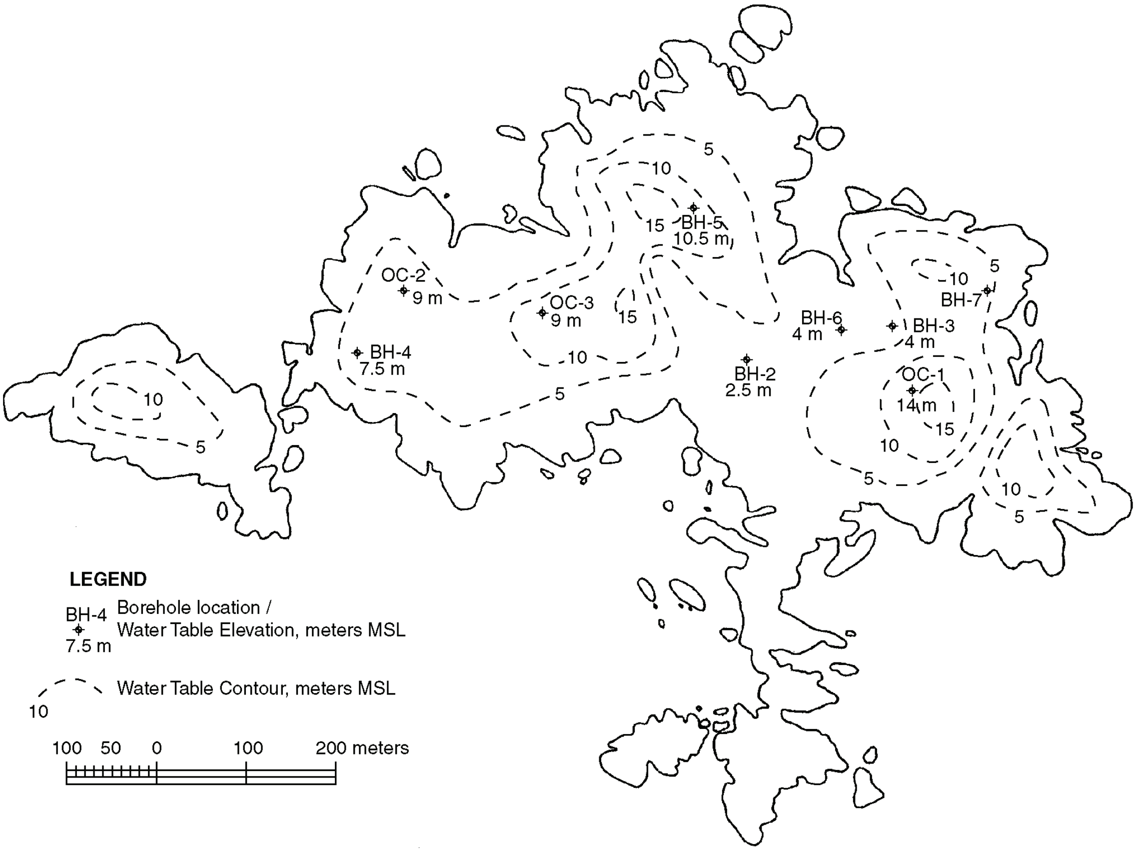


Fig. 3 Groundwater contours at the island.

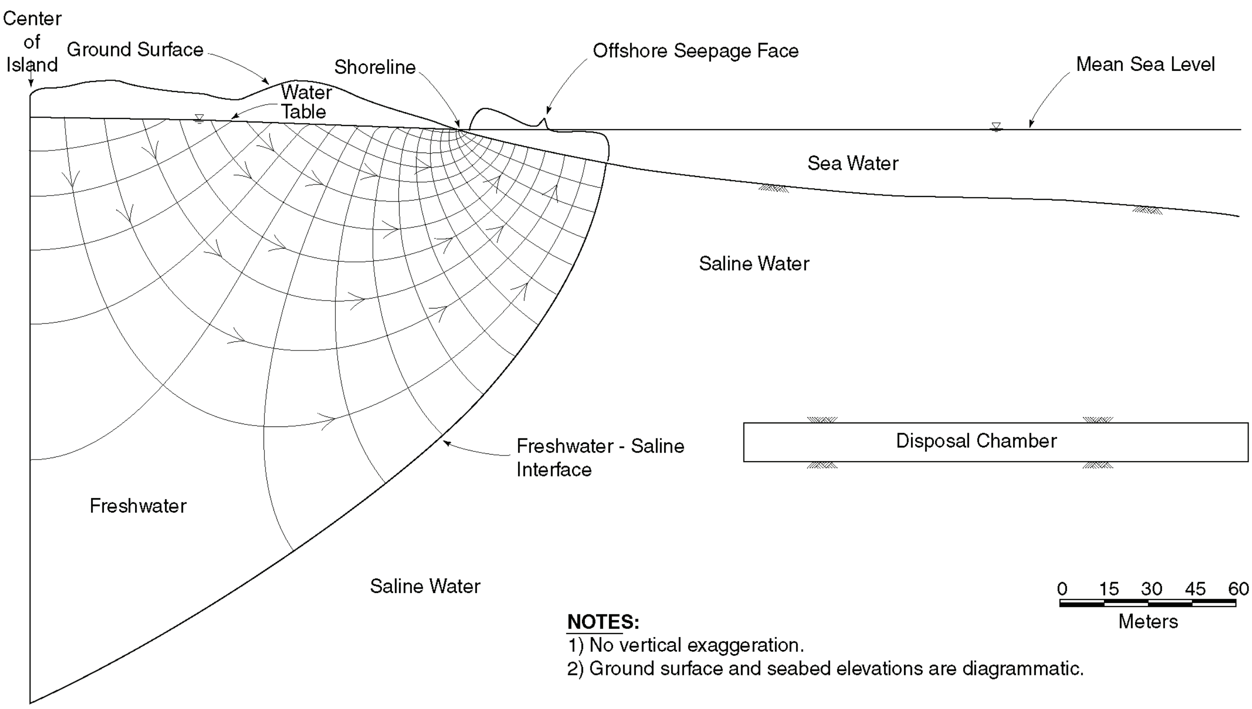


Fig. 4 Freshwater–saltwater interface.

The calculation and the analytical Flownet model assume an average recharge rate of 16 cm/year, an isotropic and homogeneous hydraulic conductivity of 3.2×10^{-5} cm, and an island width of 300 m. The island width is approximate because the actual shoreline is irregular. The hydraulic conductivity value is the mean of packer test results for depths of 10 to 178 m at BH-7. A water table elevation of approximately 4 m was back-calculated based on an assumed reasonable recharge rate of 16 cm/year. This recharge rate corresponds to 16% of an assumed precipitation rate of 100 cm/year for the island. Isohyetal contours indicate an annual precipitation of 100 cm/year at the coastline (China State Bureau of Geology, 1979).

EFFECTS OF MIXING ZONE

The actual interface between freshwater and saline groundwater will include a mixing zone, beyond which freshwater does not intermingle with saline groundwater. The mixing zone is shown as a zone of upward flow toward the seabed, with salinity greater than the freshwater and less than the seawater. The thickness of the mixing zone will be affected by seasonal and long-term variations in recharge rate, potential pumping of wells on the island, groundwater pressure fluctuations from daily tides and from storms, advective dispersion, and diffusion.

Figure 5 shows a Flownet sketch to demonstrate this conceptual model at the island. The sketch includes a freshwater lens, mixing zone, saline water beneath, and the disposal chamber location. Migration of the saline groundwater adjacent to the mixing zone would occur. Saline water entering the mixing zone is replaced by infiltration of seawater through the seabed beyond the seepage face. At the disposal chambers, the hydraulic gradient in saline water is expected to be much less than the freshwater hydraulic gradient. The hydraulic gradient within the saline water would decrease as the distance from the freshwater–saline water interface increases.

This conceptual model is consistent with field data and modelling studies by others. Figure 6 shows flowlines within freshwater and saline water based on field measurements of pressure head and salinity for a coastal aquifer in Florida (Cooper *et al.*, 1964). Saline groundwater was estimated to contribute one eighth of the total

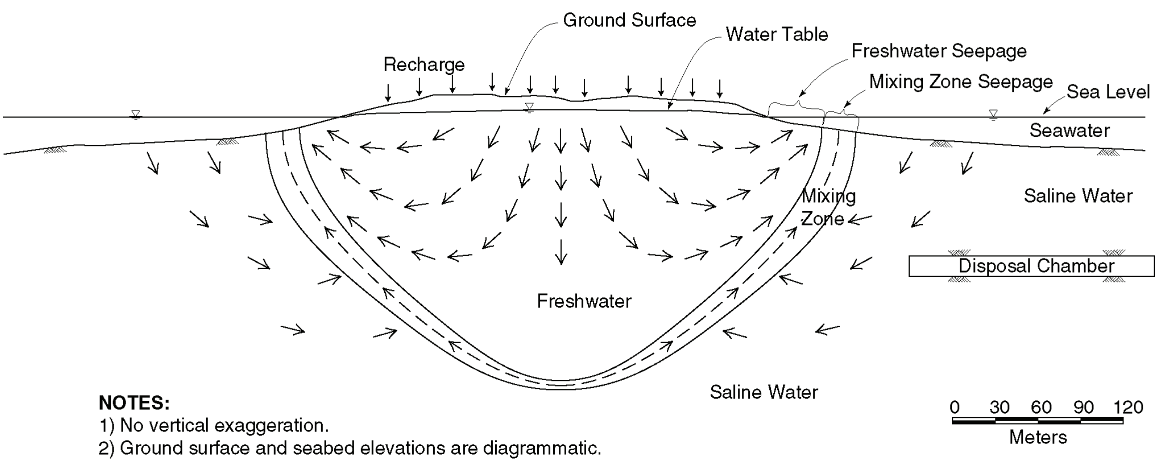
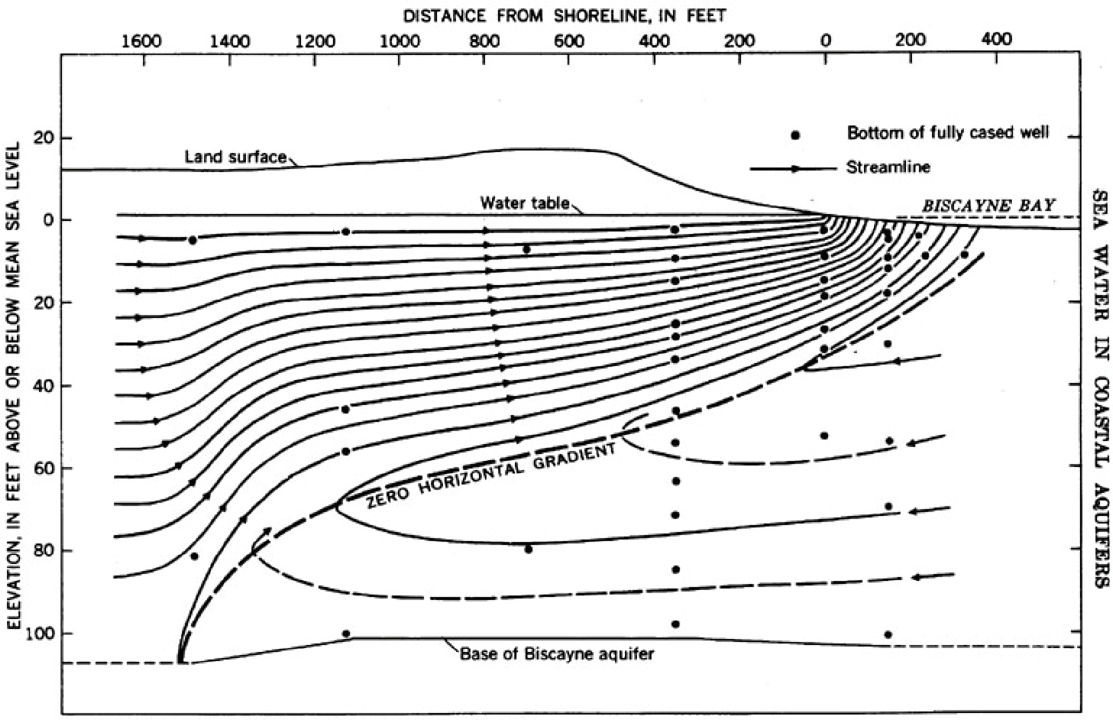


Fig 5 Hydrogeological conceptual model of the island.



SOURCE: Cooper et al. 1964. "Sea Water in Coastal Aquifers."
U.S. Geological Survey Water-Supply Paper 1613-C.

Fig. 6 Groundwater flow lines in a coastal aquifer in Florida, USA.

groundwater discharge at the seepage face. As noted by Cooper *et al*. (1964, p. v), “the circulation [of saline water] would warrant consideration in connection with proposals to inject radioactive waste into the salt water in coastal aquifers under the supposition that such water is essentially static”.

EFFECTS OF WELL-INDUCED HYDRAULIC GRADIENT

The rate of potential pumping within the freshwater lens must be less than the island-wide recharge rate. Pumping at rates greater than the average recharge would deplete the freshwater lens. Pumping is also limited by “upconing” of saline groundwater into the well, making the water quality unsuitable for consumption. At a limited pumping rate (e.g. 10 L/min), the freshwater lens will reach a new dynamic equilibrium with reduced thickness and reduced seepage face.

Figure 7 shows a revised conceptual flow model to demonstrate the effect on the freshwater lens corresponding to a permanent pumping well. Compared to Fig. 5, the interface shifts upward and inward to the island, as upconing occurs and a new equilibrium interface location is reached.

A transient condition would be imposed at the start of pumping, and saline water would move toward the island to replace the shrinking extent of the freshwater lens. When dynamic equilibrium is reached and the interface is permanently shifted upward and landward, then the zone in which saline water migrates toward the mixing zone may also be shifted further from the disposal chamber location.

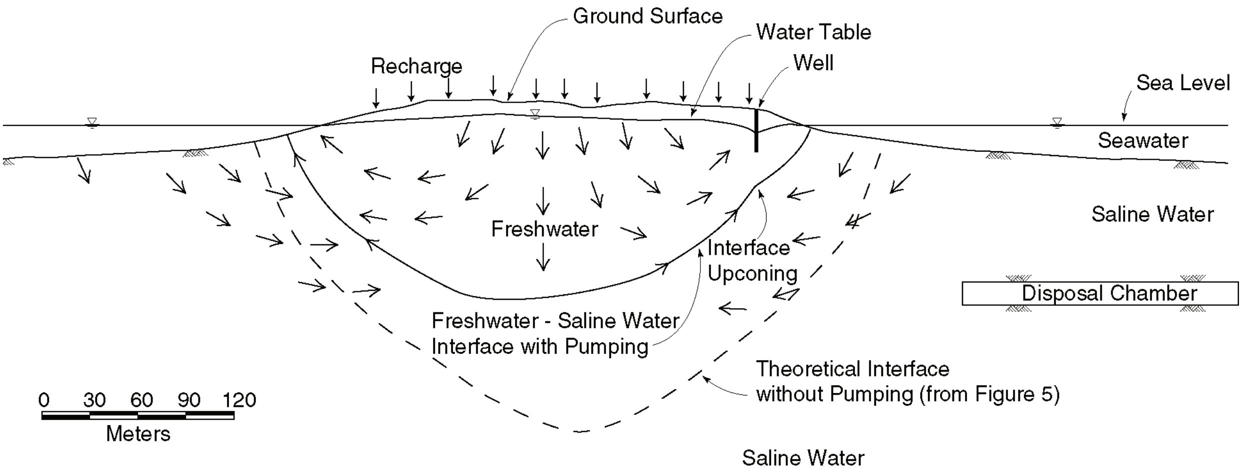


Fig. 7 Freshwater–saltwater interface with groundwater extraction.

EFFECT OF FRESHWATER LENS

The freshwater lens from a nearby second island is expected to have much less effect at the disposal chambers than the freshwater lens at the disposal island. The distance between the islands is about 1.7 km. The second island is slightly larger than the disposal island and therefore may have a slightly larger freshwater lens.

CONCLUSIONS

The evaluation of potential causes of hydraulic gradients at the disposal chambers indicates the following:

– a regional hydraulic gradient-effect unlikely;
– a local hydraulic gradient from freshwater lens-effect unlikely;
– a mixing zone-hydraulic gradient is induced within the saline ground water, but is probably low to negligible at the disposal chambers;
– pumping within freshwater lens is unlikely to affect the gradient after a new dynamic equilibrium is achieved.

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