Numerical Simulation of the Effects of Borehole Flow on Measured Vertical Salinity Profiles from Deep Monitor Wells, Pearl Harbor Aquifer, Oahu, Hawaii

Problem and Research Objectives

A recent numerical-modeling study of coastal wells in Israel indicates an upward displacement of the borehole salinity in wells located in the coastal-discharge area of the aquifer while it is at a steady-state condition. Responding to the influence of ocean tides the vertical flow in the borehole changes direction and the flow in the monitor well is three orders of magnitude larger than that in the aquifer. This indicates that the observed borehole salinity does not accurately represent the aquifer salinity (Shalev et al. 2009). Therefore these monitor wells do not accurately monitor the actual freshwater-saltwater transition zone.

The overall objective of this study is to provide information on how representative measured vertical salinity profiles from deep monitor wells are of conditions in the adjacent aquifer. A numerical modeling approach, incorporating the hydraulic characteristics and recharge data representative of the Pearl Harbor aquifer, will be used to evaluate the effects of borehole flow on measured salinity profiles from deep monitor wells. Borehole flow caused by vertical hydraulic gradients associated with both the natural regional flow system and with local groundwater withdrawals will be simulated. Model results will be used to estimate differences between vertical salinity profiles in open boreholes and the adjacent aquifer in areas of downward, horizontal, and upward flows within the regional flow system—in areas both with and without nearby pumped wells. Results from this study will provide insights into the magnitude of the discrepancy between current vertical salinity profiles from deep monitor wells and the actual salinities of adjacent aquifers. Such data is critically needed for management and predictive modeling purposes.

Methodology

A three-dimensional numerical model, SEAWAT Version 4 (Langevin et al. 2007), capable of simulating density-dependent groundwater flow and solute transport will be used in this study. Although the model will mainly be conceptual in nature and incorporate a simplified geometry, previously published values for hydraulic characteristics and recharge representative of the Pearl Harbor aquifer will be tested. A steady-state condition that generally represents the distribution of measured water levels in the aquifer will be simulated and used as an initial condition for all other simulations.

Within the model, deep open boreholes will be introduced at selected sites within the natural regional flow system in areas of downward, horizontal, and upward flows. Flow within the borehole will be simulated with a suitable model for an open conduit. Simulated salinity profiles within the borehole will be compared to 1) the pre-existing distribution of salinity in the aquifer without the borehole and 2) the distribution of salinity in the aquifer with the borehole present.

Additionally within the model, pumped wells will be introduced at selected distances from the open boreholes to evaluate the immediate effects of groundwater withdrawals on salinity profiles and saltwater intrusion into the aquifer. The depths of simulated pumped wells will correspond to the depths of typical production wells in the Pearl Harbor aquifer. The effects of both vertical wells and horizontal shafts will be simulated. Pumped wells will be located about 100 and 3,000 ft from the open boreholes and groundwater-withdrawal rates of about 4 and 17 mgd will be simulated for each pumped well.

A sensitivity analysis, in which values of hydraulic characteristics are varied one at a time, will be conducted to evaluate how the magnitudes of well hydraulic conductivity and aquifer anisotropy ratios may affect borehole flow. In addition, two simulations incorporating low- and high-permeability layers within the aquifer will be simulated.

Principal Findings and Significance

Model results indicate that borehole-flow velocities caused by the natural groundwater-flow system without local groundwater withdrawals is five orders of magnitude greater than the vertical flow velocities in the homogeneous aquifer. The contrast is consistent with the larger vertical hydraulic conductivity in the well compared to the aquifer. Directions of borehole flow are consistent with the regional flow system: downward flow in inland recharge areas and upward flow in coastal discharge areas. Displacement of salinity inside the wells does not exceed 17 ft for an effective hydraulic conductivity of the well determined from measured flow velocities (K_{well}). However, using the theoretical well hydraulic conductivity for turbulent flow (K_{tur}), borehole-flow velocities under natural groundwater-flow conditions increase more than an order of magnitude, and upward displacement of the 2 percent salinity depth exceeds 220 ft in the coastal DMW-1. Using K_{well}, the average salinity difference from the midpoint (50 percent salinity depth) upwards is 0.65 percent seawater salinity in DMW-1, which indicates that salinity in the DMWs is largely unaffected by borehole flow from the regional groundwater flow field. Commonly, a 1 percent error in salinity is acceptable for numerical modeling studies.

Borehole flow and movement of salinity in the well that is caused by local groundwater withdrawals are greater than flow and displacements under natural flow conditions. Simulated groundwater withdrawals of 4.3 Mgal/d 100 ft from a DMW causes thirty times more borehole flow than borehole flow induced by the regional flow field. The 2 percent borehole salinity is displaced 33 ft or 231 ft, depending on the assumed hydraulic conductivity of the well. Peak borehole flow caused by local groundwater withdrawals near DMWs is directly proportional to the pumping rate in the nearby production well. The upward displacement of the 50 percent salinity depth in DMW-1 increases from 4.6 to 7.1 ft (using K_{well}) and from 19 to 83 ft (using K_{tur}). The average salinity difference increases from 0.85 to 11.4 percent seawater salinity (using K_{well}) and from 6.5 to 12.5 percent salinity (using K_{tur}) in DMW-1.

Simulated groundwater withdrawals 3,000 ft away from DMW-1 are less influential on borehole flow and salinity than the withdrawals nearby. For simulated withdrawal wells 3,000 ft from DMW-1, increasing the withdrawal rate from 4.3 to 16.7 Mgal/d causes borehole flow in DMW-1 to increase by only 50 percent. However, due to the closer location of withdrawals to DMW-2, borehole-flow velocities in DMW-2 increased by 70 percent with the higher withdrawal rates. Displacement of the 2 percent salinity depth in DMW-1 increases from 25 to 114 ft, and the 50 percent salinity depth shifts from 5.8 to 6.4 ft with the higher withdrawal rate.

Effects of groundwater withdrawals from a horizontal shaft and withdrawals from a vertical well in a homogeneous aquifer were generally similar, except that borehole-flow velocities in DMW-1 were greater and upward displacement of the 2 percent salinity depth was slightly greater (123 instead of 114 ft) for the scenario that simulated withdrawal from a shaft. Generally, the 50 percent salinity depths are less affected by borehole flow than the 2 percent salinity depths. Hence, measured salinity profiles are useful for calibration of regional numerical models despite borehole-flow effects. Commonly, a 1 percent error in salinity is acceptable in numerical modeling studies.

Local withdrawals near a DMW alone cannot produce the large vertical steps observed in salinity profiles in southern Oahu when the entire well is in contact with a homogeneous aquifer. Over the length of such a step, the salinity remains constant because mixing of water in the borehole with water from the aquifer is limited. Thus, water inside the well can be more brackish than water in the aquifer under upward borehole-flow conditions. Thick zones of low hydraulic conductivity rock may limit exchange of water between aquifer and well and lead to a vertical step in the salinity profile. The heterogeneous basalt aquifer simulated in this study is one of many plausible aquifer representations. Nevertheless, simulated salinity profiles include observed vertical steps and simulated borehole flow is consistent with measured borehole flow from DMWs in southern Oahu. Due to limitations of model grid-cell size and lack of detailed information about heterogeneity in the subsurface, the inclusion of local-scale heterogeneities in regional models is not warranted.

Model results indicate that, with all other factors being equal, larger withdrawal rates, closer withdrawal locations, higher hydraulic conductivity of the well, and lower vertical aquifer hydraulic conductivity result in greater borehole flow and displacement of salinity in the well. Heterogeneity in the aquifer around the monitor well is necessary to produce vertical steps in salinity profiles in the model. Reliability in the model results can be improved by better borehole-flow measurements under different withdrawal conditions, incorporation of three-dimensional distribution of model parameters to extend the two-dimensional to a regional model, and enhanced representation of DMWs in the model.

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