Causes of Borehole Flow and Effects on Vertical Salinity Profiles in Coastal Aquifers

Delwyn S. Oki and *Todd K. Presley*
U.S. Geological Survey, Pacific Islands Water Science Center, Honolulu, HI, USA

ABSTRACT
Freshwater thickness in a coastal freshwater-lens system commonly is evaluated from vertical salinity profiles (measured by fluid-electrical-conductivity logs or water-quality samples at various depths) in deep observation boreholes. Flow within an observation borehole caused by withdrawals from pumped wells and ocean tides can significantly affect measured salinity profiles. Borehole flow can be recognized from diagnostic step-changes in a salinity profile, comparisons between salinity profiles from deep and shallow boreholes, or flow measurements. Knowledge of borehole flow is important for proper interpretation of salinity profiles by water managers and ground-water modelers.

INTRODUCTION
In coastal aquifers, vertical salinity profiles commonly are collected from open or screened observation boreholes to evaluate the thickness of a freshwater body and underlying brackish-water transition zone (Meyer and Presley 2001; Gingerich and Voss 2005). By monitoring changes in the freshwater thickness over time, water managers can determine appropriate withdrawal rates from production wells in the aquifer. Vertical salinity profiles also represent valuable data for calibration of numerical ground-water models designed to simulate density-dependent ground-water flow and transport in coastal aquifers (Gingerich and Voss 2005).

The underlying assumption in using salinity profiles is that the measured vertical distribution of salinity in a borehole is representative of salinity in the adjacent aquifer. However, natural or human-induced vertical hydraulic gradients in the aquifer can produce flow in the borehole. Complex flow patterns may exist in observation boreholes in coastal areas (Paillet and Hess 1995). Flow within an observation borehole causes water that entered the borehole in one interval to be present in another interval and, thus, the salinity profile obtained from the borehole may differ from the profile in the adjacent aquifer.

INDICATORS OF BOREHOLE FLOW
One of the diagnostic indicators of borehole flow that is commonly seen in fluid-conductivity logs is a step-like change in conductivity. These step-like changes indicate where water may be either entering or exiting the borehole (Figure 1). Fluid-conductivity logs commonly have many step-like changes, which make it difficult to uniquely determine the direction of borehole flow and whether the measured conductivity overestimates or underestimates the value in the adjacent aquifer.

Differences in fluid-conductivity profiles measured in nearby boreholes that extend to different depths also provide valuable insight into the effects of borehole flow. Conductivity profiles measured in shallow and deep observation boreholes, located about 900 m apart on Oahu, show marked differences in water quality (Figure 2). The profile from the shallow borehole indicates freshwater throughout, whereas the profile from the deep borehole indicates brackish water of nearly uniform conductivity between depths of 20 and 220 m below sea level. Because production wells in the vicinity of the boreholes produce freshwater, it is unlikely that the measured profile from the deep borehole accurately reflects conditions in the aquifer. Rather, upward flow within the deep borehole is affecting the measured profile and possibly the surrounding aquifer (brackish water flows up the well and out into the aquifer at shallow depths).

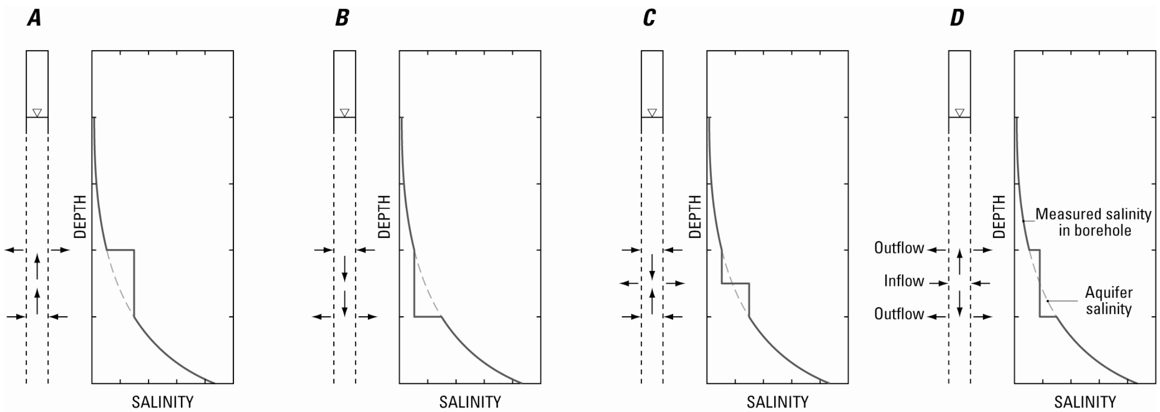

Figure 1. Schematic vertical salinity profiles in a borehole with (A) upward flow, (B) downward flow, (C) converging flow, and (D) diverging flow.

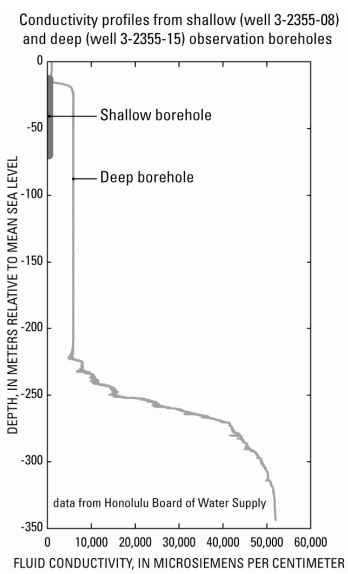

Figure 2. Comparison of fluid-conductivity profiles from shallow and deep observation boreholes, southern Oahu, Hawaii.

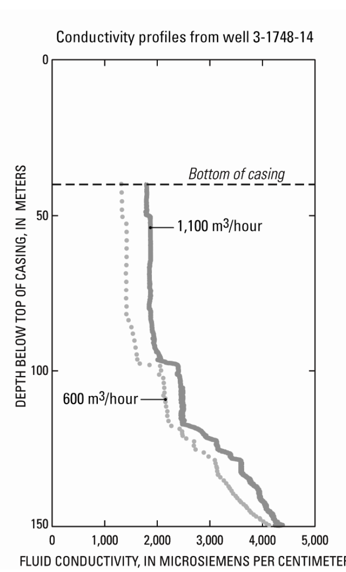

Figure 3. Fluid-conductivity profiles for nearby withdrawal of 600 m^3/hour and 1,100 m^3/hour, southern Oahu, Hawaii.

CAUSES AND EFFECTS OF BOREHOLE FLOW

Borehole flow is caused by vertical hydraulic gradients, which can be affected by both natural factors (ocean tides and variations in recharge) as well as anthropogenic factors (ground-water withdrawals). Fluid-conductivity profiles may be affected significantly by withdrawal rates at nearby pumped wells (Paillet et al. 2002). For example, measured profiles in an observation borehole on Oahu, Hawaii (Kaimuki deep monitor well 3-1748-14) indicate increased conductivity at comparable depths when nearby withdrawal wells are pumped at a higher rate (Figure 3). Electromagnetic-flow-meter measurements confirm that the increased fluid conductivity at the higher withdrawal rate is caused by increased upward borehole flow and does not reflect an overall change in water quality in the adjacent aquifer.

Continuous monitoring of fluid conductivity at fixed depths in an observation borehole also can provide an indication of borehole flow. Data from an observation borehole on Guam show diurnal variations in fluid conductivity at a depth of 35 m below mean sea level. Variations in fluid conductivity are tidally influenced and are in phase with measured water-level variations. To investigate the possibility of borehole flow, an analysis was made to determine if the conductivity variations could be explained by simple vertical shifts (no rotation or expansion) of a depth-conductivity profile by amounts equal to the water-level variations. A conductivity time series was synthesized by shifting a depth-conductivity profile according to the water-level variations and determining the conductivity variations at the desired fixed depth (Figure 4). The synthetic time series indicates only a small fraction of the measured conductivity variations at the fixed depth, which probably do not accurately reflect conductivity variations in the adjacent aquifer. Rather, the measured conductivity variations likely reflect tidally driven borehole flow. This indicates that depth-conductivity profiles measured at extremes of the tidal cycle may differ significantly.

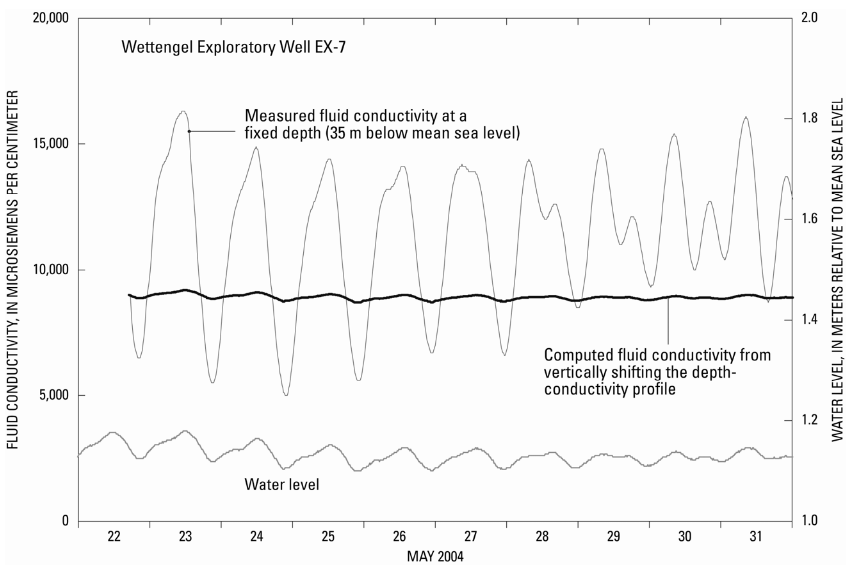

Figure 4. Time variation in measured fluid conductivity at a fixed depth and computed fluid conductivity from vertically shifting the depth-conductivity profile.

DISCUSSION AND CONCLUSIONS

For cases in which upward flow exists in an observation borehole, brackish water or saltwater from deeper zones can cause measured salinity in the borehole to overestimate salinity in the adjacent aquifer in shallower zones. In contrast, for cases in which downward flow exists, freshwater from shallow zones can cause measured salinity in the borehole to underestimate salinity in the adjacent aquifer in deeper zones. All other factors being equal, higher rates of borehole flow will have a greater effect on the measured salinity profile.

On the basis of borehole-flow measurements, Voss and Wood (1994) indicated that measured water-quality profiles from open boreholes in southern Oahu generally are representative of water quality in the aquifer, although local flow-related disturbances that affect 20 m sections of the profile may exist. Paillet et al. (2002) indicated that the shapes of fluid-conductivity profiles from open boreholes in southern Oahu and profiles of pore-water electrical conductivity from induction-conductivity logs generally are the same. However, as indicated by Paillet et al. (2002) upward flow of saline water from deeper zones can be diluted by inflows of fresher water from shallower zones. Thus, measured fluid-conductivity logs may appear reasonable at the scale of the entire profile but may not accurately reflect conductivity at a particular depth in the aquifer. Water-quality sampling in conjunction with flow-meter measurements at discrete depths in an observation borehole can be used to estimate aquifer water quality using a simple mixing cell model (Izbicki et al. 2005). In addition, piezometers installed at different depths can be used to unequivocally determine aquifer water quality.

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Contact Information: Delwyn S. Oki, U.S. Geological Survey, Pacific Islands Water Science Center, 677 Ala Moana Blvd., Suite 415, Honolulu, HI 96813 USA, Phone: 808-587-2433, Fax: 808-587-2401, Email: dsoki@usgs.gov