Resolving Discrepancies between Hydraulic and Chemical Calibration Data for Seawater Intrusion Groundwater Flow Models by Considering Climate-Driven Sea Level Change

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Abstract

Groundwater models of seawater intrusion environments can be calibrated using both hydraulic and chemical information. Typically, uncertain parameters such as hydraulic conductivity, recharge, and dispersivity will be adjusted to obtain optimum matches to calibration targets of measured hydraulic head and groundwater salinity. Transient effects on the calibration targets caused by groundwater pumping are readily recognized and can be accounted for in the process. The possible impact of the long-term transient process of sea level change is more difficult to identify and yet similarly important to accurate simulation of present conditions. The response times of the pressure and chemical fields to major sea level fluctuations are investigated for a remote island in the Aleutian chain. Amchitka Island is free from the effects of groundwater development as there is no pumping on the island, yet it has experienced changes in sea level of +/- several tens of meters during advances and retreats of Pleistocene glaciers. Groundwater data are available for the island as a result of past use of the island for underground nuclear testing.

Calibration of a steady-state model of groundwater flow for the Cannikin site on the Bering Sea coast was unable to match hydraulic head and water chemistry targets simultaneously. The response times of these targets to transient sea level change are suspected as the cause of the discrepancy. The last glacial advance ended 10,000 years ago with a sea level about 30 m lower than present. Sea level is believed to have been relatively stable for the last 2,000 to 4,000 years. Using the site's bathymetry, decreasing the sea level pressure boundary, and increasing the recharge area to include the area between the current shoreline and 30 m below current sea level, equilibrium head and chemical distributions were generated for the Cannikin flow model. Then, the sea level was instantaneously increased to its present level and the system's reaction to this change monitored for 2,000 years. The results show a difference in the response times of the pressure and chemical systems, even neglecting the effect of diffusion into the matrix blocks of this fracture flow system. Within 100 years of the sea level rise, the head in the freshwater lens and in the underlying seawater body are very close to their equilibrium values. In contrast, after 100 years, the chemical profile is little changed from the initial low sea level condition and does not approach the new equilibrium values for at least 2,000 years. Due to the effect of salinity on environmental head, heads within the transition zone take longer to equilibrate than those above and below, but generally differ from their equilibrium values by less than 10 m.

Disequilibrium due to sea level change will persist longest in situations of dual-porosity flow systems and low flow rates. Coastal aquifers in arid regions may be particularly prone to containing chemical profiles representative of previous sea level conditions because low flux rates resulting from limited recharge could require substantial time to flush a relict freshwater lens. Given the two sets of calibration data, hydraulic head data are more likely to be in equilibrium with current conditions than groundwater chemical data and thus are considered to be the most reliable targets.

Introduction

Quantitative analysis of coastal aquifers relies on defining the freshwater lens and transition zone into salt water where land-based aquifers meet the sea. This seawater intrusion problem can be described using the distribution of dissolved solids in the groundwater and by using the distribution of hydraulic head. Transient effects on head and chemistry from short-term processes such as groundwater pumping for water supply can be recognized and sometimes trigger management actions to halt degradation of the freshwater lens quality. Transient effects on head and chemistry from long-term processes, such as climate change, may be more difficult to identify.

Large changes in climate through the Quaternary period are recognized as having the potential to greatly alter groundwater conditions. Much of the focus in this regard has been in the area of relict groundwater supplies in arid regions that may have been recharged in the past and are now subject to “mining.” Groundwater systems in coastal areas are subject to alteration during climate change not only through variation in recharge rates, but perhaps more importantly through change in sea level. A change in sea level can dramatically affect the boundary conditions of a coastal aquifer: the recharge (land mass) area changes and the pressure boundary of the aquifer discharging into the ocean changes.

These altered boundary conditions can have a large impact on the configuration of the freshwater lens of a coastal aquifer. Recent work has investigated different modes of transgression and how they lead to different salinity distributions (Kooi et al., 2000). They were able to quantify situations where large freshwater lenses would persist in disequilibrium with a sea level transgression, and related these calculations to observations of relict freshwater in aquifers offshore. The work presented here relates to the same problem: the impact of marine transgression on a coastal system and the potential for persistence of disequilibrium. The focus here is on the different response times for the chemical and head distributions to attain equilibrium with a new condition of sea level and the impact of disequilibrium on calibration of a groundwater flow model. In particular, lack of agreement when calibrating to two independent targets (head and chemistry) may indicate different response times for these systems to achieve equilibrium.

The study site conditions in terms of hydrogeology and sea level variations will be described first. Two numerical flow models for Amchitka Island are then presented and the challenges of simultaneous calibration to head and chemical data described. The effect of sea level change and the response times of the chemical and pressure distributions in the coastal aquifer are then evaluated. This evaluation includes considering the differences between rising and lowering sea level and the effect of bathymetry on the response. Finally, conclusions are drawn regarding the impact of long-term transient responses on coastal aquifer model calibration.

Site Description

Amchitka Island is in the Aleutian Island chain extending southwest from Alaska, separating the Bering Sea on the northeast from the Pacific Ocean on the southwest (Figure 1). The island is 65 km long and varies between 2 and 7 km wide, with elevations from 0 to 354 m above mean sea level (AMSL). The study site is in the eastern half of the island, characterized as a lowland plateau of subdued topography below an elevation of 100 m AMSL, containing many streams and lakes. The hydrology of the island was characterized as part of an underground nuclear testing program conducted at Amchitka in the 1960s and 1970s by the U.S. government.

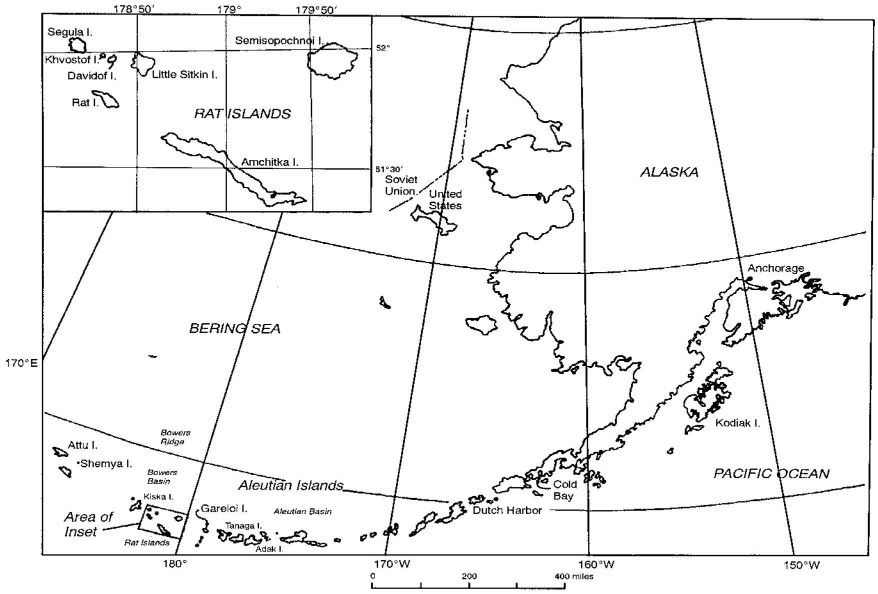

Figure 1. Location map showing Amchitka Island in the Aleutian Island chain.

Flow of groundwater at Amchitka is governed by the dynamics of density driven flow typical of coastal aquifer systems. Rainfall recharges the island's freshwater aquifer, forming a lower-density lens above the underlying saltwater (Figure 2). Circulation in the freshwater lens is directed downward at the interior of the island and upward approaching the shoreline. This is mirrored in the saltwater aquifer as recharge through the seafloor past the zone of freshwater discharge, moving inward and upward beneath the island interior, replenishing salt lost by diffusion into the overlying freshwater system. The thickness of the freshwater lens is controlled by the hydraulic conductivity, recharge rate, and ground surface elevation. The lens is apparently asymmetric at Amchitka, being about 900 m thick on the Pacific side and up to 1,500 m thick on the Bering Sea side of the island.

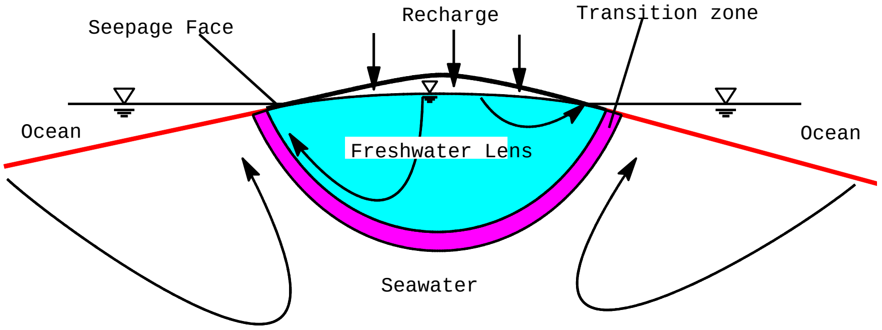

Figure 2. Saltwater intrusion beneath island aquifers. Typical flowpaths are indicated by the curved arrows.

The water table in the study area is within several meters of ground surface. Runoff of rainfall to surface water bodies occurs rapidly (Dudley et al., 1977), consistent with the saturated near-surface conditions and the generally low permeability of the rock. The lithology of the island is dominated by alternating layers of breccias and basalts. Consistent with their volcanic origin, there is a high degree of both vertical and lateral spatial variability for the rocks. Individual hydrostratigraphic units have not been identified on the island. Groundwater flow is conceptualized as fracture flow between matrix blocks of generally high porosity (Fenske, 1972; Dudley et al., 1977).

The absence of pumping on Amchitka removes groundwater development as a cause of transient hydrologic responses. Rather, the question of the applicability of steady-state conditions arises from temporal variations in natural processes. The process of interest here is long-term change in climate that could affect sea level.

Climate History of Amchitka

Sea level varied by several tens of meters at Amchitka during the advances and retreats of Pleistocene glaciers (Gard, 1977). At least four major marine terraces have been mapped above the current island shoreline. The last major interglacial period caused a significant marine transgression at a level 37 to 49 m above present sea level. This transgression is dated at about 127,000 years before present. The last glacial advance ended about 10,000 years ago, at a sea level about 30 m below present. Sea level is believed to have been relatively stable at its present level for the past 2,000 to 4,000 years.

Changes in sea level have a direct impact on the hydrology of an island. As sea level falls below current levels, the island’s recharge area increases and the head for the saltwater system decreases. The net effect is to increase the depth of the freshwater lens. When sea level rises above current levels, the recharge area decreases, the head in the saltwater system increases, and the freshwater lens shrinks. Dudley et al. (1977) suggest that freshwater circulation beneath Amchitka might have been as deep as 2,500 m during full glacial conditions.

The mode of transgression was found by Kooi et al. (2000) to be important when considering coastal aquifer response to sea level rise. They define mode based on speed of sea level rise and permeability of the substrate. Though the speed of transgression is unknown at Amchitka, Kooi et al. (2000) note that transgression rates were high during the early Holocene. The inundated substrate at Amchitka cannot be expected to have a thick layer of low permeable mud due to the high energy conditions currently observed offshore. The nature of the aquifer materials themselves, however, is low permeability. As a result, the mode of intrusion at Amchitka for the last transgression is considered to coincide with those identified by Kooi et al. (2000) that lead to salinization lagging sea level rise.

Hydraulic and Chemical Data

Most of the hydraulic and chemical data were collected and reported by the U.S. Geological Survey (USGS) in the late 1960s and early 1970s from exploratory boreholes drilled on Amchitka during site investigations for the underground nuclear testing program (Ohl, 1973). Considerable uncertainty exists in the values of the parameters governing the flow and transport processes at Amchitka. An uncertainty analysis found that the freshwater-saltwater transition zone is most sensitive to the uncertainty in the ratio of the recharge and hydraulic conductivity (Hassan et al., 2001).

The K data are derived by independent analysis of 42 straddle packer swabbing tests run by the USGS The distribution of log10-transformed K values is notable for both its wide range of variability and for its overall low values (Figure 3). Most of the Amchitka K values are between 1.0×10^{-4} and 1.0×10^{-1} m/d. A smaller number of water levels measured during the packer testing are used to represent hydraulic head in the discrete intervals, as care was taken to only use levels that clearly indicated static conditions. The influence of groundwater salinity and temperature on the measurements is unknown, as these parameters are not consistently reported with the water levels. Thus environmental head is used here rather than equivalent freshwater head.

Groundwater samples were collected during the straddle packer testing and provide information on chemistry in discrete, isolated, depth intervals. Collection of representative groundwater samples from deep wells during drilling programs is very challenging, with the primary problems being purging of drilling fluids and maintaining isolation. Many significant problems were encountered during testing at UAe-1, the primary source of data for Cannikin. These problems relate to poor borehole stability and included the need to use mud and lost-circulation materials (shredded wood and cotton hulls), and incomplete sealing of casing perforations used for squeezing cement. In addition, at least 1,890 m^3 of fresh water were unintentionally injected into the formation in the interval from 1,531 to 1,826 m and efforts to purge it were hampered by high production rates from the cementing perforations higher in the borehole (Balance, 1968).

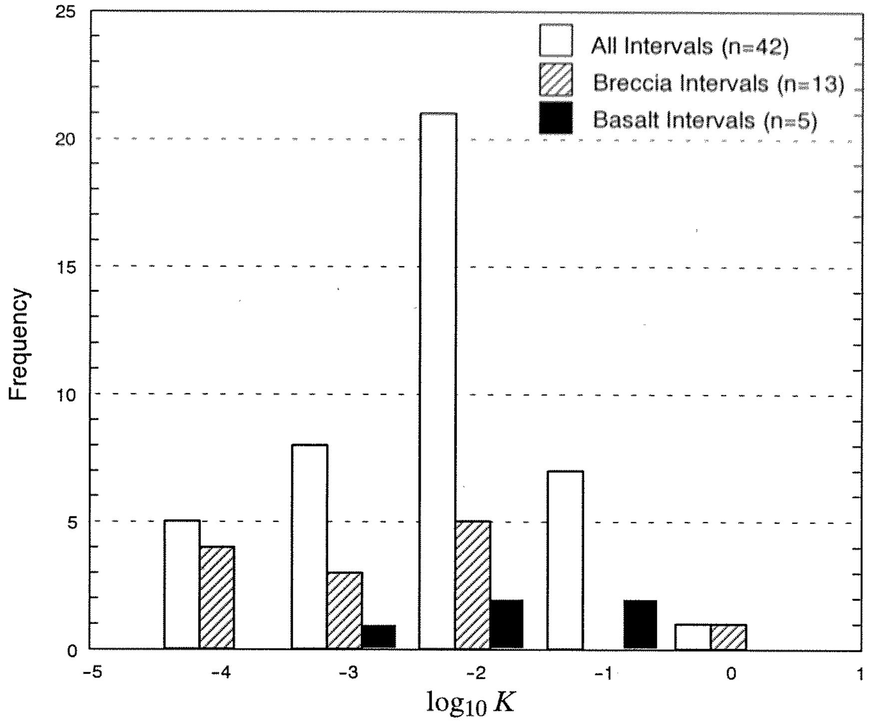

Figure 3. Distribution of $\log_{10}$-transformed K values estimated from straddle packer test data collected from Amchitka boreholes. Many intervals contain a mixture of breccia and basalt and cannot be assigned to one lithology.

Recharge rates were estimated from borehole temperature logs, using a one-dimensional model for simultaneous vertical movement of fluid and heat (Bredehoeft and Papadopulos, 1965), and compared to mass-balance evaluations of rainfall and runoff (Dudley et al., 1977; Gonzalez, 1977). Matrix porosity was measured on more than a hundred core samples and flow porosity in the fractures was estimated by Fenske (1972), using water level responses to tidal and barometric effects. Longitudinal mass macrodispersivity was chosen during the calibration process to attempt to reproduce the dispersion pattern observed in the chloride concentrations and transverse dispersivity is taken to be 1/10 of the longitudinal value.

Solving the Density-dependent Flow Problem

The variable density groundwater flow problem is solved using SUTRA (Voss, 1984) with the aid of the graphical user interface (GUI) provided by Argus ONE. The GUI allowed optimization of the finite element mesh so that the freshwater and transition zone portions of the domain can be simulated with a finer grid and the saltwater portion of the domain by a coarser, computationally efficient grid. The topographic and bathymetric features of the site are shown in Figure 4, with the corresponding geometry of the simulation domain and the boundary conditions in the lower half of the figure. To allow for the various sea levels simulated, a domain length of 12,000 m is assumed, and a domain thickness of 6,000 m. This provides the flexibility to change sea level, and thus the location of the transition zone, with no boundary effects influencing the resulting solution. The left-hand boundary is assumed to coincide with the groundwater divide at the island centerline, and as such is assumed to be a no-flow boundary. The bottom boundary is also assumed to be a no-flow boundary. The right-hand boundary is a specified pressure and a constant concentration boundary. The top boundary is divided into two segments: a freshwater recharge segment representing the island half-width and a specified pressure segment representing the seafloor (bathymetric profile). The width of these segments varies with the sea-level scenario considered.

The SUTRA code deals with the flow and saltwater transport problems simultaneously in a transient mode. The transient solution continues until a steady-state velocity distribution is achieved. The SUTRA output can be used to generate salinity and head profiles for the location corresponding to the site data. SUTRA calculates the environmental head using the specific weight corresponding to the concentration, and these are used here rather than freshwater equivalents because they better approximate the measured head values.

Steady-state Flow Model Calibration

The initial assumption, given the lack of pumping on the island, is that the Amchitka hydrologic system is at steady-state. Given this assumption, the data should provide a consistent view of the freshwater-seawater interface, within their uncertainty limits. This consistency could not be achieved.

The density-driven flow model is calibrated to provide the best possible match to the field data. The calibration targets are the measured chloride concentrations and hydraulic heads. The flow model simulates flow from the groundwater divide (assumed to coincide with the topographic divide running the length of the island) to the Bering Sea. A large number of scenarios were tested, in which the hydraulic conductivity and its anisotropy ratio, the recharge, and the macrodispersivity are varied within ranges suggested by the data, and the results are evaluated and compared to the calibration data. Porosity does not affect the head distribution nor the location and width of the transition zone; it simply speeds up or slows down the convergence of the system to steady state.

The calibration is challenging. Despite testing many parameter combinations, a single set was not identified that gave a good match to both sets of calibrations targets (head and chemistry). The chemical data indicate that the transition zone is not fully penetrated at this site, despite data from depths up to 2,000 m. The calibration problem is exacerbated by distinctions based on depth for both the head and chemistry targets such that a choice must be made to either match the data at elevations of –1,000 m and above or data collected below –1,500m.

The parameters that lead to a match of the head data above –1,500 m result in a shallower freshwater lens than indicated by the bulk of the concentration data, though the shallowest chloride measurement is approximated (Calibration 1 in Figure 5). When the chloride data below 1,500 m are matched, modeled head values are higher than measured throughout the tested interval (Calibration 2 in Figure 5). This parameter set does not fit the shallowest chloride data either. A match to the deeper heads would calibrate between these endpoints, providing a poor fit to the shallow heads and chloride measurements.

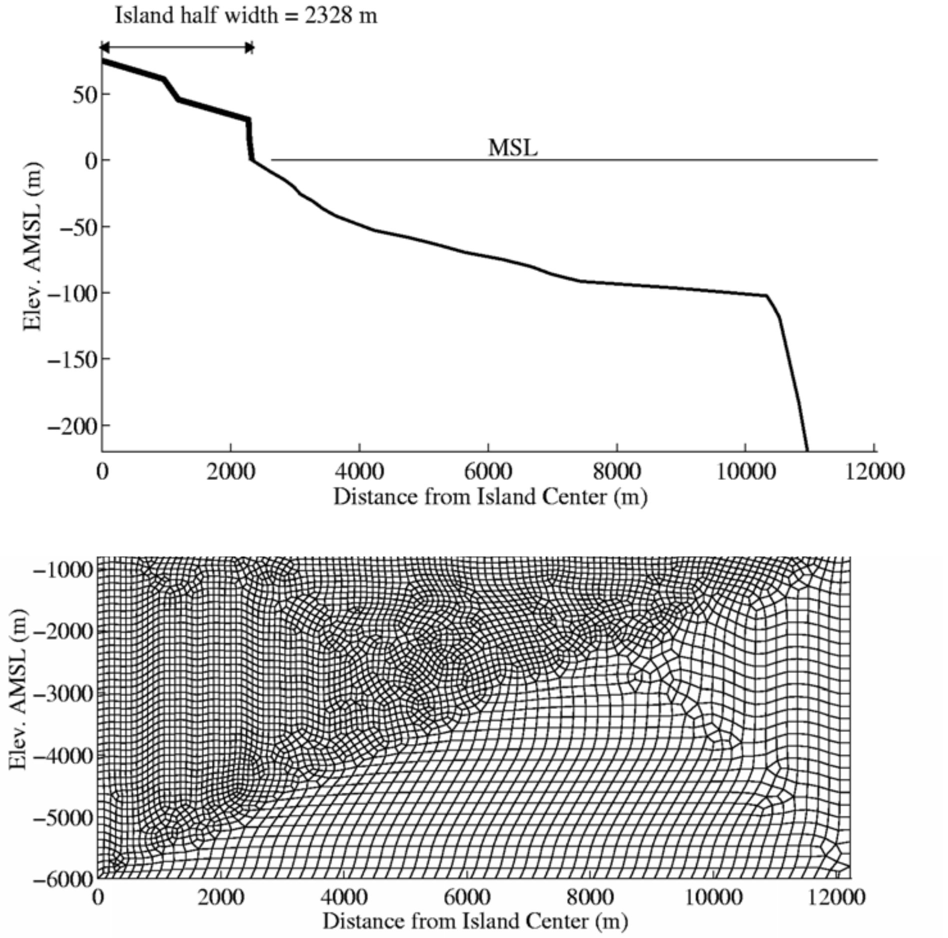

Figure 4. The topographic and bathymetric profiles at the Cannikin site showing the island half-width. The domain is discretized with a finite element mesh, which is refined in the area that encounters the transition zone.

The lack of simultaneous calibration to head and chemistry at Amchitka could reflect problems with data quality. The quality of the chemical data from the Cannikin site have been questioned (Fenske, 1972), and in general, there is greater confidence in the head data. It bears remembering, however, that fluid density is a factor in hydraulic head as well. Uncertainty in the head measurements increases with increasing depth as a result of the unknown density of the water in the well (head measurements were not made with pressure transducers). Another possible reason for the discrepancy between the equilibrium hydrologic systems suggested by these independent data sets is that they in fact do not represent a system at equilibrium. For an aquifer in transient conditions, the response times of the head and chemical components need to be considered to reconcile the calibration difficulties.

Transient Pressure and Chemical Response to Sea Level Change

Given that the last major transgression peaked in late Wisconsin time, on the order of 10,000 years ago (Gard, 1977), the scenario of concern is that of a mean sea level lower than today, followed by a rise to current sea level. The response of hydraulic head and groundwater chemistry to such a sea level increase is investigated for the Cannikin site.

The two most sensitive model parameters, hydraulic conductivity and recharge, are held constant to the values used in Calibration 1 (matching the shallow data better than the deeper data). These values are based on site data, and in the case of hydraulic conductivity, the sea level change would have only a minimal effect through the change in water density. Recharge, on the other hand, might be expected to be significantly affected by the same climate forces that cause the change in sea level. In the case of Amchitka, there is likely to be less relationship than in other environments. Current annual rainfall on the island is about 94 cm, with the estimated recharge being a small fraction of this (5.5 cm/yr at Cannikin). This low recharge rate is attributed to the generally low hydraulic conductivity of the aquifer materials and virtually saturated conditions of the island. An increase in precipitation at the island would result in more runoff, not more recharge. Conversely, precipitation could undergo a steep decline and still provide the small amount currently recharging. The impact of glaciers on parts of the island is unknown, but it is similarly assumed that the small amount of recharge considered here could occur underneath any ice sheets. The transition zone location is directly related to the ratio of recharge and conductivity, such that altering them would mask the impact of the transient simulations.

Using the bathymetry of the Cannikin site, the sea level pressure boundary was decreased and the recharge area increased to include the area between the current shoreline and 30 m below current sea level. The equilibrium head and chemical distributions resulting from these boundary constraints are taken as the initial conditions, consistent with equilibrium attained during the long Wisconsin ice age (lasting from about 12,000 to 120,000 years ago). Then the sea level was instantaneously increased to its present level and the system's reaction to this change monitored for 2,000 years. Simulating an essentially instantaneous sea level rise is consistent with a variety of climate records that indicate such transitions often occur rapidly (Taylor, 1999).

Hydrologic System During Glacial Conditions

The chemical and hydraulic system at equilibrium with a sea level 30 m below current is depicted in Figure 6 by the conditions at time equal zero. It is immediately obvious that the salinity profile calculated for these glacial conditions much more closely approximates the deeper groundwater samples from Cannikin. Indeed, a somewhat larger decline in sea level would match even better and thus allow for a lower glacial sea level, consistent with global studies suggesting Holocene sea level increases on the order of 100 m. On the other hand, the hydraulic head data do not match the profile for the lower sea level, and nor do the two shallowest water quality samples, collected above –1,500 m elevation.

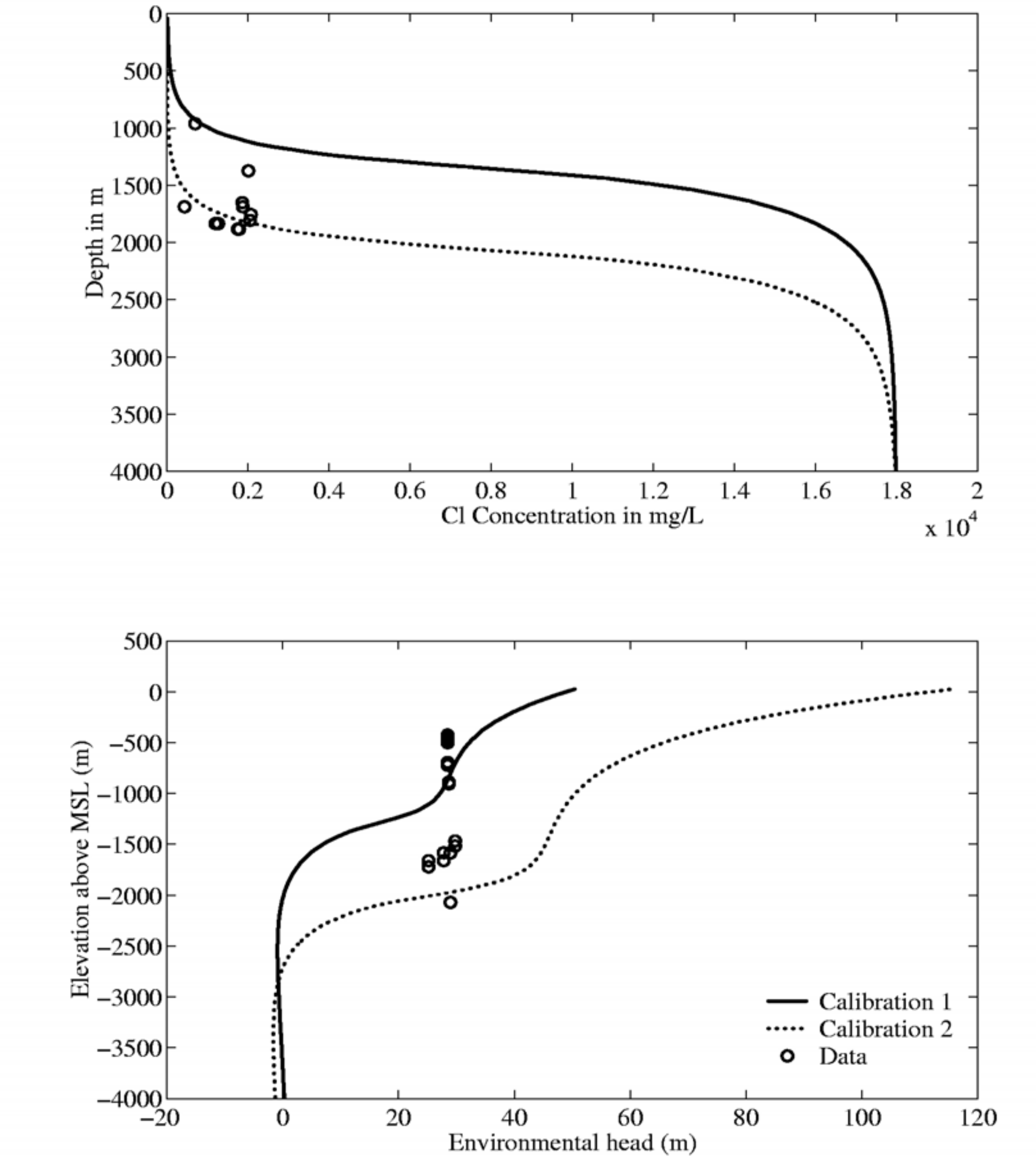

Figure 5. Calibration results for Cannikin with first calibration matching shallow data better and calibration 2 matching deeper heads and concentrations better. (Parameter values: K = 1.58x10^{2} m/d, R = *3.65* cm/y, R/K = 6.3x10^{-3}, A_L = 300 m, A_T = 100m, θ = 0.0005 for Calibration 1 and K = 6.32x 10^{-3} m/d, R = *3.65* cm/y, RIK = 1.*575 x* 10^{-2}, A_L = 300 m, A_T = 100 m, θ = 0.0005 for Calibration 2.)

Response Times to Marine Transgression

Starting with the model at equilibrium with the –30 m sea level used here for glacial conditions, the sea level was instantaneously raised to its present position. Six snapshots are presented through time to monitor the system reaction, from 50 to 2,000 years after the sea level rise.

Within 50 years of the sea level rising 30 m, the heads in the freshwater lens (elevations of –1,000 m and above) are very close to their new equilibrium values (Figure 6). Heads within the transition zone and below slowly approach their stable values during one thousand years, differing from the new equilibrium value by less than 10 m after the first 100 years. Given the difficulties of accurately measuring hydraulic head in discrete intervals at depths in excess of 1,000 m, differences of several meters are well within measurement uncertainty. The transition zone heads actually change in a rebounding fashion, re-approaching the lower initial values after rapidly increasing from the pressure change. This reflects the impact of density on the environmental head as the salinity profile slowly changes.

In the upper 1,000 m, the chloride content responds somewhat slower than the head, with the salinity at 50 years after the sea level rise still less than half the final value. Equilibrium values in the upper 1,000 m are reached within 200 years. As for the heads, the equilibration of chloride content in the transition zone takes much longer. Still, by 1,000 years after the sea level rise, the salinity profile approaches stability. Considering the transient response at an elevation of –1,500 m, the Cl concentration begins at approximately 1,000 mg/L under the low sea level conditions and increases to 12,600 mg/L after 1,000 years (Figure 6). The hydraulic head at the same depth begins at 9.5 m and ends at 6 m, but between, increases to 19.5 m at 50 years.

The modeled response in the chemical system is probably overly rapid compared to reality because the process of matrix diffusion is not included in the simulation. The equilibration is solely the result of the varying velocity field. Presuming that the low sea level stand was of sufficient duration to equilibrate the matrix blocks as well as fractures with fresh water, the equilibration time as sea level rose would exhibit a much longer tailing as fresh water diffuses from the blocks and more saline water diffuses into them.

Impact of Porosity on Response Times

The effective porosity of fractured rock aquifers is very difficult to determine and remains a highly uncertain parameter at Amchitka Island. The simulations described above use a porosity of 5×10^{-4}, derived from estimates of fracture spacing (Dudley et al., 1977). This low value was selected to be conservative for estimates of contaminant transport, as they directly lead to higher groundwater velocities. The limited data derived from analyzing hydraulic responses on the island suggest a higher porosity of 1×10^{-3} (Fenske, 1972). The impact of porosity on the response to a sea level increase is investigated by modeling, as previously, the steady-state conditions at –30 m sea level, followed by an instantaneous rise to present level, but with a two-fold increase in porosity to 1×10^{-3}.

The slower groundwater velocity resulting from the higher porosity directly translates into a slower response time to re-equilibrate the chemical system. The 30-m lower sea level steady-state conditions are unchanged from the lower porosity scenario, as is the nearly instantaneous response of hydraulic head in the freshwater lens. The profiles in Figure 6 are essentially the same for this case, but the shifting of the transition zone upward now requires twice as long, 2,000 years to approach final steady-state chloride conditions. With the impact of salinity on hydraulic head, the head response in the transition zone is also longer.

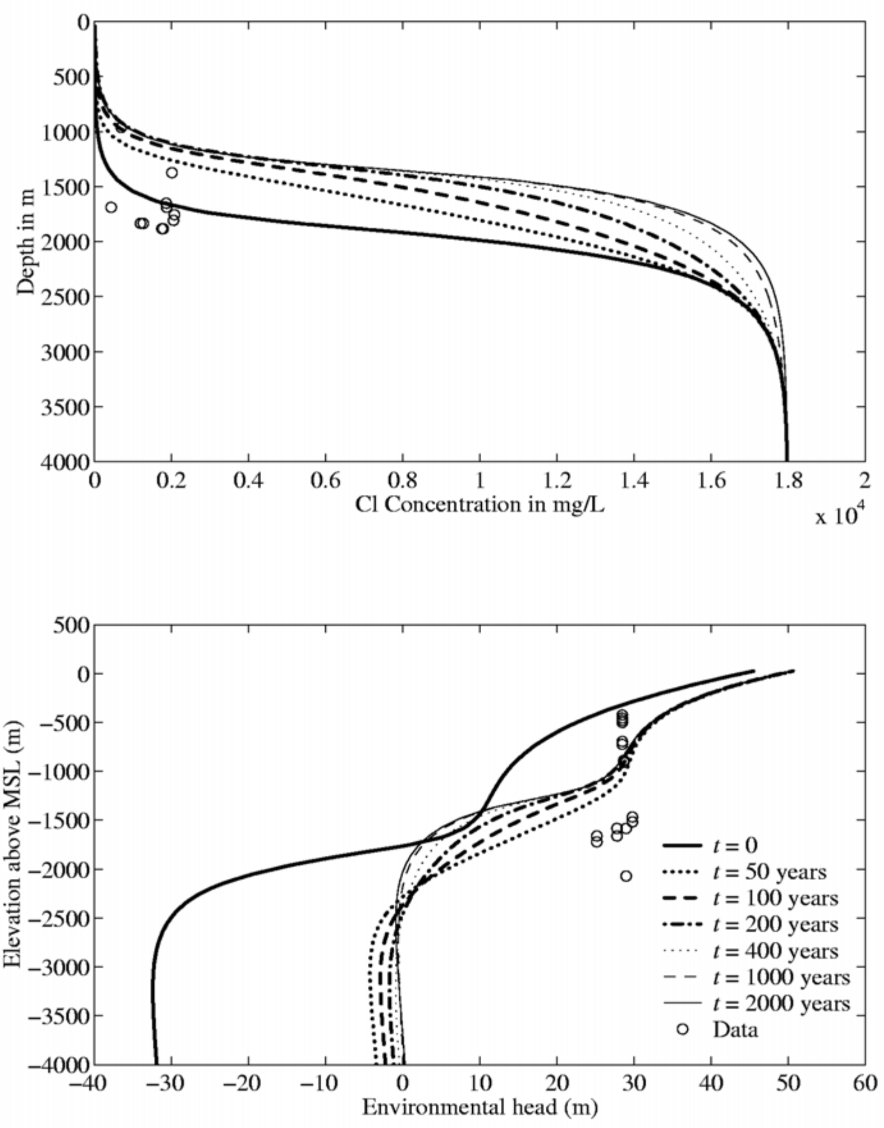

Figure 6. Response of salinity and head profiles at the UAe-1 location at Cannikin after a sudden transgression (rise in the sea level and inland advance of the shoreline) from an assumed glacial condition with 30-m lower sea level than current conditions. (Parameter values: K = 1.58x10^{-2} m/d, R = *3.65* cm/y, R/K = 6.3x10^{-3}, A_L = 300 m, A_T = 100m, θ = 0.0005.)

Impact of Topography/Bathymetry on Response Times

The influence of topography on the head and chemistry response to sea level change can be seen when considering the condition of a marine regression at the site. Marine terraces have been mapped on Amchitka and are remnant from times of sea level higher than present. In this simulation, steady-state groundwater conditions were established for a sea level 30 m higher than today, then instantaneously dropped to the present conditions. The head response is essentially instantaneous (Figure 7),

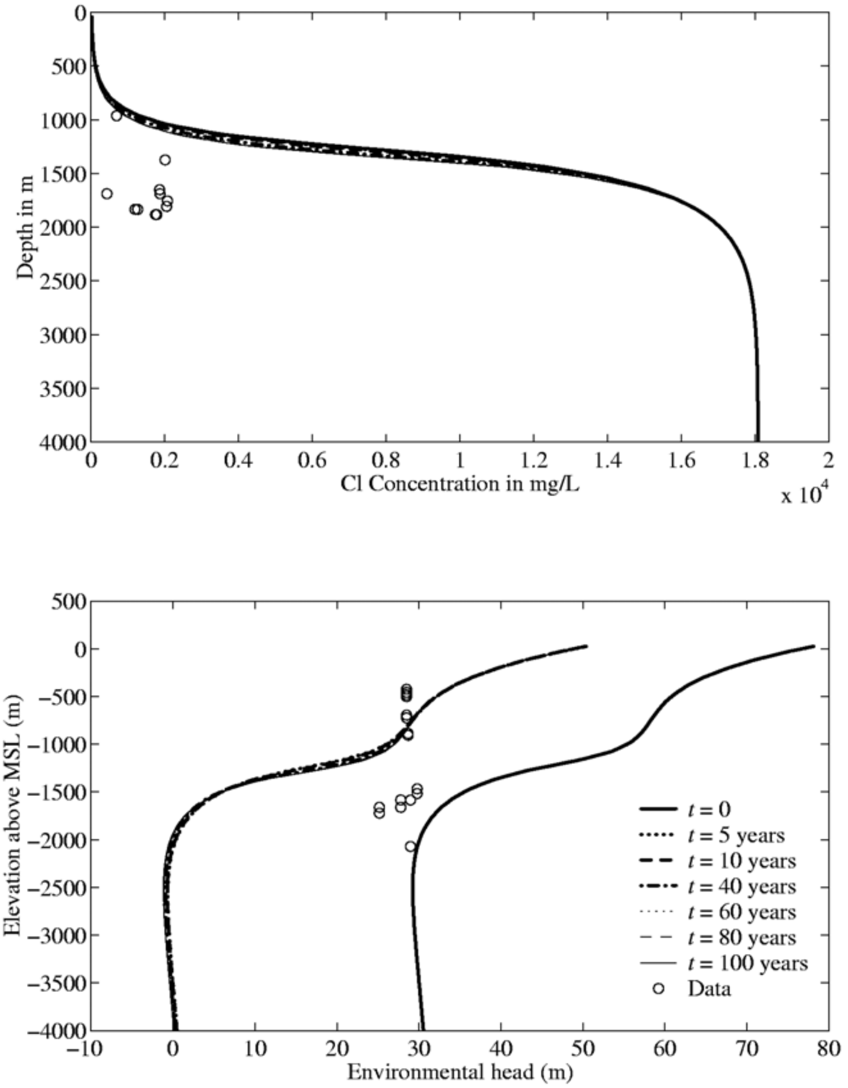

Figure 7. Response of salinity and head profiles at the UAe-1 location at Cannikin after a sudden regression (drop in the sea level and seaward movement of the shoreline) from an assumed inter-glacial condition with 30-m higher sea level than current conditions. (Parameter values: $K = 1.58x10^{-2}$ m/d, $R = 3.65$ cm/y, R/K= 6.3x10^{-3}, A_L = 300 m, A_T= 100 m, θ = 0.0005.)

achieving equilibrium with the new conditions within five years. The chloride profile remains essentially unchanged as a result of the steep shoreline topography. Though the sea level has increased dramatically, this has been primarily up a coastal cliff face such that the recharge area for the groundwater system is unaffected, and the transition zone remains virtually unchanged. The steeper the exposed and submarine topography, the less impact sea level changes will have on the hydraulic system.

Macrodispersivity

The transient response was evaluated for different combinations of macrodispersivity. For the homogeneous conductivity field used here, macrodispersivity accounts for spreading of solute pathlines due to heterogeneity and thus is a parameter to consider when modeling the salt movement caused by sea level change. Macrodispersivity does not affect the response to the transient conditions, but does strongly influence the width of the transition zone (the sharpness of the transition from seawater to freshwater) (Figure 8). By comparing the starting and ending chemical profiles in Figure 6 with the ones for the intermediate times, it is clear that the non-equilibrium chemical profiles exhibit a larger degree of spreading than those at equilibrium. This suggests another indicator for a coastal aquifer being in a transient state from sea level change: an unusually wide and disperse chemical transition zone.

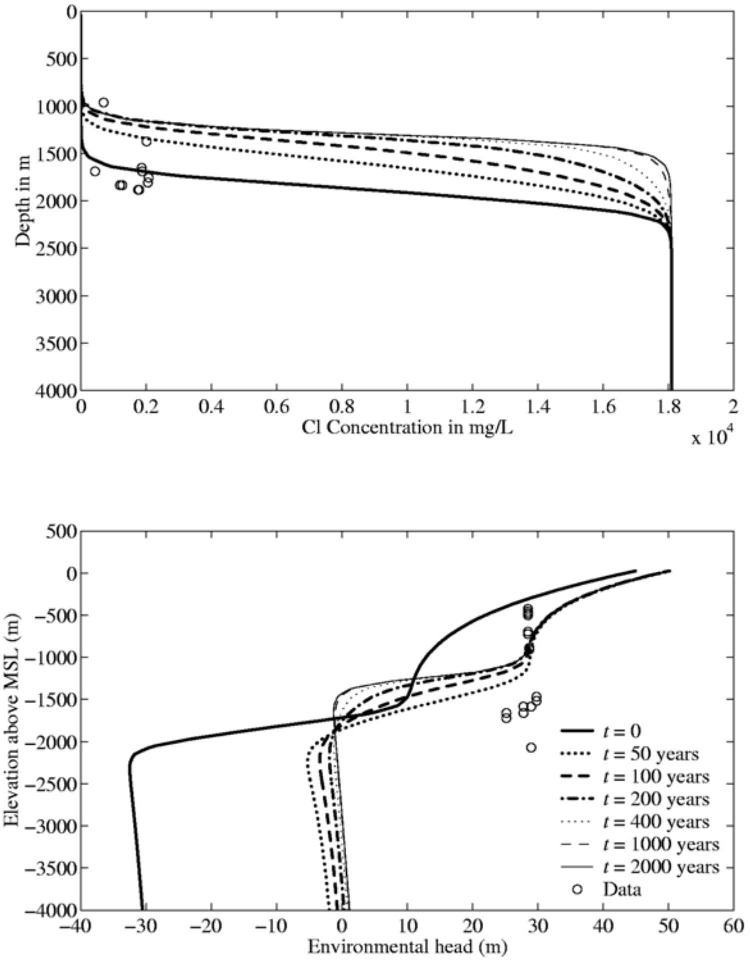

Figure 8. Impact of a lower macrodispersivity on the response of salinity and head profiles at the UAe-1 location at Cannikin after a sudden transgression from an assumed glacial condition with 30-m lower sea level than current conditions. (Parameter values: K = 1.58x10^{-2} m/d, R = *3.65* cm/y, R/K = 6.3x10^{-3}, A_L = 100 m, A_T = 20m, θ = 0.0005.)

Discussion and Implications for Cannikin Flow System

The response of the hydrogeologic system at the Cannikin site to fluctuations in sea level is most rapid in the freshwater lens at equilibrium with the final state. In the recent case of a substantial marine transgression, the rapid equilibration occurs at elevations greater than –1,000 m, coincident with the freshwater lens in equilibrium with the present sea level. Rapid equilibration of both head and chemistry corresponds to the rapid groundwater velocities observed above the transition zone.

Below the equilibrium freshwater lens, low salinity water may persist from the earlier lower sea level, but it is now in a zone of much slower groundwater velocity. As a result, the response of the chemical system to the rise in sea level takes much longer than in the overlying high-velocity zone. The exact time until a new equilibrium state is reached depends not only on the position in the velocity field, but also on the effective porosity. For the range of effective porosity considered here, $5x10^{-4}$ to $1x10^{-3}$, chemical equilibration with a 30-m sea level transgression requires several hundred to a couple of thousand years. Given the fracture flow nature of the aquifer and high porosity of the matrix blocks, matrix diffusion of freshwater out of the porous blocks to be replaced by the incurring seawater will add substantially more time to the equilibration process for the chemical system.

Environmental hydraulic head is partially dependent upon the density, and thus salinity, of the fluid. As a result, environmental head is transient in the same horizon in which the chemical changes are occurring. The magnitude of the head variation is small, however, as compared to probable measurement error at the depths in question (in excess of 1,000 m). The initial head response to the sea level rise actually overshoots the final equilibrium values; this overshoot to higher heads is later moderated as the water salinity slowly increases (decreasing the environmental head).

The modeling results lead to several conclusions regarding head and chemical data from coastal aquifers under conditions of transient sea level. Hydraulic head and water salinity data will most likely be at equilibrium with current sea level conditions in the upper portion of the aquifer. Unfortunately, this “upper portion” cannot be simply characterized as the freshwater lens because low salinity water can exist in disequilibrium with the current sea level for periods of hundreds to thousands of years after a marine transgression. The time for equilibration depends on the groundwater velocity field. Equilibration times will be longest in low conductivity aquifers of high porosity (resulting in low velocity) and under conditions of low bathymetric and topographic relief (resulting in the largest change in recharge with change in sea level). The Cannikin head and chemical data can be interpreted in light of these conclusions. The reasonable coincidence in the calibration fit that captures the shallow set of head data and the one shallow chemical sample suggests that this fit indeed represents the current hydraulic situation. This fit suggests a mid-point of the transition zone at about 1,350 m below land surface. The data in this upper zone should have equilibrated rapidly with the changing sea level conditions and thus should reflect equilibrium values within the accuracy of the field data collection conditions.

The low salinity of the groundwater collected below 1,500 m can be explained as a relict of a lower sea level condition. The salinity profile in equilibrium with a sea level 30 m lower than present somewhat overpredicts the observed salinity. Though this may suggest that actual sea level declines were in excess of 30 m (as observed elsewhere for the last regression), the match can also be improved by using a smaller macrodispersivity value. Fine tuning the match is not worthwhile given the non-uniqueness of the problem and poor quality of the data; it suffices to observe that the deeper groundwater salinity is reasonably coincident with the profile expected during glacial conditions. The persistence of this deep freshwater, out of equilibrium with the current hydraulic system, suggests that the effective porosity is at the high end of the range evaluated (0.0005 to 0.001), or higher, and reflects the influence of diffusion into matrix blocks out of the fracture flow system.

The unusually high hydraulic heads below 1,500 m occur in the same zone where high heads are calculated following a sea level rise. The environmental heads within the transition zone rebound with a sea level transgression, overshooting their final equilibrium values and slowly adjusting as the salinity increases. The high heads observed may be the result of the overshoot and have failed to equilibrate due to the slow equilibration of the chemical system and the impact of salinity on environmental head.

Conclusions

Discrepancies between the hydraulic systems calculated to be at equilibrium with chemical and head data in coastal aquifers may indicate that the system is in fact not at equilibrium. The response times of the pressure system and chemical system to changes in boundary conditions can be different. The response time is also strongly related to position in the flow field. The vertical section encompassed by the freshwater lens in equilibrium with the final seawater level is the zone of rapid equilibration because this is the region of highest groundwater velocity. Marine transgressions, the dominant sea level change worldwide in the last 10,000 years, can result in transient freshwater lenses in coastal aquifers that are thicker than equilibrium dictates and that can persist for thousands of years after the transgression. Equilibration time is inversely related to groundwater velocity, so that long equilibration times are expected under conditions of low hydraulic conductivity and low recharge. With different response times in the chemical and pressure hydraulic systems, and different response times in the freshwater and seawater portions of the flow field, discrepancies in numerical model calibrations can result and are an indicator of long-term transients in coastal systems. Identification of deep freshwater lenses relict of past, lower sea levels can be crucial for properly evaluating sustainable freshwater yields. A numerical groundwater model calibrated to a relict salinity profile could overpredict the current recharge and available resource. The most reliable calibration targets for current hydraulic conditions will be the most shallow data from the flow system.

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