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Groundwater ages in coastal aquifers

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ABSTRACT

The interpretation of groundwater ages in coastal aquifers requires an improved understanding of relationships between age distributions and the processes accompanying dispersive, density-dependent flow and transport. This study uses numerical modeling to examine the influence of mixing and a selection of other hydrogeological factors on steady-state age distributions in coastal aquifers. Three methods of age estimation are compared: the piston flow age, the direct age, and the tracer-based age. These are applied to various forms of the Henry problem, as well as to three variants of a larger, hypothetical coastal aquifer. Circulation of water within the seawater wedge results in markedly higher ages in the transition zone than in the underlying saltwater or overlying freshwater. Piston flow ages show a sharp increase where the freshwater and saltwater systems meet, whereas direct- and tracer-based simulations result in a smoother age distribution, as expected. Greater degrees of mixing result in larger differences between piston flow and direct or tracer-based ages, and bring about lower ages in the saltwater wedge. Tracer-based ages are preferred over direct- and piston flow ages for comparison with field data, especially in cases with wide transition zones. Despite the relatively simple conditions used for the simulations, complex age distributions with depth were obtained. Hence, the assessment of ages in field cases will be difficult, particularly where accurate ages in the transition zone are sought.

1. Introduction

Groundwater age, i.e. the elapsed time since a parcel of water entered the saturated zone, is a parameter of fundamental interest in hydrogeology. It has proven useful in estimating recharge rates [1–4], in characterizing rates of contaminant spreading [5–7], in the calibration of groundwater models [8–10], and for studying large-scale hydrodynamics [11]. The reader is directed to Bethke and Johnson [12] for a comprehensive review on the topic of groundwater ages. Groundwater age information can also provide critical insights into the flow and transport processes of coastal aquifer systems. For example, Michel et al. [13] determined rates of seawater intrusion in a coastal aquifer in California based on tritium (^{3}H) and chlorofluorocarbon (CFC) concentrations measured in the intruded seawater. Han et al. [14] used CFCs to estimate fractions of young and pre-modern water in shallow aquifers and to identify groundwater mixing processes during saltwater intrusion. Sivan et al. [15] also used measured ^{3}H concentrations to infer that seawater that penetrated the coastal aquifer of Israel had traveled up to 100 m inland during a 15–30 year period. Voss and Wood [16] determined the age distribution in an intruded seawater wedge in Hawaii using both a numerical model and measurements of ^{14}C, and found excellent agreement between the rates of seawater intrusion based on modeled and measured ages.

Groundwater ages can also elucidate the effects of historic sea-level fluctuations on coastal aquifers. Love et al. [17] compared observed ^{14}C ages with hydraulic travel time (i.e., the time required for water to flow between any two points in the system) calculated from Darcy's law to point to an increased hydraulic gradient during the late Pleistocene-Holocene caused by sea-level lowering in the Otway Basin, Australia. Yechieli et al. [18] and Bruce et al. [19] were able to differentiate between different stages of seawater intrusion in a multi-aquifer system in Israel, and identified seawater that intruded over 10,000 years ago in deep aquifers and seawater that intruded less than 50 years ago in the shallower aquifers. Vandenbohede and Lebbe [20] used ^{14}C and $^{3}H/^{3}He$ to show that Belgian coastal plain groundwater has a large spectrum of ages (ranging from <10^2 to 10^4 years), demonstrating the influence of the Holocene transgression on the present-day groundwater composition.

Knowledge of the ages and residence times (i.e., the age at the exit point of a streamline) of groundwater in coastal aquifers is

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further required to characterize time-dependent chemical transformation rates. Vacher et al. [21] constrained aragonite-to-calcite diagenesis rates in the freshwater lens of Bermuda based on ages obtained from an analysis of streamlines and flow velocities. Robinson et al. [22] used a numerical variable-density groundwater flow and solute transport model to calculate the residence times of fresh groundwater and intruded seawater in a tidally-influenced unconfined coastal aquifer in Australia, and related these to the geochemical conditions in different parts of the aquifer. They found that the residence times of saline groundwater in the tidally-driven circulation cell below the intertidal zone, where oxygen levels are high, were less than in the deeper wedge of intruded seawater, where oxygen levels are low. The difference in residence times was confirmed by Xin et al. [23], who further found that there was no significant difference between the residence times calculated by using tidally-averaged flow vectors, as done by Robinson et al. [22], or by explicit consideration of short-term flow velocity variations. Interestingly, Lenkopane et al. [24] arrived at the opposite conclusion. Robinson et al. [22] further recognized that neglecting dispersive mixing effects on the calculated age distributions was a limitation in their approach.

Aquifer heterogeneity and diffusion drive mixing between and along flow lines, producing parcels of groundwater that are mixtures of water of varying ages [12]. While the effect of mixing within aquifers the exchange between aquifers and confining layers have received considerable attention in the literature [25,26], there are few studies that have investigated systematically the role of mixing processes on the age of groundwater in coastal aquifers. Field cases which included age data, e.g. Voss and Wood [16] and Sivan et al. [15], are inconclusive on the effect of mixing in the transition zone. Freshwater and seawater that mix in the transition zone of coastal aquifers generally have disparate ages because of their differences in provenance, flow path lengths and flow rates [27]. The processes controlling the width and location of the freshwater-seawater transition zones of coastal aquifers are expected to affect groundwater ages in a similar manner to solute distributions, potentially leading to complex age distributions that are difficult to interpret [28].

This study examines age distributions in coastal aquifers using numerical models. The objectives are: (i) to explore the influence of dispersive and diffusive mixing and a selection of other hydrogeological factors on groundwater age distributions in coastal aquifers, and (ii) to examine differences in the coastal aquifer age distributions predicted using three common modeling approaches. The results are intended to provide intuition and guidance on the interpretation of field-measured groundwater ages that have been influenced by freshwater-seawater mixing in coastal aquifers, and the implications for age simulations based on numerical models will be discussed.

2. Methodology

The starting point of the analysis is the Henry problem [29], which was selected because its small spatial dimensions exacerbate the differences between the three approaches to calculate the groundwater age distribution. Both the original form of the Henry problem [29], which involves an unrealistically wide transition zone, as well as the anisotropic, dispersive Henry problem [30], in which the transition zone is much narrower, were considered. While the Henry problem is useful for highlighting the differences between the three age calculation methods, its small spatial dimensions and the fact that the model is truncated at the shoreline limit its applicability for analyzing groundwater ages in natural systems. Hence, a larger-scale simplified coastal aquifer was simulated, along with a selection of more complicated conditions, to extend the range of settings within which age distributions were evaluated. Flow, salinity and age distributions were analyzed for steady-state conditions to avoid the confounding factors associated with transient aquifer stresses, and to elucidate fundamental relationships between mixing and age distributions under equilibrium conditions.

2.1. Age calculation methods

In this study, SEAWAT version 4 [31] was used for the simulation of the density-dependent flow fields, which formed the basis for the subsequent calculations of the groundwater age distributions. Ages were computed using three different approaches, which are referred to here as the piston flow age (based on particle tracking), the direct age (based on the concept of age mass, after Goode [32]) and the tracer-based age (based on a simulation of either ^{3}H and ^{3}He, or ^{14}C decay).

The piston flow age τ [T] is the travel time along a flow line originating at the point where a water particle entered the domain across the system boundary (i.e., at $l = 0$, where l represents the distance along the flow line [L]) to location L [L]:

$$\tau = \int_0^L \frac{dl}{v_l} \tag{1}$$

where v_l [L/T] is the pore-water flow velocity along the flow path. In this study, piston flow ages were calculated from the simulated groundwater velocities using particle tracking, adopting a numerical scheme similar to that used by Konikow and Bredehoeft [33] and Prickett et al. [34]. Particles were placed at regular intervals in the model domain, and backtracking was used to determine their point of entry at the model boundaries.

Goode [32] showed that by considering direct age as the concentration of a solute species, it is possible to simulate the direct age distribution using the following form of the advection–dispersion equation:

$$\frac{\partial \tau}{\partial t} = \nabla \cdot D \cdot \nabla \tau - \nabla \cdot (v\tau) + R \tag{2}$$

R is the age species production rate [T/T] equal to 1, and D is the hydrodynamic dispersion tensor [L^2/T]. It is noted here that while Goode [32] provided a rigorous justification for this approach and is often credited for the derivation of Eq. (2), it had already been used earlier by Voss and Wood [16] in their study of the age distribution in the coastal aquifer of Hawaii. Direct age was calculated with Eq. (2) using age as a species in SEAWAT. The species representing direct age was assigned a zero-concentration at the start of the simulation and at inflow boundaries.

The tracer-based age was obtained by two different methods. The first, which was applied to the Henry problem, was the multi-species reactive transport simulation of ^{3}H and tritiogenic helium ^{3}He, which forms by radioactive decay of ^{3}H. These tracers have been used in field studies of coastal aquifers to determine the age of groundwater samples (e.g., [10,11]). Reactive transport simulations of ^{3}H and ^{3}He adopted the faster rate of diffusion of ^{3}He compared to ^{3}H [35,36] and the decay of ^{3}H to ^{3}He. The age was determined from the simulated concentrations of ^{3}H and ^{3}He via:

$$\tau = \frac{1}{\lambda_H} \ln\left(\frac{^3\mathrm{He}}{^3\mathrm{H}} + 1\right) \tag{3}$$

where λ_H is the decay constant (0.0558 yr^{-1}), and ^{3}He and ^{3}H are the respective isotope concentrations (TU). It was assumed that all ^{3}He had a tritiogenic source, i.e., it originated only from ^{3}H decay. The reactive transport simulations were conducted using PHT3D [37], which applied the flow field obtained using SEAWAT.