A density-dependent multi-species model to assess groundwater flow and nutrient transport in the coastal Keauhou aquifer, Hawai'i, USA

Okuhata, B. K., El-Kadi, A. I., Henrietta, D., Lee, J., ... & Shuler, C. K., 2022. A density-dependent multi-species model to assess groundwater flow and nutrient transport in the coastal Keauhou aquifer, Hawai 'i, USA. *Hydrogeology Journal*, 30(1), 231-250.

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Date: 2024/11/15

Abstract

Coastal ecosystems rely on freshwater groundwater, which provides low-salinity, nutrient-rich discharges vital for marine biodiversity. However, this resource faces threats from pollution and saltwater intrusion due to coastal urbanization and groundwater overuse. This study examines groundwater flow and contaminant transport in the Keauhou Aquifer on Hawai'i Island using a three-dimensional, density-dependent model based on MODFLOW software. The model is calibrating against multiple variables, including hydraulic head, salinity, nutrient concentrations, and groundwater flow rates, and uses $\delta^{15}NO_3^-$ isotope to trace the contamination sources. Results demonstrate the model's effectiveness in simulating submarine groundwater discharge and nutrient transport. Besides that, nutrients in the aquifer originate primarily from on-site treatment systems and wastewater treatment plants, with smaller contributions from non-point sources. Simulation scenarios assessing sea level rise and urban expansion indicate that as residential demand and pollution pressures increase, nutrient contamination and saltwater intrusion in coastal aquifers are likely to intensify. These outcomes highlight the critical need for sustainable development practices and climate change adaptation.

This study demonstrates the model's effectiveness in simulating submarine groundwater discharge and nutrient transport. However, regional geological complexity and groundwater extraction activities were not fully addressed, highlighting the need for more integrated models to provide comprehensive management strategies.

Keywords: Density-dependent model, Nutrient transport, Submarine discharge, Groundwater management, Hawai'i Island.

Hydrogeology Journal (2022) 30:231–250
https://doi.org/10.1007/s10040-021-02407-y

REPORT

A density-dependent multi-species model to assess groundwater flow and nutrient transport in the coastal Keauhou aquifer, Hawai'i, USA

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Received: 25 January 2021 / Accepted: 11 September 2021 / Published online: 8 October 2021

Abstract
Fresh groundwater is a critical resource supporting coastal ecosystems that rely on low-salinity, nutrient-rich groundwater discharge. This resource, however, is subject to contamination from point- and nonpoint-sources such as on-site sewage disposal systems (OSDS) and urban developments. Thus, the significance of flow and transport processes near the coastline due to density effects and water circulation in a complex hydrogeologic system was investigated. A three-dimensional, density-dependent groundwater model was developed for the Keauhou basal aquifer (Hawai'i Island, USA), where hydraulic head, salinity, nutrient concentrations, and submarine spring flux rates were used as calibration variables to best constrain parameters and produce a comprehensive aquifer management tool. In contrast, a freshwater-only model failed to properly simulate nutrient transport, despite the reasonable success in calibrating hydraulic head measurements. An unrealistic value for hydraulic conductivity was necessary for freshwater-only calibration, proving that hydraulic conductivity is a process-based variable (i.e., depends on model conceptualization and the simulated processes). The density-dependent model was applied to assess relative contaminant source contributions, and to evaluate aquifer response concerning water levels and quality due to changing environmental conditions. Nutrients detected in the aquifer are primarily sourced from OSDS, which was supported by a nitrogen isotope mixing model. Additionally, effects of sea-level rise emphasized the complexity of the study site and the importance of model boundaries. While the model is developed and applied for West Hawai'i, the adapted approaches and procedures and research findings are applicable to other coastal aquifers.

Keywords Numerical modeling · Coastal aquifer · Nutrient transport · Aquifer management · USA

Introduction

Groundwater is a critical natural resource required for daily human use such as potable water supply, industrial uses, and agricultural irrigation (Kemper 2004; Alley 2006). The Keauhou region, located on the west side of Hawai'i Island (USA), has approximately 97% of its freshwater demand supplied by groundwater resources pumped from the Keauhou aquifer system (Fukunaga 2017). As Hawai'i's population increases, future land development and higher water demand are inevitable, along with an expected overall decline in recharge rates due to projected climate change conditions (Elison-Timm et al. 2015). These combined factors will further exacerbate saltwater intrusion (Ferguson and Gleeson 2012), thus emphasizing the need to understand how future circumstances may affect groundwater resources.

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