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Effect of land use and groundwater flow path on submarine groundwater discharge nutrient flux

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ABSTRACT

Study region: Maui, Hawaii, United States.
Study focus: We investigated connections between land uses and submarine groundwater discharge (SGD) nutrient fluxes to coastal waters of Maui, Hawai'i. Nutrient contributions from agricultural lands, wastewater injection, and septic-cesspool systems were examined by combining a numerical groundwater model with $\delta^{18}O_{H_2O}$, $\delta^{15}N_{NO_3^-}$, and $\delta^{18}O_{NO_3^-}$ modeling to identify groundwater pathways, recharge elevations, and nitrate sources. Fresh and total SGD rates and nutrient fluxes were quantified using ^{222}Rn mass balance modeling.
New hydrological insights for the region: Low nitrate + nitrite (N + N) SGD fluxes (24 mols/d) were measured where groundwater flowed beneath primarily undeveloped land on transit to the coast. By contrast, of all land use types, sugarcane and pineapple fields contributed the largest amount of N to coastal waters via SGD (3800 mols/d). Despite their much smaller freshwater flux, these SGD sources provide substantially larger N fluxes than the State's largest rivers (avg. 700 mols/d). Septic systems, cesspools, and near coast wastewater injection wells also contribute N + N to groundwater and coastal waters, although in much smaller quantities. This study demonstrates that numerical groundwater modeling combined with geochemical modeling can be used to determine sources and flux of nutrients in SGD and provides a unique, original, and practical framework for studying the effect of land use and its impact on nutrient delivery to coastal waters.
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1. Introduction

Fertilized agricultural lands, wastewater injection, and areas with high septic-cesspool system density each have potential for contributing excess nutrients to coastal waters of islands via submarine groundwater discharge (SGD). It has been hypothesized for the island of Maui that excess nutrient loading via SGD is a causal factor fueling the macroalgal blooms that have been smothering corals and fouling beaches since the late 1980's (e.g., Soicher and Peterson, 1997; Dollar and Andrews, 1997; Laws et al., 2004; Cesar and van Beukering, 2004; van Beukering and Cesar, 2004; Street et al., 2008; Dailer et al., 2010; Dailer et al., 2012). A first step in mitigating nutrient additions to coastal waters is to identify the source of nutrients. While methodologies for source tracking of nutrients to receiving waters from overland flow are well established (Borah and Bera, 2004), methods for determining nutrient sources in SGD are less well developed. The purpose of this study is to identify the sources of nutrients delivered to coastal waters via SGD.

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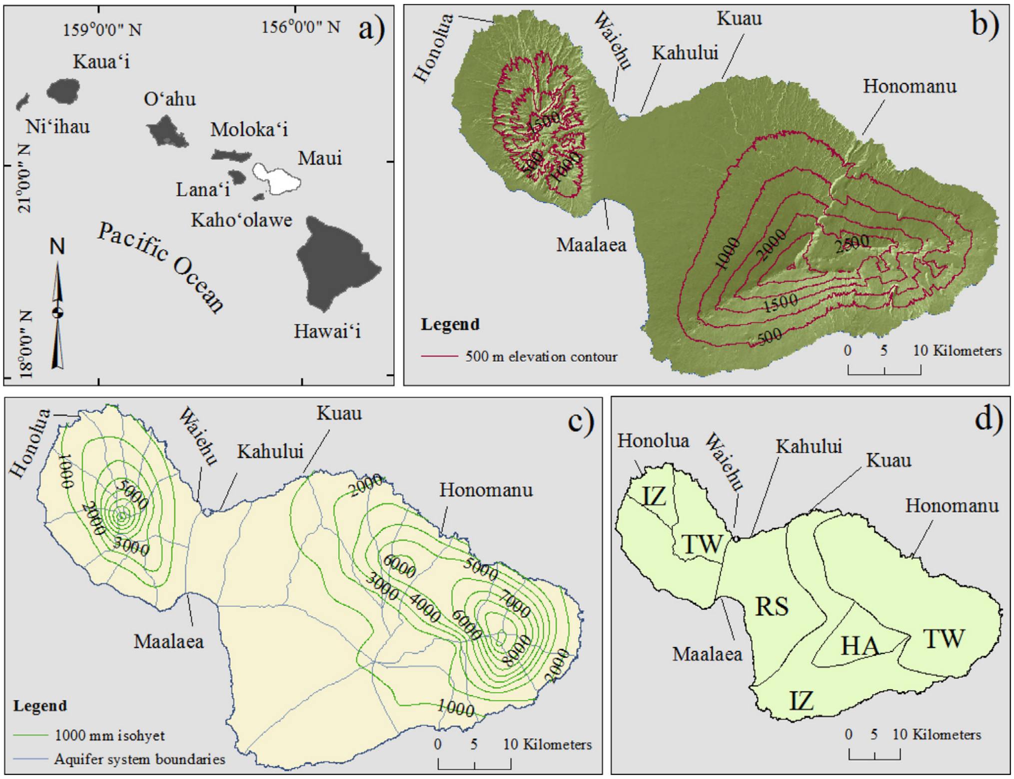

Fig. 1. (A) Hawaiian Islands with Maui shown in white. (B) Shaded relief map of Maui Island showing 500 m elevation contours. (C) Maui aquifer sectors in light blue and 1000 mm rainfall isohyets in green. (D) Local meteoric water line climate zones, adopted and modified from Scholl et al. (2002), were used in recharge elevation calculations. Coastal areas investigated during this study are indicated. Rainfall data from Giambelluca et al. (2013); DEM from NOAA (2007); aquifer sectors from State of Hawai'i (2008).

Relatively few studies have focused specifically on trying to identify the terrestrial source of nutrients in SGD. One such study on Long Island, New York found that high-density development was correlated with high nitrate discharge rates via SGD (Young et al., 2015). Another study on Kauai, Hawai'i found correlations between the amount of proximal agricultural land and nitrate plus nitrite (N + N) concentrations, which suggested fertilizers as the primary nitrogen source (Knee et al., 2008). On Hawai'i Island, similar correlations were found between N+N concentrations and proximity of golf courses, again implying fertilizer as the N source (Knee et al., 2010). Although such studies have strongly suggested a link between land use and SGD nutrient concentrations exists, they relied solely on correlations with proximal land use and did not consider the specific pathways taken by groundwater on transit to the coast.

In this paper we utilize a numerical groundwater model to identify the specific groundwater flow pathways to the coast, $\delta^{18}O$ of H_2O ($\delta^{18}O_{H2O}$) to determine groundwater recharge elevations, $\delta^{15}N$ ($\delta^{15}N_{NO3}$) and $\delta^{18}O$ ($\delta^{18}O_{NO3}$) of dissolved nitrate to determine nitrate sources, and ^{222}Rn mass balance modeling to quantify fresh and total SGD rates. With these tools we (1) quantify the flux of nutrients to coastal waters via SGD in different areas of Maui, (2) identify specific land use practices that contribute nutrients to the coastal zone via SGD, and (3) calculate the flux of nutrients delivered to coastal zones from different land use practices. Our study demonstrates that numerical groundwater modeling combined with geochemical modeling is a robust method for determining the sources and flux of nutrients in SGD. The results presented here also illustrate how such work can provide site specific information of value to land use managers and planners regarding the magnitude of nutrients contributed to coastal waters from different land use practices.

2. Regional and hydrogeologic setting

The island of Maui (Fig. 1) is the second largest island in the Hawaiian Island chain. It is comprised of two separate basaltic shield volcanoes that overlap to form an isthmus between them (Stearns and Macdonald, 1942). The West Maui volcano has a maximum elevation of 1764 meters and Haleakala, the volcano comprising East Maui, has an elevation of 3055 m. Rainfall in Hawai'i is driven primarily by a combination of trade winds and orographic effect. Trade winds are persistent and blow from the northeast resulting in the north and eastern facing (windward) slopes generally receiving higher amounts of rainfall than south and west facing (leeward) slopes. Rainfall patterns in Hawai'i are extremely diverse and rainfall gradients can be exceptionally steep (see Giambelluca et al., 2011). On Maui, northeast facing, higher elevation areas can receive rainfall

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