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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Introduction

Submarine groundwater discharge and pollution transport

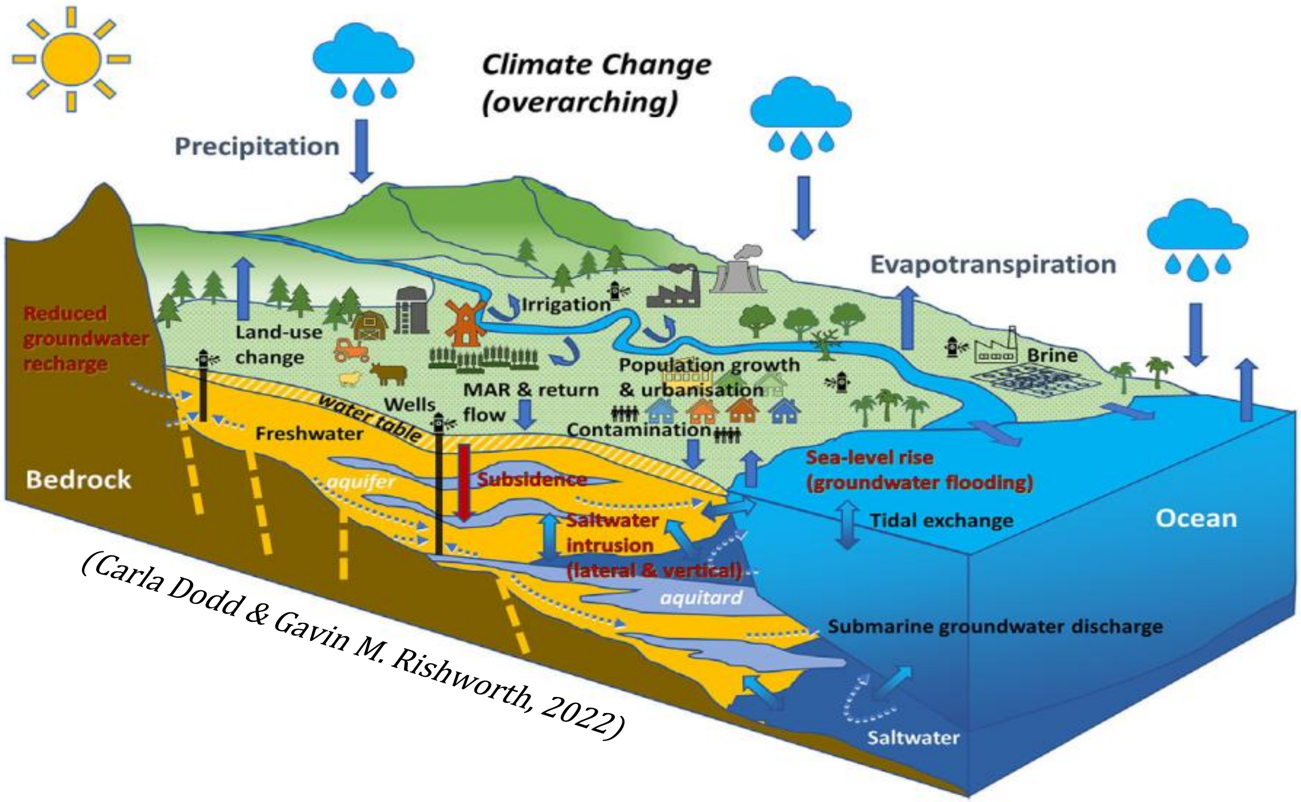


Fig: *Groundwater resources and pollutant transport process in coastal area*

- 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).***

- Coastal groundwater resources threatened by seawater intrusion and groundwater pollution caused by overexploitation and economic development.

Introduction

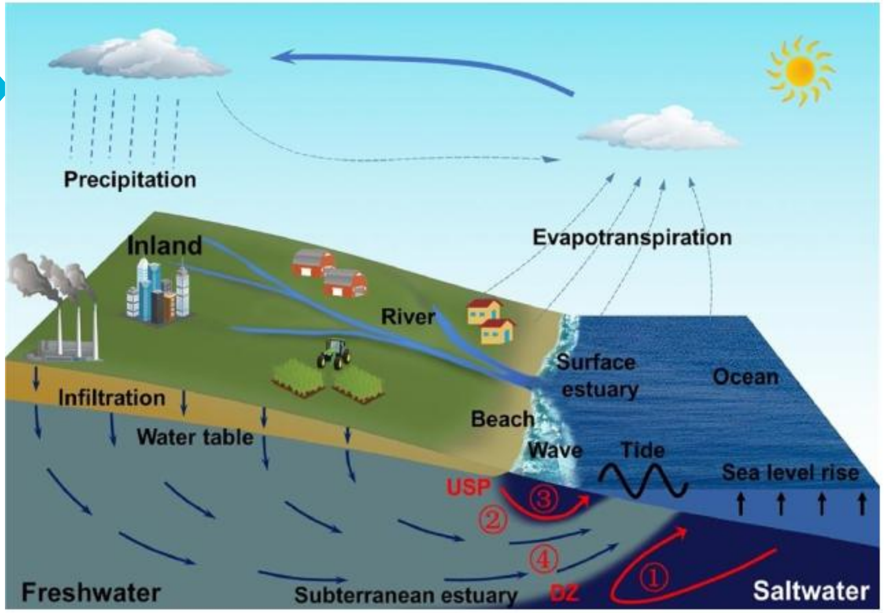


*Fig: Submarine groundwater discharge contributes to transport pollution **(Murgulet, 2021)***

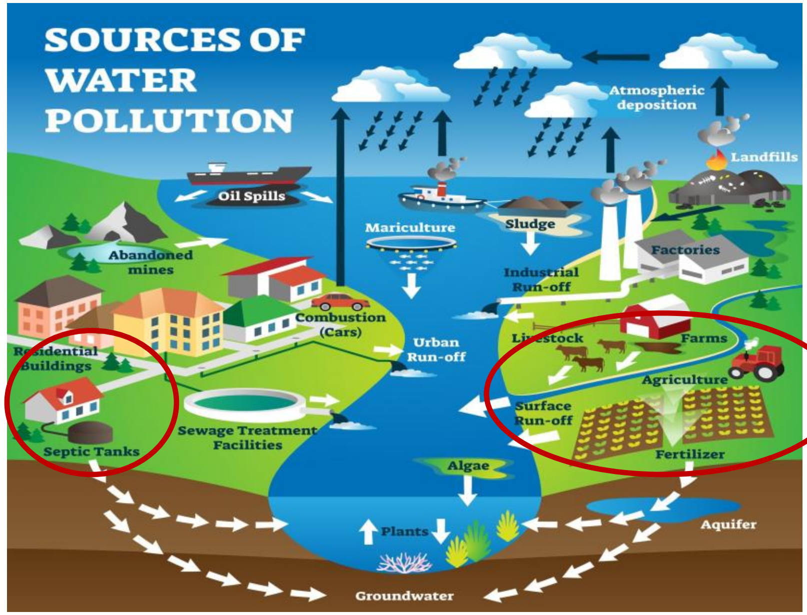


*Fig: Point source and non-point source of pollution **(www.breavardfl.gov)***

- **Overgrowth nutrients** such as nitrate (NO_3^-) and phosphate (PO_4^{3-}), have the potential to **negatively impact drinking water and the biota** of coastal ecosystems ***(Duarte et al., 2010).***
- Urban and industrial development leads to increased on-site wastewater treatment systems and land use conversion, which exacerbates this processes.
- Submarine groundwater discharge (SGD) is an important mechanism controlling the transport of pollutants from land to sea, which can aggravate pollution in this area.

Objectives

- Current studies on Nutrient pollution transport have certain limitations, such as do not consider the **fresh-saltwater interface, inland saltwater influxes**, **and model calibration accuracy**. Therefore, this research aims to:

- Investigate the **significance of flow and transport processes** near the coastline due to **density effects and water circulation in a complex hydrogeologic system**.

- Developing a model that integrates $\delta^{15}N$ measurements with an **isotope mixing equation to confirm both point-source and non-point-source nutrient** contamination in coastal aquifer.

- Applying the density-dependent model to test and develop **management scenarios for urban development, climate change, and sea-level rise.**

Study area and Model input data

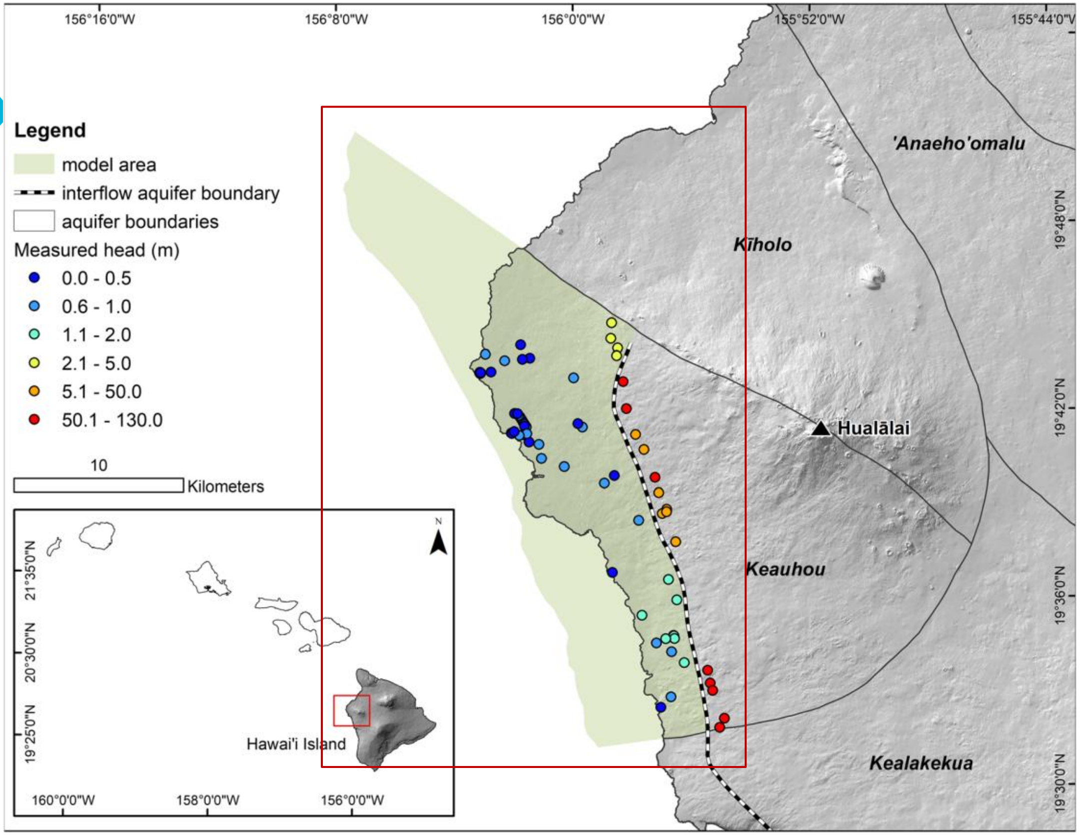


Fig: Keauhou and Kīholo aquifers with volcanics flow distribution and measured water levels.

- Hawai‘i Island’s Keauhou aquifer in Southern Kona with main composed are **volcanic material distinct basal and high-level aquifers with abrupt changes in water levels**.
- Coastal GW levels are about **1 m above MSL**, increasing **dramatically inland to over 100 m** above MSL (4-8 km inland).

Water levels

- The initial groundwater level used for model calibration, based on a total of 54 measurements with a water column range of 0–130 m, obtained from the Water Resources Management Commission.

Study area and Model input data

Recharge, pumping rates, and submarine spring fluxes

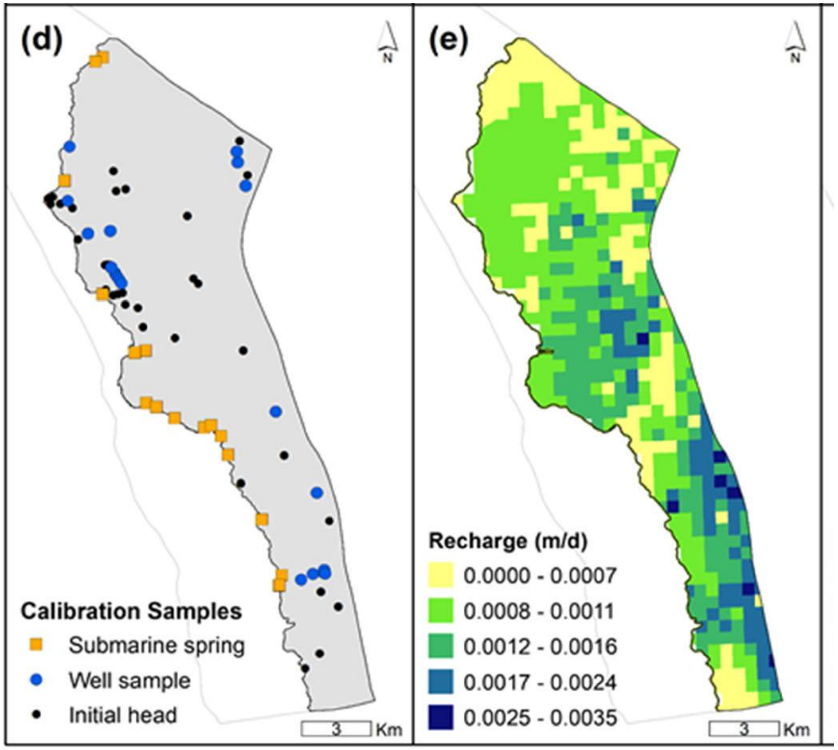


Fig: (d)Location of well and submarine spring and (e) Recharge spatial distribution (Engott, 2011)

- **A "reservoir" model calculated recharge** based on rainfall, fog interception, irrigation, with evapotranspiration and runoff as outputs. Additional data from land cover and anthropogenic sources were included.

- Pumping rates was collected from 1990-2017 show 42,000 m^3/day extracted from 28 wells in the Keauhou aquifer. 27 submarine springs along the coastline, with estimated flow rates of 370–22,000 m^3/day for 19 springs.

Methodology

Study area and Model input data

Nonpoint-source Nutrient pollution

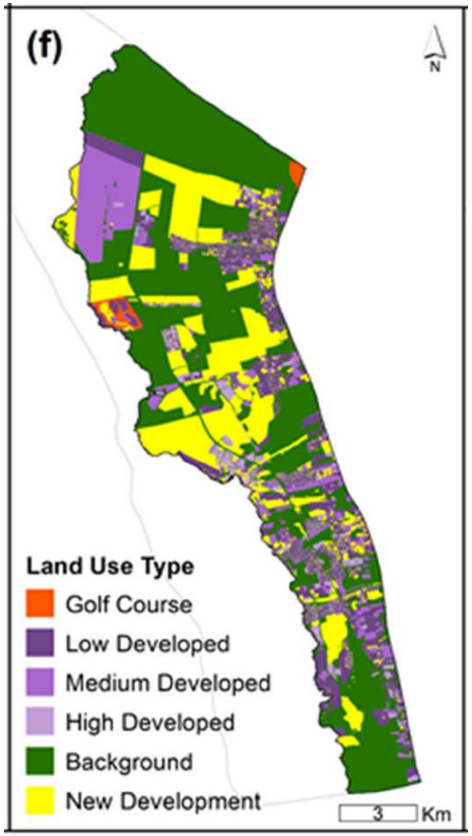


Fig: (f) Land use and Land cover map and relative of Nutrient concentration assigned to recharge

Table 1 Annual nutrient concentrations assigned to recharge based on land cover. The current land use and land cover (LULC) designations are also shown in Fig. 2f

Source	[N] (mg/L)	[P] (mg/L)
Natural (background)	1.0	0.1
Golf course[a]	7.59	0.54
Development (low intensity)[b]	1.13	0.1065
Development (medium intensity)[c]	1.07	0.1035
Development (high intensity)[d]	1.02	0.101

[a] Nutrient concentrations predetermined by Delevaux et al. (2018)

[b] [typical lawn concentration] × 0.65 + [background concentration]

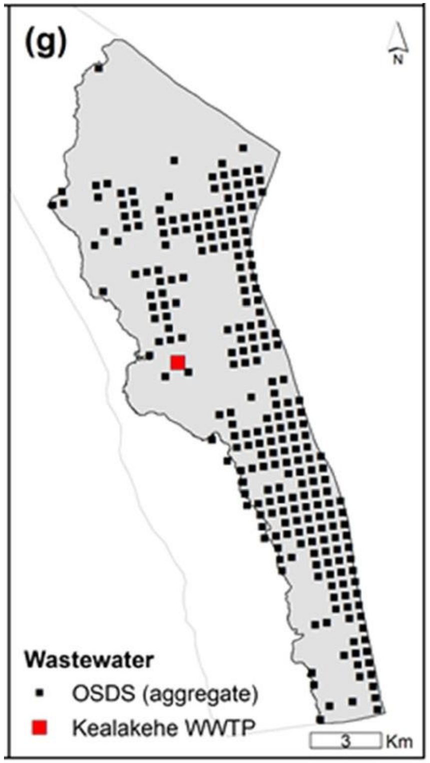
[c] [typical lawn concentration] × 0.35 + [background concentration]

[d] [typical lawn concentration] × 0.10 + [background concentration]

- Land use land cover can influence the groundwater concentrations of N and P due to **wastewater and nutrient inputs to lawns and agricultural systems**. In this model, LULC was divided into three main categories: **natural (background), Golf Course, and urban development.**

Study area and Model input data

Point-Source nutrient pollution



On-site sewage disposal systems (OSDS) and Wastewater treatment plant (WWTP) are two of the important point sources of nutrient emissions in this area.

- The study area includes 1,094 Class I (soil) units, 77 Class II (septic tank), 16 Class III (aerobic treatment), and 6,251 Class IV (cesspool) units. Nutrient mass loads for OSDS points were calculated using typical nutrient concentrations, resulting in a total load **of 890 kg/day across 250 grid cells.**
- The Kealakehe WWTP, with a 930-m^2 percolation basin, has a flow rate of 6,435 m^3/day and **nutrient loads of 144 kg/day for nitrogen and 45 kg/day for phosphorus.**

Fig: (g) Location of aggregated on-site sewage disposal systems (OSDS) and (WWTP)

Nutrient pollution data for calibration

- Nutrient and $\delta^{15}N$ samples were collected and analyzed for key nutrients (NH_4^+, $NO_3^- + NO_2^-$, PO_4^{3-}, SiO_4^{4-}, TN, and TP). Median values from **production well samples represent annual concentrations.** And NO_3^-, NO_2^-, and PO_4^{3-} concentrations from **submarine springs**, (collected by H. Dulai) contributed to model calibration.

Model domain and boundary conditions

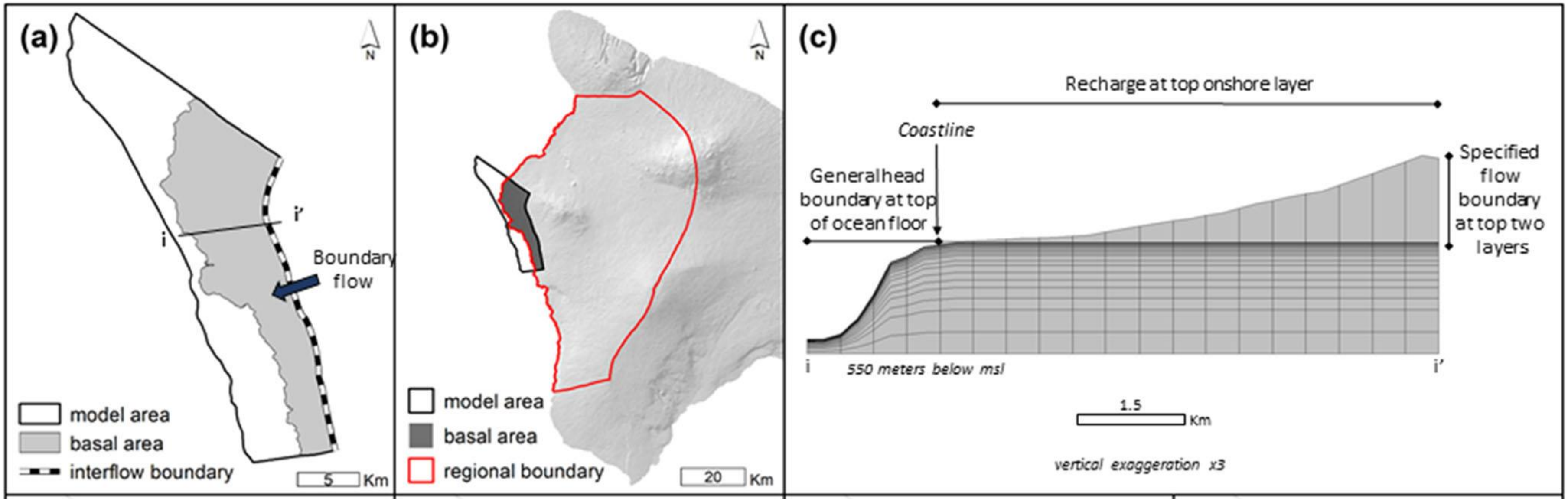


Fig: Boundary conditions and model setting

A transient density-dependent model using MODFLOW and GMS simulated the Keauhou aquifer over 30 years.

- The model, covering **21 layers** with 26,323 cells, grid size 490 m x 490 m (X,Y) spans the aquifer and ocean, with a **top elevation based on topography and a flat base at 550 m below MSL.** The bottom of the first layer is set at 1 m below MSL to avoid dry cells.

- The model estimates a **daily recharge of 470,000 m^3** into the basal aquifer. Boundary concentrations for **salinity, N, and P were set at 0.26 ppt, 1 mg/L, and 0.1 mg/L, respectively**, based on nearby well measurements. The ocean floor was treated as a general head boundary, with a salinity of 35 ppt.

Nutrient variation

- The study site's groundwater **receives nutrients from point sources** (e.g., OSDS, WWTP) and **non-point sources** (e.g., LULC), This overlap creates challenges in distinguishing nitrogen sources and model input, as the **$\delta^{15}N$ and $\delta^{18}O$** isotope ranges from these sources often intersect.

- To simulate source contributions, estimated $\delta^{15}N$ endmembers were set at 7‰ for OSDS, 1‰ for WWTP, 20‰ for LULC, and 2‰ for the eastern boundary. Validation of the modeled $\delta^{15}N$ values was based on dissolved NO_3^- levels in groundwater, where elevated $\delta^{15}N$ in some samples indicated additional nitrogen sources beyond natural soil contributions.

An isotope mixing equation provided estimated $\delta^{15}N$ values at specific wells and springs. *(Hunt and Rosa 2009):*

$$\delta^{15}N_{\text{model}} = \frac{(f_{\text{OSDS}} C_{\text{OSDS}} dN_{\text{OSDS}}) + (f_{\text{LULC}} C_{\text{LULC}} dN_{\text{LULC}}) + (f_{\text{WWTP}} C_{\text{WWTP}} dN_{\text{WWTP}}) + (f_{\text{BC}} C_{\text{BC}} dN_{\text{BC}})}{(f_{\text{OSDS}} C_{\text{OSDS}}) + (f_{\text{LULC}} C_{\text{LULC}}) + (f_{\text{WWTP}} C_{\text{WWTP}}) + (f_{\text{BC}} C_{\text{BC}})}$$

Where the model computes $\delta^{15}N$ (model) at well and spring locations by simulating each source's fraction (*f*), concentration (*C*), and $\delta^{15}N$ endmember (*dN*).

Model application

Scenario 1: Aquifer response to urban development and climate change

The study explores the impacts of new urban development on land use, water demand, and climate that include:

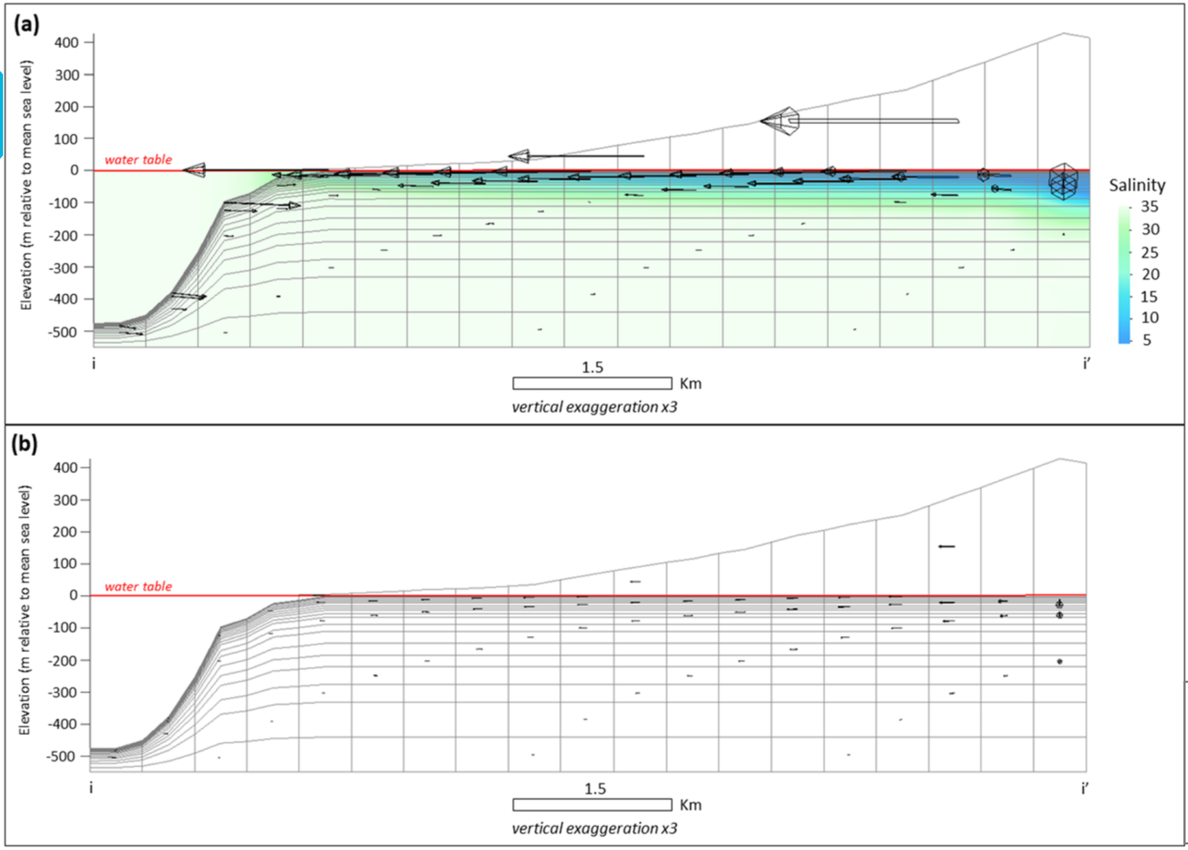
- The new residential area will increase the OSDS supply **to 724 kg N and 225 kg P per day.**
- **WWTP** will treat increase **to 868 kg of N and 270 kg of P per day.**
- **Residential demand increases by 1.5 m^3/day** lead to water pumping change to 64,080 m^3/day will be extracted from high-level wells, reducing eastern boundary flow to 324,319 m^3/day.
- **Climate Change Impact**: Rainfall is expected to decrease by 16–40%.

Scenario 2: Aquifer response to sea level rise

- Global sea level is predicted **to rise approximately 1 m by the end of the century**. To simulate future sea level rise, **the offshore head stage was set to 1 m above msl** to assess how increasing levels could potentially impact submarine spring flux rate and salinity

Results

Validity of the freshwater-only model



- **A only-freshwater model with the same setting was constructed to compare with the density dependent flow model.**

Fig: Vertical cross section i–i′ (Fig. 2a) of flow vectors for the density-dependent model and b freshwater-only model.

- Only Freshwater model shown a lower accuracy in hydraulic conductivity when K_h is only 300 m/day compared to 2,500 m/day in the density-dependent model.
- Submarine spring flux range in freshwater increases RMSE from 1,237 m^3/day to 3,273 m^3/day due to reduced flow fields.
- Nutrient pollution in submarine springs increases compared to reality when flow conditions change.

Results

Density-dependent model calibration

Table 2 Calibrated parameter values used in the Keauhou basal aquifer model

Parameter	Unit	Value
Hydraulic conductivity (K_h)	m/day	2,500
Vertical anisotropy (K_h/K_v)	dimensionless	200[a,b]
Porosity (φ)	dimensionless	0.1[b,c]
Specific yield (S_y)	dimensionless	0.06[c,d]
Specific storage (S_s)	L/m	2.6×10^{-5} [b,c]
Longitudinal dispersivity (α_L)	m	50
Eastern boundary flux	m^3/day	388,399

The study using **multi-parameters to calibrate** the model to reduce the model uncertainty.

- A **simplified K_h distribution was preferred** than heterogeneous due to data limitations and computational costs.

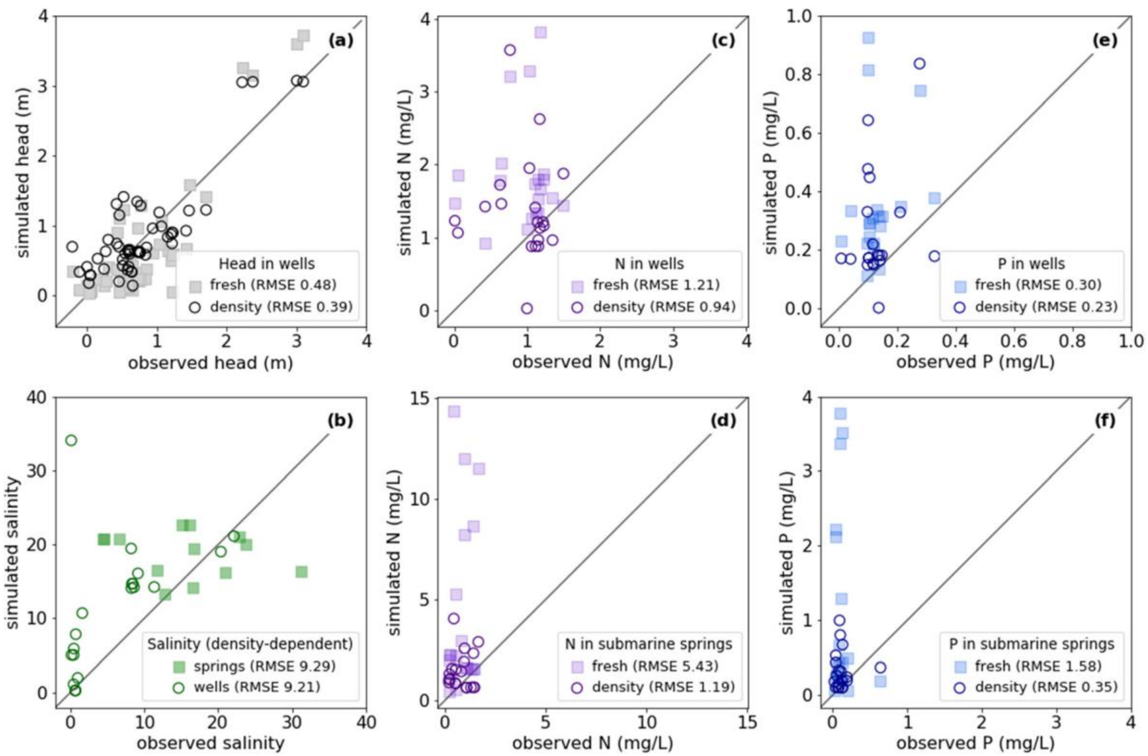


Fig: Scatter plots of density-dependent and freshwater-only model calibration results for head, salinity, N, P.

Head, salinity, N and P concentration was used to calibration.

- **Head and Nutrients (N,P) high accuracy calibrated** in the density dependent model demonstrating the validity of the continuous approach.

- However, the results for salinity and nutrients (N,P) in the underground streams were poor, possibly due to complex geological conditions and preferential groundwater flow.

Results

N source contributions and $\delta^{15}N$- NO_3 model validation

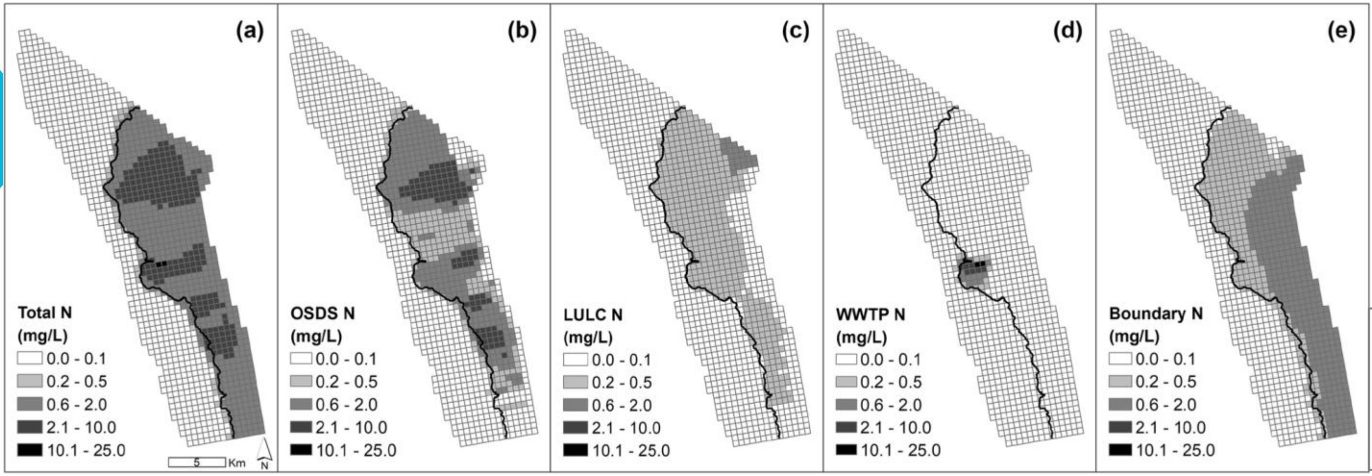


Fig: Simulated N concentration in difference sources in density-dependent model.

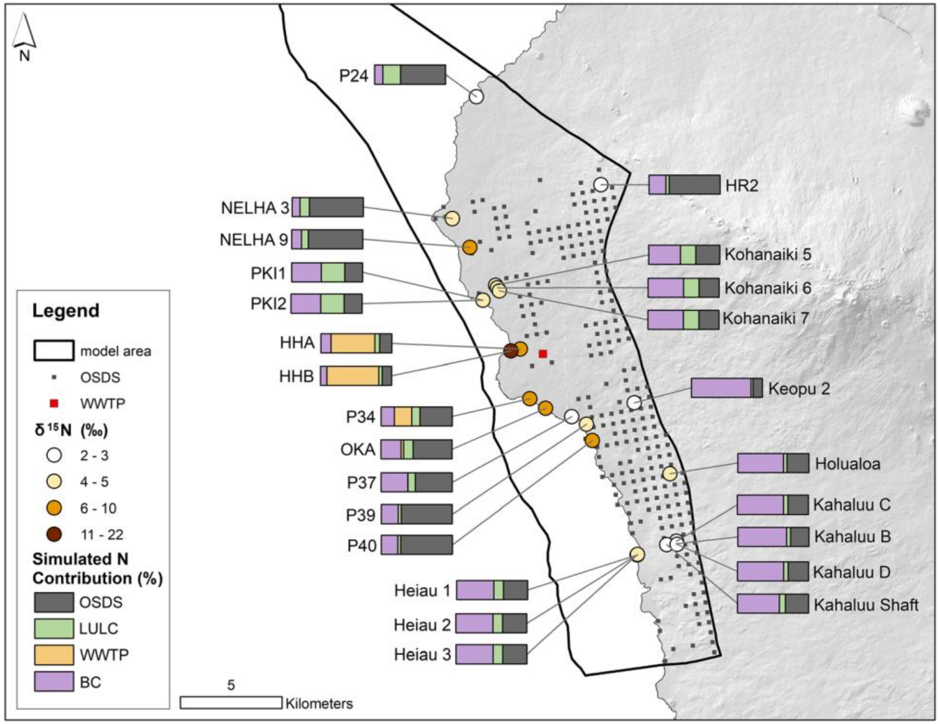


Fig: *Simulated N contributions (bar plots) from various source of pollution*

- The majority of N is sourced from OSDS (54%), while LULC contributed 10%, WWTP contributed 9%, and groundwater applied at the eastern boundary contributed 26%.
- Submarine Springs: WWTP contributes 57–71% of N at springs HHA and HHB, validated by enriched $\delta^{15}N$ values.
- OSDS present in nearly all samples, with 50% or more N from OSDS in 8 samples and from the eastern boundary in 11 samples.

Results

N source contributions and δ^{15}N-NO_3 model validation

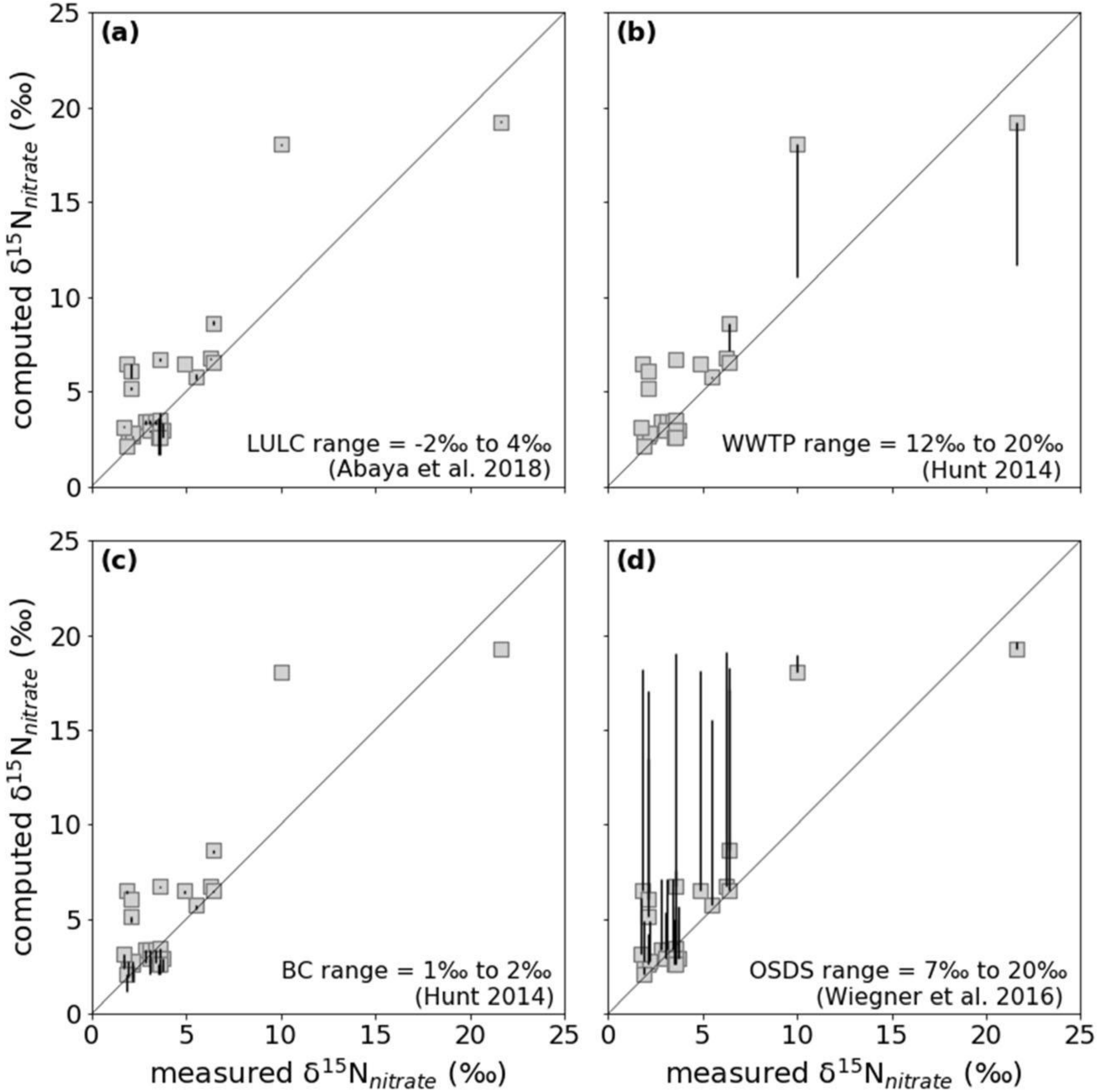


Fig: Mixing model results for measured and computed **δ^{15}N-NO_3** using simulated relative N source contributions.

Results

Scenario 1: Impact of Future Development and Climate Change on Aquifer Conditions

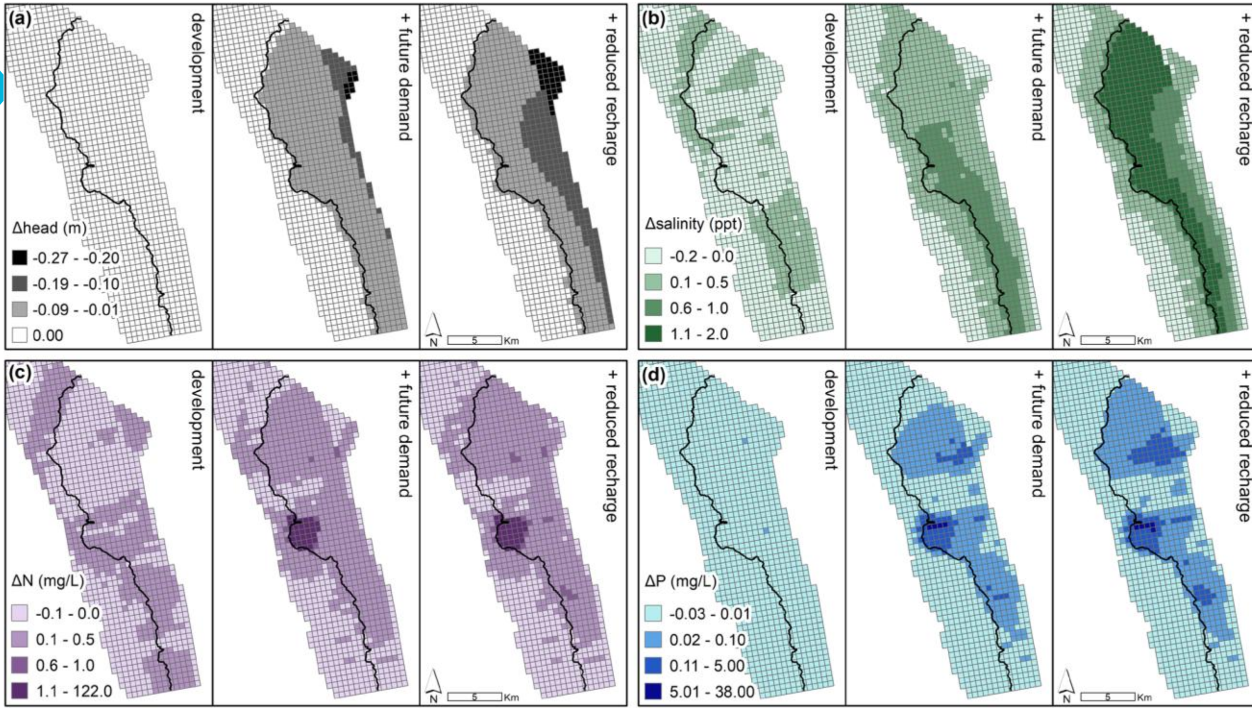


Fig: Change in (a) head, (b) salinity, (c) N, and (d) P concentrations from baseline conditions to future development.

- Reducing in green spaces from new development have **minimal influence on nutrient levels** while is an increase near wastewater treatment place and **no significant impact on sea intrusion.**

- **However, when combined with over-exploitation and reduced recharge rates** due to climate change have **significantly intensified seawater intrusion**, particularly along the southern coast, with salinity rising by up to 2 ppt**. N and P levels have also surged across the model**, especially near the WWTP, with N reaching up to 122 mg/L.

Results

Scenario 2: Sea level rise

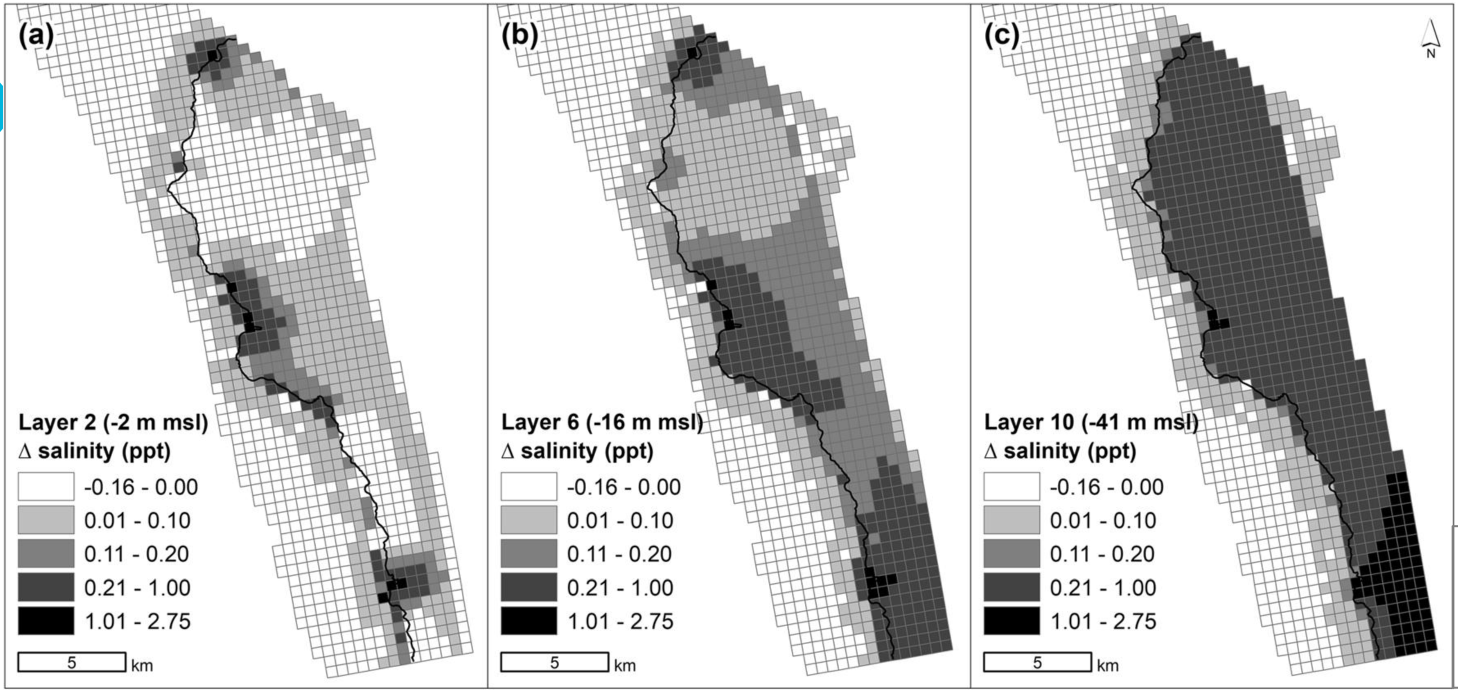


Fig: Change in salinity of aquifer layer during scenario 2.

- With 1 m of simulated sea level rise, **causing** a similar rise in the freshwater-saltwater interface leads to almost layer increase seawater intrusion with maximum change of 2.75 ppt. Greatest salinity changes in mid-layers of the freshwater lens, minimal change in upper layers.

- Rise in the freshwater-saltwater interface **creating a stronger head gradient towards the coast and encouraging more groundwater flow towards submarine springs.** This shift results in less diffuse discharge and submarine spring discharge increased, leading to a **net increase of ~10,000 m^3/day in total discharge.**

Conclusions

- The density-dependent groundwater model **provides more realistic simulations of salinity intrusion and nutrient pollution**, essential for managing coastal water resources.

- While **sustainable development can limit the impact of urban growth on eutrophication and seawater intrusion**, unmanaged climate effects could worsen these issues.

- The study identifies OSDS and WWTP as primary nitrogen sources affecting coastal water quality, particularly in springs. Enhanced wastewater treatment and refined boundary data, especially for the eastern aquifer, are key to reducing nutrient loads and improving groundwater management.

Study limitation

- The study used a simplified, homogeneous model with variable grid sizes at depth, neglecting local geological conditions, which limits result accuracy.
- Nutrient transport was simplified, treating nitrogen (N) and phosphorus (P) as conservative chemicals, thereby reducing the capture of potential chemical transformations.
- Additionally, limited water level monitoring restricts the model's ability to predict groundwater behavior over time.

Future work

- A more accurate, heterogeneous model incorporating density-dependent flow, submarine groundwater discharge (SGD), and nutrient propagation will be developed to better simulate real-world conditions.
- Future models will also integrate geological activities and land subsidence due to groundwater exploitation to enhance practical applicability, especially for groundwater management under regional development and climate change scenarios.

Thanks for your attention