

# Influence of tides and waves on the fate of nutrients in a nearshore aquifer: Numerical simulations



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## ABSTRACT

A numerical investigation is presented that demonstrates the influence of tides and waves on the transport and transformation of nutrients ( $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{PO}_4^{3-}$ ) in a homogeneous unconfined nearshore aquifer and subsequent fluxes to the sea. Simulations of an aquifer subject to semi-diurnal tides and constant waves acting on a sloping beach face were conducted using SEAWAT-2005 combined with PHT3D v2.10. Tidal amplitude ( $A$ ) and wave height ( $H_{rms}$ ) varying from 0.25 to 0.75 m and 1 to 2 m, respectively, were examined. Results show that tides and waves modify the subsurface discharge pathway of land-derived nutrients by changing the nearshore groundwater flow dynamics. More importantly, the oceanic forcing impacts nutrient cycling as it causes significant seawater exchange (along with dissolved  $\text{O}_2$  and organic matter) across the aquifer-ocean interface. Although steady wave forcing caused higher seawater influx, tides led to greater seawater-freshwater mixing in the nearshore aquifer and subsequently greater transformation of land-derived nutrients. Nutrient processing was strongly controlled by the availability and reactivity of marine dissolved organic matter (DOM) as its degradation consumed  $\text{O}_2$ , released inorganic N and P, and altered redox conditions in the salt-freshwater mixing zones. For the conditions and reaction network simulated, nutrient regeneration by marine DOM degradation was independent of the seawater-freshwater mixing intensity, and therefore was greatest for the wave case due to the high seawater influx. For simulations without marine DOM considered,  $\text{NO}_3^-$  discharge to the sea increased by 32% for the tidal case ( $A = 0.5$  m) compared to only 13% and 8% for the wave ( $H_{rms} = 1$  m) and no oceanic forcing cases. With labile marine DOM considered, the  $\text{NO}_3^-$  discharge decreased by 90% relative to the land-derived flux for the tidal case ( $A = 0.5$  m). For all simulations  $\text{PO}_4^{3-}$  removal was high due to its adsorption to Fe oxide minerals. The model enables evaluation of the complex coupled physical-biogeochemical processes controlling nutrient loading to the sea via submarine groundwater discharge in dynamic coastal environments.

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## 1. Introduction

Nutrient (nitrate [ $\text{NO}_3^-$ ], ammonium [ $\text{NH}_4^+$ ] and phosphate [ $\text{PO}_4^{3-}$ ]) concentrations are often elevated in nearshore aquifers due to agricultural, industrial and urban development in coastal areas [1–3]. Although nutrients can be naturally attenuated in the subsurface, often attenuation is limited and nutrient, particularly  $\text{NO}_3^-$ , loading to the sea via submarine groundwater discharge (SGD) is considerable [4–7]. Numerous studies have shown that SGD can be a significant source of nutrients to coastal waters,

particularly in areas where concentrations are higher in the groundwater than in the receiving waters [4,8–11]. Nutrient loading via SGD can have severe effects on coastal ecosystems including high productivity, eutrophication, and in some cases, loss of habitat and biodiversity [5,6,12–15].

The flux of land-derived nutrients to coastal waters depends on the landward groundwater sources, subsurface transport pathways and the reactions occurring along these pathways [14,16,17]. Nutrients may undergo important transformations in a subterranean estuary (STE) – defined as the zone where terrestrial groundwater and recirculating seawater mix in a nearshore aquifer [10,17–19]. A STE is often characterized by geochemical (redox and pH) gradients that influence the transformation of land-derived nutrients, and also marine-derived constituents delivered to a STE by seawater recirculating across the aquifer-ocean

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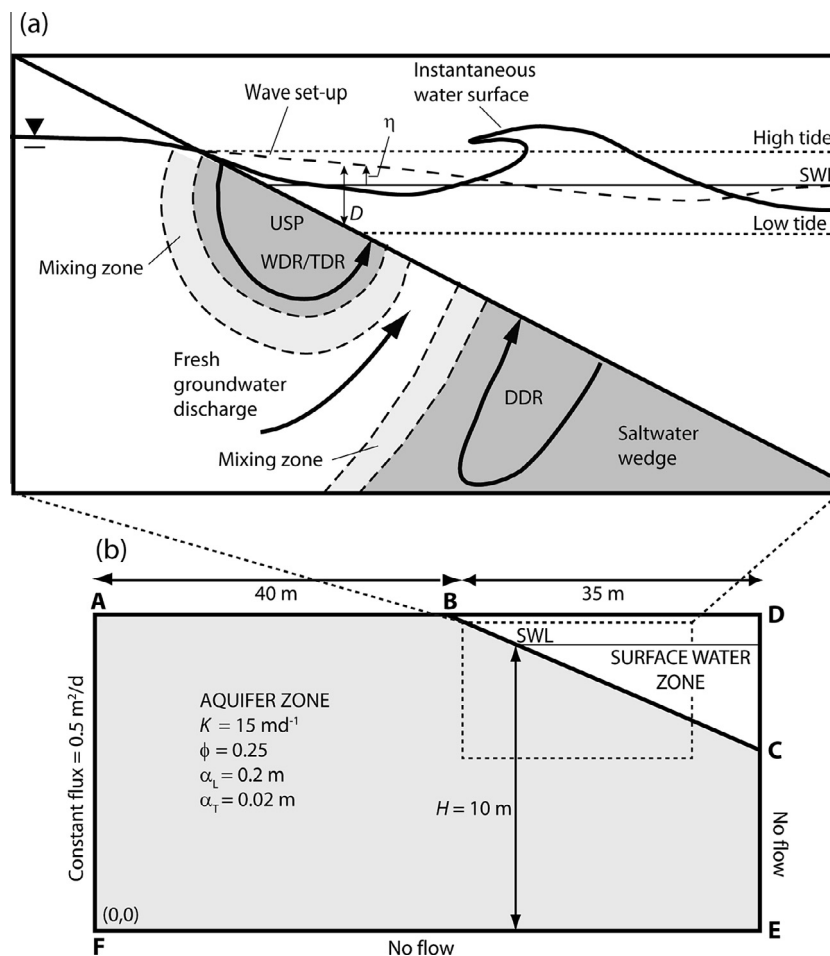
interface [10,14,20,21]. Reactions occurring in a STE have been shown to significantly modify nutrient inputs to coastal waters via SGD (e.g., [10,16,22,23]).

The groundwater flows, transport and seawater-freshwater mixing in a STE are complex. In the presence of oceanic forcing two saltwater plumes may exist: (i) a saltwater wedge that forms due to density-driven seawater recirculation [24] and (ii) an upper saline plume (USP) that forms due to tide- and wave-induced seawater recirculation [25–30]. Land-derived groundwater is generally transported between these two saltwater plumes and discharges near the low tide mark or wave set-down zone (Fig. 1) [26–28,30]. Studies have shown that the USP is a zone of high biogeochemical activity as tide- and wave-induced seawater recirculation is associated with high flow rates and provide a rapid supply of marine-derived constituents to the nearshore aquifer and to this upper mixing zone [22,25,31,32].

In recent years numerous field studies have investigated nutrient cycling in nearshore aquifers and have demonstrated its impact on absolute nutrient fluxes, and also, the ratios and chemical forms of nutrients delivered to coastal waters (e.g., [11,15,16,21,33,34]). The nearshore aquifer can act as a net sink, net source, or temporary reservoir of nutrients depending on the chemical inputs and microbial communities [21,23,35]. Biogeochemical processes affecting nutrient cycling in a nearshore aquifer are complex and include denitrification, organic matter mineralization,

dissimilatory  $\text{NO}_3^-$  reduction to  $\text{NH}_4^+$  (DNRA), nitrification, anaerobic ammonium oxidation (anammox) and adsorption of  $\text{PO}_4^{3-}$  to oxide minerals [14,16,22,23,36,37]. These processes are influenced by seasonal variability and oceanic forcing that alter seawater recirculation rates and delivery of chemical constituents to the nearshore aquifer [21–23,32,33,35].

Denitrification is often considered to be the main pathway for  $\text{NO}_3^-$  removal in groundwater, however this reaction pathway is regulated by the availability of electron donors, particularly labile organic carbon. Although some studies have shown that denitrification may be significant in removing land-derived  $\text{NO}_3^-$  prior to its discharge to the sea. [33], often coastal aquifers are organic carbon-poor and limited denitrification occurs [38]. Seawater recirculation driven by oceanic forcing however can deliver large quantities of labile marine organic matter and oxygen into nearshore aquifers. Studies conducted along tide- and wave-influenced sandy coastlines have revealed that mineralization of marine organic matter can regenerate large quantities of dissolved inorganic nitrogen (DIN) and  $\text{PO}_4^{3-}$  in nearshore sediments [22,32,39]. While  $\text{PO}_4^{3-}$  tends to adsorb to sediments and therefore accumulate in the nearshore aquifer, regenerated DIN can constitute a major portion of the total DIN loads to coastal waters [11]. In addition, high inputs of marine organic matter and oxygen to the nearshore aquifer set-up complex chemical zonations where fresh groundwater and recirculating seawater mix. These zonations have been



**Fig. 1.** (a) Conceptual diagram of the sea water levels, groundwater flows and salinity distribution in a nearshore aquifer exposed to waves or tides. The still water level (SWL), high tide level, low tide level, instantaneous water surface with waves, and wave set-up profile (phase-averaged water surface) are shown. The upper saline plume (USP) formed by wave-driven recirculation (WDR) and tide-driven recirculation (TDR), and the saltwater wedge formed by density-driven recirculation (DDR), are shown. The freshwater-seawater mixing zone associated with the saline plumes are also depicted. (b) Numerical model domain and parameters. The surface water zone (two-zone approach) is used for the simulations with tides considered. The dashed box in (b) illustrates the nearshore area depicted in (a).

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