Global Land-Ocean Linkage: Direct Inputs of Water and Associated Nutrients to Coastal Zones via Submarine Groundwater Discharge (SGD)

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ABSTRACT
Direct discharge of freshwater and associated dissolved nutrients via Submarine Groundwater Discharge (SGD) may have potentially important impacts on coastal water bodies, such as increased eutrophication or hypoxia. Yet, at the global scale, SGD has received little attention compared to efforts made to estimate other pathways of nutrients to the ocean such as riverine inputs. Most studies on the nutrient flux to the coastal zone by SGD have focused on local to regional scales, with the major part of the research being carried out in the Northern hemisphere (U.S. and Europe), and concentrating on areas of high total SGD including recycled fluxes from the saltwater / freshwater mixing zone. While at local scales, the effects of this recycling in the 'subterranean estuary' are important to understand short-term changes in nutrient availability, at the global scale, quantification of the yet poorly constrained net fluxes of freshwater and nutrients discharged via this transport path to the oceans is crucial. Here, we present the first steps towards spatially-explicit estimates of nutrient inputs to the coastal zone via freshwater SGD at the global scale, using baseflow estimates from a global hydrological model, combined with assessments of nutrient concentrations in coastal groundwater bodies.

INTRODUCTION / BACKGROUND
In many areas of the world, continental groundwater flow contributes significantly to freshwater and nutrient fluxes, not only as baseflow to rivers, but also as submarine groundwater discharge (SGD) directly to the coastal zone (Church 1996; Moore 1996). SGD can be an important freshwater source, e.g. in dry areas of the Mediterranean, and clustered assessment based on coastal attributes has been proposed for large-scale estimates of its contribution (Bokuniewicz et al. 2003). At the global scale, near-shore coastal water bodies are generally said to be nitrogen (N)-limited (Howarth and Marino 2006). Inputs from river water are mainly at or slightly below Redfield ratio (N/P~14) (Seitzinger et al. 2005). As phosphorus (P) is mostly efficiently retained in groundwater systems (Spiteri et al. 2008), continental groundwater directly discharging into the sea (SGD) mainly shows N/P ratios >> 16, especially in agricultural areas. Delayed discharge (on the order of several to tens of years) of contaminated groundwater is possible, and box modelling has shown that nutrient inputs via SGD have the potential to significantly affect coastal zone nutrient cycling at the global scale (Slomp and van Cappellen 2004). In most nutrient SGD studies, typically groundwater concentrations of nutrients are multiplied with the total SGD water flux, i.e. including the recycled seawater flux, to estimate nutrient fluxes. Separation of the seawater and freshwater components of SGD is essential, however, since only the freshwater component represents a net input to the marine environment. In this study, we quantify hydrological processes on land, taking into account local variations in topography and lithology, to identify where fresh SGD of nutrients may be important on a global scale.

METHODS
Global hydrological models are typically constructed as a set of cascading reservoirs. They generally include a highly simplified representation of groundwater bodies, and are either tuned or calibrated to a set of known total annual discharge values at the last gauging station.

Here, a new global hydrological model at 0.5° spatial resolution is used (van Beek et al. in preparation), where the parameterization of the shallow/active groundwater reservoir is based on the equation of Kraaijenhof-van de Leur (1958), formulated on the basis of Boussinesq – Dupuit assumptions, for the reservoir coefficient k_r (t^{-1}):

$$k_r = \frac{\pi^2 kD}{4fB^2} \qquad (1)$$

where: *k is the hydraulic conductivity (L t^{-1} e.g., m/day), D is the aquifer thickness (L, 50m assumed), f is the drainable porosity (dimensionless, obtained from global lithology data, together with climate data from the Holdridge life zones classification) and B is the aquifer width (L). Permeability was obtained from a global lithology map, drainage distance from the Hydro1K dataset.*

The model is calibrated on periods of low flows from 290 rivers that could be used for this procedure, drawing on the 8% of the time series with the lowest discharges, i.e. flows that are exceeded 92% of the time. As such, groundwater discharge is available for each terrestrial 0.5° grid cell, including coastal cells.

However, in order to estimate actual freshwater SGD fluxes, total baseflow per cell can only serve as a maximum number. Following the first steps taken here, some important amendments will be necessary to distinguish: i) the coastal water divide where baseflow will become SGD in contrast to groundwater discharging into coastal, but still well-defined, streams, ii) human groundwater extraction, and iii) low-lying areas where salt-water intrusion is the more pressing problem.

A range of coastal groundwater nutrient concentrations will be provided based on groundwater nutrient concentrations for nitrogen (DIN – dissolved inorganic nitrogen), obtained from a large collection of coastal and other groundwater nutrient data, and coupled to information on lithology, landuse, and population.

RESULTS AND DISCUSSION

We test various approaches for DIN transport in groundwater, by (i) assuming shallow, oxic systems with rapidly flowing groundwater to be most common, i.e. with conservative flow of DIN (Spiteri et al. 2008), versus (ii) DIN attenuation scenarios based, for example, on half-life approaches. Thus, we provide a range of coastal water and nutrient fluxes, based on the size of the coastal ribbon, and show coastal areas that are potential hotspots for elevated direct groundwater inputs of DIN. This is based on conditions of high baseflow, combined with extensive agricultural land use and a high population density.

SGD nutrient fluxes in coastal zones show a contrasting picture (Figure 1). Compared to global estimates of riverine inputs of N and P via surface water discharge (Seitzinger et al. 2005), nutrient SGD fluxes show certain similarities in many areas, but fluxes may greatly differ locally. Similarities of elevated flow can be found, for example, in highly populated areas of the US (e.g. NE coast) or SE Asia. Fluxes may be very different locally (e.g. parts of Indonesia, Indian catchments), and especially in areas where surface flow is near zero, as for example in the karstic areas of Yucatan.

Freshwater SGD is an important net pathway for nutrients to the ocean. This fresh SGD has the potential to perturb local and regional nutrient cycling at numerous coastal sites but only a very limited number of field studies have been performed in many potentially important regions, such as the (sub-) tropical areas of Africa, South America and SE Asia.

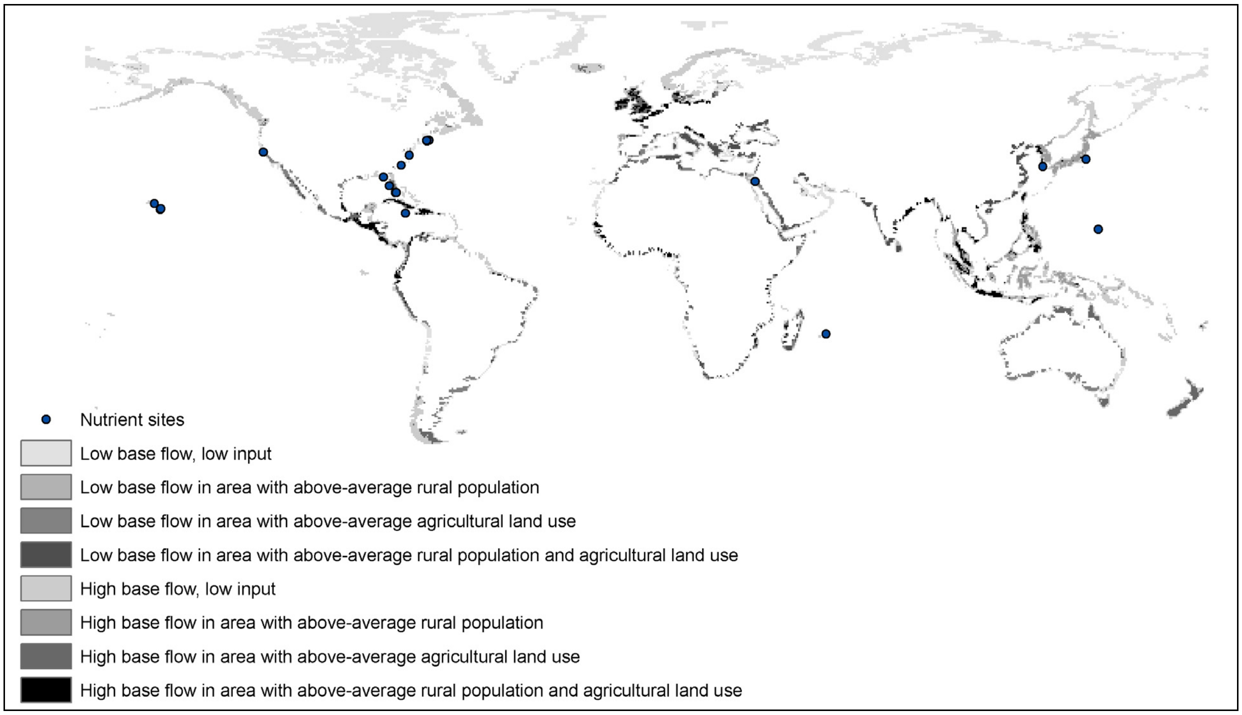

Figure 1. Potential hotspots with elevated N input. NB: Very local phenomena are not detected; the figure represents total groundwater flow in coastal cells, not SGD; groundwater abstraction, saltwater intrusion and groundwater residence time are not yet considered here.

CONCLUSIONS

First steps have been taken towards 1) obtaining spatially explicit estimates of SGD at the global scale, using baseflow estimates from a new global hydrological model and 2) identifying potential hot spots of freshwater nutrient SGD. Our results show that SE Asia, especially Indonesia, and Central America are hot spots for both river and groundwater fluxes, since they show high baseflow, high runoff and high levels of anthropogenic activity, while the exact locations and time scales of groundwater and surface water flows may be different.
As a source of 'new' nutrients, especially nitrogen (less P), freshwater SGD is potentially important for coastal nutrient cycling at the global scale, given the N-limitation of most coastal waters, and shows a strong response to human impact.

We emphasize the need to carry out field studies in (sub-) tropical areas of Africa, South America and South-East Asia. Recent publications show that efforts are now being made to study nutrient fluxes at sites where seawater recycling is relatively minor (e.g. Hawaii, Ubatuba Bay in Brazil – Special Issue of Estuarine, Coastal and Shelf Science, and others), this will facilitate actual calibration of direct SGD in the future. Further coordinated experimental and modeling efforts by biogeochemists, hydrogeologists and coastal oceanographers are needed in high 'risk' areas. Ultimately, this will allow direct groundwater inputs to be included in spatially explicit models for nutrient export to coastal waters.

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