Analysis of Submarine Groundwater Discharge to Manila Bay: Density Dependent Hydrogeological Modeling of the South-eastern coastal zone of Bataan, Philippines

Aileen Mirasol-Robert[1, 2], Gualbert Oude Essink[2], Hans H. Dürr[1]

[1] *Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands*

[2] *Subsurface and Groundwater Systems, DELTARES, Utrecht, The Netherlands*

ABSTRACT

Numerous studies show that the quality of groundwater, directly discharged as submarine groundwater discharge (SGD) to the coastal zone, around the world has declined throughout the past decades with increasing human activities. High-nutrient SGD might lead to coastal eutrophication, hypoxia and an increase of algal blooms. This phenomenon is critical for many South East Asia regions, highly SGD-prone due to climatic and geological settings, where anthropogenic induced groundwater pollution is an increasing concern for a population mostly stretched along coastlines. However, very few studies on SGD have been conducted so far in this part of the world despite the potential of this issue. Here, we present results from a modular variable-density groundwater flow model (MOCDENS3D), applied to the south-eastern coastal zone of Bataan, Philippines, on 12 km of coastline where preliminary SGD flux measurements were made earlier. Different scenarios were run to evaluate the sensitivity of SGD, mainly to presence or absence of clay layers in the subsurface, and to changes in rainfall. Model results are consistent with previously measured SGD rates using seepage meters and geochemical tracers. SGD rates peak during the rainy season. The presence of confining layers greatly affects the offshore extent of SGD, and therefore its potential impact on the regional environment.

INTRODUCTION

Submarine groundwater discharge has been recognized as a potential direct pathway for water and dissolved nutrients from land to sea (Johannes, 1980; Charette, 2001; Slomp and van Cappellen, 2007; Dürr et al., 2008; Spiteri et al., 2008). Nutrients of anthropogenic origin, e.g. from septic tanks, agricultural fertilizers or factory wastes, find their way to the ocean via SGD. SGD is a widespread phenomenon and might be of ecological significance, especially in areas where its magnitude rivals surface runoff. Occurrences can result in coastal eutrophication, bacterial development, hypoxia, increase of algal blooms, and fish/shellfish mortality. Over the years, increasing efforts have been made to study, quantify and qualify SGD around the world to understand its behavior, potential influence and related risks. Despite several initiatives to generate a well defined database for SGD, South East Asia remains in the shadow of SGD research. Yet, this area presents typical characteristics of SGD-prone areas such as high relief, high rainfall and karstic or highly permeable sediments, or volcanic terrains (Bokuniewicz et al., 2003). SGD might be critical to understand in many SE Asian regions where anthropogenic induced groundwater pollution is an increasing concern for a population mostly stretched along coastlines.

The Philippines is a region where coastal zones (Total land area=300,000km^2; Total Coastline=36,289 km) represent nearly half of the country surface area, and are thus a key SGD study site. 75% of the population live in coastal areas and the population growth is the highest of SE-Asia (National Statistics Office - Philippines), which means that anthropogenic activities potentially have a huge impact on groundwater resources in terms of quantity, and quality and thus on freshwater SGD and related nutrients. The economy of this country is largely dependent on coastal resources (e.g. fish, corals, sea grass, etc.), and its marine habitat is one of the most diverse in the world (Carpenter & Springer, 2004). It appears as a major issue to fully understand the mechanism, variability and impact of SGD in this region, as well as the factors affecting its characteristics. The results of this study also represent a significant contribution to the SGD world database.

This study focuses on the Southeastern coastal zone of the Bataan Peninsula, in the North eastern section of Manila Bay (fig. 1). Manila Bay is one of the areas heavily affected by harmful algal blooms (HAB) in the Philippines (Taniguchi et *al.*, 2008). Results of the study made by Taniguchi et *al.* (2008) confirmed the occurrence of SGD in this area, together with elevated nutrient levels. SGD flux from the surficial aquifer was estimated to be about 12.4 $m^3\ m^{-1}\ day^{-1}$ ($8.3x10^8\ m^3y^{-1}$) with magnitude range of DIN (dissolved inorganic nitrogen) input at 42-96% of river input. Thus, SGD, rather than surface loading of nutrients by rivers alone, may be triggering the observed HAB outbreaks.

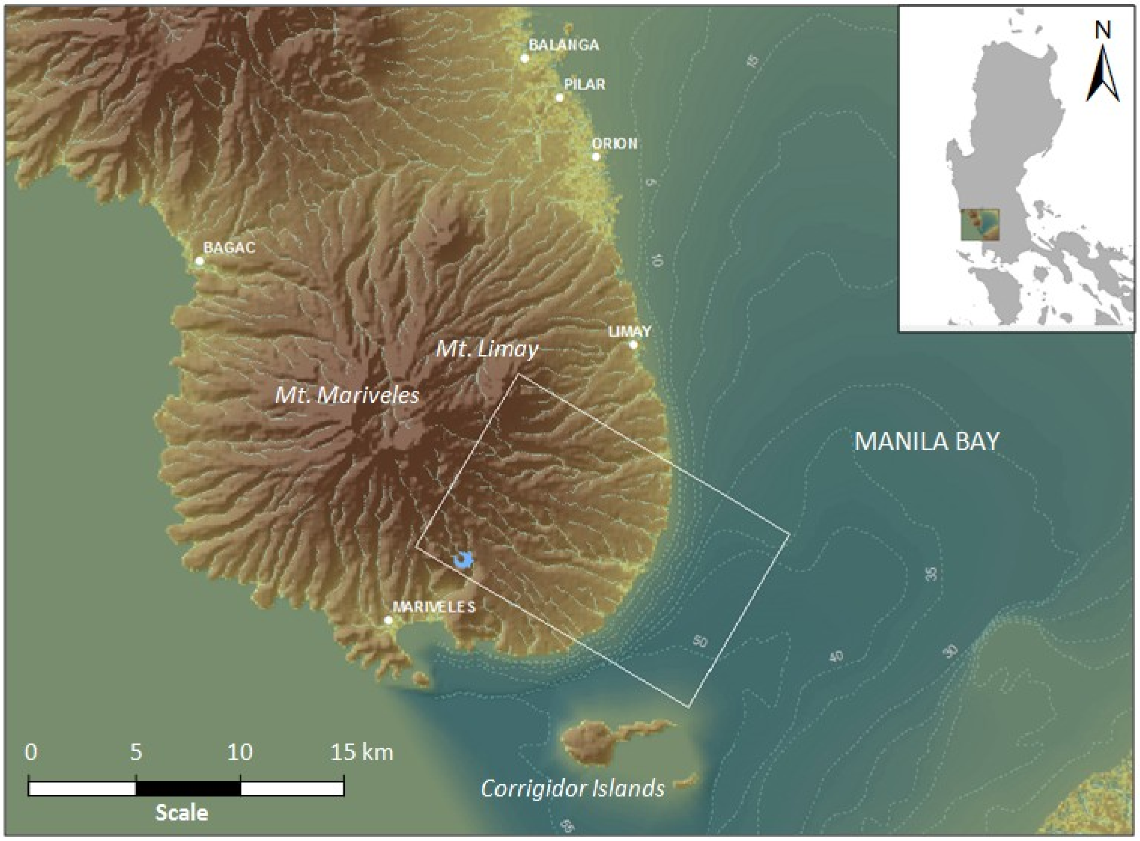

Figure1: Index map. Study area highlighted with the rectangular box. Major topographic features and Municipalities are also shown. Study area bounds 14°24’0.6” – 14°32’49.06” N and 120°29’36.5” – 120°39’48.6”

METHODS

A hydrogeological model has been created using MOCDENS3D (Oude Essink, 1998), a modular variable-density groundwater flow and solute transport code based on MODFLOW and MOC3D, to understand the behavior and sensitivity of SGD. The code was adapted for density variability to assess the hydrogeologic factors influencing the magnitude of SGD at a regional scale. A 30m digital elevation model (ASTER GDEM), precipitation data (21yr record - Lamao Nursery, Limay and 50yr record - Port Area and Science Garden, Manila), SGD field measurements, sediment core/bore logs and well information (70 wells) were used. Different scenarios were run to evaluate the sensitivity of SGD to seasonal climate variability, topography, geology, and land-use changes. The model area is 9.6 x 15.5 km and created at 100m resolution. It is run using 600 stress periods, each equivalent to 30.5 days or 1 month. Two scenarios were run with the model in steady state: 1) confining clay layers, identified from the core/bore logs, are present in the subsurface; 2) the confining clay layers are removed (a homogenous sand aquifer is assumed for the entire low-lying part).

RESULTS AND DISCUSSION

The SGD flux peaks correspond to the rainfall peaks in the system (fig. 2a). Scenario 1 and 2 display similar variations throughout time, although the presence of confining layers seems to increase the variability of SGD flux response. Modeled SGD fluxes with Scenario 1 are on average 5 times higher than with Scenario 2. This is due to the clay layers acting as a submarine tunnel for groundwater (in the form of submarine springs), whereas in Scenario 2 SGD is restricted to near shore seepage and mixing. This underlines the importance of identifying the presence of confining layers (clay layers), greatly affecting the SGD flux values and therefore its potential impact on the regional environment. The difference is also visible in the modeled offshore extent of the SGD with both Scenarios (fig. 3): with Scenario 1 freshening of coastal sediments pore water reaches up to 2.5 km offshore whereas in Scenario 2 it only extends to <1 km. The homogeneity of sediments in Scenario 2 makes the denser saline water restrict the extent of the freshwater offshore.

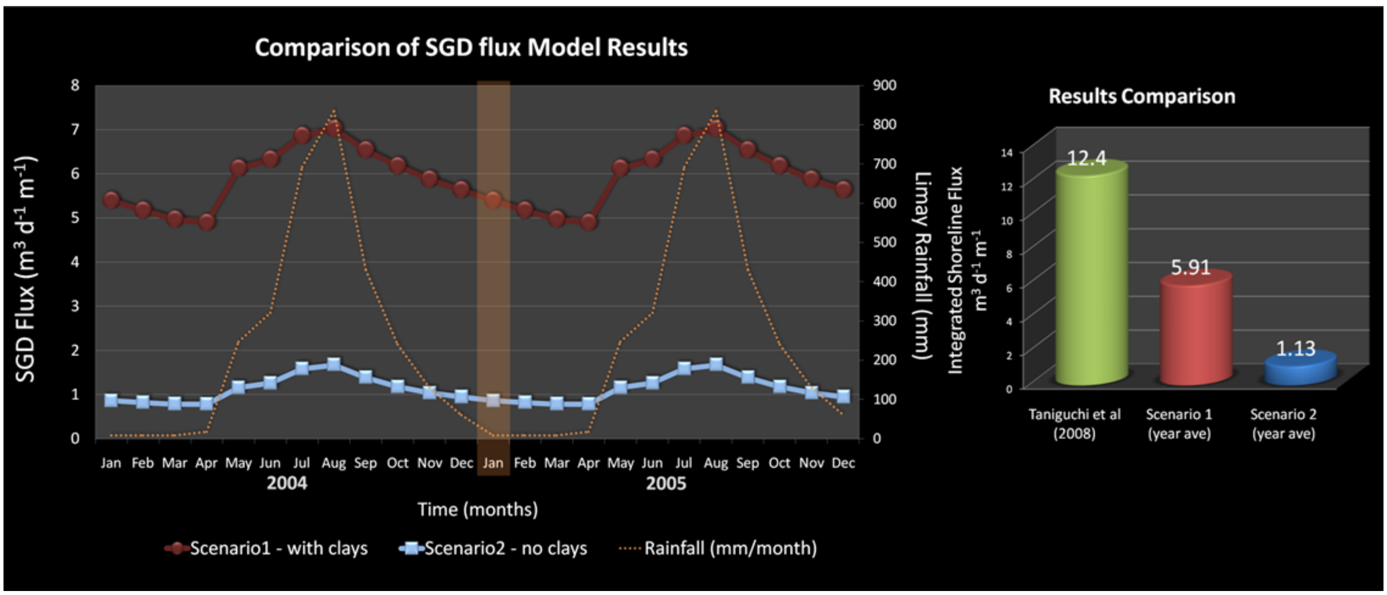

Figure 2a. Comparison of SGD flux vs. rainfall for the two scenarios. Shaded area is detailed in **Figure3,** also corresponds to the time Taniguchi et al (2008) made the SGD flux measurements.

Figure 2b. Comparison of integrated SGD flux results, model and measured (model results are averaged over the whole year (Jan-Dec, 2005; time steps 489-600).

The total integrated shoreline flux averaged over 12 months (2005) is 5.91 $m^3 day^{-1} m^{-1}$ and 1.13 $m^3 day^{-1} m^{-1}$ for the two scenarios, respectively (Fig. 2b).). Both results are lower, but in the same order as the SGD flux measured by Taniguchi et al. (2008), estimated to be about 12.4 $m^3 m^{-1} day^{-1}$. The difference in the measured SGD and standard model result (Scenario 1) could be attributed to the difference in the extent of the study area: Taniguchi et al. (2008) did their measurement within 500m offshore and 500m length of shoreline, whereas the model area in this Scenario covers the area up to 5km offshore and 11.66 km of shoreline. Also, some shoreline segments have higher SGD fluxes compared to others, which can lead to geographic variability on relative SGD contribution. Ultimately, measurements made by Taniguchi et al (2008) include the re-circulated SGD component, whereas the model result only represents the freshwater SGD flux.

CONCLUSIONS

Model results are consistent with the rates of SGD measured by Taniguchi et *al.* (2008), using seepage meters and geochemical tracers. Sensitivity analysis results allow the quantification of the considerable influence of rainfall and geology on SGD fluxes. Ideally, data from field campaigns should be coupled to hydrogeological modeling in order to establish key control factors of SGD rates and to ultimately allow coupling water fluxes to nutrient fluxes. This study enables a 3D approach and representation to the SGD systems, resulting in a more realistic model, and therefore in a better understanding of the underlying mechanisms.

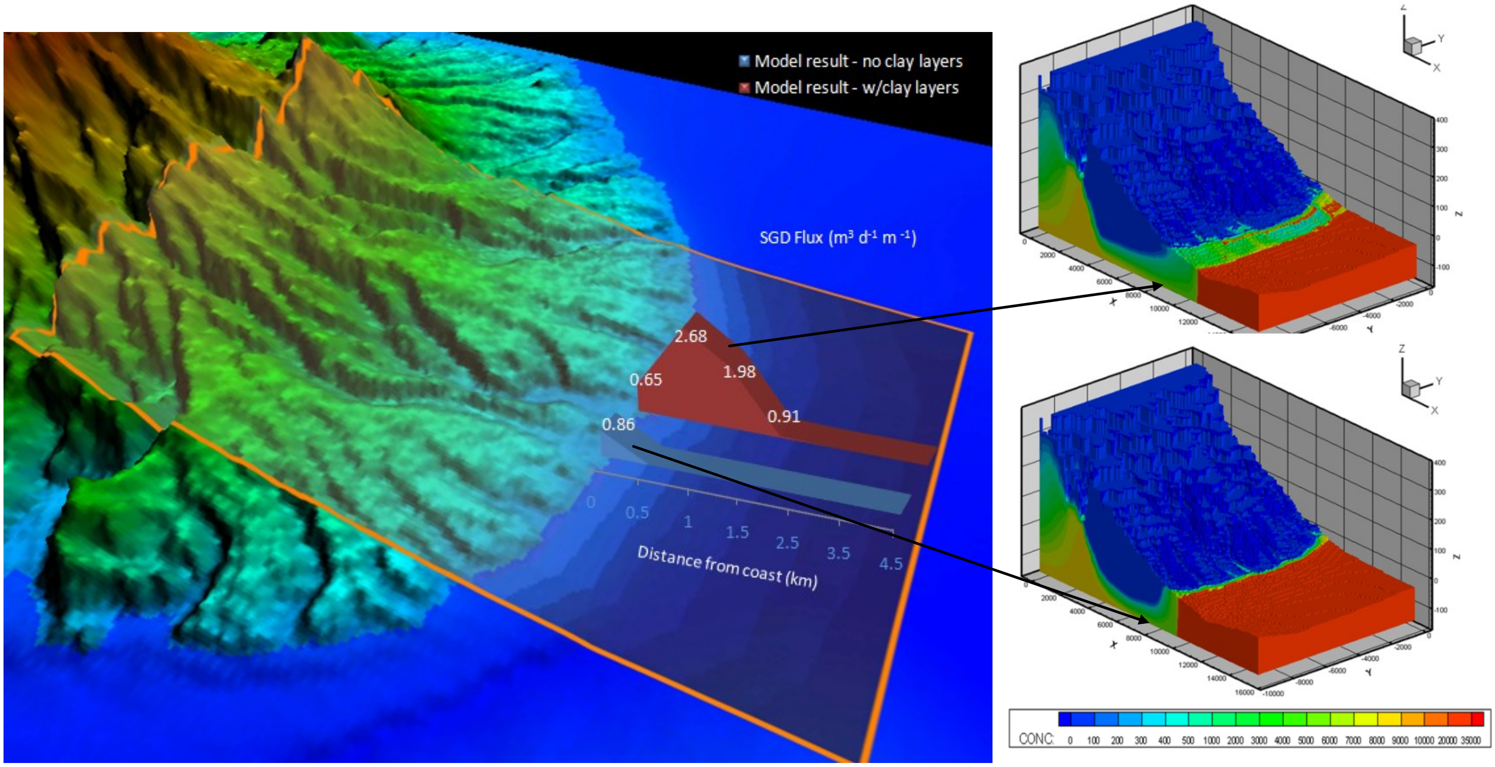

Figure 3. Effect of geology on resulting SGD fluxes. On the left hand side, Scenario1 (red graph) represents resulting SGD fluxes simulated with the clay layers and Scenario2 (blue graph) represents resulting SGD fluxes simulated with no clay layers. The extent of "freshening" offshore is shown on the right. Relative changes in fluxes with the distance to the shore are also shown. Results are both extracted from the stress period 598 (Jan-2005), corresponding to the shaded area in **Figure 2a**.

REFERENCES

Bokuniewicz, H., R. Buddemeier, B. Maxwell and C. Smith, 2003. The typological approach to submarine groundwater discharge (SGD). *Biogeochemistry,* 66(1), 145-158.

Carpenter, K.E. and V.G. Springer, 2005. The center of the center of marine shore fish biodiversity: the Philippine Islands. Environmental biology of Fishes, 72, 467-480.

Charette, M.A., K.O. Buesseler and J.E. Andrews, 2001. Utility of radium isotopes for evaluating the input and transport of groundwater-derived nitrogen to a Cape Cod estuary. *Limnology and oceanography,* 46 (2), 465-470.

Dürr H.H., L.P.H. van Beek, C.P. Slomp, H. Middelkoop and M. Bierkens, 2008. Global land-ocean linkage: direct inputs of water and associated nutrients to coastal zones via Submarine Groundwater Discharge (SGD). *Proceedings 20th Salt Water Intrusion Meeting* (June 23-27, 2008; Naples, Florida, USA), 72-75.

Johannes, R.E., 1980. The ecological significance of the submarine discharge of groundwater. *Marine Ecology – Progress Series*, 3, 365-373.

Oude Essink, G.H.P., 1998. MOC3D adapted to simulate 3D density-dependent groundwater flow. Proc. MODFLOW'98 Conference, Golden, Colorado, USA: 291-303.

Slomp, C.P. and P. Van Cappellen, 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *Journal of Hydrology*, 295, 64-86.

Spiteri, C., C.P. Slomp, K. Tuncay and C. Meile, 2008. Modelling biogeochemical processes in subterranean estuaries: The effect of flow dynamics and redox conditions on submarine groundwater discharge of nutrients. *Water Resources Research*, 44, W02430, doi:10.1029/2007WR006071.

Taniguchi, M., W.C. Burnett, H. Dulaiova, F. Siringan, J. Foronda, G. Wattayakorn, S. Rungsupa, E.A. Kontar and T. Ishitobi, *2008.* Groundwater Discharge as an Important Land-Sea Pathway into Manila Bay, Philippines. *Journal of Coastal Research*, 24 (1), 15-24.

Contact Information:

Aileen Mirasol-Robert, Subsurface and Groundwater Systems, Deltares, PO Box 85467
3508 AL Utrecht, The Netherlands, Phone: +31 684 678 981 Email: aileen_nigs@yahoo.com