POLICY BRIEF 2019/3

Coastal water management related to submarine groundwater discharge: a study case in Indonesia

SUMMARY

Fresh submarine groundwater discharge (SGD) is described as fresh groundwater flux from land to ocean through submarine ocean boundaries. It has been reported to bring land-based nutrients, heavy metals, or potentially harmful bacteria to the coastal area. Solutes delivered by SGD have been reported to cause eutrophication, change in coastal bacterial, benthic, and fish communities, as well as the deterioration of coastal ecosystems such as coral reef and mangroves. SGD rates tend to vary and fluctuate due to tidal cycle, hydraulic head, and seasonal variability, particularly in regions with high precipitation and groundwater recharge. Tropical regions, such as Southeast Asia, have been underrepresented in SGD studies. These regions are generally characterized by high aquifer permeability, fast weathering, nutrient-rich rocks, and active natural ecosystems. Thus, active SGD is expected here. Southeast Asia also has one of the most altered coastal land use worldwide, which subsequently makes SGD potentially act as an essential land-ocean delivery pathway of contaminant derived from human activities. Indonesia was chosen as a study site due to its long coastline and favorable hydrogeological conditions for SGD as mentioned above.

Based on these backgrounds, we discussed three main topics in this study:

- SGD rates and composition, particularly related to nutrients in urban areas,
- Potential environmental and health effects of SGD from urban areas, and
- Suggested coastal water management practices based on literature review and the result of the SGD studies.

KEY RESULTS

- Groundwater and SGD connect coastal waters with their hinterland. SGD delivers land-based nutrients from land to ocean.
- SGD may potentially bring human pathogens to coastal water and affect the health of swimmers.
- Geological condition and anthropogenic activities in the watershed affect SGD water quality.
- SGD may alter the physicochemical condition of the receiving coastal water and can affect the composition of coral cover and species diversity.
- In tropical regions, SGD is affected highly by seasonal dynamics and less by tidal cycle.

RECOMMENDATIONS

To reduce adverse effects of SGD on ecosystems and human health:

- Control potential pollutant or nutrient input to aquifer systems considering coastal waters as their recipients
- Improve or strengthen sanitation systems
- Implement a regular water quality monitoring scheme
- Ensure transparency of the water policy network
- Enforce established environmental regulations
- Include circumstances on both land and coast to develop strategies for proper SGD management

THE CONTEXT

Indonesia is located in tropical Southeast Asia and has favorable hydrogeological conditions for SGD with its long coastline, wet, humid climate, high precipitation rates and aquifer permeability. Coastal regions are home to almost 60% of the total Indonesian population, and this number is projected to grow in the future due to an increasing contribution of marine-based activities to the national economy. Coastal ecosystems in Indonesia contain rich biodiversity; for example, Indonesian mangrove forests account for 76% of the total mangroves in Southeast Asia; as well as 75,000-km^2 of coral reefs throughout the archipelago.

Here we report from three SGD sites in Indonesia (Figure 1). Two of them are located in Java Island, the most densely populated island in Indonesia, while the third study was implemented in Lombok Island. The first location, Jepara, is located in the northern part of Java Island. The geological setting is dominated by a strato-volcano (Mt. Muria, 1602 m) and alluvial products of the coastal flat are mostly derived from redeposited volcanoclastic materials, causing the presence of extensive aquifers. This condition leads to the occurrence of SGD as seepage at the coast and seafloor. Jepara has a population of 1.2 million inhabitants with agriculture, fisheries, tourism, and small furniture industry as primary sources of income.

Gunung Kidul, located in southern Java, is tour second SGD study site in Indonesia. The geology of this region is characterized by strongly karstified limestone. In this area, SGD occurs as underground rivers, submarine and coastal springs, which sometimes are used as water resources for the local population. Agriculture, mainly dry farming and livestock, is the dominant type of land use in this region inhabited by 730,000 people.

Lombok Island is characterized by tectonically active terrain, with known volcanic eruption as recent as September 2016, and a 6.9 SR earthquake in August 2018. In Lombok, SGD occurs as submarine freshwater springs. Eight springs were identified in this site; some of them are encased in wells and used as drinking water source by the local population. These springs discharge fresh groundwater into coral reef barriers, which stretches with a length of about 700 m along the coastline and a distance away from the shore of about 200 m.

To assess SGD rates, various methods were employed, e.g. radon as SGD tracer in Jepara, underground river discharge measurement in Gunung Kidul, and a combination of recharge estimation, echosounder profiling, and hydrochemical isotopic analyses in Lombok. Nutrient and microbial community composition were determined from the SGD sites to describe the composition of SGD.

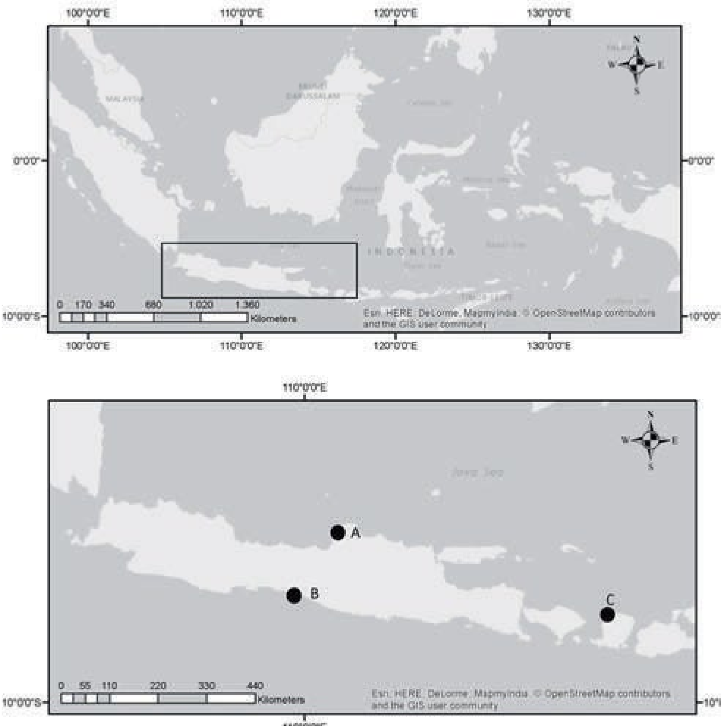

Figure 2. Map of Indonesia (top) and Java (bottom), and the location of study sites in (A) Jepara, (B) Gunung Kidul, and (C) Lombok

Figure 1. Coastal springs or seepage in Gunung Kidul (top) and submarine seepage in Lombok (bottom)

RESEARCH RESULTS

SGD rates and composition

SGD rates were measured in three locations in Indonesia. We observed distinct SGD rates between the locations due to different geological backgrounds. For example, SGD fluxes from karstic Gunung Kidul were two magnitudes higher than SGD from Jepara, due to the typical focused flow occurring in the karstic region compared to diffuse flow in the volcanoclastic lithology of Jepara. Our SGD rates measurement in Jepara showed comparable results with studies performed in other volcanic regions, but were higher than results from studies in subtropical or temperate regions. In Lombok, distinct SGD rates and hydrochemical composition were measured from different morphology of submarine springs.

We observed in our studies that high rates of SGD occurred during low tide compared to high tide, in concurrence with daily tidal cycle. In all of our sites, we discovered that SGD deliver land-based nutrient to the coastal water in the form of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). Even though DIN and DIP concentration were transformed or attenuated due to different factors, significant amount of nutrient was still discharging to the coastal area. These factors include microbial-mediated biogeochemical cycling (e.g. ammonification, nitrification, and denitrification), biological uptake by benthic and pelagic primary producers, or physical processes (e.g. dilution, absorption-desorption). In Jepara, SGD contributed to up to 23% of DIN and 20% of DIP to the coastal area in comparison to river discharge, while globally the number is expected to be in the range of 2-7.5% (Beusen et al, 2013).

High precipitation rates occurring in this tropical region also influence seasonal dynamics of SGD rates. Our 1-year measurement in the karstic area of Gunung Kidul suggests distinct SGD fluxes between dry and wet season. A notable amount of SGD-derived DIN and DIP fluxes was measured after a period of constant and heavy rain during the wet season.

Based on our land use analysis, anthropogenic activities were the origins of nutrient that composed the SGD in our study sites. In particular, agriculture and wastewater are two main contributors to the nutrient pool, as both locations did not have a sewerage system and city sanitation coverage only covered averagely 70% of the population. The contribution of wastewater was also supported by the result of our microbial community analysis. We found genera containing coliform, faecal, intestinal, and potentially human pathogenic bacteria in Jepara and Gunung Kidul, which pointed to human or livestock origins. In Gunung Kidul, large amounts of contaminants may reach the subsurface aquifer system through sinkholes, where the local population dumps their municipal garbage.

Potential environmental and health impact of SGD

In many parts of the world, nutrient-rich groundwater via SGD is reported to contribute to eutrophication or harmful algal blooms. In Jepara, where the status of the coastal water is already eutrophied, nitrogen-rich, fresh SGD may exacerbate the current environmental coastal health in this area. Along the coastline of Gunung Kidul, we observed sudden inputs of phosphorus in the wet season, which may trigger algae blooms that could harm the existing ecosystems or change the condition of various barrier reefs

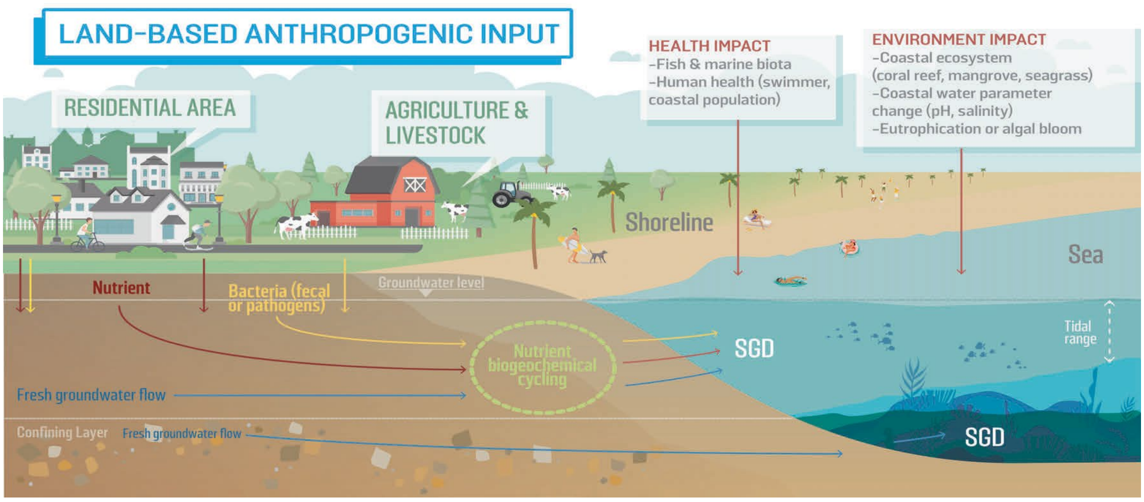

Figure 3. SGD brings material and solutes from land to ocean

and seagrass beds situated in the vicinity of SGD sites. In Lombok, we found that nutrient input, salinity stress, and low pH delivered by SGD affected the composition of coral cover and species diversity in the study site.

Our study also pointed that SGD might act as land-ocean delivery pathway of faecal indicator and pathogenic bacteria originated from human and livestock wastewater in the hinterland. We found potentially human pathogenic bacteria, e.g. *Vibrio, Mycobacterium*, and *Staphylococcus*, as well as fecal bacteria such as *Bacteroides, Escherichia-Shigella*, and *Prevotella*, in our SGD samples collected from beach pore water in Jepara. Several cases of fecal bacteria delivered by SGD to coastal water and affected the health of swimmers were found worldwide. This might be point of concern in Jepara, as its beaches and coastline are used as tourist recreational place, or in Gunung Kidul and Lombok where the local population used SGD as water resources. Thus, this finding prompts the need of further research such as functional gene testing or higher taxonomical resolution sequencing to confirm the human pathogenicity of these bacteria.

POLICY RECOMMENDATIONS

In a global context, specific regulations related to SGD are still rare. So far, only IOC-UNESCO has published an SGD guide for coastal managers, which includes controlling land use and pollution sites and applying in situ remediation technology across the groundwater system. In Indonesia, SGD has not been integrated into any environmental regulations due to the complicated nature of SGD flux. As monitoring and measuring SGD directly is difficult due to the (as of yet) uncustomary methodology, the most practical SGD management approach would be to **control potential pollutant or nutrient input to aquifer systems in the SGD recharge areas.** This method would include improving the current wastewater treatment system or modifying the current agricultural practice in areas with highly sensitive coastal ecosystems. In areas where fresh groundwater discharged mostly to the river (e.g. Jepara), the proper improvement would be establishing constructed wetland or riparian zones along the riverbank. Generally, it might be beneficial to implement SGD spatial measurement to identify point(s) of discharge prior to formulating coastal water management.

Implementation of water quality regular monitoring schemes is another factor that is important to understand groundwater-transported threats to the coastal ecosystem in our study region. This might be in the form of monitoring wells, which were still absent during our sampling periods. The local governments at our sites already had adequate regulations with quite detailed information regarding water quality standards and even fines for those who violate the laws implemented by the national and local government. However, these regulations are insufficiently implemented because there was a lack of coordination and cooperation between the interconnected agencies. Based on these observations, one suggestion would be **to map the water policy network in order to increase the efficiency of the established departments, as well as stronger enforcement of the established regulations** to create more productive and reliable results.

Furthermore, an ocean perspective is required for charac-terizing the impact of SGD in the coastal area. Even though results from both of our sites indicated that SGD might create or exacerbate the coastal water pollution, not all SGD-derived nutrient fluxes are harmful to the receiving water bodies. Nutrient delivered by SGD was reported to be beneficial in oligotrophic coastal water. In these cases, it is vital to **be informed of the circumstances on both land and coastal areas be-fore developing proper SGD management strategies.**

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