Submarine Groundwater Discharge in the Coastal Zone

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Abstract. Indonesia is one of the archipelagic countries that has the longest coastline in the world. Because it is located in the tropics, in general it has a very high rainfall. Each island has a different morphology which is composed of a variety of rocks with different hydrogeological properties. This natural condition allows for the presence of groundwater in different amount in each island. The difference in groundwater hydraulics gradients in aquifer continuous to the sea has triggered the discharge of groundwater to offshore known as submarine groundwater discharge (SGD). Its presence can be as seepage or submarine springs with components derived from land and sea and a mixture between them. The understanding of SGD phenomenon is very important because it can be useful as a source of clean water in coastal areas, affecting marine health, and improving marine environment.

1. Introduction

The phenomenon of submarine groundwater discharge (SGD) has long been known. However, the attention on this subject has been intensively developed internationally since the 90’s led by The Scientific Committee on Oceanic Research [1]. During the five years period between 2001 and 2006, the IAEA and UNESCO initiated to popularize SGD with isotope to assess the methodology and the importance of SGD for coastal area management [2]. Recognizing the importance of SGD, the Research Centre for Geotechnology, Indonesian Institute of Sciences, through the Water Resilience Group, has started researching SGD in Indonesia (especially in Jakarta) in collaboration with the Research Institute for Humanity and Nature (RIHN), Japan [3].

Globally the world's SGD is estimated at 10% of the volume of surface water flowing into the sea [4]. Meanwhile, nearly 70% of the total SGD flow in the world flows more to the pacific oceans [5]. Furthermore, it is estimated the prospect of SGD in Indonesia, especially the one flowing into the pacific oceans is 60.8 km3/year from Kalimantan Island and 27.5 km3/year from Sulawesi Island [6]. The presence of SGD is a very important component in the hydrological cycle [7]. Therefore, Indonesia as one of the most potential areas makes an important contribution to the world hydrological cycle, because geographically it is one of the archipelagic countries that has the longest coastline in the world. It is also located in the tropics which generally has a high rainfall; the recorded rainfall is between 4000 - 5000 mm/year in the mountains around the coast [6]. In addition, between one island and another island has a different morphology which is composed of various rocks [6] with different hydrogeological properties. This natural condition allows for the presence of groundwater in different amount in each island. Some of the groundwater tends to discharge near the coast and mix with sea water in the seabed [8]. This is triggered either by the difference of groundwater hydraulics gradient in aquifer [1] or due to gravity [9]. The release of groundwater into the seas in the coastal region is known as submarine groundwater discharge (SGD) [1, 10, 11]. Therefore, factors such as climate, topography, geology and hydrogeology contribute to the intensive occurrence of groundwater flowing into the oceans [6]. This
paper describes basic information on concepts, roles and SGD assessments for research conducted intensively in Indonesia.

2. Basic concept of SGD
In addition to the river water, groundwater flows into the ocean if the aquifers in the coastal areas continue to the sea [1,12,13]. SGD is defined as any flow of water out across the sea floor [1,14,15] regardless of fluid composition or major triggering mechanisms [1,10]. The definition of SGD does not include such processes as deep-sea hydrothermal circulation, deep fluid expulsion at convergent margins, and density-driven cold seeps on continental slopes [7]. SGD components come from land and sea consisting of fresh submarine groundwater discharge and recirculated saline groundwater discharge [14]. Therefore, the SGD component can be either pure freshwater or circulated water or both [10]. SGD can occur anywhere in aquifer hydraulically related to the ocean that flows through the seabed permeable sediments and its water table above sea level [4]. SGD may present in seepages or submarine springs [12,14] in unconfined aquifer systems or confined aquifers. The seepage reflects groundwater flows through the pores of rocks, which is called pore water exchange (PEX). While the submarine springs are commonly found in aquifers exposed on the seabed, it is particularly present in the continuous karst areas to the sea [16,17], or on aquifers flowing through fracture media [1,13,18]. SGD and PEX represent two transport mechanisms of groundwater (solute transport) from seabed to oceans [19]. SGD and PEX or recirculating seawater present in the sediment refer to the quantification scale to determine how much groundwater from land flows into the sea. SGD is used for assessing large-scale flow processes and PEX for groundwater flow processes on a small scale [20]. SGD positions may present as near shore seepage, seepage and submarine spring [12]. There is a tendency of SGD derived from an unconfined aquifer system found close to the shoreline. Whereas SGD as seepage is volumetrically and chemically important [4] in relation to pollution to marine areas due to the longest shoreline in the world [14].

3. The role of SGD
SGD has a very important role for both human and the marine environment. SGD is a source of soluble and dissolved materials for coastal ecosystems [1]. Long before the development of SGD research today, the SGD, which referred to the freshwater flow of submarine springs in the Latakia region of Syria near the Island of Aradus, the Mediterranean Sea, was recorded by the Roman geographer Strabo who lived from 63 B.C. To 21 A.D. And at that time the submarine springs had been used as a source of clean water [1,10,11]. In addition SGD has social functions such as a source of clean water, health, agriculture, fishing/diving, spiritual and navigation [21]. In Indonesia, SGD as a source of clean and spiritual water has been used for a long time. Traditionally, coastal communities typically take fresh water directly from SGD sources at low tide (Figure.1a) and fishermen also use it for clean water supplies during fishing. But for the SGD that has been dammed, the community uses an electrical pump to directly distribute it to the houses (Figure.1b). As a spiritual function SGD is usually given to people who ask for bath water. Another example in the western coastal area of western Java, it is used as drinks in certain rituals.

SGD affects marine ecology in productivity, biomass, species composition and species zonation. Changes in the amount and quality of groundwater due to human behavior in coastal areas result in changes in water salinity, dissolved nutrient concentration or increased pollutant levels [4]. SGD is a nutrient source [22] other than river water, which plays a role in nutrient cycles [23], and primary productivity in marine areas [23,24] dependent on hydrogeological variables such as SGD type whether as seepage or as springs [24].

The high supply of nutrients from SGD results in harmful algae blooms (HABs) or red tide at Yeoja bay, Korea [25] and west-central Florida [26], while in Monterey bay, California the incident was not only related with nutrients but also with silica [27]. Therefore, SGD can be a path for nutrients from land that have implications for biogeochemical and ecology in the tropics and oceanic islands [28].
addition to nutrient sources, SGD is also a source of metals, carbon, and geochemical tracers to marine areas [22].

![Figure 1. SGD presents as submarine springs used for clean water sources for coastal populations, (a). Natural example in Bosnik Beach, Biak Island, (b) in the plaster, an example in Seruni-Mumbul village, Labuhan-East Lombok](image)

4. SGD assessments

Since the importance of the presence of SGD to the oceanic region, the world's experts have developed quantification of SGD by various methods. Quantification is done directly by measuring the SGD insitu field in a narrow area. Manual seepage meter [29], automatic seepage meter [30] and, continuous heat automatic seepage meter [31] are used to measure the SGD in seepage form out of the sandy sedimentary. The manual seepage meter was first used to measure seepage in lakes and deltas in Minnesota and Nova Scotia, US. This tool is very simple and cheap which consists of 55-gallon-drum on top of which is given a hole for water discharge. Water coming out of the sediment will accumulate in the plastic bag on the drum. Changes in the volume of water in certain intervals in the plastic bags are measured as flux measured water flow per unit time. The drum is buried in a sea-based sediment with the remaining drum appearing approximately 2 cm from the seafloor. The automatic seepage meter is based on the heat travel (heat pulse) within a certain time in the pipe thermistor. The continuous heat automatic seepage meter is designed to measure the continuous flowing water gradient between two sensors in a 1.3 cm diameter tube. Based on the temperature, the difference is converted to voltage and is measured as SGD flux.

Indirectly quantification of SGD can be done with modeling approach: basically using three categories of analytical or numerical solutions of Darcy law on porous media; the mass balance approach of water or based on the amount of salt; and, hydrograph techniques by looking at the base flow of river water and extrapolating as groundwater flows to shore [12]. Qualitative analysis of SGD can be estimated regionally in a watershed directly adjacent to the sea [6]. Locally, SGD as submarine springs can be calculated based on chloride mass balance. The EC of the coastal and submarine discharges is an important tool for identifying the percentage of available freshwater from the shallow submarine springs. The use of hydrochemical techniques to measure shallow submarine discharges may provide more accurate results. However, the hydrochemical measurement depends on many internal and external factors, including the density equilibrium between fresh and saline waters and other physical and structural properties of the coastal water-bearing formations [32].

Measurement of groundwater seepage use some piezometer wells at a certain depth [8, 33]. Using the estimation or observation result of hydraulic conductivity of the aquifer in the assumption of constant will make it easier to calculate the velocity of the flow of groundwater discharge into the oceans. The Darcy formula for the flow flux is $q = -K \frac{dh}{dL}$, where $q$ is the Darcy flux (the volume of groundwater flow per unit area per time); $K$ is the hydraulic conductivity; and, $\frac{dh}{dL}$ is the hydraulic gradient with $h$ is the hydraulic head and $L$ is distance between wells [11].
Another accurate method for evaluating groundwater flux in coastal areas is a natural tracer using radon and radium \[11, 34\]. Radon is a gas derived from uranium and radium decay with a relatively short time of 3.82 days \[35, 36\]. Radon in groundwater is derived from radium decay in rocks, soils and mineral grains \[37\]. The concentration of radon (\(^{222}\text{Rn}\)) in groundwater is higher when compared to surface water or seawater \[38, 39\]. Two to four times higher when compared to surface water \[39\], 3-4 times larger than in seawater \[40\], even greater than a thousand times richer when compared to surface water \[41\]. Radon is conservative \[42\], so it is used for qualitative and quantitative tracer of SGD \[39\]. Likewise, the radium (Ra) concentration is relatively higher in groundwater when compared to surface water \[11\].

Quantification of SGD flux based on radon tracer can be determined by continuously measuring radon in seawater in the field and radium measurement (\(^{226}\text{Ra}\)) is spotted as correction for Rn activity \[10\]. A number of natural processes affect dynamics such as sedimentary resuspension, waves, water currents, tides etc. SGD flux is based on mass balance \(^{222}\text{Rn}\) \[34\]. The \(^{222}\text{Rn}\) equilibrium balance model is \(F_{\text{SGD}} + F_{226} + F_{\text{fin}} + F_{\text{sed}} + F_{\text{out}} = F_{\text{mix}} + F_{\text{dec}} + F_{\text{atm}} + F_{\text{mix}} + F_{\text{dec}} = \Delta F\). \(F_{\text{SGD}}\) is the total \(^{222}\text{Rn}\) of SGD flux in \(^{222}\text{Rn}\) of activity unit per unit area per unit time (ex. Bq m\(^{-2}\) hour\(^{-1}\)); \(F_{226}\) is a flux produced from \(^{226}\text{Ra}\); \(F_{\text{fin}}\) is flux entry caused by sea tides; \(F_{\text{sed}}\) is a flux of sediment diffusion; \(F_{\text{out}}\) is the flux coming out of the system due to the tides; \(F_{\text{atm}}\) is a flux that comes out of the system into the atmosphere; \(F_{\text{mix}}\) is the flux that comes out of the system due to the process of mixing with sea water from outside the area under review; \(F_{\text{dec}}\) is a flux lost due to decay of \(^{222}\text{Rn}\); And \(\Delta F\) is the flux change in the system under review at specified time intervals \[43\]. Flux \(^{222}\text{Rn}\) (\(F_{\text{SGD}}\)) can be converted to SGD flux divided by radon activity on groundwater, assuming benthic fluxes of radon are driven mainly by groundwater (pore water) advection \[34\]. Estimated submarine springs discharge can be identified from the SGD flux multiplied by the extent of plume submarine springs influence or the width of the submarine springs appearance radius on the seafloor \[44\].

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