Journal of Hydrology 565 (2018) 662–671

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Seasonal variability of land-ocean groundwater nutrient fluxes from a tropical karstic region (southern Java, Indonesia)

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ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief

Keywords:
Groundwater discharge
Nutrients
Tropical karst
Ecosystems
SGD
Seasonal

ABSTRACT

In tropical karstic regions, knowledge about the timing and quantity of land-ocean groundwater nutrient fluxes is important, as those nutrients may affect sensitive coastal ecosystems such as coral reefs. High permeability of karst aquifers, combined with high discharge during heavy rain events, lead to a close connectivity between groundwater in the hinterland and the coastal zone. Alteration between dry and wet periods can lead to a temporal variability of groundwater discharge volume and its associated nutrient fluxes. We studied the seasonal variability of land-ocean groundwater nutrient fluxes in the tropical karstic region of Gunung Kidul (southern Java, Indonesia) from November 2015 to December 2016. Satellite thermal infrared imagery revealed two major areas of direct submarine and coastal groundwater discharge. Nutrient fluxes were estimated at the largest coastal spring using a discharge dataset from a subsurface river dam and a monthly record of nutrient concentrations sampled from the spring. Nitrate fluxes ranged from 6×10^6–245×10^6 mol/day, dissolved silicon fluxes from 58×10^6–546×10^6 mol/day and phosphate fluxes from 17×10^3–1571×10^3 mol/day. Nutrient fluxes are mostly controlled by discharge and show a high variability through time. Extraordinarily high nitrate and phosphate fluxes were observed after a period of constant and heavy rain. Most likely a nutrient pool in the top soil in the hinterland from untreated sewage or fertilizer is flushed during rain events through the aquifer to the coast. In tropical karstic regions sudden inputs of large amounts of nutrients via groundwater discharge may affect coastal ecosystems such as coral reefs making them especially vulnerable during high discharge events.

1. Introduction

Groundwater discharge into the coastal ocean occurs along the worlds coastlines at the land-ocean interface and has been identified as an important source of nutrients to many coastal ecosystems (Szymczycha et al., 2012; Rodellas et al., 2015; Tamborski et al., 2017). Nutrients delivered to coastal ecosystem via groundwater discharge can lead to a shift in phytoplankton community structure, degradation of health of coral reefs and seagrass beds as reported in a number of locations all over the world (Lapointe, 1997; Lecher et al., 2015; Amato et al., 2016). In tropical karstic regions high groundwater discharge is expected, due to high aquifer permeability, coupled to a high recharge during the wet season and heavy rain events. Combined with high groundwater nutrient concentrations (e.g. transported from the unsaturated soil into the aquifer) and low retention times of nutrients in the aquifer, these conditions lead to high groundwater nutrient fluxes (Moosdorf et al., 2015). Nutrient inputs into groundwater from anthropogenic sources in the hinterland such as fertilizers or sewage may thus rapidly reach the coastal ocean (Tamborski et al., 2017). These conditions may further lead to temporal variations with high and low land-ocean groundwater nutrient fluxes (ArandaCirerol et al., 2006; Mallast et al., 2013). Sensitive coastal ecosystems along tropical karstic coasts (e.g. coral reefs) may thus be affected by sudden inputs of large amounts of nutrients via groundwater discharge.

Several studies describe the transport of nutrients via groundwater towards the ocean in tropical karstic regions as in northwest Yucatan (Mexico) (Hanshaw and Back, 1980; Herrera-Silveira, 1998; Young et al., 2008; Null et al., 2014), Bermuda (Lapointe and O'Connell, 1989; Simmons and Lyons, 1994), Barbados (Lewis, 1987) and Guam (Redding et al., 2013), while some studies investigated their temporal variability (Lewis, 1987; Lapointe et al., 1990; ArandaCirerol et al., 2006; Tapia González et al., 2008). Southeast Asia belongs to one of the

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https://doi.org/10.1016/j.jhydrol.2018.08.077
Received 19 July 2018; Received in revised form 28 August 2018; Accepted 29 August 2018

regions with the strongest human modifications in the coastal zone (Elvidge et al., 1997) where significant groundwater nutrient fluxes to the coastal zone were observed in Bangkok, Manila and Jepara (Burnett et al., 2007; Taniguchi et al., 2008; Adyasari et al., 2018). However, a seasonal record of groundwater nutrient fluxes from a karstic region in Southeast Asia has not yet been investigated, even though one of the strongest impacts on coastal ecosystems can be expected in these regions. Hence, at the example of the tropical karstic coastal area of Gunung Kidul (southern Java, Indonesia) we investigated the seasonal behavior of groundwater nutrient fluxes to the ocean.

2. Study site

2.1. Climate, geology and land use

The karstic region of Gunung Kidul is located in southern central Java (Indonesia). The area has a tropical climate with a mean annual temperature of 27 °C (Haryono and Day, 2004), a high humidity of ~80% (Flathe and Pfeiffer, 1965), and an annual precipitation of up to 2000 mm (Brunsch et al., 2011). The amount of precipitation is controlled by the Australian-Indonesian Summer Monsoon (Brunsch et al., 2011). The wet season lasts from November until April with precipitation rates of 150–350 mm per month. During dry season (May until October) precipitation rates are much lower with 25–150 mm per month (Brunsch et al., 2011). The El Niño–southern oscillation (ENSO) has a considerable impact on the amount of annual rainfall (Aldrian and Dwi Susanto, 2003). While during El Niño years, the wet season starts later in the year and during the dry season precipitation is below average (Aldrian and Dwi Susanto, 2003), during La Niña the rainy season lasts longer with larger amounts of rainfall (Brunsch et al., 2011).

Three different geological sections can be distinguished in the study area. The north and north-east section comprise mountain ranges (Fig. 1) which mainly consist of sediments and volcanic deposits of Eocene and Miocene age. Further to the south the Miocene Wonosari formations represent the second section, which mainly consists of bedded lagoonal limestones (Sir MacDonald and Partners, 1984). The third section, the Gunung Sewu area, is morphologically known for its mature Kegelkarst hills. Common to all is the southward dipping towards the Indian Ocean. At the coast, cliffs with heights of 25–100 m are composed of strongly karstified massive coral reef-limestone, with intercalated clay and volcanic ash lenses (van Bemmelen, 1949; Flathe and Pfeiffer, 1965; Waltham et al., 1983; Haryono and Day, 2004).

The combination of low rainfall amounts during dry season and quick infiltration due to strong karstification leads to severe water scarcity mainly in the southern Kegelkarst area. Consequently, more than 250,000 people depend on onshore, coastal and submarine karstic springs, rain water cisterns, water trucks or subsurface rivers as water resource (Sir MacDonald and Partners, 1984; Matthies et al., 2016; Moosdorf and Oehler, 2017). This is one reason why the region is considered to be one of the poorest regions in Indonesia with a relatively low population density of 388 inhabitants per km^2 in the coastal area (Dittmann et al., 2011). At Bribin Sindon, the karst river is dammed up by a concrete barrage, which completely closed the elliptic cross section of the cave, creating an underground water storage which is managed by means of a hydropower-driven pumping system. This hydropower plant supplies water for more than 75,000 people in the area. More than 90% of the population depends on agriculture often with less than 0.3 ha land per family. Dry farming with soy, corn, peanuts and cassava is the dominant type of land use. Some families additionally have cattle to work on the fields and as source for manure. Artificial fertilizer is mainly applied in addition to cattle manure to balance the nutrient deficiency of the soils. Wastewater in Gunung Kidul is partly discharged directly into the subsurface or collected in unsealed septic tanks (Fach and Fuchs, 2010; Nayono et al., 2010). Additionally, solid waste enters into the underground river system via sinkholes (Nayono, 2014).

2.2. Subsurface hydrology

Perennial rivers are absent in the coastal area and scarce in the whole Gunung Kidul due to high karst permeability. Considerable surface runoff only takes place after major rain events. In the underground, however, a complex network of caves and conduits has developed due to karstification. Consequently, subsurface discharge dominates the area. Groundwater flow paths and discharge rates in the area were mapped in the recent years (Sir MacDonald and Partners, 1984; Eiche et al., 2012) (Fig. 1 and Electronic supplementary material). Also flow paths between subsurface rivers and coastal springs could be negotiated (Fig. 1, red dotted lines). The coastal freshwater spring at Pantai Baron is connected with the Wonosari-Bribin-Baron aquifer system in the hinterland, which is fed by different small rivers from the volcanic Panggung Masif in the north (Sir MacDonald and Partners, 1984). Discharge measured at the 25 km upstream located subsurface river dam Bribin Sindon reaches Pantai Baron with a travel time of 14 days during dry season (Sir MacDonald and Partners, 1984) and 4 days during wet season, as deduced from a tracer test (Eiche et al., 2012). In addition, several smaller tributaries feed the freshwater spring (see Electronic supplementary material). Discharge rates have been measured continuously every 10 min at the subsurface river dam Bribin Sindon since 2010 and discharge varies between $< 1\ \mathrm{m^3/s}$ in the dry and up to $12\ \mathrm{m^3/s}$ in the wet season (Oberle et al., 2016).

Groundwater in Gunung Kidul was classified as Ca-HCO_3 dominated, with varying hydrochemistry between the wet and the dry season (Eiche et al., 2016). During the dry season diffuse matrix-flow is dominant and assures a year-round flow of water. During wet season, matrix flow is regularly overprinted by piston flow and recharge occurs dominantly through larger cracks and sinkholes. These conditions are also reflected in the physio-chemistry of the groundwater with higher electrical conductivity (EC) values during matrix flow conditions and a rapid decline in EC as discharge increases (Eiche et al., 2016).

3. Material and methods

3.1. Investigation of groundwater discharge to the ocean

Groundwater discharge towards and into the ocean was investigated based on precipitation data, discharge measured at the subsurface river dam Bribin Sindon, remote sensing and by physio-chemistry (EC, T) of groundwater and coastal water.

Rainfall data was obtained from four climate stations (Fig. 1), operated by the Indonesian governmental agency BMKG on a daily interval from October 2015 until December 2016. Stations were chosen in a way that they most likely reflect the recharge area of the Wonosari-Bribin-Baron hydrogeological system. The first station ("Nglipar", Fig. 1) is located in the northern part of the Wonosari plateau at an elevation of 190 m above sea level. The second climate station "Ponjong" is located at an elevation of 242 m above sea level next to the subsurface river Gunung Kendil and close to the subsurface river dam Bribin Sindon (Fig. 1). The third station ("Semanu", Fig. 1) is located close to the subsurface river Kali Suci at an elevation of 198 m above sea level, while the fourth station "Tepus" is located closer to the coast at an elevation of 198 m above sea level.

Groundwater discharge was monitored at the subsurface river dam Bribin Sindon with 10 min intervals from October 2015 until December 2016. Discharge was monitored in a way that a defined flume was present and the water level behind the dam was measured.

Discharge areas into the coastal ocean were identified using a multi-temporal satellite-based thermal infrared approach and validated using in-situ offshore electrical conductivity measurements. The multi-temporal satellite-based thermal infrared approach exploits thermal radiance information of the sea-surface given in five Landsat TIRS scenes