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Quantification of tidally-influenced seasonal groundwater discharge to the Bay of Bengal by seepage meter study

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SUMMARY

Submarine groundwater discharges (SGD) play a major role in solute transport and nutrient flux to the ocean. We have conducted a spatio-temporal high-resolution lunar-tidal cycle-scale seepage meter experiment during pre-monsoon and post-monsoon seasons, to quantify the spatio-temporal patterns and variability of SGD, its terrestrial (T-SGD) and marine components (M-SGD). The measured daily average SGD rates range from no discharge to 3.6 $m^3\ m^{-2}\ d^{-1}$ during pre-monsoon season and 0.08–5.9 $m^3\ m^{-2}\ d^{-1}$ during post-monsoon seasons, depending on the tidal pattern. The uncertainty for SGD measurement is calculated as ±0.8% to ±11% for pre-monsoon and ±1.8% to ±17% for post-monsoon respectively. A linear, inverse relationship was observed between the calculated T-SGD and M-SGD components, which varied along the distance from the coast and position in the tidal-cycle, spatial and temporal (daily) variations of seepage rates within the lunar tidal cycle period distinctly demonstrate the influence of tides on groundwater seepage rate. As an instance, for the identification of the bulk discharge location, the centroid of the integrated SGD rate has been calculated and found to be near 20 m offshore area. The average discharge rate per unit area further extrapolated to total SGD fluxes to the Bay of Bengal from eastern Indian coast by extrapolation of the annual and seasonal fluxes observed in the study area, which are first direct/experimental estimate of SGD to the Bay of Bengal. Approximations suggest that in present-day condition, total average annual SGD to the Bay of Bengal is about $8.98 \pm 0.6 \times 10^8\ m^3/y$. This is suggested that the SGD input to the ocean through the Bay of Bengal is approximately 0.9% of the global input from the inter-tidal zone and that has an implication on the mass balance of discharging solutes/nutrients to the global oceans. High T-SGD input is observed for all season, which is largest toward landward direction from the delineated saltwater–freshwater interface. The high magnitude of T-SGD could play an important role in mass balance of fresh water discharge and solute transport to the global ocean, thereby influence coastal ecohydrological systems.

1. Introduction

Groundwater discharge studies in coastal areas have received wide attention over the past decades to understand the groundwater–seawater interaction and its hydrodynamics. Groundwater discharges to the sea (SGD) from coastal aquifers is considered as a potential source for transport of solutes, anthropogenic contaminants and nutrients to seawaters. Discharging groundwater from coastal aquifers may adversely affect the coastal ecosystems and marine biota (Johannes, 1992; Simmons, 1992). Freshwater inputs to the ocean by groundwater discharge will vary from region to region based on the local geology, climate, and geomorphology of the area and the subsurface structure of the aquifer. SGD contain both the terrestrial component (T-SGD) and the marine component (M-SGD), which is discharged as recirculated brackish water. Both the T-SGD and M-SGD, while discharging, may influence the geochemistry and redox behavior of the groundwater–seawater (GW–SW) interaction zone (Kohout, 1960; Michael et al., 2003). Since groundwater is enriched in solute and nutrients, discharge groundwater via SGD can lead to a large solute flux and nutrient flux to the coastal ecology (Simmons, 1992; Corbett et al., 1999; Slomp and Van Cappellen, 2004; Burnett et al., 2006). In some coastal areas, SGD is identified as the major source of nutrient flux to the ocean which further suggested to be the primary process of eutrophication (Paerl, 2009; Valiela et al., 2002; Null et al., 2012). So measuring the groundwater discharge rate is one of the primary

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concerns for the coastal areas. Solute and nutrient flux via SGD can be calculated based on the dissolved solutes and nutrients present in the discharged water and the water flux rates. The solute and nutrient composition can be measured easily, but it is very difficult to measure the groundwater seepage rate quantitatively. In the last few decades, several methods have been applied to evaluate SGD across the globe, which include tracers, piezometers, water balance calculations and numerical modeling. However, the use of seepage meters is the only way to directly measure groundwater flux when groundwater discharges in large amounts through the intertidal zone (Michael et al., 2003; Shaw and Prepas, 1989). The exact volume of the discharging groundwater can be used to derive the nutrient and chemical dynamics of the coastal sites. The eastern coast of Indian Subcontinent is indented by a number of rivers, form estuaries at their confluence with the sea. Hence, the study of SGD rate and pattern of the SGD variation with tidal cycle would be extremely important for delineating the solute and nutrient flux to the ocean and its environmental implications to the coastal region of the eastern coast of India.

It has been estimated that at the beginning of every year 4000 billion m^3 of water enters the Indian hydrologic system. Almost 50% of this 4000 billion m^3 is lost in unaccounted processes, including evaporation, flowing to very deep aquifers or escape to the ocean as SGD (Verma and Phansalkar, 2007). Of these, a major portion of the SGD is believed to be discharged through the ~2200 km long eastern Indian coast adjoining to the Bay of Bengal. Hence, the present day estimation of SGD to Bay of Bengal is very important to derive the nutrient and solute fluxes through SGD. In this study we have provided the SGD estimating pattern from a coastal aquifer to the Bay of Bengal for varied temporal scales (seasonal, tidal and daily). The extrapolated annual scale estimation of present day SGD can be used further for delineating the dissolved solutes and nutrient transport to Bay of Bengal via SGD.

Previous studies at very focused sites e.g. Indian River Lagoon (Martin et al., 2006, 2007), Waquit Bay (Michael et al., 2003), Gulf of Mexico (Cable et al., 1997a), Northern part of Gulf of Mexico (Taniguchi et al., 2003) have helped to directly measure and determine the SGD flux at the specific coastal study sites and have been up-scaled to delineate implications to global oceans (Burnett et al., 2003, 2006). Here, following similar philosophy, at a focused site on the eastern coast of India, we have measured the tidally influenced to SGD rates by densely gridded seepage meters and delineated its implication to the Bay of Bengal. Since, tidal patterns are believed to significantly influence the temporal patterns of SGD (Taniguchi, 2002; Taniguchi et al., 2003), we have tried to accurately measure the discharge rate in pre-monsoon and post-monsoon seasons for full scale lunar tidal cycles in our micro-tidal study area.

2. Study site

The study site Chandipur (21°26′11.6″N and 87°01′3.1″E) in the state of Odisha, India is a micro tidal coastal zone adjoining the Bay of Bengal in eastern Indian coast (Fig. 1a). The coast can be described as a tidal or marshy flat that emerges during low tide and submerges during high tide, with an extensive intertidal zone (>4 km) (Mukherjee et al., 1987; Mukhopadhyay et al., 2011; Debnath et al., 2015). The inter-tidal zone is formed by the recent and palaeo-aeolian dunes and further land-ward, by recent alluvium deposits. The coastal aquifers in the area are composed of unconsolidated quaternary marine sediments and fluvio-deltaic deposits, with grain size mostly varying from medium sand to clay, with occasional iron nodules, calcareous concretions, etc. representing both fluvial and fluvio-marine facies (Chakrabarti, 1991; Debnath et al., 2015). The study area has tropical monsoon climate with mean annual temperature of 27 °C, which varies between 13 °C and 37 °C. The average precipitation in the study area is about 1500 mm, with maximum rainfall (>70%) occurring during the monsoon season. The water table in the shallow and the unconfined aquifers of the area are at a depth range of 2–4 m below the ground. The sandy shoreward zone (~30 m) has a slope of 6° with a recharge rate of 22 cm/y. Nearest tidal measurements station of the study site is at Chandbali, India, 20.7833°N, 86.9667°E.

3. Methods

3.1. Seepage meter experiment

The seepage meter experiment, for the pre-monsoon and post-monsoon season of 2014–15, at the inter tidal zone within an area with dimension of 110 m × 50 m starts from the high tide line (HTL) and extends towards the offshore, to measure the time variant groundwater discharge rate at specific intervals. In both season, 120 seepage meter have been installed in six different transects, (transect A, transect B, transect C, transect D, transect E and transect F respectively) perpendicular to the HTL. The seepage meter experimental zone was arrayed in three different zones from the high tide line (HTL). HTL to 40 m offshore (near to shore) the seepage meters were installed every 5 m interval. Similarly from 40 to 70 m offshore each seepage meters were installed at an interval of 10 m, while from 70 to 110 m offshore seepage meters, were installed at an interval of 20 m (Fig. 1d). During the fieldwork most of the seepage faces were found to be diffused ones, while few of the seepage points were observed between 5 and 10 m offshore zone, however no seepage point were observed at the backshore (Debnath et al., 2015). To measure and crosscheck landward groundwater discharge we have also installed 8 seepage meter at 5 m and 10 m backshore from HTL as a measurement of control discharge at transect B, C, D and E. All the installed seepage meters have been designed following the design of Lee (1977) type seepage meter, each seepage meter have 4 cm vent hole, which was connected to a 5-L polyethylene bag, attached with a 4 mm PVC quick connect fitting. Each polyethylene bag at 40–110 m offshore zone was prefilled with 500 ml seawater to prevent displacement of seepage bag during high tide and protection of discharge groundwater. The seepage meters were sampled after every 3 h for a sixteen days period starting one day before new moon to the day after the full moon to complete a lunar tidal cycle in each season. The spatial variations of the time averaged groundwater discharge rate were calculated from the each seepage meter after averaging the discharge data for the 16 day experimental period. Similarly temporal variation was calculated over the 9 h time period after averaging the discharge through each of the transects.

Every seepage meter across the transect C–C′ was sampled for high tide and low tide time period for hydrochemical analysis. Infield parameters like salinity, TDS, pH and DO, were measured immediately after decanting these seepage meters using multi-parameter probe (Hanna Inc, USA). Seepage meter and porewater samples were further collected for laboratory analysis for the transect C–C′ following the hydrogeochemical sampling procedure of Wood (1981). Seawater and local groundwater tube well (6 m depth) samples were also collected and measured following the same procedures and infield parameters were measured at both the low and high tide period.

3.2. Cluster experiment

Forty-eight (48) seepage meter were installed for the cluster experiment along the transect C–C′ to observe the spatial and