Bulletin of the Geological Society of Malaysia, No. 66, December 2018, pp. 39 – 46

Groundwater processes in a sandbar-regulated estuary, Mengabang Telipot, Peninsular Malaysia

Mei Kee Koh[1], Edlic Sathiamurthy[2,*] & Peter Robertson Parham[3,4,5]

[1]Institute of Oceanography and Environment, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia
[2]School of Marine and Environmental Sciences, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia
[3]Earth Observatory of Singapore, Nanyang Technological University, Singapore
[4]Southeast Asia Disaster Prevention Research Initiative (SEADPRI), Univ. Kebangsaan Malaysia, 43600 Bangi, Malaysia
[5] Centre of Tropical Geoengineering, Universiti Teknologi Malaysia
*Corresponding author email address: edlic@umt.edu.my

Abstract: A study of groundwater processes in a sandbar-regulated estuary has been conducted at Mengabang Telipot, located in Terengganu State, Peninsular Malaysia. Beach groundwater level, salinity and dissolved phosphate (PO_4^{3-}) were investigated at high spatial and temporal resolutions. Establishment of distinctive hydrodynamic characteristics in the beach groundwater system were observed as the mouth of the estuary varied between an open sea connection and closure resulting from sandbar development. Sandbar and tidal dynamics regulate the interactions between beach groundwater, estuary and sea. When the estuary was closed, intertidal activities had minor effects on groundwater level. The groundwater level increased through time due to rainfall infiltration and seepage from barrier bar and inland sand ridges. When the sandbar opened, the beach groundwater level was tidally-controlled and the interactions between groundwater, estuary and sea were dependent on the tidal-induced hydraulic gradient. Hydraulic head difference between the beach groundwater system and the inland water table aquifer, which was controlled by the closing and opening of the estuary, strongly influenced salinity and PO_4^{3-} distributions. High PO_4^{3-} concentrations in beach groundwater was attributed to density-driven circulation and low seepage velocity.

Keywords: sandbar-regulated estuary, groundwater monitoring, groundwater/surface-water relations, fresh-saline water interface, density-driven circulation

INTRODUCTION

Estuaries, the mixing region of terrestrial freshwater and seawater, are often characterized by complex processes (e.g. dissolved organic matter trapping, transformation and recycling) that form a natural regulating system in which pollutants can be removed between rivers and the open sea (Markager *et al*., 2011). These natural regulating systems are highly influenced by tides, wave direction and river discharge. For a sandbar-regulated estuary (SRE), the natural regulating system becomes more complex since water exchange between sea and estuary is periodically obstructed by a sandbar. The mechanisms of sandbar formation depend on wave direction and are influenced by long-shore transport (LST) and cross-shore transport (CST) of sediment (Cooper, 1994; Ranasinghe *et al.*, 1999; FitzGerald *et al*., 2000; Ranasinghe & Pattiaratchi, 2003). The development of a sandbar closes the estuary while its deformation or breaching opens the estuary. The alternation between open and closed states exerts strong hydrodynamic and hydrochemical impacts on the estuary.

Previous SRE studies have focused primarily on the influence of openings and closings on estuarine biology (Gaughan & Potter, 1994; Perissinotto *et al*., 2002; Perissinotto *et al*., 2003; Froneman, 2004; Santangelo *et al.,* 2007; Pereira Coutinho *et al*., 2012; Ortega-Cisneros *et al.,* 2014), hydrodynamics and hydrochemistry (Koh *et al*., 2012). Whether the estuary mouth is closed or opened strongly influences river water level, flow conditions, discharge characteristics and hydrochemical equilibrium (Koh *et al*., 2012). It is important to assess the impacts of estuary mouth sandbar on the barrier-beach groundwater system because water exchange between the estuary and sea occur mainly through groundwater flow (seepage) when the estuary is closed (Cooper *et al*., 1999). This, in turn, can increase our understanding of pollutant transport and distribution in coastal areas. A small discharge of groundwater may deliver a large amount of pollutants into coastal waters or estuaries since their concentrations can be substantially higher than in surface water (Slomp & Van Cappellen, 2004; Burnett *et al*., 2007; Lee *et al*., 2009). However, barrier-beach groundwater dynamics in SRE systems remain poorly understood.

Investigation by Suzuki *et al*. (1998) of Grussai Lagoon SRE, Brazil included groundwater quality testing of samples collected at a station along the barrier beach approximately 8 km away from the closed estuary mouth. However, the long distance between monitoring well and estuary mouth may have obscured the effects of sandbar openings and closings on groundwater quality. Although Gobler *et al*. (2005) concluded the pivotal role of groundwater in contributing nutrients to a SRE on Long Island, New York, USA, their sampling activities were only conducted while the estuary mouth was open. To bridge the gaps in knowledge, this report provides insight into the processes occurring in the barrier-beach groundwater system of a tropical SRE through periods of open and closed states.

MATERIALS AND METHODS

The study was conducted at Mengabang Telipot estuary (5° 25.0' N, 103° 05.2' E), which is a SRE located along the northeast coast of Peninsular Malaysia (Figure 1). This coastal plain is characterized by regressive Holocene sandy beach-ridge series (Mallinson *et al*., 2014; Parham *et al.,* 2014) aligned roughly parallel to the modern shoreline and interspersed with muddy swales (paleo-lagoons that are now wetlands).

The catchment size is about 16.2 km^2 and is drained by two small river systems that flow through swales before discharging into a lagoon. The normal river discharge is less than 2 m^{3}s^{-1} when the estuary is open and peak flow does not exceed 7 m^3 s^{-1}. River outflow is mainly controlled by receding tide water during periods of low rainfall and runoff. There is almost no outflow when the estuary is closed regardless of rainfall-runoff conditions (Koh *et al*., 2012; Pauzi & Sathiamurthy, 2013). The Mengabang Telipot estuary mouth sandbar tends to form during southwest monsoon (May-August) as long-shore transport (LST) carries and deposits sediment northward along the beach. During northeast monsoon (November-March), the formation of the sandbar is by wave energy that transports sediment shoreward through the process of cross-shore transport (CST). The catchment discharge is not high enough to prevent these processes from forming a sandbar that closes the estuary. The closed estuary could open either by natural breaching when river water level overtops the sandbar or by dredging work.

Six monitoring wells (W1-W6) were built on the stable area of the beach, forming two transect lines. The well lengths (same as sediment core depths) and corresponding bottom elevations are shown in Table 1. The locations of monitoring wells (W1-W6), stick gauge to monitor estuary

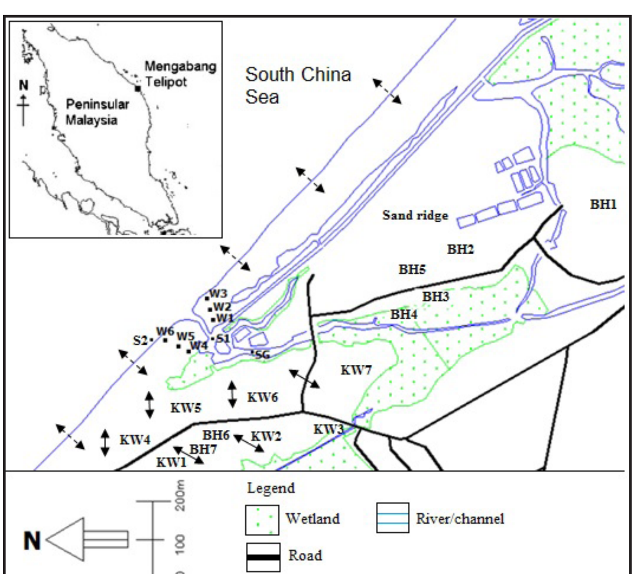

Figure 1: Mengabang Telipot estuary.

Table 1: Vertically averaged weight percentage of each sand type.

Monitoring well	Depth of sediment core (m)	Weight fraction of sand		
		Coarse	Medium	Fine
W1	4.5 (-2.9)	0.78	0.20	0.02
W2	5.4 (-2.6)	0.79	0.16	0.05
W3	6.0 (-2.2)	0.71	0.25	0.04
W4	3.5 (-1.8)	0.84	0.15	0.01
W5	4.4 (-2.0)	0.65	0.31	0.04
W6	6.2 (-3.1)	0.78	0.18	0.04

*Sand particle size: coarse (1.00-0.50 mm), medium (0.50-0.25 mm) and fine (0.25-0.10 mm); Values in bracket are bottom elevations of wells in m NGVD (National Geodetic Vertical Datum); 0 m NGVD is the local mean sea level for this study.

water level (SG), estuary and nearshore surface water sampling sites (S1 and S2), boreholes for deep ground sediment texture analysis (BH1-BH7) and existing wells distributed in study area (KW1-KW7) are shown in Figure 1. The general groundwater flow directions are indicated by dashed-arrows (represent saline water) and solid-arrows (represent fresh-groundwater). The distance between wells in each transect ranged between 20-25 m. Sediment samples were collected at every 1 m depth during well installation and were analysed for grain size using the dry sieving method (ASTM International, 2007). Deeper subsurface data were obtained from soil investigation borehole records used for construction purposes (BH1-BH7 in Figure 1). Groundwater levels were measured using self-logging pressure transducer sensors at 5-10 minute intervals when the sandbar was closed and open. Pressure transducer sensors detected and recorded hydrostatic pressure changes in the water column. Hydrostatic pressure measurements were compensated with atmospheric pressure variations and converted to water level. To assess the effect of estuarine water on beach groundwater, estuary water level was measured using pre-installed stick gauges (SG) (Figure 1) at 6-hour intervals. The influence of tides and rainfall on groundwater level was also examined. Hourly tidal data was obtained from Department of Survey and Mapping Malaysia and rainfall data was obtained from an on-site automatic rain-gauge and the Malaysia Meteorological Department (MMD). In addition to W1-W6, seven existing wells distributed in Mengabang Telipot area (KW1-KW7 in Figure 1) were used to measure salinity distribution. A total of 190 and 42 conductivity readings were collected at W1-W6 and KW1-KW7, respectively, using conductivity-temperature-depth sensor (CTD Diver) during both sandbar closed and open conditions. The conductivity readings were then converted to salinity in practical salinity unit (p.s.u). Groundwater samples were collected daily from top and bottom layers of W1-W6 during high and low tide using peristaltic pumps equipped with Teflon tubing. The top layer is approximately 10% of the water column depth whereas the bottom, 90%. These depth percentages were employed to ensure effective operation of the pumps. Surface estuarine water was sampled for comparison purpose. Nearshore surface seawater was also sampled when the sandbar was open. All the samples were analysed for dissolved phosphate (PO_4^{3-}) in the laboratory. For PO_4^{3-} determinations, samples were filtered (with 0.45 µm pore size membrane) and the filtrates were analysed using molybdenum blue colorimetric method (APHA–AWWA–WEF, 2005). PO_4^{3-} concentrations in groundwater were reported as an average value of top and bottom layers due to insignificant difference. PO_4^{3-} is one of the key elements in controlling the productivity of aquatic ecosystems (Billen *et al*., 2007). Though important for supporting lives, the over-enrichment of PO_4^{3-} could create undesirable disturbance on water quality. At concentration as low as 105 nM, PO_4^{3-} could bring harmful impact to rivers and streams (EPA, 2006). Over the years, the extensive use of phosphate has been linked with the widespread of eutrophication phenomenon (Nixon, 1995; Valsami-Jones, 2004). Therefore, the monitoring of PO_4^{3-} in aquatic environment is a routine strategy for water quality assessment.

RESULTS AND DISCUSSION

Sediment texture profile

Vertically averaged weight percentage of each sand type was determined and the results are presented in Table 1. Fractional differences were insignificant within the sampling depth, indicating high homogeneity. Subsurface sediments collected from W1-W6 are dominantly quartz sand from top to the bottom of wells. Sand was categorized into coarse (1.00-0.50 mm), medium (0.50-0.25 mm) and fine (0.25-0.10 mm) fractions (Table 1).

A sandy-mud layer was found during the installation of W6 at 6 m depth (approximately -3 m NGVD), signifying the existence of a muddy layer underlying portions of the study area. The sandy-mud layer was not found in other monitoring wells (W1-W5) since these wells are shallower. Inference on the broad distribution of the muddy layer is supported by occurrence in borehole logs from various sites within Mengabang Telipot area (BH1-BH7). Sediment textures recorded in borehole logs are presented in Table 2 in supplementary information. A common muddy layer (clay, silty clay, clayey silty sand, clayey sand, clayey silt) is found in BH1-BH7 at -3 to -5 m NGVD. The muddy layer may serve as an aquitard that impedes water infiltration and subsequently prevents the transport of dissolved matter into deeper aquifers, owing to its low hydraulic conductivity compared to sand.

Beach groundwater and estuary water levels

While the sandbar was closed, three phases of water level change were recorded due to dredging work (Figure 2). With reference to Figure 2, in Phase I, beach groundwater and estuary water levels gradually increased through time and exhibited minor fluctuations in response to tides. The water level increment accelerated from 3.5 cmday^{-1} to 21 cmday^{-1} in the estuary and 6.4 cmday^{-1} to 21 cmday^{-1} in beach groundwater when continuous rainfall began at 30th-hour. The beach groundwater and estuary water levels were above tide level when the sandbar was closed (approximately 0.3-0.7 m higher). Hydrostatic pressure while the sandbar was closed increased landward. Beach groundwater and estuary water levels decreased to 5.2 cmh^{-1} and 14 cmh^{-1}, respectively, when the sandbar opened in Phase II and showed greater fluctuations in response to tides. As the sandbar re-closed in Phase III, the fluctuations of beach groundwater and estuary water levels gradually reduced, indicating the restoration of sandbar closed hydrodynamic behaviours as in Phase I.

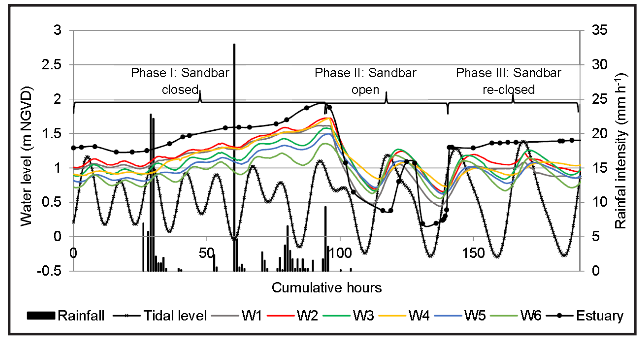

Figure 2: Recorded beach groundwater and estuary water levels for closed sandbar event.
Note: A sequence of closed, opened and re-closed event is shown; NGVD – National Geodetic Vertical Datum

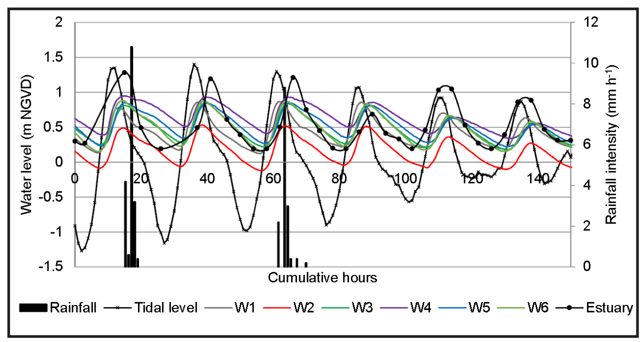

Figure 3: Recorded beach groundwater and estuary water levels for opened sandbar event.

Compared to periods when the estuary mouth was closed, distinct beach groundwater and estuary water level fluctuations were observed when the estuary was open (Figure 3). During these times groundwater and estuary water levels changed in response to tidal oscillations. Because the runoff generated was low, rainfall had little effect on water levels.

Groundwater salinity

No substantial difference in groundwater salinity was recorded in response to tidal oscillations under open and closed estuary mouth conditions. This may be because groundwater movement was slow (computed as < 4 cmh^{-1} based on Darcy's velocity equation) compared to the rate of tidal change. The horizontal shift of the fresh-saline interface in correspondence to tidal fluctuation was 2 to 3 m, hence implying impeded groundwater movement (Pauzi

Table 2: Borehole logs for BH1 - BH7.

Level (m NGVD)	BH1	BH2	BH3	BH4	BH5	BH6	BH7
4						Sand	Sand
3		Sand			Silty sand	x	x
2	Clayey sand	Silty sand	Sandy silt	Sandy silt	x	x	x
1	X	Sand	x	x	x	x	x
0	X	Silty sand	Clayey sand	x	Sand	x	x
-1	X	x	Silty sand	x	Silty sand	x	x
-2	X	x	Sand	Clay	x	Clay	x
-3	X	Sand	Clayey sand	x	Sand	x	Clay
-4	X	Clayey sand	x	Clayey sand	x	x	x
-5	X	x	Sand	x	Clayey sand	x	x
-6	X	Gravel	x	Silty sand	Sand	x	x
-7	X	x	Silty sand	x	Silty sand	x	x
-8	X	Silty sand	x	x	x	x	x
-9	X	x	x	x	Clay	x	x
-10	X	x	x	Silt	Silty sand	x	x
-11	X	x	x	x	x	Sand	x
-12	X	Silty clay	Silt	x	Clay	x	x
-13	X	Silt	Silty clay	Clayey sand	x	x	Sand
-14	X	x	Silt	x	x	x	x
-15	Silty clay	Sandy clay	x	x	x	x	x
-16	X	x	x	x	Silt	x	x
-17	X	x	x	x	x	x	x
-18	X	x	x	x	Sand	x	x
-19	X	x	x	Sand	Silty sand	x	x
-20	X	x	x	Silty sand	x	x	x
-22	X	x	x	x	Silt	x	x
-23	X	x	x	Sandy clay	x	x	x
-24	Clayey silty sand	x	x	x	x	x	x
-25	X	Sandy clay	x	Silty sand	x	x	x
-26	X	x	Sand	x	x	x	x
-28	X	Silty sand	x	Silty sand	x	x	x
-30	X	x	Silt	x	Silty sand	Clay	Clay
-32	X	x	x	x	x		x
-34	X	x	Silty gravel	x	Granite		
-35		x	Gravel	x			

(yellow)	Sand
(pink)	Silt
(pale green)	Clay
(tan)	Gravel
(olive)	Granite
x	Same texture as above

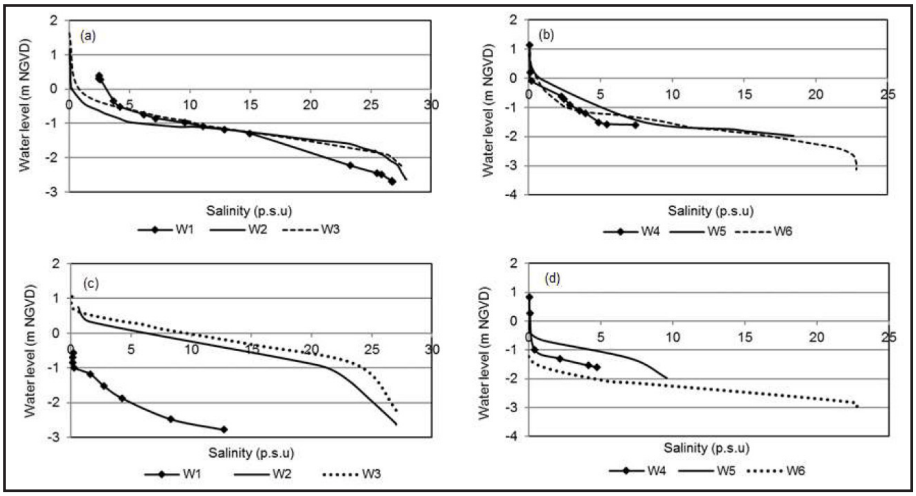

Figure 4: Vertical salinity profiles at W1-W6 recorded while the sandbars were closed (a and b) and opened (c and d).

Table 3: Groundwater salinity at KW1-KW7.

Monitoring wells	Salinity (p.s.u)		
	Mean (n=6)	Minimum	Maximum
KW1	0.06	0.04	0.09
KW2	0.17	0.11	0.33
KW3	0.13	0.08	0.23
KW4	0.08	0.03	0.16
KW5	0.08	0.05	0.18
KW6	0.12	0.04	0.28
KW7	0.10	0.07	0.16

p.s.u = practical salinity unit

& Sathiamurthy, 2013). Representative vertical salinity profiles of W1-W6 while the sandbar was closed (Figures 4a and 4b) and open (Figures 4c and 4d) show that spatial distribution of salinity varies between parallel wells W1-W3 and W4-W6.

Salinity measured in W4-W6 was lower than in W1-W3 both when the estuary was closed and open (Figure 4). Salinity was found to increase seaward at well transect W4-W6 while this trend was less prominent between W1-W3. Salinity in KW1-KW7 is summarized in Table 3. The salinity in KW1-KW7 was uniform throughout their water columns and was consistently freshwater dominated, suggesting that the higher freshwater hydraulic head prevents saltwater intrusion.

Dissolved phosphate (PO_4^{3-}) distributions

Spatial and temporal distributions of PO_4^{3-} during sandbar closed and opened events are shown in Figures 5 and 6. When the sandbar was closed, it was noted that wells located closer to the estuary within each set of parallel wells (i.e. W1 and W4) had relatively higher PO_4^{3-} concentrations. This was attributed to seepage of estuarine water which contained high PO_4^{3-} concentrations. The mean PO_4^{3-} concentrations in the estuary (S1), nearshore seawater (S2), inland groundwater (KW5) and each transect of monitoring wells are summarized in Table 4. The high concentration of PO_4^{3-} in estuarine area was associated with impeded river

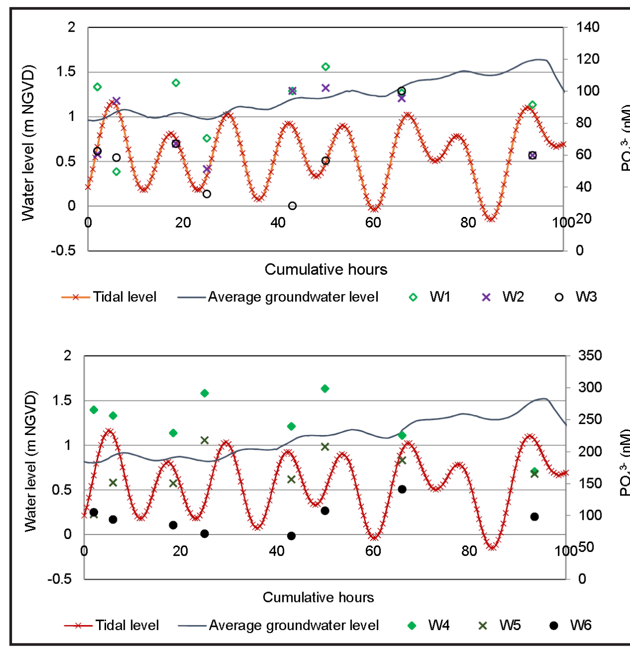

Figure 5: Dissolved phosphate (PO_4^{3-}) concentrations in beach groundwater when the sandbar was closed.

discharge into the sea when the sandbar was closed and this has been extensively discussed in earlier our contribution (Koh *et al*., 2012).

An exception occurred at parallel wells W4-W6 when the estuary mouth was open. Highest PO_4^{3-} concentrations were consistently found in W5 (145 ± 54.0 nM). This observation indicates that the distance of W5 from the river bank (about 90 m away) could affect PO_4^{3-} distribution. The tidal intrusion into the opened sandbar through the river bank could have impeded fresh groundwater discharge and hence caused the concentration of PO_4^{3-} at W5 to remain high. Overall, the mean PO_4^{3-} concentrations were higher at parallel wells W4-W6 compared to W1-W3, when the estuary mouth was closed and open.

Discussion

When the estuary mouth was closed, runoff and direct rainfall caused water to back up in the estuary and enhanced

Table 4: Mean PO_4^{3-} concentrations recorded in the estuary, nearshore seawater, monitoring well transects and inland groundwater.

Location	**PO_4^{3-} concentration (nM)**	
	Sandbar closed (n=8)	**Sandbar opened (n=10)**
Estuary (S1)	240 ± 92.2	54.2 ± 16.8
Nearshore seawater (S2)	68.6 ± 20.9	60.6 ± 24.3*
W1-W3	76.4 ± 24.7	79.5 ± 30.8
W4-W6	170 ± 71.0	103 ± 50.4
inland groundwater (KW5)	Nd	30.9 ± 15.2

Nd = not determined
* n = 8

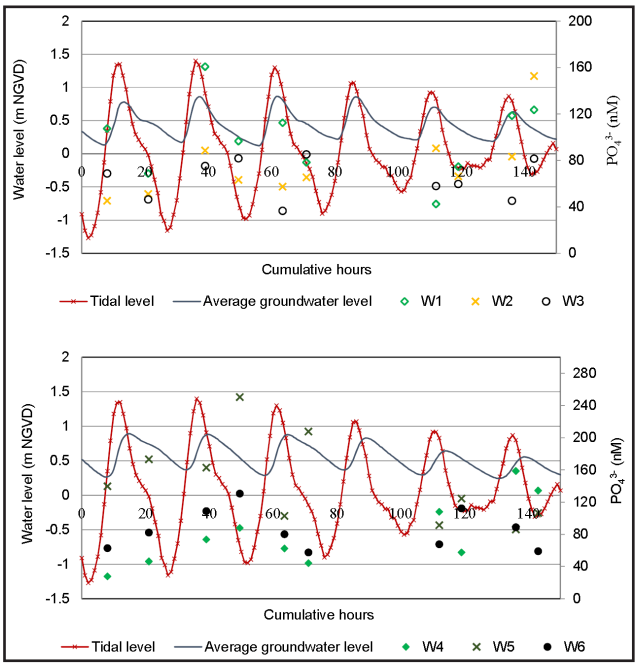

Figure 6: Dissolved phosphate (PO_4^{3-}) concentrations in beach groundwater when the sandbar was opened.

seepage into beach groundwater due to hydrostatic pressure differences. It can be inferred that the rate of groundwater discharge into the sea was low because flow was impeded by the sandbar though water levels in beach groundwater and the estuary were consistently higher than tide levels (approximately 0.7-0.3 m higher). Results from water level monitoring show that tidal fluctuations had less influence on beach groundwater and estuary water levels. It is conceivable that, when the estuary mouth is blocked by a sandbar, the bar plays a more significant role than tides in regulating the interactions between beach groundwater, estuary and sea. However, when the estuary mouth is open, two-way water exchange between land and sea is restored and the tidal-induced hydraulic gradient regulates this interaction.

Based on salinity results, beach groundwater flow directions in the study area can be inferred as in Figure 1. As observed, W1-W6 were influenced by saline seawater and brackish estuarine water that intruded into the beach while W4-W6 received freshwater discharged from the inland water table aquifer. The presence of the inland freshwater water table aquifer is indicated by patterns observed in KW1-KW7 because these wells were always freshwater dominated (Table 3). This deduction is supported by spatial variations of salinity in W4-W6, where salinity increased seaward (Figure 4). The influences of the freshwater aquifer are less pronounced in W1-W3 because these wells are isolated on the barrier beach ridge by the Mengabang Telipot estuary (Figure 1).

Water level and salinity results reveal that the presence of a sandbar obstructing the mouth of the estuary can influence the hydraulic gradient between beach groundwater and the inland aquifer. Such influence was more prominent at W4 and W5, probably because these wells were located near the fresh-saline water interface. When the sandbar was closed, high beach groundwater level reduced hydraulic gradient between beach groundwater and the inland aquifer. When this occurred, less freshwater was discharged from the inland aquifer resulting in more saline groundwater in W4 and W5. On the other hand, the decrease in beach groundwater level when the sandbar was open created greater hydraulic gradient between beach groundwater and the inland aquifer. Hydraulic gradient, which typically drives groundwater discharge in a seaward direction, promoted the discharge of freshwater from the inland water table aquifer into the beach and hence, resulted in less saline groundwater at W4 and W5.

Sediment textural analysis showed a high fraction of coarse sand, indicating that horizontal and vertical groundwater transmission was active within the top 5 m of the beach deposits (Table 1). Evidence from deeper wells (W4-W6) and bore hole logs (BH1-BH7) suggests that the active unconfined aquifer layer may occupy the upper 8-15 m of beach sediments with a fresh-saline water interface cutting diagonally through it (Figure 7). The interface was almost immobile laterally hence it could impede groundwater discharge into the sea (Pauzi & Sathiamurthy, 2013). Considering these results, it can be deduced that groundwater residence time within the top 8-15 m of the beach could be long as the vertical transmission of groundwater is impeded by clayey sediment, the horizontal transmission is sandbar-dependent and tidal-dependent and more importantly, the presence of the fresh-saline water interface impedes

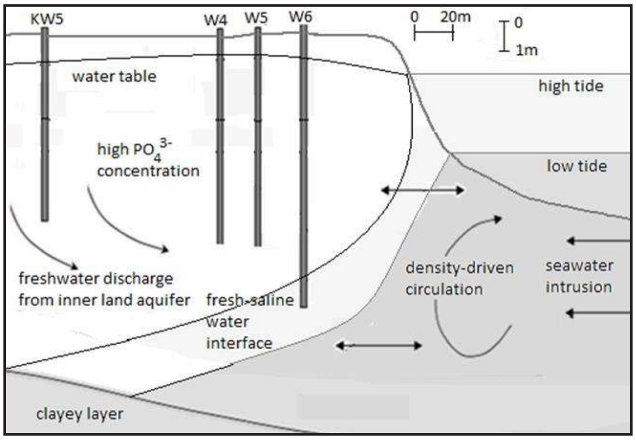

Figure 7: Density driven circulation at wells W4-W6 (a general view).

groundwater transmission. This deduction is also supported by the low seepage velocity in study area (computed as < 4 cm h^{-1} based on Darcy's velocity equation) compared to the interchange between high and low tides. A large volume of groundwater could be re-circulating in the beach due to density-driven circulation.

Density-driven circulation at parallel wells W4-W6 is illustrated in Figure 7. The circulation occurs as a result of salinity difference between groundwater and seawater (Robinson *et al*., 2007; Nakada *et al*., 2011).

The underlying clayey layer acts as a confining layer that hinders vertical transport of groundwater deeper into the subsurface. Thus, freshwater discharge from the inland aquifer intrudes more horizontally. The fresh-saline water interface and low seepage velocity obstruct further seaward transmission, forcing fresh groundwater to circulate around parallel wells W4-W6 and consequently increases the residence time.

Density-driven circulation and low seepage velocity (mainly horizontal) could be attributed to higher PO_4^{3-} concentrations in parallel wells W4-W6 compared to W1-W3 and explain the highest PO_4^{3-} concentration detected at W5 (145 ± 54.0 nM) when the sandbar was open. To further verify that high PO_4^{3-} concentrations at parallel wells W4-W6 were influenced by prolonged groundwater residence time, water samples were collected from an inland well (KW5) and a nearshore sampling station (S2) for comparison. Results reveal that PO_4^{3-} concentrations at KW5 and S2 were significantly lower than at W5, with mean values of 30.9 ± 15.2 nM and 60.6 ± 24.3 nM, respectively. The finding further suggests that high PO_4^{3-} concentrations at W5 were the result of prolonged groundwater residence time rather than groundwater recharge (from the inland aquifer or intruded seawater).

CONCLUSION

To the best of our knowledge, this is the first report on groundwater processes in a sandbar-regulated estuary. Hence, the comparison study is limited to the surface water of this estuarine system. The responses of the groundwater system to closed- and open-states were found to be similar to those of the surface water system. The water levels of both systems increase through time when the estuary is closed and rapidly decrease when the estuary is open (Lawrie *et al.*, 2010; Nunes & Adams, 2014). When the estuary is closed, surface water level is independent of tides (Niekerk, 2007; Koh *et al*., 2012). However, groundwater levels exhibit minor fluctuations in response to tides. Greater fluctuation of groundwater level was observed when the estuary was open. When the estuary is closed, surface water salinity and PO_4^{3-} characteristics are mainly determined by flow conditions, duration of closed state and bathymetry (Snow & Taljaard, 2007; Niekerk, 2007). Salinity and PO_4^{3-} characteristics in the groundwater system are influenced by horizontal and vertical transmission of groundwater (seepage velocity, sediment texture), the inland freshwater aquifer, seepage of estuarine water and density-driven circulation.

This research ascertains that distinct hydrodynamic characteristics are developed in the beach groundwater system of SRE as it varies between a closed- and open-state. More importantly, this study reveals the interchanging-role of presence or absence of an estuary mouth obstructing sandbar and tides in regulating the interactions between beach groundwater, estuary and sea. The closing and opening of estuary mouth sandbar also regulate hydraulic head difference between beach groundwater and the inland freshwater water table aquifer, hence, affected salinity and PO_4^{3-} distribution. Density-driven circulation and low seepage velocity were attributed for high PO_4^{3-} concentrations in the beach groundwater system.

ACKNOWLEDGEMENTS

This work was funded by the Ministry of Higher Education Malaysia (FRGS 59113). We are grateful to all the research assistants involved directly and indirectly in the fieldworks.

REFERENCES

American Public Health Agency, American Water Works Association and Water Environment Federation (APHA-AWWA-WEF), 2005. Standard methods for examination of water and wastewater (21st ed.). Washington: APHA-AWWA-WEF.

American Society of the International Association for Testing and Materials (ASTM International), 2007. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, C136-96a. West Conshohocken: ASTM International.

Billen, G., Garnier, J., Nemery, J., Sebilo, M., Sferratore, A., Barles, S., Benoit, P. & Benoit, M., 2007. A long-term view of nutrient transfers through the Seine river continuum. Science of the Total Environment, 375, 80-97.

Burnett, W. C., Wattayakorn, G., Taniguchi, M., Dulaiova, H., Sojisuporn, P., Rungsupa, S. & Ishitoba, T., 2007. Groundwater-derived nutrient inputs to the upper Gulf of Thailand. Journal of Continental Shelf Research, 27, 176-190.

Cooper, J.A.G., 1994. Sedimentary processes in the river-dominated Mvoti estuary, South Africa. Geomorphology, 9(4), 271-300.

Cooper, J.A.G, Wright, I. & Mason, T., 1999. Geomorphology and sedimentology. In: B. R. Allanson & D. Baird (Eds.), Estuaries of South Africa, 5-26. Cape Town, Cambridge University Press.

Environmental Protection Agency (EPA), 2006. Nutrients: nitrogen and phosphorus. In: National coastal condition report II. Available at: http://www.epa.gov/owow/oceans/nccr/2005/downloads.html.

FitzGerald, D. M., Kraus, N. C. & Hands, E. B., 2000. Natural mechanisms of sediment bypassing at tidal inlets. ERDC/CHL CHETN-IV-30, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Froneman, P. W., 2004. Food web dynamics in a temperate temporarily open/closed estuary (South Africa). Estuarine, Coastal and Shelf Science, 59, 87-95.

Gaughan, D. J. & Potter, I. C., 1994. Composition, distribution and seasonal abundance of zooplankton in a shallow, seasonally closed estuary in temperate Australia. Estuarine, Coastal and Shelf Science, 41, 117–135.

Gobler, C. J., Cullison, L. A., Koch, F., Harder, T. M. & Krause, J. W., 2005. Influence of freshwater flow, ocean exchange and seasonal cycles on -nutrient dynamics in a temporarily open estuary. Estuarine, Coastal and Shelf Science, 65, 275-288.

Koh, M. K., Sathiamurthy, E., Suratman, S. & Mohd. Tahir, N., 2012. Sandbar-regulated hydrodynamic influences on river hydrochemistry at Mengabang Telipot River, Peninsular Malaysia. Environmental Monitoring Assessment, 184, 7653-7664.

Lawrie, R. A., Stretch, D. D. & Perissinotto, R., 2010. The effects of wastewater discharges on the functioning of a small temporarily open/closed estuary. Estuarine, Coastal and Shelf Science, 87(2), 237–245.

Lee, Y. W., Hwang, D. W., Kim, G., Lee, W. L. & Oh, H. T., 2009. Nutrient inputs from submarine groundwater discharge (SGD) in Masan Bay, an embayment surrounded by heavily industrialized cities, Korea. Science of the Total Environment, 407(9), 3181-3188.

Mallinson, D. J., Culver, S. J., Corbette, D. R., Parham, P. R., Shazili, N. A. M. & Yaacob, R., 2014. Holocene coastal response to monsoons and relative sea-level changes in northeast Peninsular Malaysia. Journal of Asian Earth Sciences, 91, 194-205.

Markager, S., Stedmon, C. A. & Sondergaard, M., 2011. Seasonal dynamics and conservative mixing of dissolved organic matter in the temperate eutrophic estuary Horsens Fjord. Estuarine, Coastal and Shelf Science, 92, 376-388.

Nakada, S., Yasumoto, J., Taniguchi, M. & Ishitobi, T., 2011. Submarine groundwater discharge and seawater circulation in a subterranean estuary beneath a tidal flat. Hydrological Processes, 25, 2755-2763.

Niekerk, L. V., 2007. Hydrodynamics. In A review of information on temporarily open/closed estuaries in the warm and cool temperate biogeographic regions of South Africa, with particular emphasis on the influence of river flow on these systems. In: A. Whitfield and G. Bate (Eds.), WRC Report No. 1581/1/07, Water Research Commission. South Africa.

Nixon, S. W., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia, 41, 199-219.

Nunes, M. & Adams, J. B., 2014. Responses of primary producers to mouth closure in the temporarily open/closed Great Brak Estuary in the warm-temperate region of South Africa. African Journal of Aquatic Science, 39(4), 387–394.

Ortega-Cisneros, K., Scharler, U. M. & Whitefield, A. K., 2014. Inlet mouth phase influences density, variability and standing stocks of plankton assemblages in temporary open/closed estuaries. Estuarine, Coastal and Shelf Science, 136, 139-148.

Parham, P. R., Saito, Y., Noraisyah, S., Rokiah, S. & Noor Azariyah, M., 2014. Evidence for ca. 7 ka maximum Holocene transgression on the Peninsular Malaysia east coast. Journal of Quaternary Science, 29, 414-422.

Pauzi, N.S. & Sathiamurthy, E., 2013. Hydrodynamic behaviour and saline interface in a temporary open and closed (TOCE) system under closed condition. In: Proceedings of the 12th International Annual Seminar on Advances in Marine and Freshwater Sciences, Malaysia.

Pereira Coutinho, M. T., Brito, A. C., Pereira, P., Goncalves, A. S. & Moita, M. T., 2012. A phytoplankton tool for water quality assessment in semi-enclosed coastal lagoons: open vs. closed regimes. Estuarine, Coastal and Shelf Science, 110, 134-146.

Perissinotto, R., Walker, D. R., Webb, P., Wooldridge, T. H. & Bally, R., 2002. Relationship between zoo- and phytoplankton in a warm-temperate, semi-permanently closed estuary, South Africa. Estuarine, Coastal and Shelf Science, 51(1), 1-11.

Perissinotto, R., Nozais, C., Kibirige, I. & Anandraj, A., 2003. Planktonic food webs and benthic-pelagic coupling on three South African temporarily-open estuaries. Acta Oecologica, 24, S307-S316.

Ranasinghe, R. & Pattiaratchi, C., 2003. The seasonal closure of tidal inlets: causes and effects. Coastal Engineering Journal, 45(4), 601-627.

Ranasinghe, R., Pattiaratchi, C. & Masselink, G., 1999. A morphodynamic model to simulate the seasonal closure of tidal inlets. Journal of Coastal Engineering, 37, 1-36.

Robinson, C., Li, L. & Barry, D. A., 2007. Effect of tidal forcing on a subterranean estuary. Advances in Water Resources, 30, 851-865.

Santangelo, J. M., Rocha, A. M., Bozelli, R. L., Carneiro, L.S. & Esteves, F. A., 2007. Zooplankton responses to sandbar opening in a tropical eutrophic coastal lagoon. Estuarine, Coastal and Shelf Science, 71, 657-668.

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

Snow, G. & Taljaard, S., 2007. Water quality. In A review of information on temporarily open/closed estuaries in the warm and cool temperate biogeographic regions of South Africa, with particular emphasis on the influence of river flow on these systems. In: A. Whitfield and G. Bate (Eds.), WRC Report No. 1581/1/07, Water Research Commission. South Africa.

Suzuki, M. S., Ovalle, A. R. C. & Pereira, E. A., 1998. Effects of sand bar openings on some limnological variables in a hypertrophic tropical coastal lagoon of Brazil. Hydrobiologia, 368, 111-122.

Valsami-Jones, E., 2004. Phosphorus in environment technology: Principle and applications. United Kingdom, IWA Publishing. 656 p.

Manuscript received 16 September 2017
Revised manuscript received 25 May 2018
Manuscript accepted 30 May 2018