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Flow velocity model for a coastal estuarine sandbar using multivariate regression

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Abstract: Flow velocities through an estuarine sandbar under closed estuary condition for a temporary open/close estuary system (TOCE) corresponding to relation between river, groundwater and tidal levels were studied. Multivariate regression analysis was used to construct a model for estimating flow velocities. Validated model result shows a very good prediction for flow velocities in the sandbar ($R^2 = 0.9999$). This simple approach could describe the effect of the transition phase (flow through a closed estuary) on channel flow and backwater behaviour in relation to tidal forcing into a sandbar. It implies a broader usefulness in channel flow routing in coastal areas with TOCE system for flood modelling and management purpose.

Keywords: Estuary, TOCE, flow velocity, multivariate regression, Mengabang Telipot

INTRODUCTION

Coastal drainage is a complex hydro-system affected by interaction between outflow and tidal flux. The condition is more complex when the outlet is regulated by the formation and deformation of estuarine sandbar that creates temporarily closed/open estuaries (TOCE) system (Figure 1). The duration of the closed and open phases are determined by the interaction of river runoff, and wave over-wash in the estuary region. Marine currents, long-shore sand movement, and tidal action also have a profound impact on estuary dynamics (Smakhtin, 2004).

Although TOCE systems could be found worldwide, studies on its hydrodynamic characteristics under closed condition are limited. Existing studies does not focus directly on river flow through an estuarine sandbar using either numerical or statistical/empirical approach (Li *et al*., 2000; Robinson *et al*., 2007; Suzuki *et al*., 2002; Tracy-smith, 2006; Lawrie *et al*., 2010; Gibbes *et al*., 2008). They are mostly on environmental issues like description of spatial-temporal pattern of pollutants and many are insufficient in terms of spatial or temporal resolution of observations (Koh *et al*., 2012; 2018). Yuan *et al*. (2011) had introduced a coupled model for simulating surface water and groundwater interactions in coastal wetlands. However, the model is a loose coupling of *ELCIRC* (a three-dimensional, 3-D, finite-volume/finite-difference model for simulating shallow water flow and solute transport in rivers, estuaries and coastal seas) and *SUTRA* (a 3-D finite-element/finite-difference model for simulating variably saturated, variable-density fluid flow and solute transport in porous media) and it was validated using experimental results and not actual data. A 3-D finite element model that coupled Navier Stokes and Darcy equations had also been developed. It is used for the prediction and quantitative analyses of the hydrodynamic behaviour encountered in industrial filtrations and environmental flows (Hanspal *et al*., 2013). The 3D model is very complex to understand and to use for those who are not familiar with modelling. Hence, a simpler model that is able to give good estimate of flow in a TOCE system may be more practical.

This study aimed to construct a rating curve where the groundwater flow velocities through the estuarine sandbar are inferred from river, tidal and groundwater levels using multivariate regression analysis. Direct measurement of groundwater velocity is difficult, and usually time consuming and expensive especially in a complex system, i.e. TOCE.

Figure 1: Mengabang Telipot estuary under different conditions. Note: Satellite images adapted from Google Earth images.

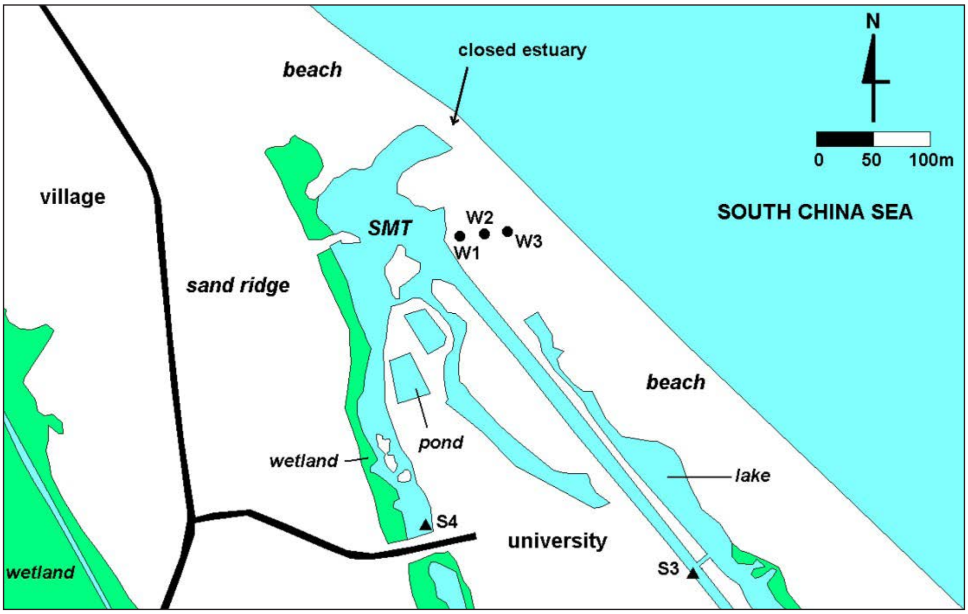

Figure 2: Study area and sampling stations.
Note: W1-W3 – monitoring wells; S3 & S4 – river water level stations; SMT – Sungai (River) Mengabang Telipot.

Therefore, this rating curve could provide a simple way to determine flow velocity and hence estimate flow through a closed estuary. It could enhance existing channel flow models that at present could not be applied to a closed estuary condition.

This research area is a small tidal affected drainage system, i.e. Sungai (river) Mengabang Telipot (SMT). It is located beside University Malaysia Terengganu campus, Kuala Terengganu, Malaysia, i.e. 5°25.0′ N, 103°05.2′ E (Figure 1 and 2). The length of SMT trunk river is approximately 1.7 km. SMT flow rate varies from almost 0 m^3/s for estuary closed condition to 9.6 m^3/s under opened condition. Backwater rise would occur when the estuary is closed and under prolonged closure would flood low lying areas and also caused water pollution (Koh *et al*., 2018). By estimating the flow rate through the sandbar during closed conditions with regards to tidal fluctuations, the backwater rise could be predicted. That would be important for flood management purposes.

Estuarine sandbar: formation, breaching and hydrodynamics

Figure 3 shows a simplified illustration on how an estuarine sandbar is formed and subsequently breached. This is based on field observations carried out from October 2007 to March 2010 and Google Earth satellite imagery (Figure 1).

Stage 1: Sediments transported by longshore transport (LST) formed a small spit on the edge of the southern end. This occurs after an episode of breaching. This LST process is caused by waves diagonal to the beach front, coming from the southeast direction during the summer or southwest monsoon season.

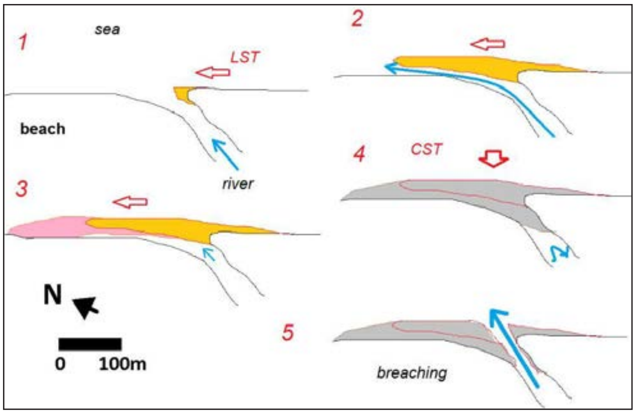

Figure 3: Formation and breaching of an estuarine sandbar.

Stage 2: As the LST process continues, the spit or sandbar becomes longer and wider and starts to close the estuary creating an elongated river parallel to the shore. This process occurs as a result of the interaction between the LST and river flows. River flows are able to partially offset the effect of LST, hence forming the elongated river.

Stage 3: The sandbar finally closes the estuary as lowered river flows are no longer able to offset the effect of LST. It was observed that this phenomenon usually occurred middle of the year as drier season reduced river flow.

Stage 4: Towards November, as the northeast monsoon sets in, waves direction comes from northeast direction and are parallel with the beach front. This creates cross shore transport (CST) process that made the sandbar wider and thicker. Heavy rains during the northeast monsoon season caused water to accumulate behind the closed sandbar.

Stage 5: If the water level reaches the same height as the crest of the sandbar, river water level would overtop the sandbar. This will result in the rapid erosion and eventual breaching of the sandbar. However, this natural breaching rarely occurred. During the observation period, only one natural event was recorded. Most of the time, breaching was done by human intervention in order to avoid flooding in the river catchment.

The typical relation between groundwater level (on the beach, i.e. Well 2, Figure 2), river water level and tidal levels is shown in Figure 4. It clearly demonstrates that during sandbar closed events, both groundwater and river water levels showed an upward trend with minor fluctuations. Tides did not have a significant effect on the river system. The water level rise could cause floods. However, when sandbar was opened or breached, the river water and groundwater level fluctuated according to tidal oscillations. In this figure, the breaching was man made in order to reduce flood risk as it was in the middle of the northeast monsoon season in 2010.

With reference to Figure 5, vertical salinity profiling was conducted during sandbar closed event for the same period. This was done by recording the changes conductivity in the monitoring wells (Figure 2) using a conductivity-temperature-depth probe (CTD). The saline-freshwater interfaces were plotted for average high and low tides under neap and spring tide conditions. The results indicated an insignificant lateral movement. The boundary at 50 mS/cm was almost fixed through time. This could explain why even under low tide condition freshwater generally could not flow through the sandbar effectively into the sea. If river water could flow through more effectively, there should

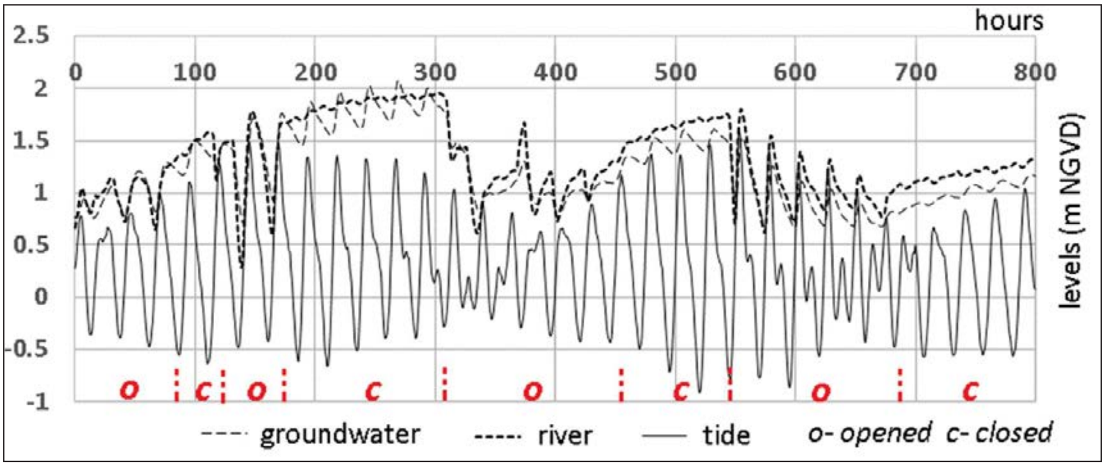

Figure 4: Estuary water levels and tidal levels under sandbar opened and closed conditions – 7/1/2010 – 9/2/2010. Note: NGVD – National Geodetic Vertical Datum.

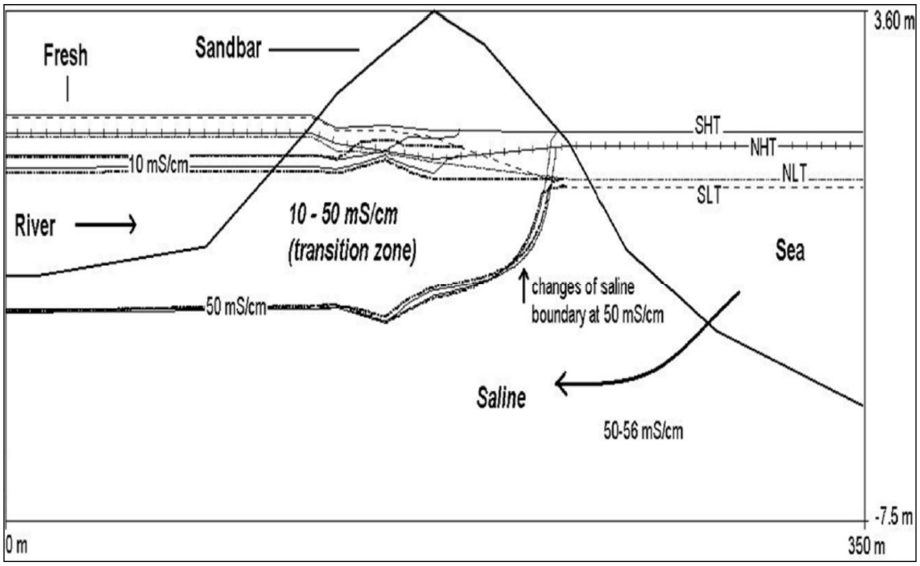

Figure 5: Saline-freshwater boundary.
Note: SHT – spring high tide; SLT – spring low tide; NHT – neap high tide; NLT – neap low tide; seawater has conductivity value of about 54 mS/cm.

be a significant seaward shift of the boundary indicating movement of low salinity water out of the river system. The closed sandbar in itself already greatly impeded the flow but this saline interface behavior made flow through the sandbar even more difficult. Figure 6 showed the differences in river water level, flow velocity and discharge between sandbar closed and opened conditions. It is clear that flow velocity and discharge were virtually zero and river water level remained high through time compared to an open event. In an open event, the flow velocity, discharge and water level fluctuated following tidal oscillations indicating greater river water outflow and, tidal intrusion and recession into the river system.

METHODOLOGY

Data collection

Field measurement was conducted periodically at the outlet of SMT from October 2007 to March 2010. Data from January 2009 to March 2009 were used for modelling flow velocity as they are more detailed. Wells 1, 2 and 3, were built for measuring groundwater levels whereas S3 and S4 for river water levels (Figure 2). The distance between wells was 20 m whereas Well 1 to river is 10 m and Well 3 to sea was 37 m. The average dimensions of sandbar were 78 m wide, 330 m long and 12 m – 15 m thick (to the first confining layer). These dimensions were mapped using global positioning system (GPS) and electrical resistivity (ER) survey. ER survey was conducted on the study area following shore parallel and shore perpendicular transect lines. A 81 m electrode cable was used, which gives a sub-surface penetration of about 16 m.

Linear pore velocity through the sandbar is calculated by dividing Darcy's flux with effective porosity, n_e as follows (Todd & Mays, 2005):

$$v = K_{sat}\; i / n_e \tag{1}$$

In which v = average linear pore velocity of groundwater between two point of length; K_{sat}= saturated hydraulic conductivity; $i = \Delta h/\Delta l$, hydraulic gradient measured in the direction of flow. Δh is obtained from the difference of hydraulic heads of Well 1, 2 and 3 whereas Δl is the distance between wells. At the present research stage, we assume $K=0.1178$ m/h and $n_e=0.04$ for sand sediment. Both values are obtained from Rawls *et al*. (1983). These values are valid for the research area. The sediment type (i.e. sand) was verified by field samples analysis taken at various depths. The sediment layer is also assumed to be homogeneous as sieving analysis of those field samples showed minor variation in particle size distribution. Actual flow velocity through the sandbar was not measured because of equipment unavailability. Tidal data was taken from Cendering tidal station located 20 km south. Figure 7 showed the field measurement concept in general. Tidal, groundwater and river water levels were made comparable by using the same vertical datum of the National Geodetic Vertical Datum or NGVD. This datum is used in Peninsular Malaysia for all elevation survey work.

Groundwater mean velocity model

The relationship between mean groundwater velocity, river water level, groundwater level for the monitoring wells 1, 2 and 3 and tidal level for closed sandbar event was constructed using multivariate regression. Dataset from 28 February 2009 - 3 March 2009 with 1 minute time step was used to build an initial model. The mean velocity generated from the equation/model was compared to the mean velocity calculated from field data using R^2 to test the model reliability. The standard error was calculated. Then, the model was calibrated by curve fitting it to the observed curve. It was done this way because the value of the standard error is small. The small standard error indicated that the pre-calibrated model gave good results.

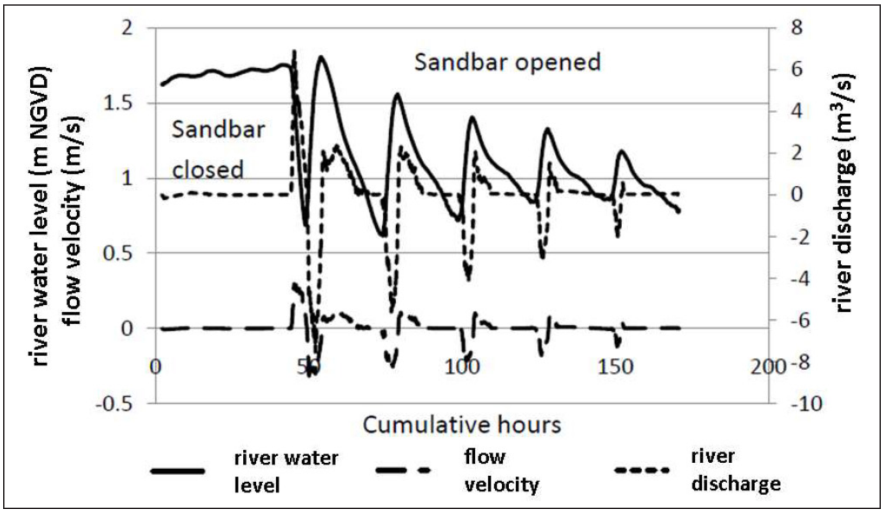

Figure 6: Estuary hydrodynamics – 28/1/2010 – 2/2/2010 (adapted from Koh *et al*., 2018).

Hence, adjustments to the variable ‘K_{sat}’ values which was approximated from published values are not needed. The average standard error was added into the constant parameter to fit the model output better with the actual mean velocity.

Verification data

The model was verified by comparing the calibrated model results with datasets from a different time period, 18 January 2009 - 21 January 2009 and 7 March 2009 - 10 March 2009 under closed estuary condition.

RESULT AND DISCUSSION

The established model estimates the groundwater mean velocity corresponding to tidal and river water level. Field observations found that groundwater velocity is controlled by the difference of hydraulic head between river and sea. The groundwater mean velocity model under closed estuary condition is determined by the regression curve is as follows Eq. (2):

$$V = 8.988e^{-11} + 1.500e^{-2} R - 1.100e^{-2} W_1 + 3.827e^{-10} W_2 - 1.319e^{-10} W_3 - 4.000e^{-3} T \quad (2)$$

V: groundwater mean velocity, ms^{-1}; R: river water level in m NGVD; T: tidal or sea level in m NGVD; W_1 - W_3: groundwater level in m NGVD for wells 1, 2 and 3.

Table 1 shows the table of the value of Nash-Sutcliffe analysis, R^2 and its standard error before and after the model calibration. The standard error value (before calibration) is added into the data set in order to produce a calibrated model shown in Eq. (3). Such calibration step would reduce standard error further and improve the model.

$$V = -4.200e^{-4} + 1.500e^{-2} R - 1.100e^{-2} W_1 + 3.827e^{-10} W_2 - 1.319e^{-10} W_3 - 4.000e^{-3} T \quad (3)$$

Figures 8 and 9 showed the comparison between the observed mean velocity (based on water level and Darcy’s velocity) and the predicted mean velocity (using Eq. (3)) for 18-21 January 2009, and 7-10 March 2009. Both results indicated a very good prediction. The standard error for March 2009 is ±$5.390e^{-5}$ and its R^2 is 0.9998. As for January 2009 dataset, the standard error is ±$1.759e^{-4}$ with R^2 of 0.9995.

Sensitivity analysis was done to determine the effect of input parameters (i.e tidal, river and groundwater levels) on the variation of predicted mean velocity and estimated mean velocity. It was necessary process in order to identify key parameters and parameters precision required for calibration (Moriasi *et al*., 2007). Based on the analysis (Table 2), tide (T) gave the highest value of the explained variation (R^2) for velocity which is 0.661, followed by river water level (R) (R^2=0.315), well 1 (W_1) (R^2=0.244), well 2 (W_2) (R^2=0.0.199) and well 3 (W_3) (R^2=0.113), respectively. This means that velocity fluctuates more with the tidal effects compared to other parameters. The variation of velocity is much smaller when T and R are used together (R^2=0.976) compared to any combination of either T or R with well data. In order to improve the model while making it simple, groundwater parameters are added, i.e. W_1 and W_3. The combination of R, W_1 and T gave a significance effect to the result (R^2=0.9993) whereas addition of W_2 data made no difference. It could be concluded that the combination of river water level with W_1, W_3 and tidal level produced the best prediction.

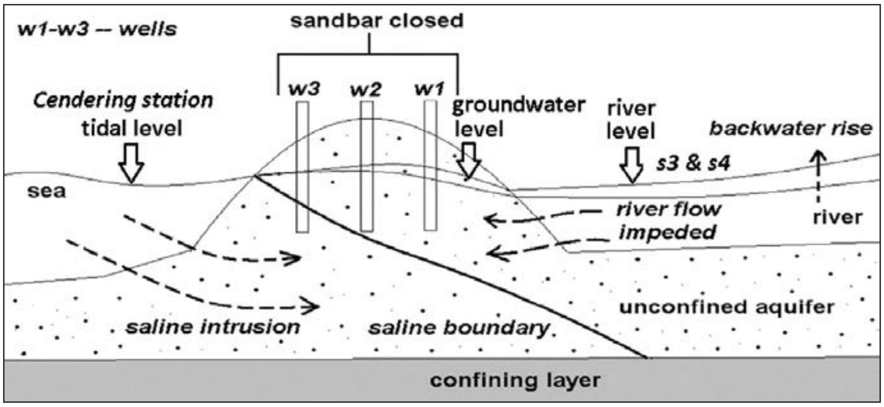

Figure 7: Generalized river water –sandbar groundwater-sea level measurement concept.

Table 1: Table of the comparison between before and after model calibration.

	Nash-Sutcliffe	R^2	Standard Error
Before Calibrate (Eq. 1)	0.9412	0.9999	±$4.161e^{-4}$
After Calibrate (Eq. 2)	0.9946	0.9999	±$6.598e^{-11}$

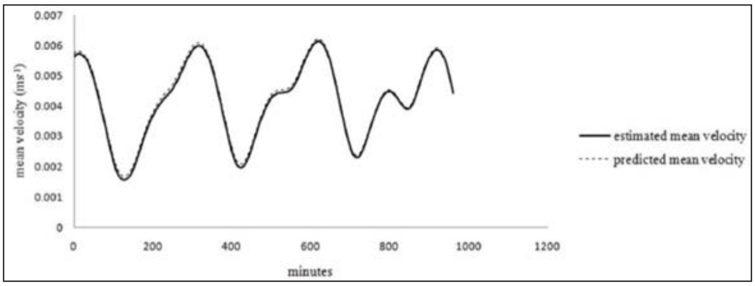

Figure 8: Estimated mean velocity and predicted mean velocity, 7-10 March 2009.

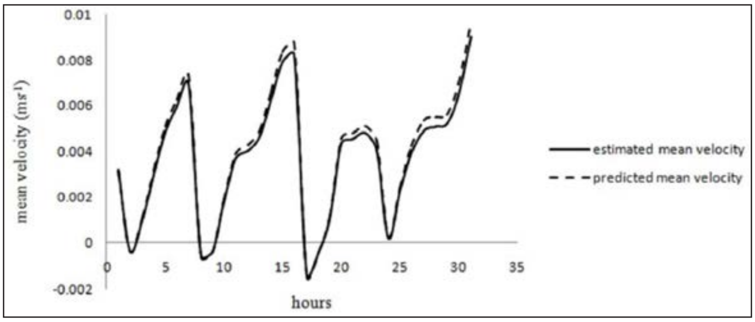

Figure 9: Estimated mean velocity and predicted mean velocity, 18-21 January 2009.

Table 2: Results of sensitivity analysis.

Parameters	R^2
V=f(T)	0.661
V=f(R,)	0.315
$V=f(W_1)$	0.244
$V=f(W_2)$	0.199
$V=f(W_3)$	0.113
V=f(R,T)	0.976
$V=f(R,W_1)$	0.545
$V=f(R,W_2)$	0.684
$V=f(R,W_3)$	0.673
$V=f(T,W_1)$	0.957
$V=f(T,W_2)$	0.947
$V=f(T,W_3)$	0.912
$V=f(R,W_1,T)$	0.990
$V=f(R,W_2,T)$	0.998
$V=f(R,W_3,T)$	0.998
$V=f(R,W_1,W_2,T)$	0.998
$V=f(T,W_1,W_2,W_3)$	0.976
$V=f(R,W_1,W_2,W_3,T)$	0.999
$V=f(R,W_1,W_3,T)$	0.999

Thus, the groundwater velocity model based on the sensitivity analysis after calibration is as follows:

$$V=0.007*R-0.003*W_1-0.003*W_3-0.002*T+0.0012 \quad (4)$$

The new simplified groundwater velocity model Eq. (4) produced a very good prediction. Its Nash-Sutcliffe value is 0.9993 and standard error is ±0.001384. Its R^2 value indicates that the model could explain 99.93% of variability of the groundwater mean velocity. This implies that the proposed model is reliable.

CONCLUSION

Groundwater flow through a closed estuary estimates are essentially for determining flood causing backwater effect in a TOCE system. This is vital for coastal drainage work with regards to flood modelling and management activities conducted by town or city councils and federal government agencies. As the direct measurement of groundwater velocity is time consuming and expensive, this model would be a practical alternative. It is a simple and reliable way to estimate the groundwater velocity for the purpose of flow estimation. Hence, this paper presents a viable approach for estimating flow through sandbar. Direct field measurements of hydraulic conductivity and groundwater velocity in a sandbar would further improve the model. However, such tasks may be time consuming and not cost effective.

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