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Investigation of Salt Intrusion Condition in the Belat Estuary

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Abstract. Awareness on salt intrusion problem is still lacking in Malaysia due to high precipitation in the region. However, the El-Nino phenomenon that occurred recently has caused extremely low fresh water discharge in the Kuantan River which allowed the sea water to intrude further into its water intake region. Consequently, the Belat River may become potential water resources alternative to build new water intake station for the water supply in the Kuantan River Basin. The aims of this study are to: 1) investigate the salinity distribution in the Belat Estuary; 2) evaluate the applicability of the 1-D analytical salt intrusion solution; 3) determine the calibration parameters in the salt intrusion model. Salt intrusion measurements was conducted during the dry season at spring tide when the fresh water discharge is the minimum. Collection of data such as hydrological data, river cross section and salinity were collected to be used in the salt intrusion analysis. The results obtained show good agreement between the simulated and observed salinity distribution in the estuary with low RMSE and high NSE values. This indicates that the model is reliable and can become an important tool for water manager in conducting salt intrusion study for this area.

1 Introduction

Nowadays, salt water intrusion problems have become critical and serious issues that need to be addressed, especially in arid and semi-arid region. The concentration of salinity level is vital especially when the water in an estuary is used for human consumption. High salt concentration in water can bring harm to human health. This problem also can affect the natural cycle of the estuarine ecosystem especially the biodiversity in the region. Uncertainties of climate change, rapid population growth and industrial advancement nowadays also affect the water quality in rivers. Apart from that, human activities such as dredging and construction of dams potentially causing salt intrusion problems that affect the quality of water resources and give a threat to marine species. Therefore, the study of salt intrusion necessary to ensure the quality of the intake water can be consumed for human use [1].

There are many research studies have been conducted to investigate the saline intrusion in the estuaries worldwide such as along the Bay of Bengal in Bangladesh [2], the Mekong Estuary [3], Chao Phraya Estuary [4], and the Red River Delta [5]. In Malaysia, several studies have been done by different researchers such as H.R Wallingford [6] for Kuantan Estuary, SMHB et al. [1] for the Rompin and Ulu Sedili Besar Estuary, Van Breemen [7] for the Selangor Estuary, and Gisen et al. [8] for six estuaries in the region. The six estuaries covered includes the Kurau, the Perak, the Bernam, the Selangor, the Muar and the Endau Estuary. HR Wallingford [6] conducted the salt intrusion study in the Kuantan Estuary following the case where the Kobat water intake station was affected by saline water. Thus, a barrage was built to prevent the salt water intrusion. For the Rompin and Ulu Sedili Besar Estuary, SMHB et al. [1] carried out the salt intrusion investigation to fulfil the requirements stated in the National Water Resources Study in which potential water intake stations are to be identified for water supply purposes. Van Breemen [7] study shows that the changes of the salinity levels in the Selangor Estuary may contribute to deterioration of the mangroves and Berembang Trees which consequently causing the fireflies population moving towards extinction. The latest studies by Gisen et al. [8] in the six estuaries in Malaysia have shown that the salt intrusion problem in those areas are still under control without any major issues.

There are several salt intrusion model available in the market including one-dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-D) models. These models have been widely applied in simulating salinity distribution in estuaries worldwide. 2-D and 3-D models are preferably use in cases where high accuracy is required for the modelling results. Meanwhile, 1-D analytical solution is sufficient for cases in which

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moderate accuracy is required. The benefits of using a 1-D model compared to 2-D and 3-D models are its simplicity and ability to be applied in data-poor environments. These type of model only requires only requires directly measurable parameters such as geometry, fresh water flow and tide, and most importantly it is costs effective [9]. 1-D analytical salt intrusion model developed by Savenije [9-11] has been tested in many estuaries globally and proven reliable particularly in minimally gauged estuaries [5, 8, 12]. The researchers confirmed that the 1-D Salt intrusion model can be used not only for single reach estuaries but also multi-branch estuaries.

In March 2016, Malaysia was hit by extreme El-Nino phenomenon. Due to this extremely dry weather, the water supply system in the Kuantan River Basin have been affected. Several complaints were received by the water authority from the Kuantan citizen claiming that the tap water has a taste of saltiness. The authority also confirmed that this is due to the pumping of saline water into the treatment plant. Although the Kobat Barrage that has been built in 1980's to prevent the salt water intrusion, but the problem still occur after 30 years. Hence, salt intrusion investigation in the Belat Estuary was conducted in this study to introduce the Belat River as potential water resources alternative where new water intake stations can be built for the future water supply in the Kuantan River Basin. The aims of this study are to: 1) investigate the salinity distribution in the Belat Estuary; 2) evaluate the applicability of the 1-D analytical salt intrusion solution; 3) determine the calibration parameters in the salt intrusion model. It is believed that the results obtained from this study can provide useful information for water manager in managing the saline intrusion condition in the estuary.

2 Background theories

There are two components in the 1-D analytical salt intrusion model of Savenije [9-11] which are the geometry and longitudinal salinity distribution analyses. The geometry analysis involved several parameters namely the channel cross sectional area, width and depth. According to Savenije [10], the geometry of an estuary can be presented in exponential functions as shown below:

$$A = A_O e^{-\frac{x}{a_1}} \quad \text{for} \quad 0 < x \leq x_1 \qquad (1)$$

$$A = A_1 e^{-\frac{(x-x_1)}{a_2}} \quad \text{for} \quad x > x_1 \qquad (2)$$

$$B = B_O e^{-\frac{x}{b_1}} \quad \text{for} \quad 0 < x \leq x_1 \qquad (3)$$

$$B = B_1 e^{-\frac{(x-x_1)}{b_2}} \quad \text{for} \quad x > x_1 \qquad (4)$$

$$h = h_O e^{\frac{x(a_1-b_1)}{a_1 b_1}} \quad \text{for} \quad 0 < x \leq x_1 \qquad (5)$$

$$h = h_1 e^{\frac{(x-x_1)(a_2-b_2)}{a_2 b_2}} \quad \text{for} \quad x > x_1 \qquad (6)$$

where parameters A [m^2], B [m] and h [m] are the cross sectional area, width and average depth at any distance x [m]. Subscription (0) in the equations represents the location of $x = 0$ which in this case the mouth of the estuary. The longitudinal distance, x_1 [m] is the inflection point where the convergence length changed. For the inflection point, all the symbols for the geometry characteristics are accompany by a subscription (1). Meanwhile, for the cross-sectional and width convergence lengths, the downstream part is given the symbols a_1 [m] and b_1 [m], respectively. As for the upstream reach, they are given the subscription (2). In this geometry analysis, the average depth is computed by dividing the area over the width. Generally, in a natural alluvial estuary, the ideal convergence lengths a and b are equal lading to a constant depth [10].

Substituting the geometry Equations (1) to (6) and integrating the Van der Burgh (1972) equation into the salt balance equation, the longitudinal salinity distribution for a steady state condition can be written as:

$$\frac{S-S_f}{S_0-S_f} = \left(\frac{D}{D_0}\right)^{\frac{1}{K}} \quad \text{for} \quad 0 < x \leq x_1 \qquad (7)$$

$$\frac{S-S_f}{S_0-S_f} = \left(\frac{D}{D_1}\right)^{\frac{1}{K}} \quad \text{for} \quad x > x_1 \qquad (8)$$

where S [kgm^{-3}] and D [m^2 s^{-1}] are the salinity and dispersion as a function of any distance. The freshwater salinity is expressed by S_f [kgm^{-3}], which is normally close to 0. The salinity and dispersion equations are expressed as:

$$\frac{D}{D_0} = 1 - \frac{K a_1}{\alpha_0 A_0}\left(\exp\left(\frac{x}{a_1}\right) - 1\right) \quad \text{for} \quad 0 < x \leq x_1 \qquad (9)$$

$$\frac{D}{D_1} = 1 - \frac{K a_2}{\alpha_1 A_1}\left(\exp\left(\frac{x-x_1}{a_2}\right) - 1\right) \quad \text{for} \quad x > x_1 \qquad (10)$$

With:

$$\alpha_0 = \frac{D_0}{Q_f} \quad \text{for} \quad 0 < x \leq x_1 \qquad (11)$$

$$\alpha_1 = \frac{D_1}{Q_f} \quad \text{for} \quad x > x_1 \qquad (12)$$

where Q_f [m^3 s^{-1}] is the freshwater discharge and K is the Van der Burgh coefficient, which ranges between 0 and 1; Since the data for freshwater discharge is always not available in the tidal region and the dispersion is not measurable, their ratio is then expressed as the mixing number, α_0 [m^{-1}] and α_1 [m^{-1}] in the calibration process. The ultimate objective in the salt intrusion study is to determine the furthest distance the salt water intrudes into the river system. Thus, from Equations (9) and (10), the salt intrusion length L are computed for $D=0$ at tidal average condition by the following equations:

$$L^{TA} = \alpha_1 ln\left(\frac{1}{\beta_0} + 1\right) \quad \text{for} \quad 0 < x \leq x_1 \qquad (13)$$

$$L^{TA} = x_1 + \alpha_2 ln\left(\frac{1}{\beta_1} + 1\right) \quad \text{for} \quad x > x_1 \qquad (14)$$

In order to convert the intrusion length from tidal average to high water slack (HWS) condition where the salinity length is the most, Equations (7) and (8) are shifted for $x = -E/2$ are shown as below:

$$S^{HWS}(x) = S^{TA}\left(x - \frac{E}{2}\right) \qquad (15)$$

Hence, the salt intrusion length equation becomes:

$$L^{HWS} = \alpha_1 ln\left(\frac{1}{\beta_0{}^{HWS}} + 1\right) \qquad (16)$$

3 Study Area

The Kuantan River Basin is situated within the East Coast Range next to the Pahang-Terengganu border with the catchment area of 1630km². The Belat Estuary is one of the tributaries for the Kuantan River and is situated near Kampung Belukar Baharu, Kampung Baharu Batu Empat, and Perumahan Sungai Isap Satu residential area. Meanwhile, Sungai Air Hitam and Sungai Soi are the tributaries of the Belat River. The exact location of the Belat Estuary is at the coordinate of 4° 08' 00" N and 103° 24' 00" E on the east coast of Peninsular Malaysia. Belat Estuary meets the Kuantan River at the confluence of about 6.5km from the Kuantan River mouth as displayed in Figure 1.The main economic activities surround the mouth of the Belat Estuary is the large scale commercial fishing activities. In terms of flora and fauna, mangrove plants can be found along the river bank of the Belat Estuary. The topography of the Belat River is shallow and flood tends to occur at the residential area around the region during heavy rainy season.

Figure 1. Aerial view of the Belat Estuary

In normal condition, freshwater discharge from the Belat River is drained into the Kuantan River. However, during the dry and hot season which occur from April to September, the freshwater discharge is reduced to a low level causing the saltwater from the tide to intrude into the Belat Estuary. Since the Belat River is a tributary of the Kuantan River, the tidal mixing pattern at the confluence is rather complex. During the ebb and flood event, part of the saltwater from the Kuantan Estuary may flow into the Belat Estuary causing instability in the salinity distribution.

The tidal information of the Kuantan Estuary are used as a reference since the location of the Belat Estuary mouth is not open to the ocean. Figure 2 shows the tidal oscillation of the Kuantan Estuary in April 2017. From the tidal oscillation pattern, it can be seen that the tidal mechanism in the studied area is mixed-diurnal with 12 hours tidal cycle.

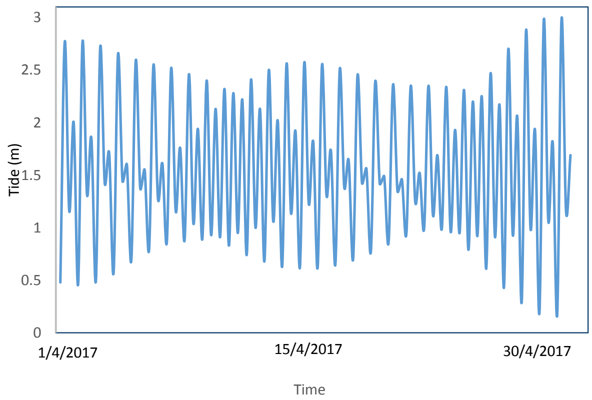

Figure 2. Tidal oscillations for Kuantan Estuary in April 2017

4 Methodology

4.1 Data Collection and Observation

A salinity field survey was conducted on 28 April 2017 when the dry season began in the region. The correct timing and tidal condition are crucial for the survey because salt intrusion is most severe during the dry season in conjunction with the spring tide (maximum high water). Field survey were carried out for both high water slack (HWS) and low water slack (LWS) when the water is stagnant at zero velocity. The salinity measurements were conducted by adopting a moving boat technique starting from the estuary mouth moving towards the inlands with the speed of the tidal wave celerity. Measurements stopped when the salinity level reads 0.1ppt. A Global Positioning System (GPS) was used to record the waypoint of each measurement while the portable handheld depth sounder was used to capture the water depth at every salinity measurement points. For the salinity measurement, a Horiba Multi-Parameter Water Quality Meter attached with 30 m cable was used. Water temperature, conductivity, turbidity, salinity and pH values of the river water were measured simultaneously with this instrument. A weight was attached to the cable of the water quality meter so that the measuring probe can submerge in the water at all time during the measurement.

4.2 Geometry analysis

For the geometry analysis, measurement at the Kuantan Estuary was not carried out on the first and second survey as existing data was available. The geometry analysis for the Belat Estuary was carried out based on Savenije's [9] theory for alluvial estuaries, where the change in the geometry of estuary varies exponentially over the distance. In this study, the width, depth and cross section of the Belat estuary was determined and plotted in a semi-log graph according to Equations (1) to (6). Then from the analysis, the value for A_0, B_0, and h_0 were obtained by fitting the simulated geometry characteristics to the observed data. This geometry information was used as boundary input data for the salinity analysis.

4.3 Salt intrusion modelling

For the salinity analysis, the 1-D analytical salt intrusion solution developed by Savenije [9-11] was applied for the Belat Estuary. In this model, the salinity distribution was simulated at Tidal Average (TA) condition and later converted to HWS and LWS situation to determine the maximum and minimum salt intrusion length. These boundary condition are important to determine the salt water intrusion limit. The governing equations applied to generate the simulated salinity profile are Equations (7) to (12). From the TA simulated curve, the salinity profile for HWS and LWS was generated by shifting the TA salinity seaward and landward by half of the tidal excursion (*E*). Salinity curves at HWS and LWS represent the envelopes of the salinity variation in a tidal cycle.

4.4 Model Calibration

The parameters that were calibrated in the salt intrusion analysis are the Van der Burgh's coefficient *K*, Dispersion coefficient *D*, Tidal Excursion E, and the Sea salinity S_0. *K* is the 'shape factor' which influence the shape of the salt intrusion curve at the toe. It is dependent on the changes in channel topography. Dispersion is a mathematical artefact that cannot be directly measured [13]. Since *D* is highly influenced by the discharge in which the data is always unavailable, the dispersion is calibrated in term of the mixing number α representing the ratio between dispersion *D* and discharge *Q*. In this study, tidal excursion has to be calibrated because the tidal velocity amplitude was not measured.

4.5 Error Analysis

RMSE is the one of the error analysis tools used to validate the reliability and performance of the salt intrusion model. The equation of RMSE is as below:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (20)$$

Where P_i is the predicted value and O_i is the observed value.

NSE coefficient was also used to access the predictive power of the salt intrusion model. The equation of NSE is as below:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (21)$$

Where P_i is the predicted value and O_i is the observed value and $\bar{O}$ is the average of the observed value.

5 Result and Discussion

5.1 Geometry of the estuary

The geometry analysis for the Belat River Estuary was performed by utilizing the Equations (1) to (6). Data of the observed and simulated geometry characteristics of the estuary were plotted in a logarithmic scale which is shown in Figure 3. For the simulated geometry, the computed results were analysed and presented in a regression form. The geometry of the Belat Estuary consists of two reaches, Kuantan Estuary at the downstream and the Belat Estuary at the upstream (starting from distance about 6.5km from the mouth). From the plots, it can be seen that the shape of the estuary is well expressed by exponential function, confirming the theory of Savenije [11]. Table 1 shows the geometry characteristics results obtained from the best fit regression analyses. The inflection point was identified at distance 6km where the cross sectional area and width convergence length changed.

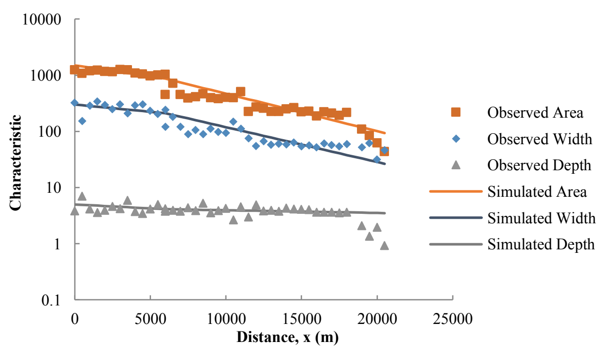

Figure 3. Geometry of Belat Estuary

Table 1 Geometry characteristics

Characteristic	Mouth, x_0	Inflection point, x_1
Area, A (m^2)	1500	870
Width, B (m)	300	210
Area convergence, a (m)	11000	6500
Width convergence, b (m)	17000	7000
Average depth, h (m)	3.82	3.82

5.2 Salinity Distribution

Figures 4 and 5 show the vertical salinity distribution of the Belat Estuary during both High Water Slack (HWS) and Low Water Slack (LWS). From the patterns displayed, the mixing mechanism for the Belat Estuary can be classified as well-mixed because the distribution of saline water is almost evenly mixed from the bottom to the surface. Well-mixed mechanism in estuaries occurs when the discharge of fresh water is small compared to the tidal flows (tidal dominant). In Figure 5, there is a significant stratification occurs at distance 6.5km. The stratification is identified at the confluence of the Kuantan-Belat Estuary. When there is a split in the river system, the confluence receives fresh water discharge from both rivers where the amount of total discharge increase drastically. From the plot, there is no significant deviation of salinity level in the Belat Estuary during the LWS. This means that the confluence does not affect much on the vertical salinity distribution during ebb tide and the results are satisfying.

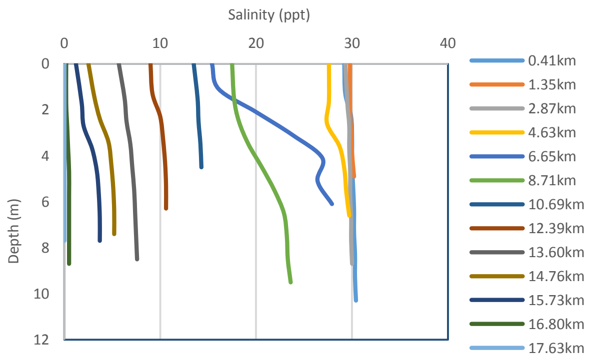

Figure 4. Vertical salinity distribution of the Belat Estuary during HWS

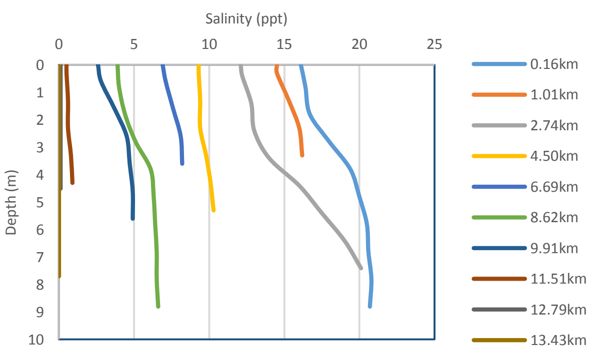

Figure 5. Vertical salinity distribution of the Belat Estuary during LWS

Figure 6 displays the measured and simulated longitudinal salinity profile of the Belat Estuary. As can be seen from the plot, the 1-D salt intrusion model is able to simulate the salinity profile in the Belat Estuary very well when compared to the observed data. From the simulation, the calibration parameters K and α obtained to fit the curve against the observed data are 0.45 and 13m^{-1}, respectively. Since the velocity amplitude was not measured in this study, the tidal excursion E was calibrated based on the HWS and LWS tidal envelop. The values obtained for the tidal excursion are 11000m at the mouth and 7800m at the inflection point with a convergence length e of 20000m.The salinity at the mouth for the HWS is 34ppt while for the LWS is about 22ppt indicating a difference of 12ppt.

In overall, the simulated longitudinal profile has a good fit with the observed data. However, at distance 6.5km, there are some outliers. These is due to the split in the Kuantan River (Belat – Kuantan). For the downstream part near the mouth, it can be seen the salinity distributions show some inconsistency, this is because the downstream part of the Belat Estuary belongs to the Kuantan River and this river is no longer in an equilibrium condition due the construction of the Kobat Barrage.

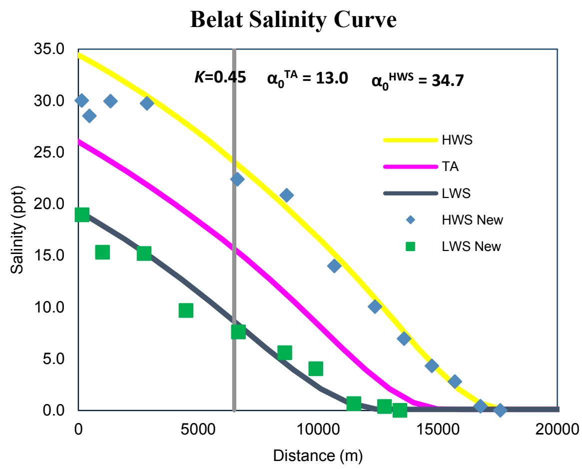

Figure 6. Measured and simulated longitudinal salinity profile of the Belat Estuary

5.3 Error Analysis

For the model performance, the RMSE obtained for the Belat River Estuary during HWS and LWS are 2.18ppt and 3.58ppt, respectively. At LWS, the RMSE value is higher because the difference between the observed and simulated values is bigger for the outliers. On the other hand, analysis shows high NS efficiency for both HWS and LWS conditions with the factor of 0.998 and 0.993, respectively which is very near to unity. This means that the salt intrusion model is very reliable and has very high efficiency.

6 Conclusions

In a nutshell, the investigation of salt intrusion in the Belat River Estuary has been successfully carried out. The geometry profile of the Belat Estuary has been well analysed adopting an exponential function and is proven valid in this case study. Salinity intrusion investigation have been successfully conducted for the Belat Estuary during both High Water Slack (HWS) and Low Water

Slack (LWS). The vertical salinity distribution results show that the mixing mechanism in the Belat Estuary can be classified as well-mixed. The calibration parameters, Van der Burgh coefficient K, mixing coefficient α, and tidal excursion E, give the values of 0.45, 13m^{-1} and 11000m, respectively. The performance of the 1-D analytical salt intrusion model has been evaluated and the results show accuracy. The average RMSE and NSE values obtained for both the HWS and LWS are 2.88ppt and 99%, respectively. The calibrated values had successfully fit the simulated data and the observed data. As a conclusion, the salt intrusion model is very reliable for the salt intrusion investigation in the Belat River Estuary. Hence, it is believed the 1-D salt intrusion model can be a useful tool to the water manager in deciding the appropriate location to install any water intake station according to the salinity distribution of the Belat River Estuary.

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