APPLICATION OF 1-D ANALYTICAL SOLUTION FOR SALT INTRUSION INVESTIGATION IN THE BELAT ESTUARY

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APPLICATION OF 1-D ANALYTICAL SOLUTION FOR SALT INTRUSION INVESTIGATION IN THE BELAT ESTUARY

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ABSTRAK

Secara umumnya, penerobosan air masin di kawasan hilir sungai telah menyebabkan banyak masalah kepada masyarakat di Kuantan terutamanya dalam aktiviti harian yang melibatkan penggunaan air bersih. Terbaru, dilaporkan air yang digunakan oleh penduduk sekitar Kuantan didapati masin. Ini menandakan kesan penerobosan air masin yang kian ketara di stesen pengambilan air Kampung Kobat, Sungai Kuantan disebabkan oleh kapasiti air tersedia yang terlampau rendah susulan fenomenan El-Nino. Oleh itu, kajian terhadap kesan penerobosan air masin di dalam sistem air bersih adalah sangat penting untuk menentukan tahap kemasinan di muara sungai supaya langkah-langkah pencegahan boleh diambil sekiranya tahap kemasinan yang dipantau di kawasan muara telah mencecah tahap optimum. Dalam kajian ini juga, pengukuran tahap kemasinan air di kawasan Muara Sg. Belat telah dijalankan untuk memastikan bahawa penduduk di sekitar kawasan Muara Sg. Belat mendapat air yang sesuai untuk digunakan. Antara objektif kajian ini adalah untuk mengkaji profil kemasinan air di Muara Sg. Belat semasa air surut, mengaplikasikan analisis 1-D dalam kajian profil kemasinan air di Muara Sg. Belat dan juga menentukur faktor bentuk Muara Sg. Belat. Dua parameter yang perlu ditentukur serta sesuai untuk dalam simulasi ialah pekali Van der Burgh, K dan kadar pergerakan pasang surut air, E. Data bagi kajian ini telah dikumpulkan pada 28 Apr 2017 dan keputusan yang diperolehi daripada analisis geometri menunjukkan bahawa bentuk Muara Sg. Belat didapati mengikut fungsi eksponen. Daripada analisis kemasinan air, nilai pekali Van der Burgh, K yang telah ditentukur adalah 0.65 dan kadar pergerakan pasang surut air, E adalah 6500m. Prestasi model 1-D juga telah dinilai berdasarkan analisis ralat RMSE dan NSE. Keputusan yang diperolehi telah menunjukkan bahawa model 1-D adalah tepat dan sesuai untuk diaplikasikan dalam kawasan kajian di Muara Sg. Belat.

ABSTRACT

In general, saline intrusion into the upper reach of river has caused problems especially for water intake activity. Recently, the water intake for human consumption in Kuantan has been reported to be salty. This means that the salt intrusion has reached the water intake station at Kampung Kobat, Kuantan river due to extreme low fresh water discharge as a result of El-Nino phenomenon. In this case, salt intrusion investigation is vital to determine the salinity level of the estuary so that the preventive measures can be taken if the observed salinity level in an estuary is near to the optimum level. In this research study, the salinity measurement in the Belat Estuary will be conducted. This is to make sure that residents around the Belat Estuary will have healthy water intake for consumption. The aims of this research are to: 1) investigate the salt intrusion in the Belat Estuary during spring tide; 2) apply the 1-D analytical solution for salt intrusion investigation in the Belat Estuary; 3) calibrate the shape factor for the Belat Estaury. The two parameters that need to be calibrated to fit the simulated salinity curve and the observed salinity data which are the Van der Burgh coefficient, K and tidal excursion, E. The data was collected on 28 Apr 2017. Result obtained from the geometry analysis shows that the shape of the Belat Estuary follows an exponential function. From the salinity analysis, the calibrated Van der Burgh's coefficient, K obtained is 0.65 and the value of tidal excursion, E is 6500m. The performance of the 1-D salt intrusion model was evaluated based on RMSE and NSE error analyses, and the results indicate that it is sufficiently accurate and reliable to be applied in the Belat Estuary.

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LIST OF SYMBOLS

a	Cross-sectional convergence length [L]
a_1	Cross-sectional convergence length of the seaward reach of estuary [L]
a_2	Cross sectional convergence length of the landward reach of estuary [L]
A	Cross-sectional area [L^2]
A_0	Cross-sectional area at estuary mouth [L^2]
A_1	Cross-sectional area at inflection point x_1 [L^2]
b	Width convergence length [L]
b_1	Width convergence length of the seaward reach of estuary [L]
b_2	Width convergence length of the landward reach of estuary [L]
B	Estuary width [L]
B_0	Width at estuary mouth [L]
B_1	Width at inflection point x_1 [L]
c	Wave celerity [L/T]
D	Longitudinal dispersion [L^2/T]
D_0	Longitudinal dispersion at estuary mouth [L^2/T]
E	Tidal excursion [L]
g	Acceleration due to gravity [L/T^2]
h	Estuary depth [L]
h_0	Estuary depth at the mouth [L]
h_1	Average depth of estuary after the inflection point x_1[L]
K	Dimensionless Van der Burgh's coefficient [-]
L	Salt intrusion length [L]
P	Flood volume [L^3]
Q_f	Fresh water discharge [L^3/T]
S	Steady state salinity [M/L^3]
S_0	Steady state salinity at the estuary mouth [M/L^3]
S_f	Fresh water salinity [M/L^3]

T	Tidal period [T]
u_T	Maximum tidal velocity at a section [L/T]
x	Distance [L]
x_1	First inflection point [L]
α	Mixing coefficient [L^{-1}]
β	Dispersion reduction rate [-]
ϵ	Phase lag between HW and HWS, or LW and LWS [-]
ρ	Density of the water [ML^{-3}]

LIST OF ABBREVIATIONS

TA	Tidal Average
HWS	High Water Slack
LWS	Low Water Slack
RMSE	Root Mean Square Error
NSE	Nash- Sutcliffe Efficiency

CHAPTER 1

INTRODUCTION

1.1 Background

Salinity intrusion is a natural phenomenon in estuary due to the tidal effect. During high tide, the sea water intrudes further into the river system causing the estuary to become brackish. Salt water intrusion is most crucial when the highest tide (spring tide) occurs in conjunction with the extreme dry season. This is because during the dry season, the amount of rainfall is less leading to low fresh water discharge into the estuary. Thus, it allows the tidal to carry the salt water further inland. Although the tide variation is peculiar to the location of the river itself, factors like river deepening, widening of river mouth and reduction of freshwater flow due to water abstraction also substantially increase the saline intrusion length towards the upstream of the river (SMHB,2000).

For the management of estuarine water resources, it is essential for water manager to determine the salt intrusion length and longitudinal salinity distribution in the estuary of interest especially when water intake station is to be built. This is to avoid salt water being extracted for water supply purposes. Hence, salt intrusion modelling tool is required to carry out the salinity study.

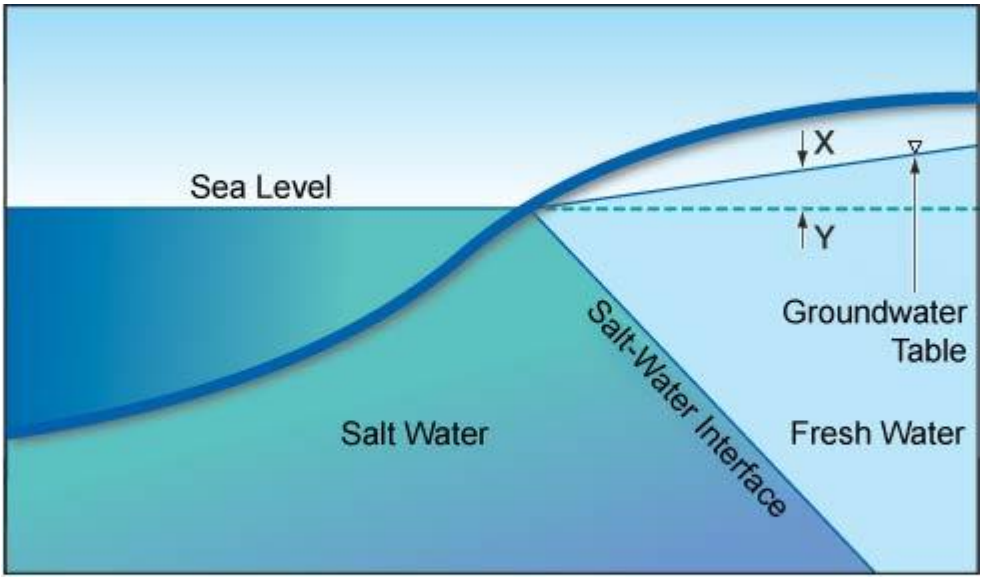


Figure 1.1 Salinity Intrusion in a River

Source: Solinst (1997).

There are several salt intrusion model available nowadays ranging from one-dimensional (1-D) to three-dimensional (3-D) model. These models have been widely applied in simulating salinity distribution in estuaries worldwide. In cases where highly accuracy on the modeling is required, 2-D and 3-D are preferable, but for moderate accuracy, 1-D analytical solution is sufficient. The benefits of using a 1-D model compared to 2-D and 3-D model are its simplicity as it only requires directly measurable parameters such as geometry, fresh water flow and tide, and most importantly it is much cheaper (Savenije, 1993). Besides that, the minimum requirement of data allows the model to be used in situation where data is poor or ungauged.

Savenije (2005) has developed a 1-D salt intrusion analytical model that only requires spreadsheets to perform computation. This model has been widely tested in many estuaries in countries such as Netherlands, Korea, China, Mozambique, Japan and Malaysia for its reliability and performance. In Malaysia, Gisen et al. (2015) used the one dimensional analytical solution to investigate saline water distribution in several estuaries namely Kurau, Perak, Bernam, Selangor, Muar, Linggi and Endau Estuary.

1.2 Problem Statement

In general, saline intrusion into the upper reach of river has caused problems especially for water intake activity. According to the WHO International Standards for Drinking Water, the maximum acceptable content of chloride ion in water is 200mg/L if the water intake is for the purpose of human consumption. The concentration of saline in the water has become one of a major concern in Malaysia. In some water intake stations, the concentration of the chloride ion in the water is more than the acceptable value, which is not recommended for consumption unless proper treatment is being applied to the water. Recently, the water intake for human consumption in Kuantan has been reported to be salty. This means that the salt intrusion has reached the water intake station at Kampung Kobat, Kuantan river due to extreme low fresh water discharge as a result of El-Nino phenomenon. In this case, salt intrusion investigation is vital to determine the salinity level of the estuary so that the preventive measures can be taken if the observed salinity level in an estuary is near to the optimum level. Belat River is one of the major tributaries in the Kuantan River Basin. It is located at about 17 km from the Kuantan River mouth and is affected by tidal movement which subsequently lead to salt intrusion in the river. Since Belat Basin is the largest sub-catchment in the Kuantan River Basin, it may become a potential water intake source for increasing water demand in the area. Hence, it is essential to conduct saline intrusion study in the Belat Estuary to identify suitable area for potential water intake. This is to make sure that residents around the Belat Estuary will have healthy and adequate water for consumption.

1.3 Research Objectives

The objectives of this research study are stated as follows:

1) To investigate the salt intrusion in Belat River Estuary during spring tide.
2) To determine the applicability of the one-Dimensional analytical solution for salt intrusion investigation in Belat River Estuary.
3) To calibrate the van der Burgh coefficient, K to fit the simulated salinity curve and the observed salinity data.

1.4 Scope of Research

This research focused the application of one-dimensional analytical solution for salt intrusion investigation in the Belat River Estuary. In this study, survey and field survey will be carried out during the dry season for both spring and neap tide. During the fieldworks, cross section, water level and salinity measurement will be collected. Followings the data collection, geometry and salt intrusion will be performed according to the 1-D model introduced by Savenije (2005). There are two parameters to be calibrated to fit the simulated salinity curve and the observed salinity data which are the Van der Burgh coefficient, K and dispersion coefficient, *D*. This also means that the longitudinal profile of the salinity distribution can only be simulated with the presence of salinity measurement (J.I.A Gisen, 2005). To validate the results in this research, repetitive measurements will be analysed and compared to ensure consistency in the *K* coefficient. The performance of the 1-D analytical salt intrusion model in simulating salinity profile in the Belat Estuary will be done by using the Root Mean Square Error (RMSE) and Nash-Sutcliffe efficiency error analysis method.

1.5 Significance of Research

The salinity level in an estuary is vital as the concentration of salt in the water especially water intake for human consumption cannot be too high. This is because high salinity level of water for consumption will bring harm to the health of human body. Unfortunately, there is no salinity study available for the Belat Estuary. Hence, this study is a pioneer study for the salt intrusion in the Belat Estuary adopting a simple 1-D analytical solution. Although currently there is no water intake station along the Belat River but with the increasing population, more water intake may be required in the future. Consequently, this pilot study will provide useful information to the authority (water manager) in deciding the appropriate location of the water intake station if it is to be built along the Belat River.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Estuary is a partially enclosed, coastal water body in which river meets the sea. It is called as "nurseries of the sea" because of its protective environment and the abundant food availability provided in the region (URI, 2001). With these characteristics, estuary is a perfect habitat for the aquatic life. Estuary is also rich in nutrients as it receives natural fertilizers collected from agricultural activities at the upstream area (Gisen, 2015).

The existence of the mangrove plants around the estuaries provides calm environment which becomes suitable place for the aquatic animals to nest and breed between the mangrove roots (Gisen, 2015). Mangrove roots are also important for bank erosion control as they are capable to dissipate wave energy, which subsequently helps to reduce the impact of flood and storm (Spalding M et al., 2014). Estuary also plays an important role in maintaining the health of the ocean. Since it is a buffer zone between river and the ocean, it filters the sediments and pollutants from the upstream flow before discharging the water to the ocean. By this, the pollution of the ocean can be reduced.

Based on water circulation, estuary can be classified into four types which are salt wedge estuaries, partially mixed estuaries, well- mixed estuaries and fjord type estuaries. Salt wedge estuaries occur when the water from the river mouth flows directly into the salt water. The circulation of the water is controlled by the river in which the river will push back the seawater. In this case, a sharp boundary will be produced to separate the upper less salty layer from the wedge-shaped salty bottom layer. Partially mixed estuaries have a tidal flow that can eliminate the salt wedge. The salt water is mixed upward and the fresh water is mixed downward. Throughout the shallow estuary, well-mixed estuaries have strong tidal mixing and low flow of river that mix the sea water. This has caused the same salinity level from top to bottom and decrease in salinity level from the ocean to the river. Meanwhile, Fjord type estuaries have moderately high input of river and weak tidal mixing. There will be a U-shaped basin and a barrier that separate the basin from the sea at Fjord-type estuary (URI, 2001).

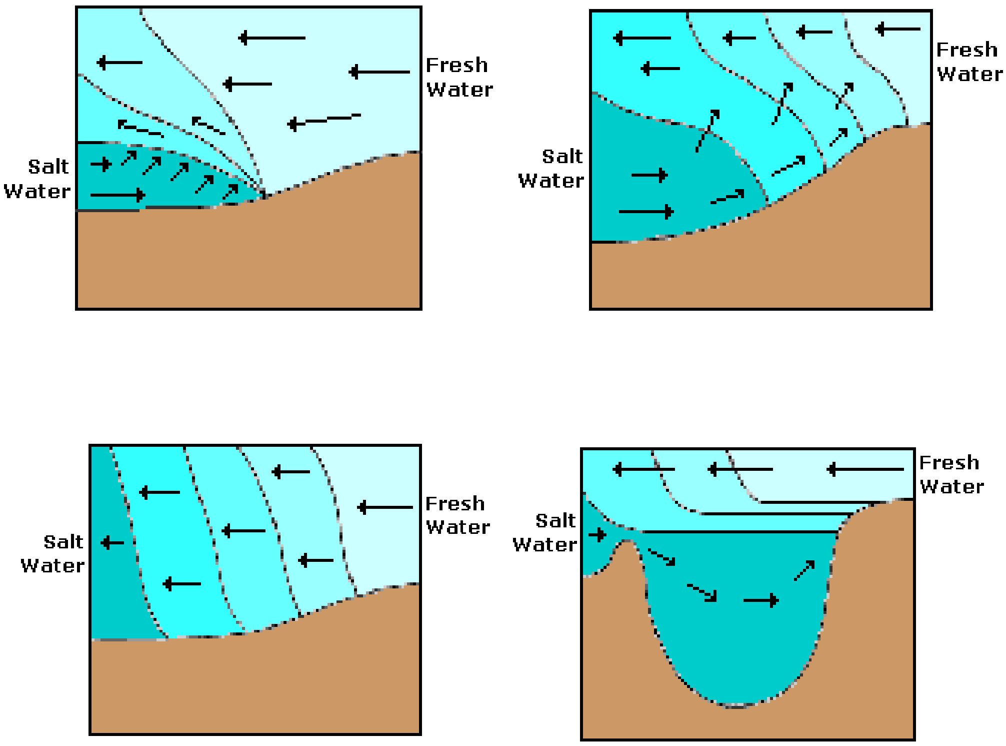


Figure 2.1 Type of Estuaries (from top left: salt wedge estuary, partially mixed estuary, well mixed estuary, and Fjord-type estuary)

Source: University of Rhode Island (2001).

2.2 Classification of Estuaries

In order to understand the way to classify the estuary, it is vital to define the main drivers that may affect the character of the estuary. There are five main drivers, which are the tide, the discharge of the river, the waves, the lateral sediment transport along the coast, the density difference and the climate (Savenije, 2012).

The combined effects of the gravitational force exerted by the Moon and the Sun and the rotation of the Earth cause the occurrence of tides. Tides will cause the sea levels to rise and fall. The level of sea levels may affect the flow of salt water to the estuary system. The tide is responsible for the harmonic pumping of water into and out of the estuary with an erosive power that is neutralized only if the banks converge at an exponential rate (Savenije, 2012).

The discharge of the river will provide fresh water and sediments to the estuary system. During a flood, when the fresh water enters the estuary, the settlement of river sediment will occur. Additionally, the bank will start to widen, the cross section will increase and the velocity of the fresh water will reduce due to the flood (Savenije, 2012).

For the waves, it depends on the meteorological conditions and it may affect the formation of the estuary mouth. The dissipation of wave energy will be concentrated near the mouth of the estuary only (Savenije, 2012).

Meanwhile, the formation of spits and bars are caused by the lateral sediment transport along the coast. If the lateral sediment support is stronger than the erosive power of tide and river discharge, then a “blind” estuary may be formed. “Blind” estuary is estuary that are closed off from the sea by a temporary bar (Savenije, 2012).

Additionally, the density difference is responsible to transport marine sediments into the estuary. Generally, flocculation happens when the fine sediments come into contact with saline water. This will lead to the formation of sand bar at the upstream limit of the salt intrusion (Savenije, 2012).

From all of the drivers mentioned above, tide and river floods are the main drivers in determining the shape of the estuary. However, all of the drivers need to be considered to lead to the wide range of estuary shapes and behaviours (Savenije, 2012).

2.2.1 Classification by Shape

Generally, there are five types of characteristic shapes of estuary that have been distinguished by Savenije (2012) which are prismatic, delta, funnel or trumpet shape, fjors and bays.

In prismatic-shaped estuary, the banks of the estuary are parallel. Prismatic-shaped estuary is only existed in a man-made environment in which the banks of the estuary are already fixed.

Figure 2.2 The Estuary of the Scheldt (Prismatic-shaped estuary)

Source: Tidal River Development (2013).

Meanwhile, the delta shaped is formed near prismatic estuary where the influence of tidal is small compared to the amount of river water. Additionally, delta will only happen in rivers in the situation of small tidal range and in high amount of sediment. Examples of delta river include the Mississippi, the Nile and the Mekong.

Figure 2.3 Mekong River (delta)

Source: Vriend (2009).

For the funnel or trumpet shaped estuary, the banks will converge in the upstream direction and this shape is the natural shape of alluvial estuary. Examples of funnel or trumpet-shaped estuary are the Maputo, the Pungue and the Schelde.

Figure 2.4 Pungue River (funnel-shaped estuary)

Source: Huh et al. (2004).

Generally, fjords- shaped estuary has irregular banks with several side channels and embayment. It is U-shaped and it has a barrier that separate basin from the sea.

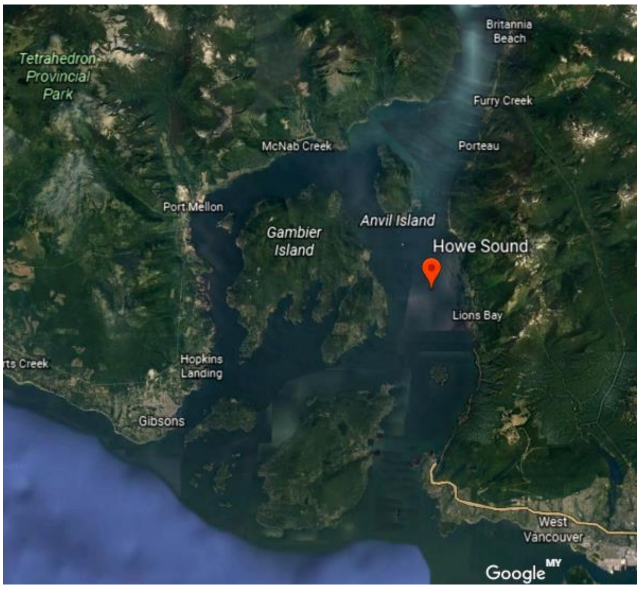


Figure 2.5 Howe Sound, Canada (Examples of Fjords)

Source: Google Earth (2016).

For bays, there will be no significant input from the river and bays are semi-enclosed bodies.

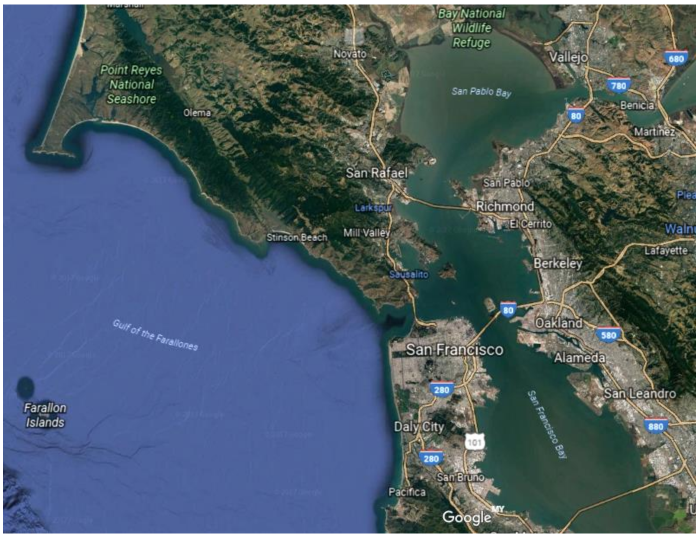


Figure 2.6 San Pablo Bay and San Francisco Bay (Example of bays)

Source: Google Earth (2016).

2.2.2 Classification by tidal influence

Based on the tidal condition, Davies (1964) has classified the geometry of the estuaries into three types which are micro-, meso- and macro-tidal estuaries.

Table 2.1 Classification of Estuaries by Tidal Influence

Tidal influence	Variation of H	Description
Micro-tidal estuary	H < 2m	Formation of sand bar and pit caused by sedimentation
Meso-tidal estuary	2m < H < 4m	Flood-ebb dominated estuaries
Macro-tidal estuary	H > 4m	Strong funnel shaped estuaries

Referring to the tidal period, tides can be classified into three types which are diurnal, mixed diurnal and semi diurnal. A semi-diurnal tide will have two nearly same tidal cycles in a day (two high and two low water). Meanwhile, a diurnal tide will only have one complete tidal cycle (one low and high water) (Pond and Pickard, 1983). For the mixed diurnal, the difference of the tidal range between the two tidal cycles in a day is large and the effect of the smaller tidal range is almost insignificant compared to the larger ones (Gisen et al., 2015).

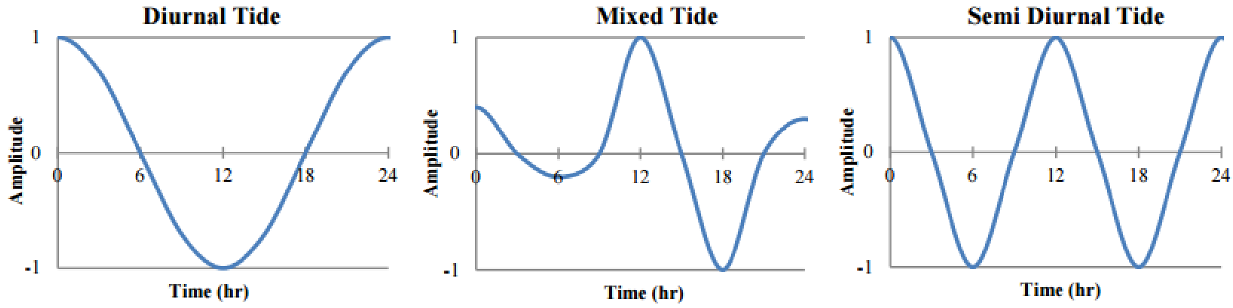


Figure 2.7 The Tidal Oscillation of the Diurnal Tide, Mixed Tide and Semi Diurnal Tide in One Day

Source: Gisen (2015).

Additionally, it is vital to identify the types of tidal wave in an estuary. A fully standing wave will only occur in semi-enclosed body in which the wave can be reflected when it hits the boundary. Besides, the standing wave will reach its highest level when the velocity is zero. Meanwhile, a progressive wave will only occur in prismatic-shaped channel with unlimited length. In this type of wave, the velocity and the amplitude of water level will be in phase. However, none of these apply in funnel-shaped estuaries (Gisen and Savenije, 2014).

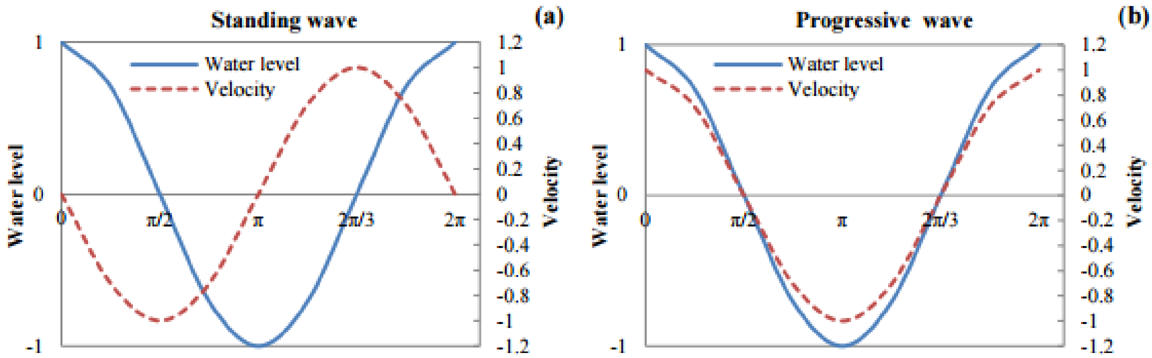


Figure 2.8 Types of Tidal Waves (Standing wave and Progressive wave)

Source: Gisen (2015).

Slack moment will occur in convergent estuaries in which the water will reach the highest point and the lowest point before the tidal velocity becomes zero. The phase lag, ϵ , which is the delay between the high water or low water and high water slack or low water slack, will lie between 0 to π/2 (Gisen, 2015). It is vital to know the phase lag in tidal wave in order to understand the propagation of tidal wave. It also acts as an important parameter to predict the average tidal depth where minimal data are available.

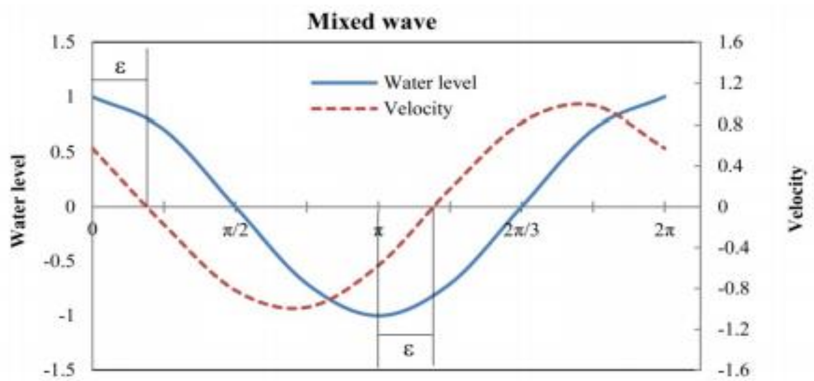


Figure 2.9 A Mixed Type Tidal Wave in Converging Estuary

Source: Gisen (2015).

2.2.3 Classification by river influence

In term of river influence, estuaries can be classified into two types which are riverine estuary and marine estuary. Riverine estuary is dominated by the river flow, discharge and supply of sediment (Savenije, 2012). The water in riverine estuary is fresh and the type of wave propagation involved is progressive wave. Meanwhile, marine estuary is sea-dominated estuary. The water in marine estuary is completely saline and the banks of the estuary are muddy. The propagation of wave involved in the marine estuary is standing wave (Savenije, 2012).

2.2.4 Classification by geology

Based on classification by geology, the estuary has been distinguished into three types which are fixed bed estuary, short alluvial estuary and coastal plain estuary. An estuary with a fixed bed is a remnant of a different geological era (Savenije, 2012). Short alluvial estuaries are not able to develop an equilibrium length. This is because they are too short and they have steep topography which will result in standing wave. In coastal plain estuary, it will consist of sediments which are deposited by the river and the sea. This type of estuary is long enough, has an exponentially varying cross-section and does not have bottom slope (Savenije, 2012).

2.2.5 Classification by salinity

For the classification by salinity, there are two types of estuaries which are positive or normal estuaries and negative or hypersaline estuaries. Positive estuaries are estuaries where the salinity level decreases steadily in the upstream direction. Generally, this type of estuary will form in wet tropical climates. Meanwhile, estuaries that are shallow and have an increasing level of salinity in the upstream direction are known as hypersaline estuaries. This type of estuary is not fully alluvial because of the low fresh water discharge and the low sediment level (Savenije, 2012).

Table 2.2 Summary of Estuary Classification

Shape	Tidal wave	River influence	Geology	Salinity
Bay	Standing wave	No river discharge	-	Sea salinity
Ria	Mixed wave	Small river discharge	Drowned drainage system	High salinity; often hypersaline
Fjord	Mixed wave	Modest river discharge	Drowned glacier valley	Partially mixed to stratified
Funnel	Mixed wave; large tidal range	Seasonal discharge	Alluvial in coastal plain	Well mixed
Delta	Mixed wave; small tidal range	Seasonal discharge	Alluvial in coastal plain	Partially mixed
Prismatic channel	Progressive wave	Seasonal discharge	Man-made	Partially mixed to stratified

Source: Gisen, (2015).

2.3 Geometry Analysis

There are two components which are involved in salt intrusion model which are the shape and the longitudinal salinity distribution of an estuary. The geometry of an alluvial estuary can be presented by exponential functions. The equations for the shape analysis are as below (Savenije, 1989):

$$A = A_0 e^{-\frac{x}{a}} \quad 2.1$$

$$B = B_0 e^{-\frac{x}{b}} \quad 2.2$$

$$h = h_0 e^{\frac{x(a-b)}{ab}} \quad 2.3$$

where A, B and h are the cross sectional area, width and average depth at distance x. x is the distance from the upstream of the estuary mouth. A_0, B_0 and h_0 are the cross sectional area, width and average depth at the estuary mouth. The parameter a and b are the cross-sectional and width convergence length (Savenije, 1989).

$$A = A_1\, e^{-\frac{x-x_1}{a_2}} \qquad for\; x \geq x_1 \qquad 2.4$$

$$B = B_1\, e^{-\frac{x-x_1}{b_2}} \qquad for\; x \geq x_1 \qquad 2.5$$

$$h = h_1\, e^{\frac{(x-x_1)(a_2-b_2)}{a_2 b_2}} \qquad for\; x \geq x_1 \qquad 2.6$$

Meanwhile, for estuary that has two branches, the cross sectional area and width convergence lengths at a distance of x_1 are represented by symbols a_1 and a_2 , and b_1 and b_2. x_1 is the inflection point where the wave dominated region ends. This type of estuary is a trumpet in shape (Gisen, 2015).

2.4 Salt Intrusion Model

The salinity distribution is simulated at Tidal Average (TA) and later converted to High Water Slack (HWS) situation. Equations 2.1 to 2.6 are substituted with the salt balance equation to yield the salinity distribution along the estuary based on the Van der Burgh (1972)'s theory for longitudinal dispersion. The equation for salinity distribution is as below:

$$\frac{S^{TA}-S_f^{TA}}{S_0^{TA}-S_f^{TA}} = (\frac{D^{TA}}{D_0^{TA}})^{\frac{1}{K}} \qquad 2.7$$

where S^{TA} and D^{TA} are the salinity and dispersion as a function of the distance. S_0^{TA} and D_0^{TA} are the salinity and dispersion at the estuary mouth and S_f^{TA} is the fresh water salinity which is normally near to zero.

The equations for dispersion are as below:

$$\frac{D^{TA}}{D_0^{TA}} = 1 - \beta_0^{TA}\, (e^{\left(\frac{x}{a_1}\right)} - 1) \qquad for\; 0 < x \leq x_1 \qquad 2.8$$

Where

$$\beta_0^{TA} = \frac{Ka_1}{a_0^{TA}A_0} \qquad for\ 0 < x \le x_1 \qquad 2.9$$

$$\alpha_0^{TA} = \frac{D_0^{TA}}{|Q_f|} \qquad for\ 0 < x \le x_1 \qquad 2.10$$

where Q_f is the fresh water discharge, K is the Van der Burgh coefficient, D_0 is the dispersion coefficient and β_0 is the dispersion reduction rate at the estuary mouth and inflection point respectively.

Dispersion is a mathematical artefact representing the mixing of fluids with different properties. Discharge is difficult to measure accurately due to the tidal effect. Hence, discharge is combined with dispersion coefficient in the mixing number α to facilitate the calibration process (Gisen, 2015).

2.5 Salinity Length

The equation for salt intrusion length L can be expressed as:

$$L^{LWS} = a_1 \ln\left(\frac{1}{\beta_0^{TA}} + 1\right) - E/2 \qquad for\ 0 < x \le x_1 \qquad 2.11$$

Determining salt intrusion length is vital for water resource management because most of the fresh water supply are pumped from the river estuary. In this case, knowing the intrusion length of the estuary can help in arrangement of extraction frequency if pumping stations have to be built within the salt intrusion area (Gisen, 2015).

2.6 Past Studies

There are many researchers studies have been conducted to investigate the saline intrusion in the estuaries worldwide. Lepage and Ingram (1986) used 1-D numerical model to carry out saline intrusion investigation in the Eastmain River Estuary, Canada. The study proved that the model is capable to follow the observed salinity changes satisfactorily. Moreover, the computed values of salinity, velocity and water elevation were in good agreement with the actual observations. Nguyen and Savenije (2006) applied the 1-D analytical salt intrusion model for the Mekong delta. The main finding of this study indicated that the model is applicable not only in a single channel estuary, but also performed well for multi-branches estuary. The multi-channel estuarine system functions as an entity and the paired branches should be considered as a single estuary branch. Other researchers who used the same 1-D analytical model for different estuaries globally are Grass and Savenije (2008), Deynoot (2010) and Gisen (2014) to carry out the salinity investigation in Pungue Estuary, Kapuas Estuary and Malaysia Estuaries respectively. In Pungue Estuary, the salt intrusion model can be adequately modelled. However, the estuary experiences constriction by sand banks causing reduction in salinity level at approximately 50km from the mouth. In Kapuas Estuary, there is overall increase of salinity during spring tide in the River Landak whereas there is only increase in amplitude in the upstream part of the Kapuas Kecil. Additionally, the analytical salt intrusion model has a very good fit for all the estuaries in Malaysia. In short, all the studies showed that the salt intrusion in the alluvial estuaries can be adequately modelled using the 1-D salt intrusion theory of Savenije (2005).

Apart from 1-D model, there are also 2-D model and 3-D model being used by other researchers to carry out the salt intrusion investigation in different estuaries worldwide. In 2014, Liu et al. used 2-D numerical model to carry out salt intrusion investigation in the Tanshui River Estuary in Taiwan. The overall performance of the model showed reasonable agreement with the field data and the study found that the combined effect of freshwater withdrawal at the reservoir and the enlargement of river channel has caused the salinity level to increase. Breemen applied a 3-D salt intrusion model in the Selangor Estuary. Although the 3-D model has shown a very accurate result but it is time consuming method to derive boundary conditions for the Selangor Estuary. Similar result was obtained by Gisen et. Al on the research conducted using the 1-D analytical salt intrusion solution, which is simple and cheap.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains the materials and methods that were used to carry out the salt intrusion study in the Belat Estuary. The methodologies adopted in this study include data collection, geometry and salinity analysis, calibration, and validation processes. The salinity study will be conducted during the dry season for spring tide. Data that were collected during the fieldwork includes the salinity along the estuary and the water depth along the salt intrusion length.

3.2 Study Area

The Belat Estuary is one of the tributaries of the Kuantan River as shown in Figure 3.1. It 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. The main economic at the mouth of the Belat River Estuary is of large scale of commercial fishing activities. In terms of flora and fauna, mangrove plants can be found along the river bank of the Belat Estuary. These mangrove plants are useful as breeding habitats for the aquatic life. Moreover, mangrove forests also act as natural vegetation to protect the coastal region from erosion as their roots are able to dissipate wave energy. The topography of the Belat River is shallow and flood tends to occur at the residential area around the Belat Estuary during rainy season.

Figure 3.1 Aerial View of the Belat River Estuary

Source: Google Earth (2016).

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 River system. 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.

Considering the Belat Estuary mouth is not open to the ocean, tidal data has become unavailable. However, the tidal information of the Kuantan Estuary can be used as a reference since the location of the Belat Estuary mouth is only 17km from the Kuantan Estuary. Figure 3.2 shows the tidal oscillation of the Kuantan Estuary in April 2016. From this figure, it indicates that the tidal in the studied region is of the mixed-diurnal types with 12 hours tidal cycle.

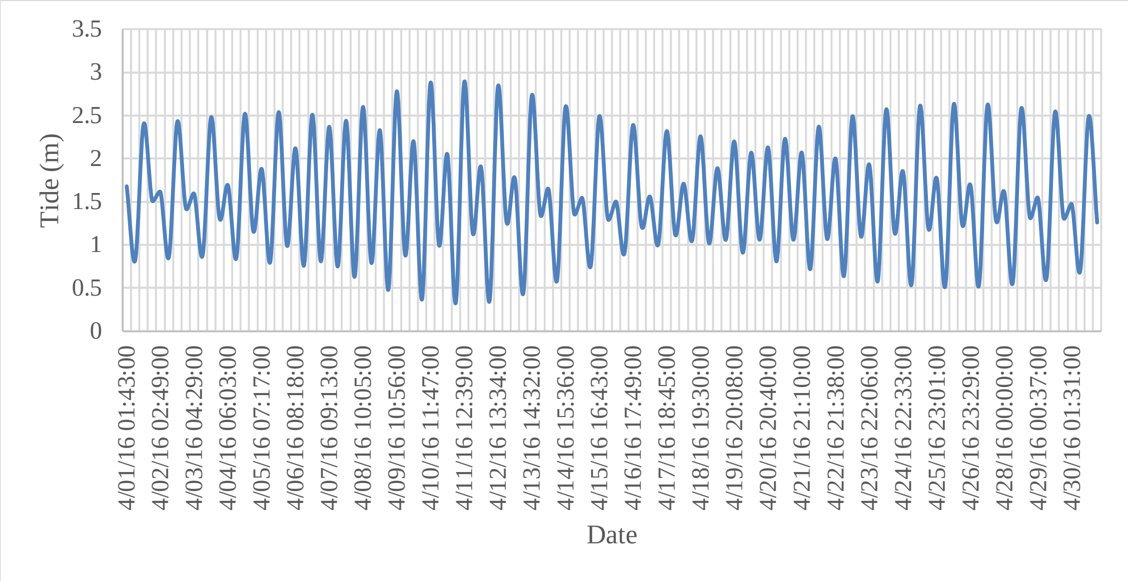
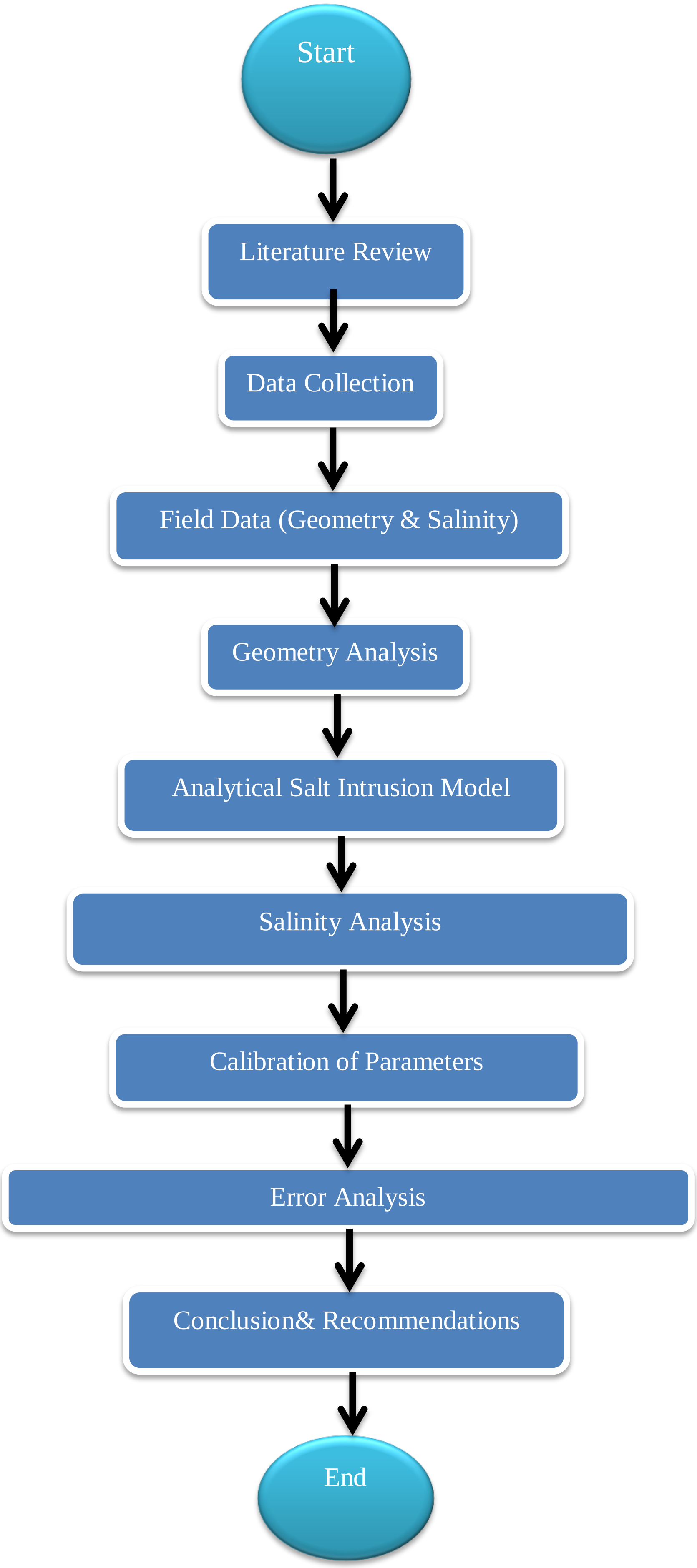


Figure 3.2 Tidal Oscillations in the Kuantan Estuary in April 2016

3.3 Flowchart

Firstly, the theory of salt intrusion must be understood by studying the journals available. After understanding all the concepts, fieldwork was conducted to collect the necessary data which are water depth and salinity distribution along the Belat Estuary. After data collection, the geometry and salinity levels of the Belat Estuary were analysed. Then, two parameters, the Van der Burgh's (K) and dispersion coefficient (D) were calibrated to fit the simulated salinity curve against the observed salinity data. For error analysis, Root Mean Square Error (RMSE) and Nash- Sutcliffe model efficiency coefficient (NSE) were used to validate the reliability of the salt intrusion model.


Start
Literature Review
Data Collection
Field Data (Geometry & Salinity)
Geometry Analysis
Analytical Salt Intrusion Model
Salinity Analysis
Calibration of Parameters
Error Analysis
Conclusion& Recommendations
End

3.4 Equipment

To conduct the salinity and depth measurements, some equipment such as Global Positioning System (GPS), handheld depth sounder, and conductivity meter as shown in Figure 3.3 are required. For the purpose of recording the location of every measurement points, Global Positioning System (GPS) was used.

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.

Figure 3.3 Equipment Used in Field Survey (from left: handheld depth sounder, GPS and water quality meter)

Salt intrusion survey can be completed within a day and the data processing period can take less than a week. Although the equipment seems simple, they are cost effective and capable to provide sufficient and accurate measurements.

3.5 Survey

3.5.1 Preliminary Observations

For the purpose of understanding the study area better before the survey, preliminary observation was carried out. During this task, informal interviews were made with the local people living near the Belat Estuary to gain better view of the situation around the area for safety purposes. By understanding the condition of the river and identifying the location for the salinity measurements, surveyors were able to minimize the errors and unwanted troubles during the survey. Furthermore, proper information from the local people helped the surveyors to know and be aware of any dangers that may occur such as crocodiles' habitat (Figure 3.4) and subsequently take any necessary precautions.

Figure 3.4 The Existence of Crocodile in the River

3.5.2 Salinity Measurement

A moving boat technique was implemented for the salinity measurement in which the boat has to move with the speed of the tidal wave. Salinity data was captured during the High Water Slack (HWS) and Low Water Slack (LWS) when the water is stagnant with zero velocity. A Horiba Multi-Parameters Water Quality Device attached with a 30 m cables as shown in Figure 3.5 was used to measure the salinity at every meter from the bottom to the water surface during the slack moment. A modest weight was attached on the measuring probe to enable it to penetrate into the water. Without the weight, the probe will tend to float and it is impossible to take the measurement vertically from the bottom to the top. The salinity survey was carried out from the estuary mouth moving upstream until the salinity level is reduced to 0.1ppt. Conductivity, salinity level, turbidity, water temperature and pH values of water captured by the water quality monitoring device were recorded manually on a spreadsheet. The locations of each points were also noted based on GPS reading. Salinity measurements were carried out twice in the same day to cater for the high water and low water longitudinal salinity distributions.

Figure 3.5 The Use of Conductivity Meter for Salinity Measurement

3.6 Salt Intrusion Modelling

3.6.1 Geometry analysis

The geometry analysis for the Belat Estuary was based on Savenije (1986) theory for alluvial estuaries, where the change in the geometry of estuary varies exponentially over the distance (Gisen, 2015). Figure 3.6 shows the sketch of the geometry analysis in general form. Through this study, the width, depth and cross section of the Belat estuary was determined and plotted in a semi-log graph according to Equations 2.1 to 2.3. 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.

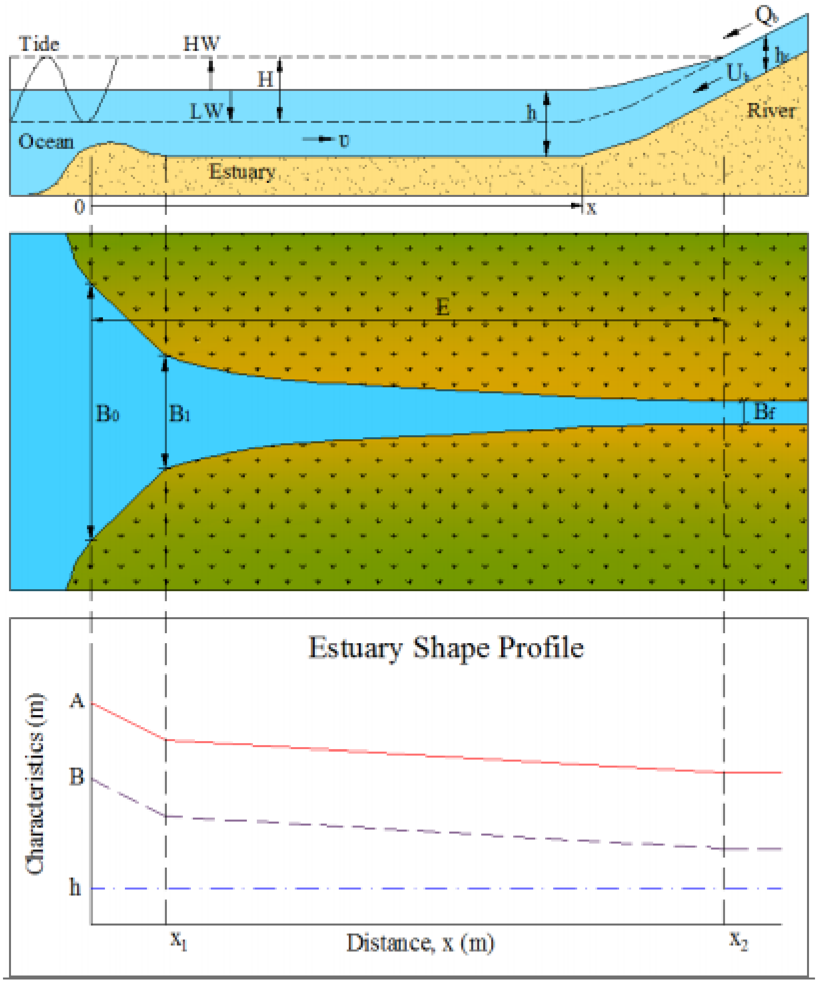


Figure 3.6 Illustration of the Longitudinal Section, Top View and the Geometry Analysis of an Estuary

Source: Gisen (2015).

3.6.2 Salinity analysis

In this study, one dimensional analytical solution for salt intrusion investigation was applied for the Belat River Estuary. The one dimensional model was chosen over the two or three dimensional model because this method is simple to implement and require minimum amount of data. In this model, the salinity distribution was simulated at the Tidal Average (TA) condition and was later converted to the HWS situation to determine the maximum salt intrusion length. The governing equations applied to generate the simulated salinity profile are Equations (2.7) to (2.11). 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.

3.7 Calibration

In this research, there are two parameters that were calibrated to fit the simulated salinity curve against the observed salinity data. These two calibration parameters are the Van der Burgh's (K) and dispersion coefficient (D). K is a 'shape factor' which influence the shape of the salt intrusion curve at the toe (Savenije,1993a). Furthermore, K depends on the topography and tidal characteristics and is time independent. Dispersion coefficient is scale dependent and cannot be directly measured in salt intrusion modelling. The role of dispersion can only be applied if it is related to the tidal period (time scale), tidal excursion (longitudinal mixing length), estuary width (lateral mixing length) and depth (vertical mixing length). Generally, the fresh water discharge drained into the estuary is mostly unknown. Hence, to simplify the salinity analysis, the calibration for dispersion coefficient is done by taking the ratio of dispersion and discharge. This ratio is called the mixing number α.

3.8 Error Analysis

For the purpose of validating the reliability and performance of the salt intrusion model, two types of error analyses were performed using the Root Mean Square Error (RMSE) and Nash-Sutcliffe model efficiency coefficient. RMSE was used to measure the average differences between the values of the simulated data and the observed data. The formula of RMS is as below:

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

where $\boldsymbol{P_i}$ is the predicted value for the $\boldsymbol{i}$ observation and $\boldsymbol{O_i}$ is the observed value. The difference between the predicted value and the actual value can be positive or negative as the predicted value might be lesser or greater than the actual one.

Meanwhile, the Nash-Sutcliffe model efficiency coefficient was used to access the predictive power of the salt intrusion model. The equation of Nash-Sutcliffe efficiency, NSE is as below:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(\boldsymbol{P_i} - \boldsymbol{O_i})^2}{\sum_{i=1}^{n}(\boldsymbol{O_i} - \boldsymbol{\overline{O}})^2}$$

where $\boldsymbol{P_i}$ is the predicted value and $\boldsymbol{O_i}$ is the observed value. $\boldsymbol{\overline{O}}$ is the average value of the observed values. The value of NSE can vary from 1.0 to -∞. If the model efficiency is high, the value of NSE will be closer to 1.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results obtained from the geometry and salt intrusion analyses based on the data collection from the Belat River Estuary are presented and summarized. There are three components involved in the salt intrusion model which are the shape, the vertical salinity distribution and the longitudinal salinity distribution. The geometry profile of the Belat River Estuary and the salinity level of the Belat Estuary during High Water Slack (HWS) and Low Water Slack (LWS) are discussed in this chapter.

4.2 Geometry Analysis

The geometry analysis for the Belat River Estuary was perfomed by utilizing the Equations from (2.1) to (2.3). Data of the observed and simulated geometry characteristics of the estuary were plotted in a logarithmic scale which is shown in Figure 4.1. For the simulated geometry, the computed results were analyzed and presented in a regression form.

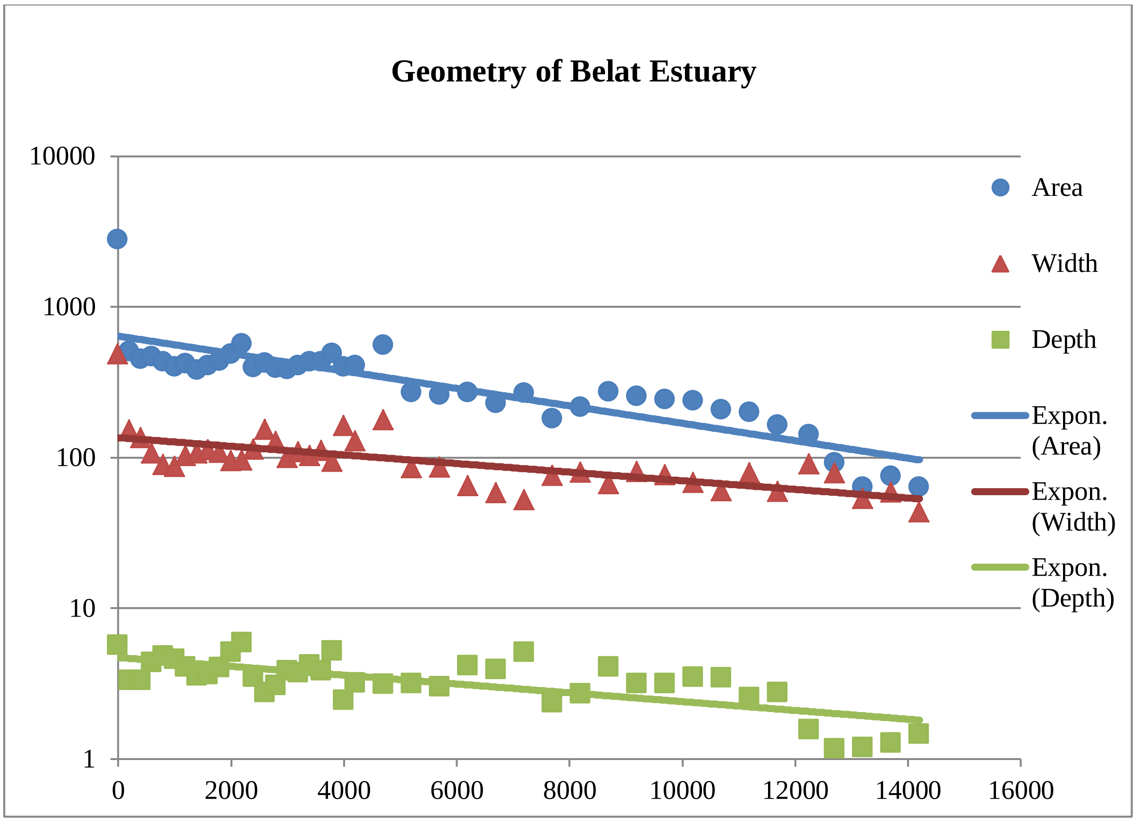


Figure 4.1 Geometry Analysis of the Belat River Estuary

In Figure 4.1, the blue, red and green solid lines indicate the simulated cross-sectional area, width and depth of the Belat Estuary. The observed data collected from existing available survey in 2015 was plotted at the blue, red and green markers representing the cross-sectional area, width and depth, respectively. From the plots, it can be seen that the shape of the estuary is well expressed by exponential function, confirming the theory of Savenije(1986). Since the Belat Estuary is a natural estuary with least disturbance, the width and cross-sectional area are converging towards inland fulfilling the pattern for natural alluvial estuary.

From the analysis, the Belat Estuary is identified as a single reach estuary because it consists only one cross sectional area convergence length and one width convergence length which are *a* and *b*, respectively. Generally, the depth of an estuary is constant throughout the region in which the convergence length *a* and *b* are equal. However, Figure 4.1 shows that the Belat Estuary has different convergence length *a* and *b* which indicate the increasing in depth towards inland. This phenomenon may seems unusual but it could happens due to river deepening on bed materials mining activities. However, the cause of the increasing depth is not investigated in this study.

The results from the best fit regression analyses in the geometry study yield an average depth of 4.29m. Meanwhile, cross sectional area, A_0 and width, B_0 at the estuary mouth are obtained to be $1200m^2$ and $280m$ respectively. Additionally, the convergence lengths of cross sectional area, a_1 and width, b_1 are 10000 and 14286 respectively.

4.3 Salinity Analysis

Figure 4.2 and Figure 4.3 shows the vertical salinity distribution of the Belat Estuary during both High Water Slack (HWS) and Low Water Slack (LWS). The vertical salinity distribution at each point is based on the vertical salinity reading taken from every 1m vertical during the survey. From the patterns displayed in Figure 4.2 and 4.3, 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 Estuary occurs when the discharge of fresh water is small compared to the tidal flows (tidal dominant). Generally, an estuary becomes tidal dominant during the dry season and discharge dominant during the wet season. During the dry season, the rainfall intensity is low leading to lowest water availability. Thus, the tidal movement can have induced well mixing mechanism between the saline and fresh water when it changes direction from flood to ebb and vice versa.

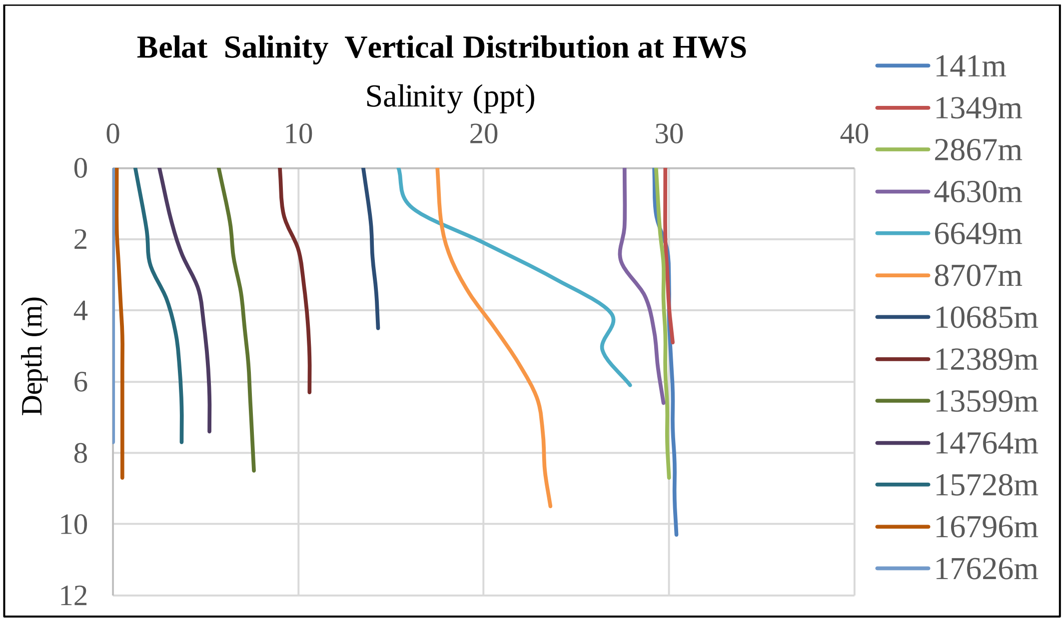


Figure 4.2 Vertical Salinity Distribution of the Belat Estuary during HWS

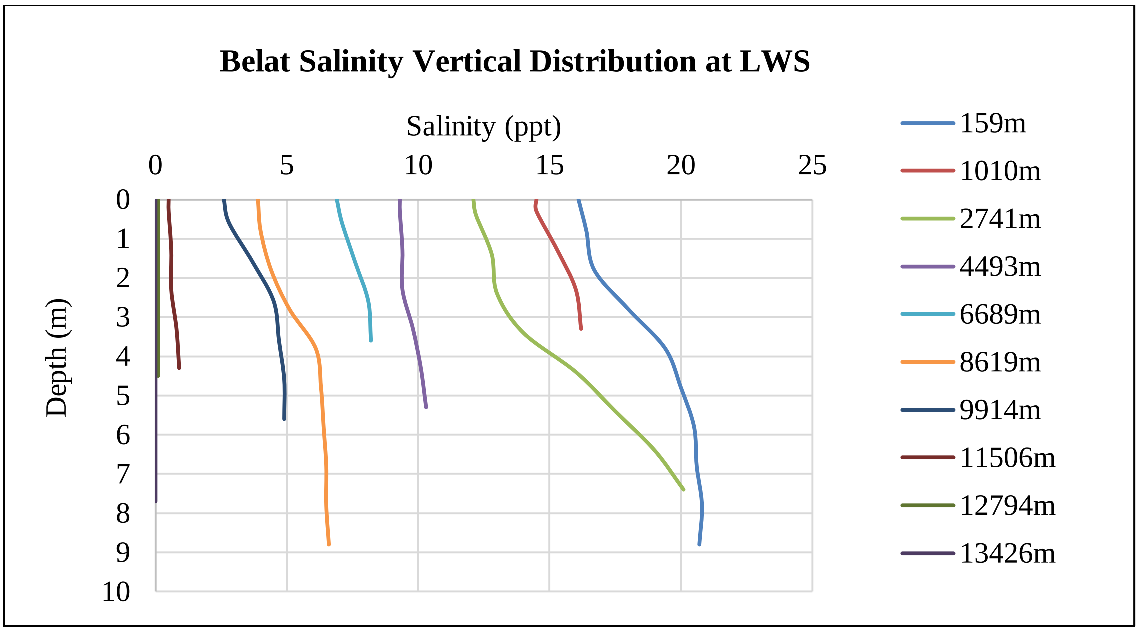


Figure 4.3 Vertical Salinity Distribution of the Belat Estuary during LWS

In Figure 4.2, there is a significant stratification occurs at a 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 increases drastically. This will caused significant stratification where the fresh water accumulated on the surface and denser saline water accumulated at the bottom. 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 level distribution during ebb tide and the results are satisfying.

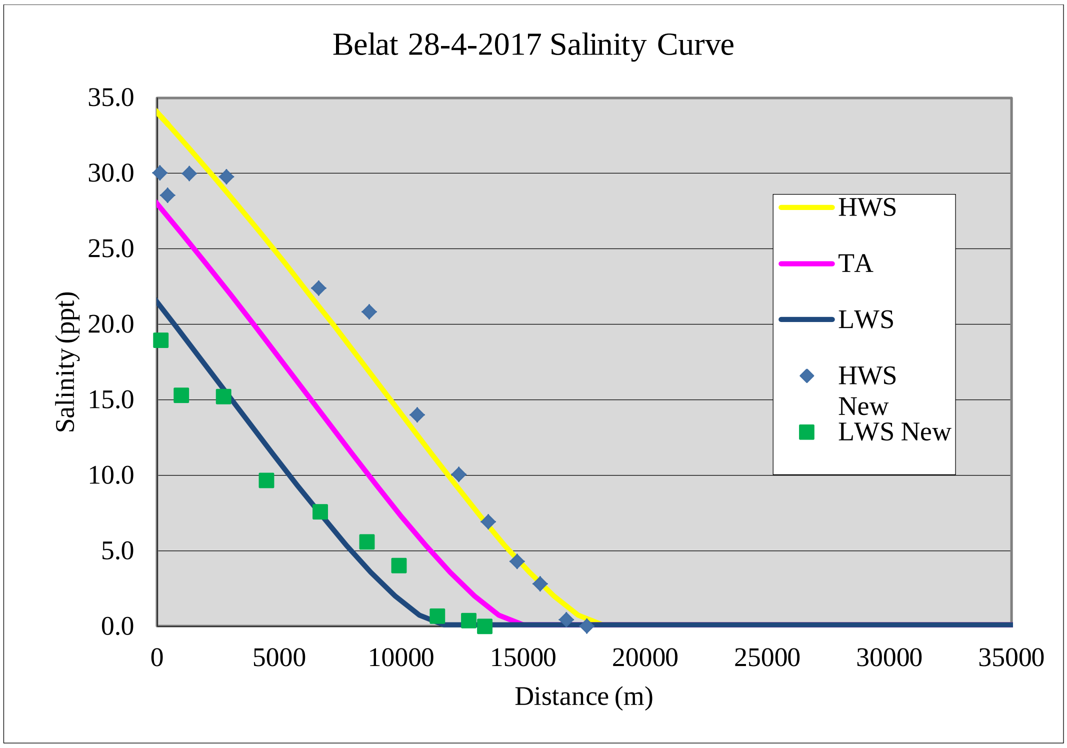


Figure 4.4 Measured and Simulated Longitudinal Salinity Profile of the Belat Estuary

Figure 4.4 displays the measured and simulated longitudinal salinity profile of the Belat Estuary. As can be seen from the plot, the shape of the salt intrusion curve is showing a Bell shape. Bell-shaped estuary starts with a concave shape but it changes to convex shape within 50% of the salt intrusion length (Savenije, 2012). The figure also shows that 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 0.65 and $12m^{-1}$ 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 which has the value of 6500m. The salinity at the mouth for the HWS is 34ppt while for the LWS is about 22ppt indicating a difference of 12ppt. The maximum salt intrusion length during the HWS (critical length) is obtained to be 18162m. In overall, the simulated longitudinal profile has a good fit with the observed data. However, at the distance of 6.5km, there are some outliers. These are 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 to the construction of the Kobat Barrage.

4.4 Error Analysis

For the purpose of validating the reliability and performance of the salt intrusion model, two types of error analyses were carried out using the Root Mean Square Error (RMSE) and Nash-Sutcliffe model efficiency coefficient (NSE). The error analyses were performed for the longitudinal salinity distribution during both the HWS and LWS.

Table 4.1 to 4.4 shows the error analysis process and results for the RMSE and NSE during both HWS and LWS.

Table 4.1 RMSE during HWS

x (m)	Observed, $\boldsymbol{O_i}$	Simulated, $\boldsymbol{P_i}$	Residuals, $\boldsymbol{P_i - O_i}$	Square Residuals, $(\boldsymbol{P_i - O_i})^2$
140	29.99	33.8	-3.81	14.52
1349	29.94	31.6	-1.66	2.76
2867	29.73	28.7	1.03	1.06
463	28.51	33.2	-4.69	22.00
6649	22.36	21.2	1.16	1.35
8707	20.81	16.8	4.01	16.08
10685	13.98	12.6	1.38	1.90
12389	10.03	9	1.03	1.06
13599	6.92	6.6	0.32	0.10
14764	4.29	4.4	-0.11	0.01
15728	2.79	2.8	-0.01	1E-04
16796	0.4	1.2	-0.8	0.64
17626	0	0.4	-0.4	0.16
				61.63

$$RMSE = \sqrt{\frac{61.63}{13}}$$

= 2.18ppt

Table 4.2 RMSE during HWS

x (m)	Observed , O_i	Simulated, P_i	Residuals, $P_i - O_i$	Square Residuals, $(P_i - O_i)^2$	Square Observed Residual, $(O_i^t - \bar{O})^2$
140	29.99	33.8	3.81	14.52	213.74
1349	29.94	31.6	1.66	2.76	896.40
2867	29.73	28.7	-1.03	1.06	883.87
463	28.51	33.2	4.69	22.00	812.82
6649	22.36	21.2	-1.16	1.35	11.83
8707	20.81	16.8	-4.01	16.08	30.36
10685	13.98	12.6	-1.38	1.90	1.46
12389	10.03	9	-1.03	1.06	0.14
13599	6.92	6.6	-0.32	0.10	0.44
14764	4.29	4.4	0.11	0.01	1.66
15728	2.79	2.8	0.01	1E-04	1.50
16796	0.4	1.2	0.8	0.64	0.06
17626	0	0.4	0.4	0.16	0.14
	199.75			61.63	2854.42

$$\bar{O} = \frac{199.75}{13}$$

= 15.37ppt

$$NSE = 1 - \frac{61.63}{2854.42}$$

= 0.98

Table 4.3 RMSE during HWS

x (m)	Observed , O_i	Simulated, P_i	Residuals, $P_i - O_i$	Square Residuals, $(P_i - O_i)^2$
159	18.92	21.1	2.18	4.75

1010	15.3	19.4	4.1	16.81
2741	15.19	15.7	0.51	0.26
4493	9.66	12	2.34	5.49
6689	7.58	7.4	-0.18	0.03
8619	5.58	3.8	-1.78	3.17
9914	4.01	1.8	-2.21	4.90
11506	0.65	0.1	-0.55	0.30
12794	0.38	0.1	-0.28	0.08
13426	0	0.1	0.1	0.01
				35.80

$$RMSE = \sqrt{\frac{35.80}{10}}$$

$$= 1.89$$

Table 4.4 NSE during LWS

x (m)	Observed , $\boldsymbol{O_i}$	Simulated, $\boldsymbol{P_i}$	Residuals, $\boldsymbol{P_i - O_i}$	Square Residuals, $(\boldsymbol{P_i - O_i})^2$	Square Observed Residual, $(\boldsymbol{O_i^t} - \boldsymbol{\bar{O}})^2$
159	18.92	21.1	2.18	4.75	125.58
1010	15.3	19.4	4.1	16.81	234.09
2741	15.19	15.7	0.51	0.26	230.71
4493	9.66	12	2.34	5.49	93.26
6689	7.58	7.4	-0.18	0.03	57.46
8619	5.58	3.8	-1.78	3.17	31.14
9914	4.01	1.8	-2.21	4.90	16.11
11506	0.65	0.1	-0.55	0.30	0.42
12794	0.38	0.1	-0.28	0.08	0.14
13426	0	0.1	0.1	0.01	0

	77.27		35.80	788.6

$$NSE = 1 - \frac{35.80}{788.6}$$

$= 0.95$

The RMSE obtained for the Belat River Estuary during HWS and LWS are 2.18ppt and 1.89ppt respectively. At HWS, 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 0.98 and 0.95 respectively which is very near to unity. This means that the salt intrusion model is very reliable and efficient.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In a nutshell, the field survey for the investigation of salt intrusion in the Belat River Estuary has been successfully carried out. All the necessary data has been collected for the salt intrusion study analysis. There are a few conclusions have been drawn in accordance to the objectives in this study:

1) The geometry profile of the Belat Estuary has been well analysed adopting an exponential function and is proven valid in this case study. Belat Estuary is categorized as a single reach estuary because it consists only one cross sectional area and width convergence length.

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 because the distribution of saline water is evenly mixed from the bottom to the surface. However, there is a deviation of salinity pattern during the HWS at 6.5km which is caused by the split in Kuantan river. The maximum salt intrusion length during the HWS (critical length) is obtained to be 18162m.

2) The calibration parameters, Van der Burgh coefficient, mixing coefficient α, and tidal excursion, E, give the values of 0.65, $12m^{-1}$ and 6500m respectively.

3) The performance of the 1-D analytical salt intrusion model has been evaluated and the results show high accuracy. The average RMSE and NSE values obtained for both the HWS and LWS are 2.961ppt and 99% respectively. In short, the salt intrusion model is very reliable for the salt intrusion investigation in the Belat River Estuary.

Hence, it is believed that 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.

5.2 Recommendations

Proposed recommendation has been made to improve on this research as well as to give suggestions for future researchers in the Belat River Estuary. More data collection should be carried out in order to validate the calibration parameters obtained in this research. This is essential to improve the accuracy of the results. Furthermore, the salt intrusion investigation in this research was conducted only during the spring tide only. It is recommended to carry out the salt intrusion investigation during the neap tide as well to evaluate the fluctuation in the salinity distribution for the entire tidal cycle.

REFERENCES

Deynoot, F. J. C. G. (2011). Analytical modeling of Salt Intrusion in the Kapuas Estuary, 1–65.

Dronkers, J., and van de Kreeke, J. (1986). Experimental determination of salt intrusion mechanisms in the Volkerak estuary. *Netherlands Journal of Sea Research*, *20*(1), 1–19.

Gay, P. S., and O'Donnell, J. (2009). Buffering of the salinity intrusion in estuaries by channel convergence. *Hydrology and Earth System Sciences Discussions*, *6*(5), 6007–6033.

Gisen, J.I.A. (2014). *Ungauged Estuaries*.

Gisen, J. I. A., Savenije, H. H. G., and Nijzink, R. C. (2015). Revised predictive equations for salt intrusion modelling in estuaries. *Hydrology and Earth System Sciences*, *19*(6), 2791–2803.

Gisen, J. I.A., and Savenije, H. H. G. (2011). Salt Intrusion in Malaysian Estuaries, *13*, 3070.

Graas, S., and Savenije, H. H. G. (2008). Salt intrusion in the Pungue estuary, Mozambique: effect of sand banks as a natural temporary salt intrusion barrier. *Hydrology and Earth System Sciences Discussions*, *5*(4), 2523–2542.

High, N., Liquid, P., and Method, C. (1978). Prediction of Salt Intrusion in Kuantan River, (April), 254–258.

Huh, O.K., Coleman, J.M., Braud, D.W., and Kiage, L. (2004). The Major Delta Rivers of the World. Retrieved from http://www.geol.lsu.edu/WDD/AFRICAN/Pungue/pungue.htm

Lepage, S., and Ingram, R. G. (1986). Salinity intrusion in the Eastmain River estuary following a major reduction of freshwater input. *Journal of Geophysical Research*, *91*, 909.

Liu, W.-C., Hsu, M.-H., Wu, C.-R., Wang, C.-F., and Kuo, A. Y. (2004). Modeling Salt

Water Intrusion in Tanshui River Estuarine System—Case-Study Contrasting Now and Then. *Journal of Hydraulic Engineering*, *130*(September), 849–859.)

Nguyen, A. D., and Savenije, H. H. G. (2006). Salt intrusion in multi-channel estuaries: a case study in the {Mekong} {Delta}, {Vietnam}. *Hess*, *10*, 743–754.

Nguyen, A. D., Savenije, H. H. G., Pham, D. N., and Tang, D. T. (2008). Using salt intrusion measurements to determine the freshwater discharge distribution over the branches of a multi-channel estuary: The Mekong Delta case. *Estuarine, Coastal and Shelf Science*, *77*(3), 433–445.

Pump/Recharge Rate Affects Saltwater Intrusion. (2007). Retrieved from https://www.solinst.com/resources/papers/101c4salt.php

Savenije, H. H. G. (1986). A one-dimensional model for salinity intrusion in alluvial estuaries. *Journal of Hydrology*, *85*(1–2), 87–109.

Savenije, H. H. G. (1989). Salt intrusion model for high-water slack, low-water slack, and mean tide on spread sheet. *Journal of Hydrology*, *107*(1–4), 9–18.

Savenije, H. H. G. (2012). Salinity and tides in alluvial estuaries.

Savenije, H. H. G. (2016). Predicting the salt water intrusion in the Shatt al Arab estuary using an analytical approach, (April), 1–23.

Savenije, H. H. G., and Veling, E. J. M. (2005). Relation between tidal damping and wave celerity in estuaries. *Journal of Geophysical Research C: Oceans*, *110*(4), 1–10.

Solinst. (1997). Pump/ Recharge Rate Affects Saltwater Intrusion. Retrieved from https://www.solinst.com/resources/papers/101c4salt.php

Spalding. M., Mclvor. A., Tonneijck. F. H., Tol. S. and van Ejik.P. (2014). Mangroves for coastal defence, 42p.

Tidal River Development. (2013). Retrieved from http://tide-project.eu/index.php5?node_id=Scheldt;54

University of Rhode Island. (2001). Retrieved from http://omp.gso.uri.edu/ompweb/doee/science/descript/esttype2.htm

Van Breemen, M.T.J. (2008). Salt intrusion in the Selangor Estuary in Malaysia Model study with Delft3D, (June), 47.

Viet, N., and Tanaka, H. (2009). Simulation of Salinity Intrusion Into Nanakita River, Japan, Taking Into Account Effects of Morphological Changes And Wave Set-Up. *Advances in Water Resources and Hydraulic Engineering SE - 245*, 1401–1406.

Vriend, H.D. (2009). Mekong delta. Retrieved from http://www.delta-alliance.org/deltas/mekong-delta

Waite, P. J. (1980). Control of salt water intrusion in estuaries by means of a dual purpose reservoir. *Hydrological Forecasting IAHS Publ. No 129*, (129), 507–513.