APPLICATION OF 1-D ANALYTICAL SOLUTION FOR SALT INTRUSION INVESTIGATION IN THE KUANTAN ESTUARY DURING LOW WATER

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ABSTRAK

Peningkatan paras laut dan cuaca kering yang melampau disebabkan oleh perubahan iklim telah meningkatkan kemasinan muara air. Sebagai akibatnya, air laut mengalir ke dalam kawasan air tawar dengan lebih jauh. Pada bulan Mac 2016, penduduk di Kuantan membuat tuntutan bahawa bekalan air itu masin dan punca hal ini adalah disebabkan oleh stesen pengambilan air di Kobat terjejas oleh air masin. Oleh itu, matlamat untuk kajian ini adalah untuk 1) menyiasat profil kemasinan di muara Kuantan semasa air surut; 2) untuk menguji kesesuaian 1-D penyelesaian analisis untuk siasatan kemasinan di muara Kuantan; dan 3) untuk membuktikan dan mengesahkan pekali Van der Burgh. Pengumpulan data kemasinan bermula dari mulut muara Kuantan sehingga empangan Kobat yang meliputi jarak 18.40km. Semasa dalam keadaan air pasang surut, pengedaran kemasinan membujur telah berjaya disimulasi dengan menggunakan model 1-D walaupun terdapat beberapa unsur luaran yang berpunca daripada perubahan geografi. Berdasarkan keputusan yang ada, ia telah menunjukkan bahawa sebahagian besar taburan kemasinan di muara Kuantan telah diganggu dalam tahap yang tidak stabil selepas pembinaan empangan itu. Pekali Van der Burgh K yang diperolehi daripada penentukuran mempunyai nilai 0.40 dan pekali ini telah disahkan dalam kajian yang kedua.

ABSTRACT

The increase of sea level and extreme dry weather due to climate change has increased the estuary water salinity. As the consequences, the sea water intrudes further into the fresh water region. In March 2016, the residents in Kuantan claimed that the water supply was salty and this happened because the water intake station at Kobat was affected by saline water. Hence, the aims of this are to 1) investigate the salinity intrusion profile in Kuantan Estuary during low water; 2) to test the applicability of 1-D analytical solution for salt intrusion investigation in the Kuantan Estuary; and 3) to verify and validate the Van der Burgh's coefficient. Data collection of salinity started from the mouth of Kuantan Estuary up to the Kobat Barrage covering a distance of 18.40km. During the spring tidal condition, the longitudinal salinity distribution has been successfully simulated using the 1-D salt intrusion model despite of several outliers caused by some geographical changes. From the results, it shows that the salinity distribution in the Kuantan Estuary has been largely disturbed with certain level of instability after the construction of the Barrage. The Van der Burgh's coefficient K obtained from the calibration has the value of 0.40 and this coefficient has been validated from the 2nd survey.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

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

HW	High Water
LW	Low Water
TA	Tidal Average
HWS	High Water Slack
LWS	Low Water Slack

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent times, salt intrusion turns out to be the noteworthy issue around the globe especially near the coastal area. In water supply system where water extraction work is operating, the fresh water discharge into the estuary decreased, which at the same time permitting the sea water to intrude into fresh water region (Barlow, 2003). When this phenomenon occurs, salty water will be extracted if the pumping station is located within the salt intrusion region. There are several factors that contribute to the salt intrusion which consist of the rise of sea level, low precipitation regimes in conjunction with high tide, and over water discharge extraction.

Salt intrusion incidents have been identified to occur as ahead of schedule as 1845 in Long Island, New York. Salt intrusion happens especially in coastal aquifers around the world and is becoming a developing issue in the region of North Africa, the Middle East, the Mediterranean, China, Canada, Mexico, and United States (Richard, 2008).

1.2 Background of Study

In 1970’s, the salt intrusion region in the southwestern part of City of Laizhou has been expanded by $4km^2$ every year. It shows the sign of warning to emphasize and strengthen the requirement for proper monitoring and strategies for salt intrusion before it is out of control (Xue et al., 1993).

In Atlantic Canada, the hiking of temperature and dropping of precipitation had unquestionably reduced the amount of fresh water discharge and subsequently causing salt intrusion problem (ACASA, 2011). Besides global warming, the thermal expansion of ocean will generally cause the glacial melting which prompts the ocean level to ascent. When this happens, it permits the sea water to interrupt the freshwater.

On the other hand, the coastal development for commercial and tourism activities are some of the contributing factors towards destroying the estuaries. Due to the rapid growth population, developments on the coastline and near to the river bank are unavoidable. For example in the Kuantan Estuary (one of the estuary in the Pahang State). Mangrove trees were logged to give ways for housing developments along the river banks at Tanjung Lumpur. This has disrupted the balance of estuarine ecosystem, depleted the species of marine organism, which led to erosion and flood occurrence.

Another factor contributing to the salt intrusion problem is dredging activity. Dredging is required for navigation purposes especially for big ships that can only travel in very deep channel. This causes the imbalance between the sea water and fresh water (Cai et al., 2012, 2014b; Gisen 2015). The depletion of estuary also affected the supply of fresh water as drinking water to the residential area since water consists of higher salinity. Besides, the intrusion of sea water which flows into irrigation area where the water is used for agricultural activities due to the dredging. For example in the Selangor Estuary, high salinity has threatened the habitat of fireflies in Kampung Kuantan (one of the largest firefly colonies in the world) as a result of dredging activities (Breemen, 2008; Gisen, 2015).

Hence, it is crucial to carry out salt intrusion study to gain some understanding on the current salinity condition in the Kuantan Estuary. By this, water manager will be able to monitor and manage the estuarine ecosystem accordingly.

1.3 Problem Statement

In the past few years, Kuantan City has developed rapidly to cater the needs for residential, agricultural and industrial demand resulting from increasing population growth. This situation has brought the negative impacts to the Kuantan Estuary ecosystem especially the threat to mangroves forest. Mangroves in Malaysia covered 52% of the total length of the coastline, and in Kuantan City 2159.90 hectares are occupied by mangrove trees (Saad et al., 2009). Mangroves is important to human beings and also the environment as they supply materials for construction such as timber and plywood, and at the same time raises the growth of fisheries stock by providing food source to marine organisms (Tse et al., 2008).

The massive coastal development along Kuantan Estuary such as construction of jetty for tourism and fisheries purposes had caused the degradation of mangrove forest. Developments involving buildings, residential areas, shop lots and roads require a huge vacant mangrove area. Furthermore, the local people in the fishing villages cut down the mangrove trees to build houses along the riverbank. Consequently, erosion happened as the mangrove forest degraded. This is because when heavy flow or strong tidal wave occurs, the current energy can no longer be dissipated because of the non-existence of the mangrove roots. The function of mangroves roots is to retain the soil from waves during the monsoon season. Increase in atmospheric carbon dioxide concentration is the main cause of climate change. The increase of sea level due to climate change will increase the surface salinity as well. The salinity increases when the sea water intrudes and move further into the fresh water region.

Lately, the residents in Kuantan claimed that the water supply is salty due to the El-Nino phenomenon since March ago. The El-Nino phenomenon causes the low water discharge to reach the residential area. Salt intrusion study must be carried out at Kuantan Estuary in order to determine the salinity level and also propose the prevention and control measure when necessary.

1.4 Objectives of Study

The main objective of this study is to identify the level of saline water distribution in the Kuantan Estuary which includes the followings:

1. To investigate the salinity intrusion profile in Kuantan Estuary during low water.
2. To test the applicability of 1-D analytical solution for salt intrusion investigation in the Kuantan Estuary.
3. To verify and validate the Van der Burgh's coefficient.

1.5 Scope of Study

This study focused on the salt intrusion problem in the Kuantan Estuary. The area of the region covered in this research is the downstream part of the Kuantan River. A 1-D analytical salt intrusion model is used due to the minimum amount of field work needed and the ability to produce high accuracy of results (Savenije, 1986). Since the hydrological and geometrical data for the Kuantan Estuary is insufficient as the previous research was done 39 years ago, 1-D analytical solution has become a good approach because it is applicable to be used in poor data environment (Gisen, 2015). The study is limited only till the Kobat Barrage as we need to seek for permission from responsible authority if we want to access it. For this study, fieldworks will be conducted for neap tidal condition in February 2017 during the short dry season. For this study, neap tidal is chosen as the previous research only involved spring tidal. During the fieldworks, water level, cross sectional and salinity measurement will be collected. The Van der Burgh's coefficient, K and the dispersion coefficient, D are the calibration parameters to obtain the best fit between simulated and observed datasets.

1.6 Significant of Study

The only available research that has been done on salt intrusion problem in the Kuantan Estuary was in the year 1977, when the water intake station at Kg. Kobat receives saline water. With the rapid development and extreme climate uncertainties over the past 39 years, new study is essential to re-evaluate the salinity condition in the Kuantan Estuary. The needs for the study is strengthen by the event in which the water company encounter saline water in the water supply system due to El-Nino effect recently during low water in spring tide. According the previous study carried out in 1977, the salt intrusion during low water does not affect the pumping station, but the extreme dry season that occur in the recent years shows otherwise. Hence, this study will re-investigate the salinity distribution during low water which is very important for the evaluation on the current barrage efficiency. By this, appropriate suggestion can be addressed to the water manager for system improvement.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cameron and Pritchard (1963), Dalrymple et al. (1962), Dionne (1963), Perillo (1965), Savenije (2005), and Gisen et al. (2015), define estuary as the region where the freshwater meets the seawater. This region is an ideal place for aquatic life to breed as there is much nutrient supply. For human benefits, estuaries play a vital role in transportation and food supply. However, massive developments along the river bank to fulfil human demand have destroyed the ecosystem in estuaries. Hence, authorities must take actions to overcome and handle this issue in order to maintain and preserve the ecosystem.

2.2 Classification of Estuaries

Mostly, estuaries can be categorised based on their shape, tidal, geology and salinity (Gisen et al., 2015). The overall classification of the estuaries is as shown in Table 2.1.

Table 2.1 Classification of estuaries

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 Shape of Estuaries

Prismatic and trumpet shapes are the most common geometry found in estuaries (Gisen, 2015). The shapes can be differentiated based on some characteristics.

Prismatic shape only can be found in artificial environment where the banks of estuaries are parallel to each other. Trumpet or funnel shape can be found in the natural estuary where the banks are irregular leading to inconsistent cross-section. The wave action near the mouth of estuaries formed the trumpet or funnel shape.

The shape of estuary can be represented by using exponential function (Savenije, 1989).

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

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

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

where $A, B\ and\ h$ are the cross-sectional area, width and depth at the distance x respectively.

$A_{0,}\ B_0\ and\ h_0$ represent the cross sectional area, width and depths at estuary mouth.

Equations 2.1 to 2.3 often are used in geometry analysis and the validity of the equations have been proven by Nguyen and Savenije (2006); Zhang et al. (2011) and Gisen (2015). The shape analysis is crucial as the boundary conditions for tidal dynamics, salinity and hydraulic geometry.

According to Gisen (2015), for shape study, equations are as follow:

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

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

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

The inflection point where the wave dominated region ends and there is a change in the convergence length is known as longitudinal distance, x_1. At this point, the cross-sectional area, width and average depth known as A_1 , B_1 and $h_1$respectively. At the same time, the convergence lengths change from a_1 to a_2 and from b_1 to b_2. According to Savenije (2005), the convergence length $a_{1,2}$ and $b_{1,2}$ are mostly equal to each other in ideal alluvial estuaries.

2.4 Tidal Wave

According to Savenije (2005, 2012), the shape of estuary affects the water level and velocity of the tides and also the river flow. In salt intrusion study, the geometry of estuaries can be categorised based on the tidal conditions as shown in Table 2.2 (Davies, 1964; Dyer, 1997; Gisen, 2015):

Table 2.2 Geometry of estuaries based on the tides condition

Tidal Condition	Water Level	Geometry of Estuary
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.

Source: Gisen (2015).

There are three types of tides which are diurnal, semi diurnal and mixed diurnal which are distinguished according to tidal period. The differences between each tide and their descriptions are listed in table 2.3 below.

Table 2.3 Differences between three types of tides

Types of tide	Description
Diurnal	Has only one complete tidal cycle
Semi diurnal	Has two alike tidal cycles in a day
Mixed diurnal	The tidal range difference between two tidal cycles in a day is huge and only has impact on large tidal range than small one

Source: Pond and Pickard (1983); Gisen (2015).

The tidal oscillations of three types of tides during the tidal in 24 hours are shown in Figure 2.1.

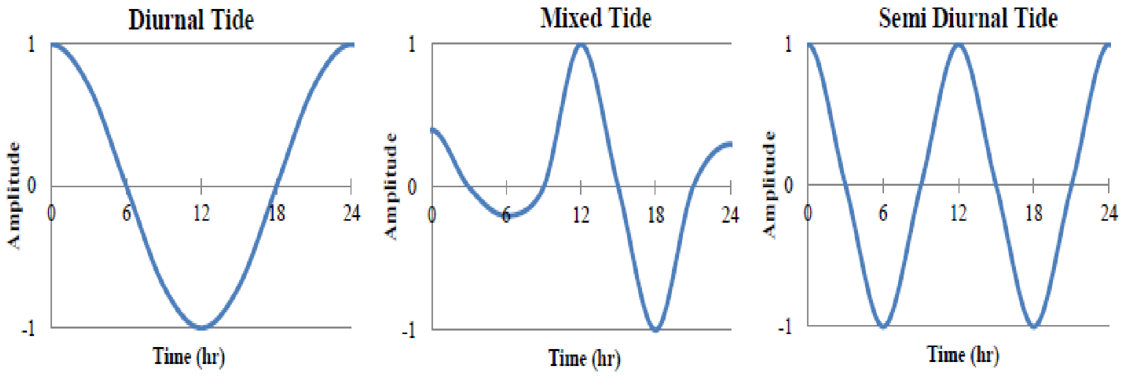

Figure 2.1 Tidal oscillations of diurnal, mixed and semi diurnal tides
Source: Gisen (2015).

There are three types of tidal waves differentiated with the respect of the wave celerity, *c* which are standing wave, progressive wave and mixed wave. In the estuary, high water (HW) or low water (LW) occur at almost the same time for a standing wave. Along the estuary, a standing wave could reach its extreme water levels when the velocity equal to zero as shown in Figure 2.2 (a). In the condition of constant cross-section and infinite length, a progressive wave will occur. There is no phase difference between water level and flow velocity in a progressive wave as shown in Figure 2.2 (b). According to Gisen and Savenije (2015), these two waves normally cannot be achieved in trumpet or funnel shaped of estuaries.

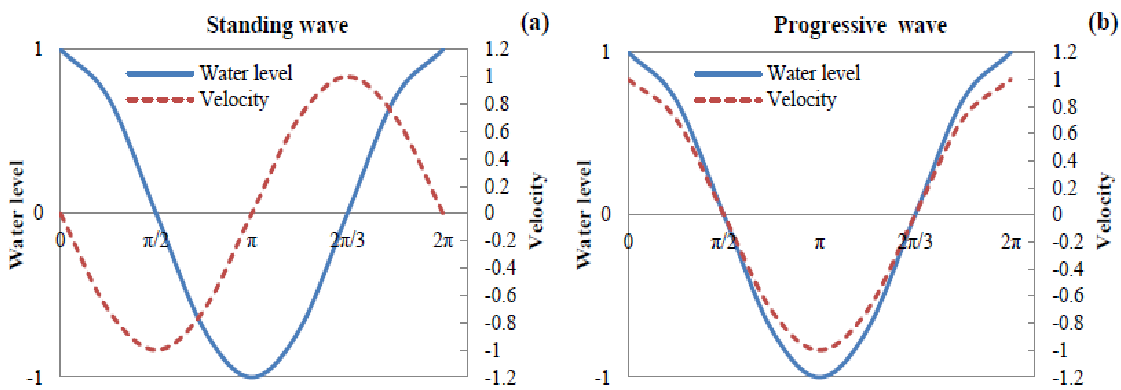

Figure 2.2 Types of tidal wave: (a) Standing wave and (b) Progressive wave
Source: Gisen (2015).

Before the tidal velocity reaches zero or in slack moment, the water level will achieve its highest or lowest point in a convergent estuary. The phase lag ϵ is known when there is a delay between the HW or LW and high water slack (HWS) or low water slack (LWS) which lies between 0 to $\pi/2$ as shown in Figure 2.3.

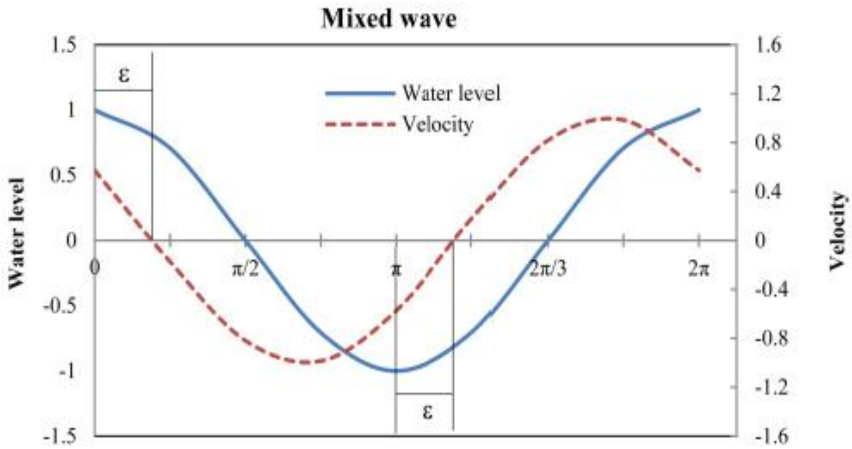

Figure 2.3 Mixed type tidal wave with phase lag ϵ

Source: Gisen, (2015).

Phase lag ϵ is important to achieve the understanding in the tidal wave propagation. On the other hand, it also acts as a parameter to predict the average tidal depth when there is limited data available.

2.5 Mixing

The differences in density, tidal shear, residual currents, tidal pumping, turbulence and tidal trapping are the main contributors to the main mixing processes. Each contributor and its description are discussed in table 2.4 below.

Table 2.4 Types of mixing and its descriptions

Types of Mixing	Description
Turbulent or shear mixing	✓ Tidal driving force equals to friction. ✓ Different water particles are mixed by tidal driving force.

	✓ Roughness of the river bed causes the friction forces are transported by a shear stress.
Gravitational mixing	✓ Cross section with lower density tends to flow in seaward direction. ✓ Higher density flows along the bottom in landward direction. ✓ When salinity gradient is high, gravitational will take place.
Tidal trapping	✓ Crucial mechanism in estuaries with tidal inlets and tidal flats. ✓ Tidal flats release their water in the flow channels with salinity.
Tidal pumping	✓ The differences in vertical and lateral velocity in the cross section affect the remaining currents with different densities during filling and emptying of an estuary over several tides.

Source: Deynoot (2011).

2.6 Background Theories

Referring to the previous survey for the Kuantan Estuary in 1977, a mathematical model was utilised as a part of the study known as 'high water slack approximation' to define the movement and distribution of salinity (Hydraulics Research Station Wallingford, 1978) .The conservation of salt was represented in a single unsteady equation, one dimensional in space. The equation used in the study was:

$$A\frac{\partial c}{\partial t} - \frac{\partial}{\partial x}\left(u_f c A\right) = \frac{\partial}{\partial x}\left(A\, D\, \frac{\partial c}{\partial x}\right) \qquad (2.7)$$

Where

A is the cross section area of estuary at x

c is the salinity at position x at time t

u_f is the freshwater flow velocity at (x, t)

D is the longitudinal dispersion coefficient for the high water slack approximation

The salinity measurements must be carried out during high water slack to ensure that:

1. The salinity at the boundary condition is consistent throughout the vertical level.
2. Salinity contribution is in well-mixed condition giving highest peak.

The empirical form of D which is longitudinal dispersion coefficient is used to develop equation 2.8:

$$D = D_1 \frac{Au_T}{A_o u_{T_0}} + D_2 [\frac{Pu_T^2}{Q_f Tgh(1-\rho/\rho_0)}]^n \frac{c_x L}{c_0} \qquad (2.8)$$

where

u_T is the maximum tidal velocity at a section

P is the tidal prism volume of sea water entering the estuary during flood tide

Q_f is the fresh water flow

T is the tidal period

G is the acceleration due to gravity

h is the mean depth

ρ is the density of the water at a section

$c_x = \frac{\partial c}{\partial x}$

L is the length of estuary

And the suffix zero represents the values of quantity at the estuary mouth, x= 0.

The density which is related to salinity is shown in Equation 2.9 below

$$p = \rho_0 \frac{(1+\alpha c)}{(1+\alpha c_0)} \qquad (2.9)$$

where

α = 1.38 x 10^{-3} where c is in ppt Cl^{-}.

At the initial of the profile,

$$c\ (x, 0) = f(x)$$

where $f(x)$ is represents the initial profile.

On the other hand, salinity of estuary mouth ought to be equal the oceanic salinity.

$$c\ (0, t) = c_0 \tag{2.10}$$

By using computer programme, salinity in Kuantan Estuary in 1977 is calculated using Equation 2.7 and plotted in a graph which shown in Figure 2.4.

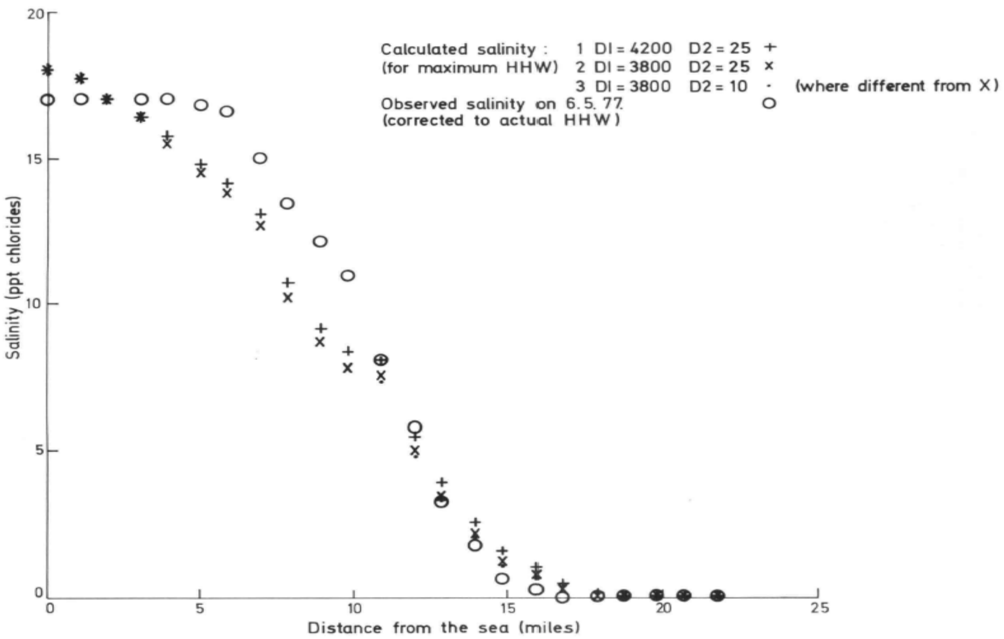

Figure 2.4 Longitudinal salinity profile

Source: Hydraulics Research Station Wallingford (1978).

There are several methods to be used in analysing the salt intrusion including one-dimensional analytical, two or three-dimensional numerical models such as DELFT 3D, MIKE 21, HYDRUS, and SWIM. According to Gisen (2015), the 1-D analytical model that developed by Savenije (1986, 1993, 2005, 2012) can be applied in Kuantan Estuary. The reliability of the model has been proved by some researchers including Zhang (2011) and Nguyen (2012).

In salinity theory by Gisen et.al (2015), the salinity distribution is simulated at tidal average (TA) condition and later changed to HWS situation. Based on the van der Burgh (1972)'s theory for longitudinal dispersion, Equations 2.1 to 2.6 are substituted with the salt balance equation that yields the salinity distribution along the estuary which is from the mouth to a point where the water is fresh at steady state condition (Savenije, 2005, 2012; Gisen, 2015).

$$\frac{S^{TA}-S_f^{TA}}{S_0^{TA}-S_f^{TA}} = \left(\frac{D^{TA}}{D_0^{TA}}\right)^{\frac{1}{K}} \quad (2.11)$$

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.
S_f^{TA} is the fresh water salinity which normally near to zero.

The equations for dispersion are given as below:

$$\frac{D^{TA}}{D_0^{TA}} = 1 - \beta_0^{TA}\left(e^{\left(\frac{x}{a_1}\right)} - 1\right) \qquad for\ 0 < x \leq x_1 \quad (2.12)$$

With

$$\beta_0^{TA} = \frac{K a_1}{a_0^{TA} A_0} \qquad for\ 0 < x \leq x_1 \quad (2.13)$$

And

$$\alpha_0^{TA} = \frac{D_0^{TA}}{|Q_f|} \qquad for\ 0 < x \leq x_1 \quad (2.14)$$

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.

Mixing number α_0 is used to facilitate calibration as discharge and dispersion estimates are hard to be achieved.

The equation of salt intrusion length L when D= 0 can be computed from the Equations 2.12 to 2.14 as follows:

$$L^{LWS} = a_1 \ln\left(\frac{1}{\beta_0^{TA}} + 1\right) - E/2 \qquad for\ 0 < x \leq x_1 \tag{2.15}$$

The theories of classification and shape of estuary, tidal wave and mixing are described in this chapter. Equations to be used in the study are introduced and background theories of the previous study in the Kuantan Estuary are explained as guidance for further salinity distribution analysis.

CHAPTER 3

METHODOLOGY

3.1 Study Area

The Kuantan River Estuary as shown in Figure 3.1 is located in the coastal of Pahang state with the latitude of N 3˚48’00” and longitude of E 103˚21’00”. This river basin is originated from the East Coast Range which is next to the Pahang-Terengganu border with the catchment area of 1630km^2. Main tributaries of Kuantan River Basin include the Belat River, Riau River, Pandan River, Pinang River, Lembing River and Lebir River. The Kuantan and Belat rivers meet at the confluence at about 6.44km from the South China Sea. Approximately 10-15% of freshwater inflow to Kuantan River Basin is generated by Belat stream while Riau stream created 20% of daily inflow. Another 2% and less than 1% of inflow to Kuantan River is contributed by Pandan stream and Pinang stream respectively (Hydraulics Research Station Wallingford, 1978).

A water gate namely the Kobat Barrage was built in 1977 at the location 17.54km away from the Kuantan Estuary as shown in Figure 3.2. The purpose of building this barrage is to prevent the salt water entering the water intake area during the high tidal cycle. Tides in the Kuantan Estuary have a mixed diurnal characteristic as shown in Figure 3.3. For this type of tidal characteristics, there are two low and two high peaks in a single day, indicating 12 hours of tidal cycle.

Figure 3.1 Location of Kuantan Estuary

Source: Google Earth, (2016).

Figure 3.2 Closer view of Kobat Barrage

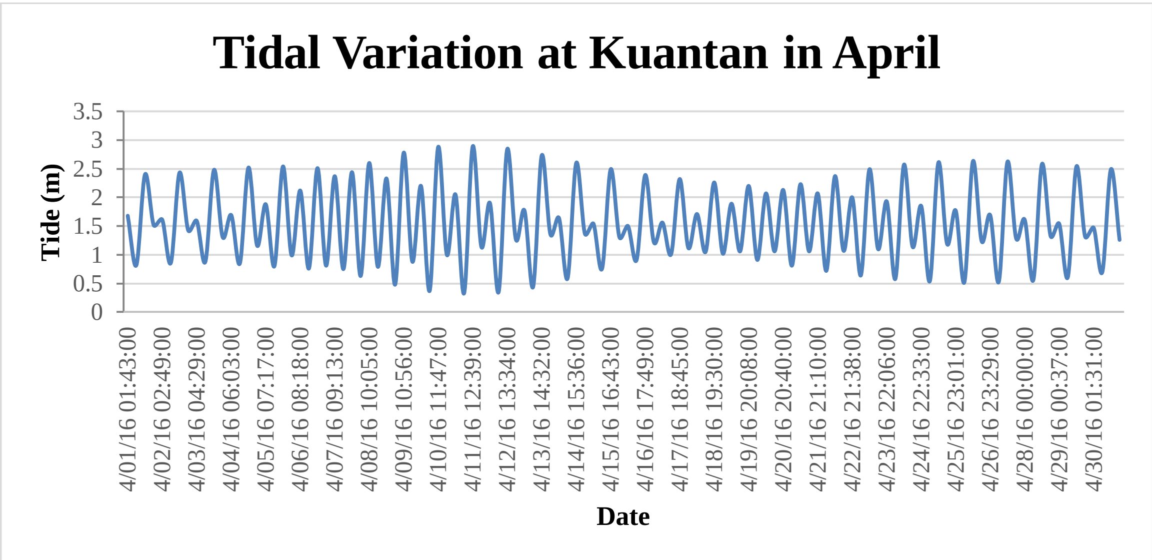

Figure 3.3 Tide level at Kuantan Estuary mouth (Period from 1 April 2016 to 30 April 2016)

Basically, agricultural and fishing are the main economic activities near the Kuantan Estuary. Statistically, mangroves forest and agricultural activities which occupy about 56% and 32% of the total land use in this area, respectively as shown in Figure 3.4 (Fahmi et al., 2012). Kuantan Estuary is the habitat for the main mangrove species which are Sonneratia Alba and Rhizophora mucronata to breed (Shahbudin et al., 2015) whereas the fish species in this estuary are dominated by Ariidae, Lutianidae and Lactaridae (Jalal et al., 2012). Several fishing villages can be found at Tanjung Lumpur, a coastline area along the Kuantan Estuary. Besides, agriculture and fisheries activities, the estuary also serves as spot for families to have a leisure time during the weekends. Recreational parks such as the Taman Gelora and Esplanade Park are situated along the Kuantan Estuary.

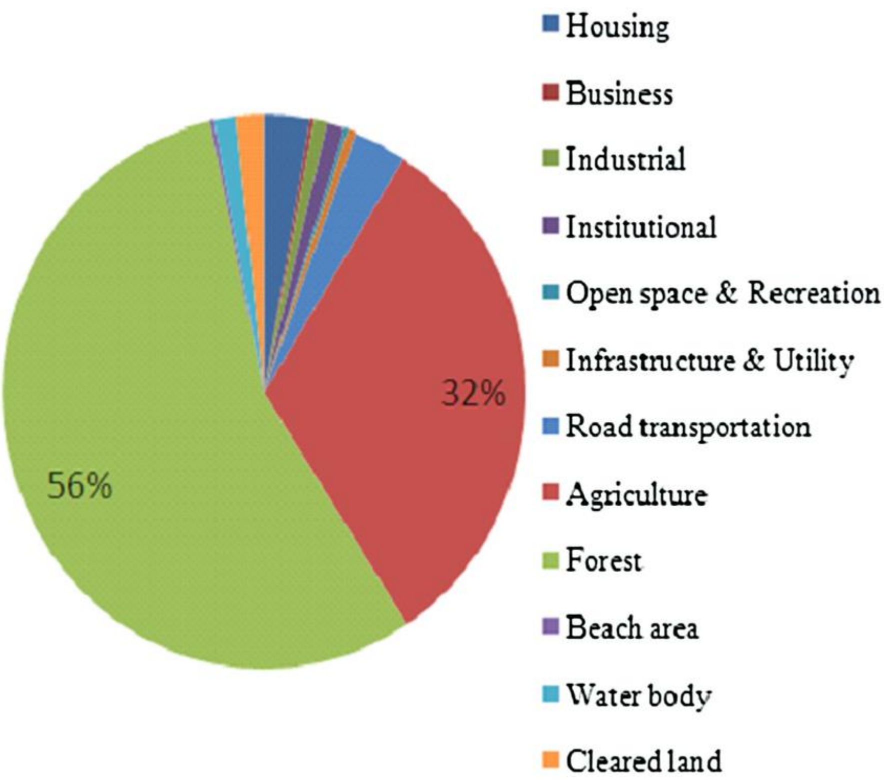

Figure 3.4 Percentage of land use in Kuantan River Estuary
Source: Fahmi et al. (2012).

3.2 Research Flow Chart

Before conducting the fieldwork to collect the data, theories of the study must be understood through literature study. The fieldworks data include water depth and salinity distributions along the estuary were collected to perform the geometry and salinity analysis. Later, the two parameters, K and D were be calibrated in the first survey to adjust the simulated salinity curve to fit the observed data and the calibrated K was validated based on the results from the second survey.

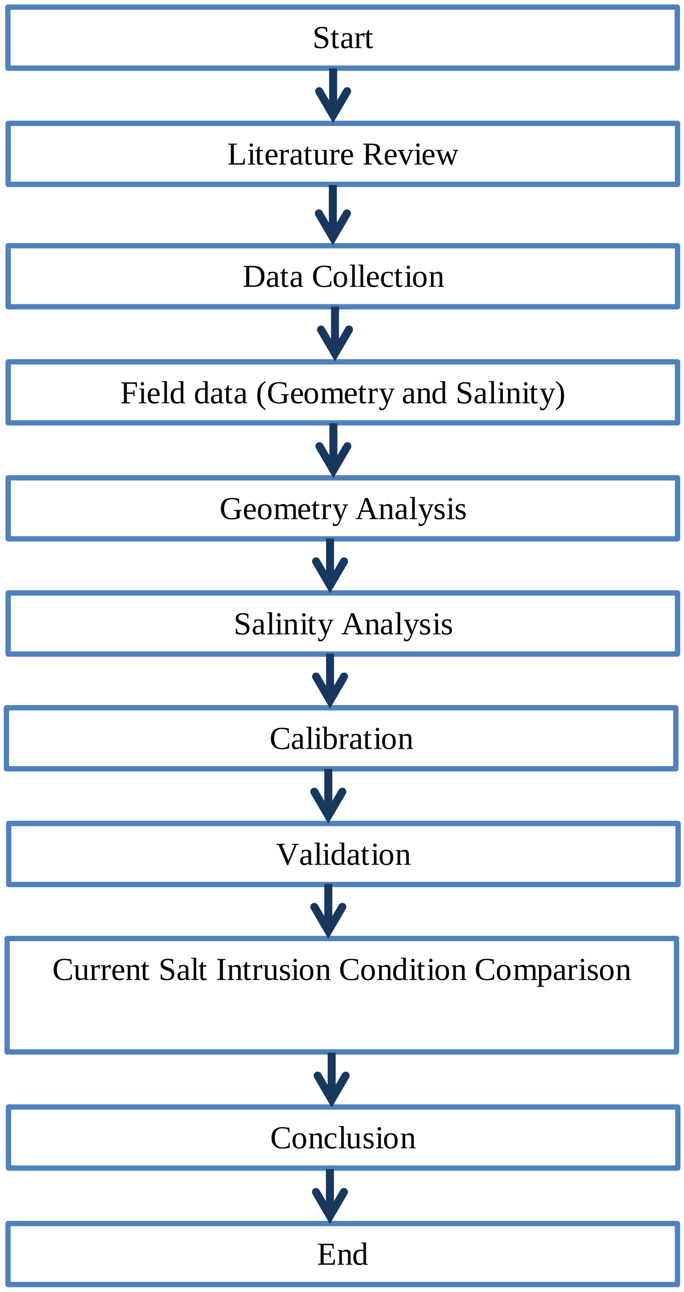

Figure 3.5 Research flow chart

3.3 Data Collection and Equipment

Prior to salinity analysis, necessary data related to the salinity study in the Kuantan Estuary were collected on-site, acquired from local authorities (Department of Irrigation and Drainage, Malaysia), and retrieved from reports done by other researchers. Data that were collected from the fieldwork includes water depth and salinity distribution along the estuary. For the channel cross-sectional area, it was based on available existing data. In the present study, salinity measurements were carried out on 27 March 2017 and 29 March 2017 when dry season began.

To conduct the fieldworks, some equipment as shown in Figure 3.6 is required. A GPS (Global Positioning System) was used during the field studies to record the location of every measurement points. Maximum water depths at every point were also captured with handheld depth sounder as displayed in Figure 3.7. A Horiba Water Quality Meter connected with a 30m long of cable was used to read the water temperature, conductivity, turbidity and salinity.

With the equipment shown in Figure 3.6, field survey can be conducted in a simple and financially savvy way. In short, salinity measurement can be done within a day and in addition, a set of required data for the salt intrusion analysis can be gathered within a week.

Figure 3.6 Equipment used in fieldwork (from top left GPS, handheld depth sounder, and conductivity meter)

Figure 3.7 The water depth was captured with handheld depth sounder

3.4 Survey

3.4.1 Preliminary Observations

Before commencing any survey work, preliminary observations were carried out to identify the possible and conceivable area conducting the measurements. An informal interview of the local people has been done to understand more about the study area, particularly on the possible dangers that might be faced during the survey. Additionally, preliminary survey also helped the surveyor to rule out technical hitches and reduced mistakes during the fieldworks.

3.4.2 Salinity Measurement

Salinity measurement was conducted by using moving boat technique in which the boat travels with the speed of tidal wave. It is worth noted that this measurement must be done during the High Water Slack (HWS) and Low Water Slack (LWS). HWS and LWS occur just before the flow changes its direction. Salinity measurement was conducted at several locations (at least 10 points) along the estuary, where at each point the salinity readings were recorded for every one-meter vertical from the bottom to the water surface as shown in Figure 3.8. A weight was attached on the probe of the conductivity meter to allow the sensor to submerge into the water until just above the river bed. The weight also prevented the probe to drift when it reached the surface.

Salinity data obtained was recorded manually as displayed in Figure 3.9. The location of each salinity measurements points was identified using a GPS.

Figure 3.8 Horiba Water Quality Meter is used to record salinity readings for every one-meter vertical from the bottom to the water surface

Figure 3.9 Salinity data was recorded in a manual sheet

3.4.3 Geometry Analysis

The cross section and depth of the Kuantan Estuary was determined to analyse the geometry of the Kuantan Estuary. Based on Savenije (1986)'s theory, the geometry analysis can be conducted for alluvial estuaries in which the geometry of estuary varies exponentially over the distance as explained in Equations 2.1 to 2.3 (Gisen and Savenije, 2015). Figure 3.10 shows the illustration of geometry analyses in the general form. In the end of the study, the geometry of Kuantan Estuary was tabulated and estuary profile was plotted.

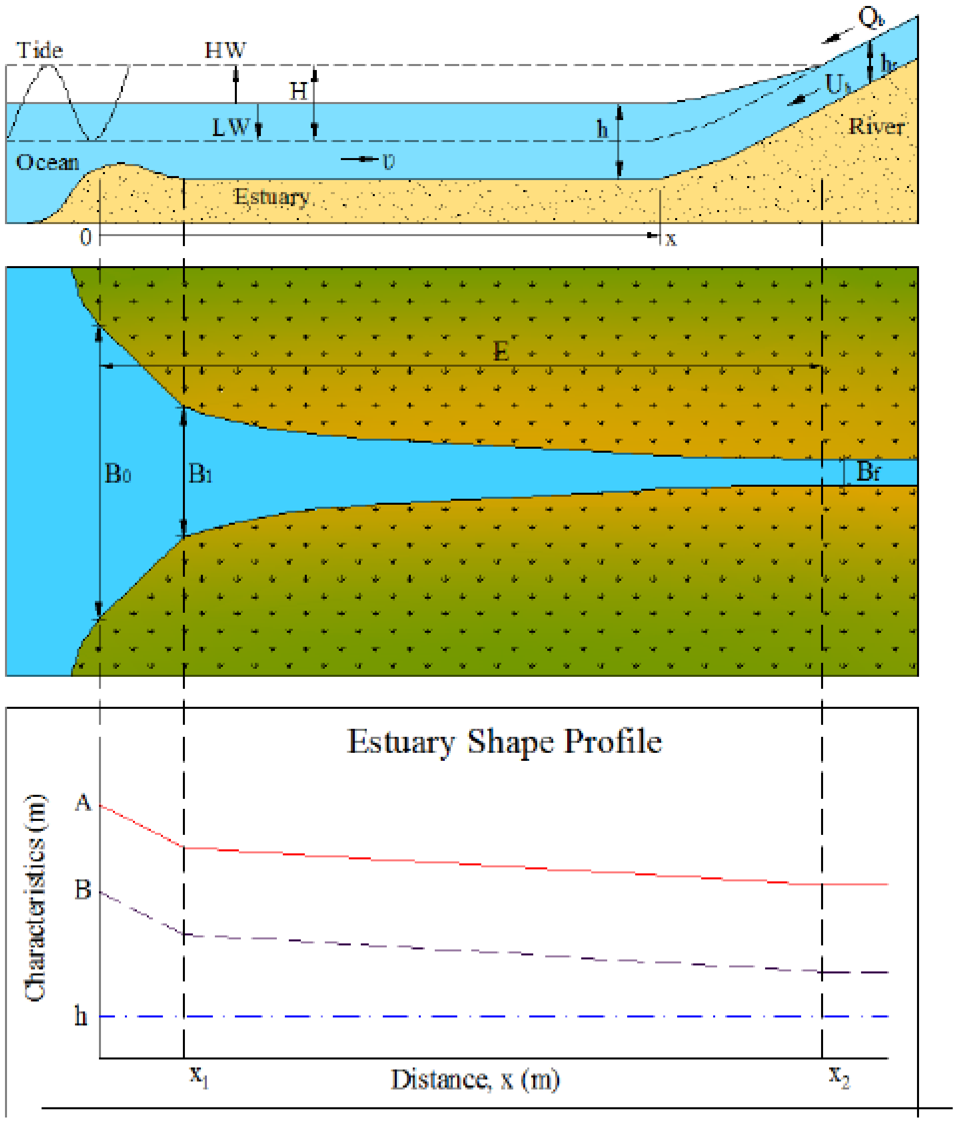

Figure 3.10 Illustration of geometry analyses in the general form

Source: Gisen, (2015)

3.4.4 Salinity Modelling

In this study, 1-D analytical modelling was adopted to test its applicability for salt intrusion investigation in the Kuantan Estuary during low water spring tidal cycle. Cross-sectional data (width and depth) and initial salinity along the estuary were the data input required for the model. The Van der Burgh's coefficient, *K* and the dispersion coefficient, *D* were the calibration parameters to obtain the best fit between simulated and observed datasets. Also, tidal excursion, *E* was calibrated in the condition as the velocity amplitude was not available in this study.

3.5 Calibration Process

Calibration process was performed to adjust the simulated salinity curve to fit the observed data. This was done by calibrating the two parameters, *K* and *D*. Since the velocity amplitude was not measured in this study, the parameter *E* was also calibrated based on the HWS and LWS salinity measurement data. The dispersion coefficient is a mathematical artefact that is closely related to the fresh water discharge. When the tide meets the river flow, the salt particles will be dispersed in every direction due to the mixing mechanism between the fresh and salt water. It is worth to note that the dispersion is not physically measureable and the discharge data is often unavailable in the estuary. Due to this reason, the dispersion was calibrated in the form of the mixing coefficient (α) which represents the ratio of dispersion over the discharge.

3.6 Validation

The importance validation process is to investigate the applicability of the 1-D salt intrusion model to simulate the salinity distribution in the Kuantan Estuary. Furthermore it was also performed to confirm the correctness of the calibration parameters. The calibrated coefficient *K* was validated based on the results from the second survey. In the validation process, only *K* was compared in all the salinity studies whereas the mixing number, α cannot be compared as it varied with the daily flow discharge.

3.7 Error Analysis

There were two methods used in performing the error analyses: Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE). These analyses were conducted to evaluate the reliability of the model. RMSE was used to evaluate the average gaps between the observed and simulated data. The RMSE value was computed with the equation:

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

where O_i is the observed value of the variable of interest while P_i is the predicted value.

The Nash-Sutcliffe Efficiency was used to determine the overall performance of the model. The NSE equation is expressed as:

$$E = 1 - \frac{\sum_{i=1}(P_i - O_i)^2}{\sum_{i=1}(O_i - \bar{O}_i)^2}$$

where O_i is the observed discharge while P_i is the predicted value. $\bar{O}_i$ is the average of the observed value from the survey. The range of Nash-Sutcliffe efficiency is from -∞ to 1. Efficiency of 1 symbolised the perfect match of model discharge to the observed data, whereas efficiency of 0 shows that the accuracy of model predictions to the mean of the observed data. Next, efficiency less than zero indicates that the observed mean is a better than the model. By using this model, higher accuracy of results are achieved by comparing the model results with the observed data.

In this chapter, the method and equipment used in conducting the fieldwork to collect the data of water depth and salinity distribution along the Kuantan estuary are discussed. The two parameters, K and D were calibrated in the first survey to adjust the simulated salinity curve to fit the observed data. The calibrated K was then validated based on the results from the second survey. RMSE and NSE analyses were performed to evaluate the accuracy of 1-D model.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Geometry Analysis

By using Equations 2.1 to 2.3, the geometry analysis was performed for the Kuantan Estuary. The results of the analysis show that the shape of estuary is indeed following an exponential function. The Kuantan Estuary consists of only one width and two cross-sectional convergence lengths which are a_1 and b_1. Figure 4.1 shows the geometry analysis for the Kuantan Estuary where the data obtained from the existing survey in 2015 was compared with the previous study conducted in 1977. The summary of the geometry characteristics for the Kuantan Estuary are presented in Figure 4.1 and Table 4.1.

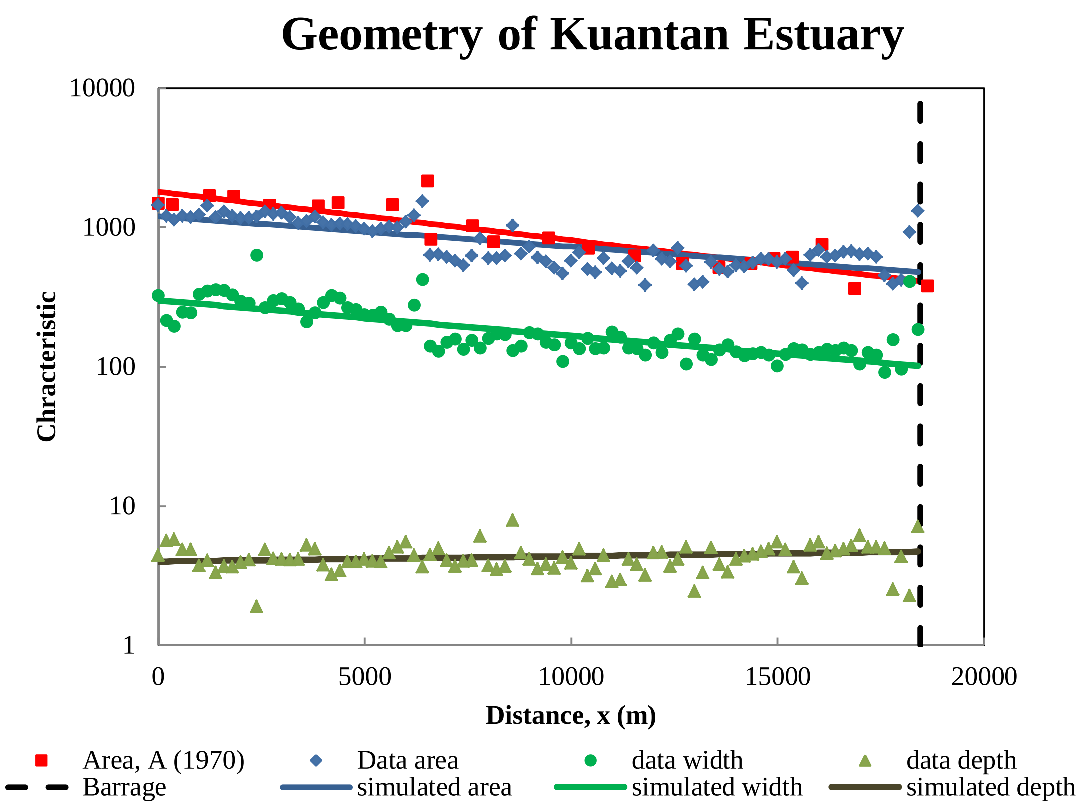

Figure 4.1 Results from geometry analysis of the Kuantan Estuary.

In the semi-logarithmic plot shown in Figure 4.1, the latest simulated cross-sectional area is represented by the solid blue line while the solid red line indicates the cross-sectional area from the previous study in 1977. The cross sectional area that was obtained in the recent survey demonstrates significant change at the downstream part when compared to the previous survey which was done 39 years ago. This change is probably caused by the construction of the Kobat Barrage in which the river flow from the upstream has been blocked reducing the flushing of sediments into the ocean. Consequently, the accumulation of sediment has reduced the area of the conveyance. From the results, the fitting point for cross sectional area A_0 and width B_0 at the estuary mouth is 1200 m^2 and 300 m respectively, whereas for the convergence lengths for cross sectional a_1 and width b_1 are 20000 m and 17000 m. The average depth of the estuary h is 4.34 m.

Table 4.1 Summary of geometry characteristics in Kuantan Estuary

Kuantan Estuary	$A_0(m^2)$	$a_1(m)$	$B_0(m)$	$b_1\ (m)$	$\bar{h}\ (m)$
New (2017)	1200	20000	300	17000	4.34
Old (1977)	2000	11000	-	-	-

As shown in Table 4.1, in the previous study which conducted 39 years ago did not display any information related to the channel width, width convergence length and average depth since there are no data available.

4.2 Salinity Analysis

Figure 4.2 and 4.3 demonstrate the vertical salinity distribution at low water slack (LWS) for the Kuantan. From the plots, the mixing mechanism can be categorized as partially mixed to well-mixed condition.

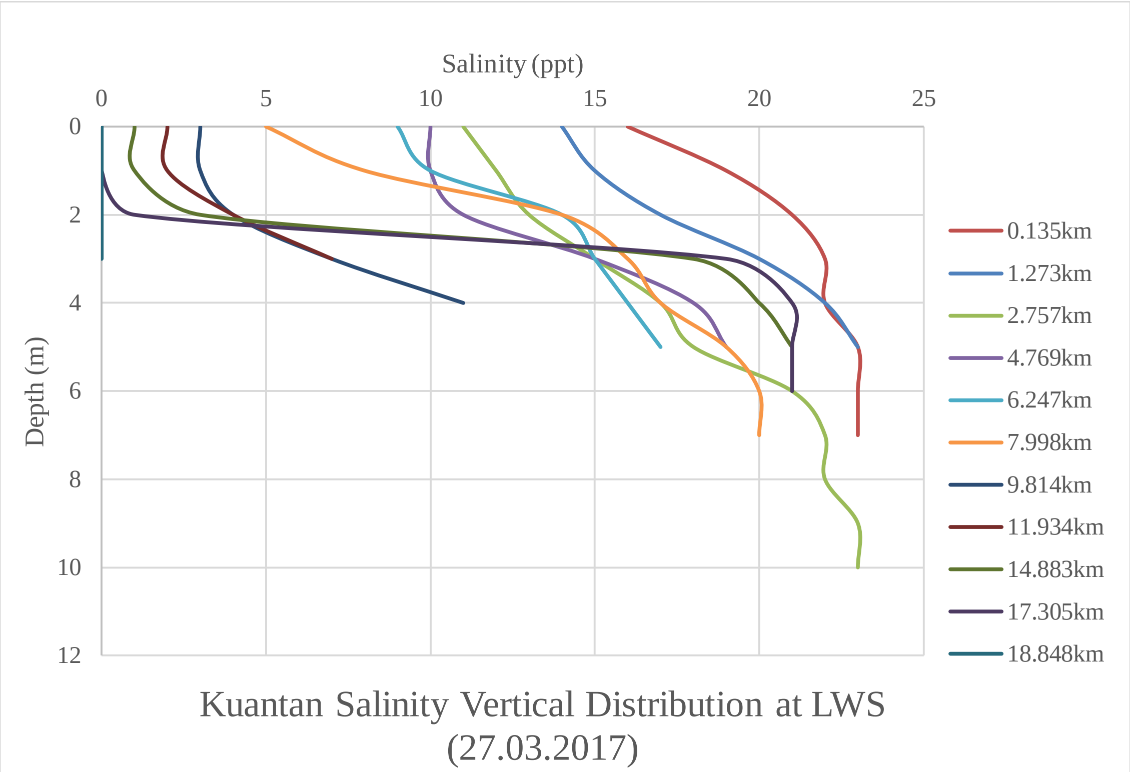

Figure 4.2 Kuantan Vertical Salinity Distribution at Low Water Slack (LWS) on 27 March 2017

On the 27 March 2017, the first salinity survey in the Kuantan Estuary was conducted. The results obtained from the survey (Figure 4.2) shows partially stratified pattern in the vertical salinity distribution which may be caused by the difficulty in identifying the timing for the low water slack. This difficulty is very common for the first measurement as the surveyors were still not familiar with the condition in surveyed estuary. For the second measurement on 29 March 2017 as shown in Figure 4.3, the results obtained shows better well-mixed distribution compared to the first survey. However, the salinity at distance around 16 km to 18 km is still displays stratified patterns.

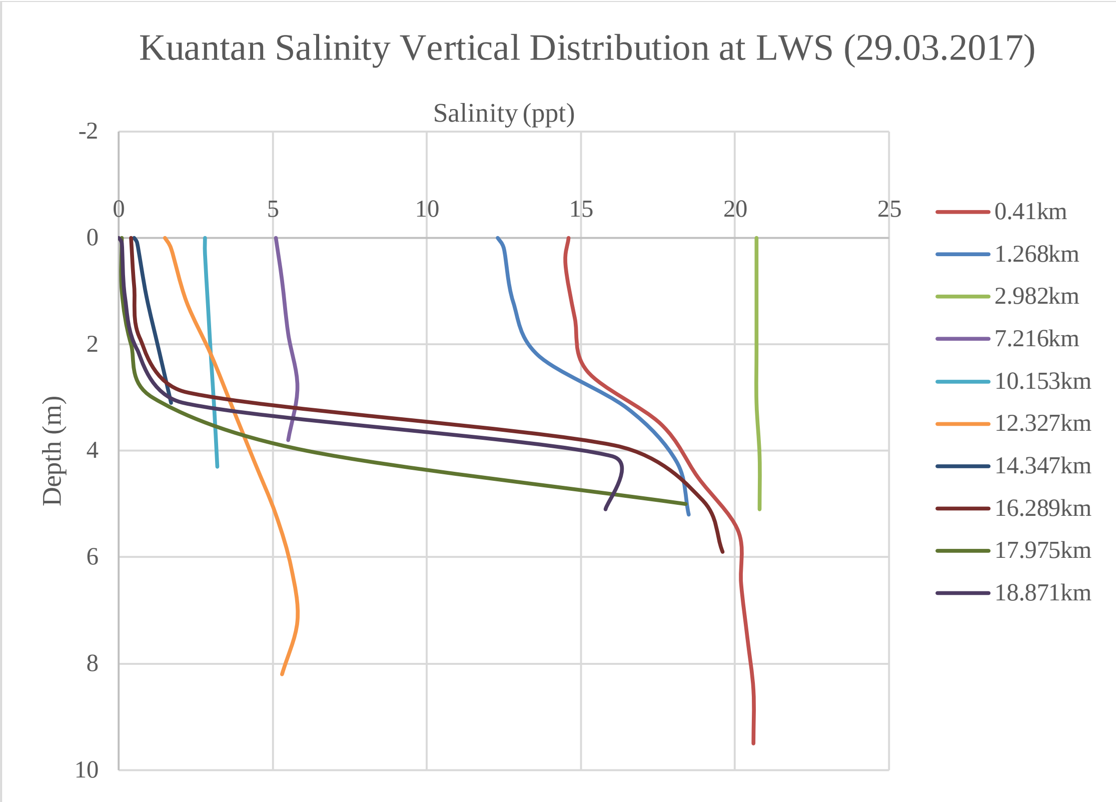

Figure 4.3 Kuantan Vertical Salinity Distribution at Low Water Slack (LWS) on 29 March 2017

This situation is probably influenced by the change in morphology after Kobat Barrage was built. During the site measurement, it was noticed that there is a sudden increase in the water depth within that distance. This unusual phenomenon may be due to the sediment upstream is being blocked by the barrage from entering into the downstream area and thus deepen the river bed. Due to this reason, the saline water has accumulated at the deeper part of river bed during the high tide and stayed stagnant during the ebb tide. In normal condition, the salt water will be flushed out by the fresh water upstream together during the ebb tide. However, the barrage has stopped the fresh water from the upstream catchment into the downstream region. Hence, the force to flush out the salt water at the deeper part of the river is no longer adequate and causing the long term accumulation. The salinity at the distance 18 km from the mouth of the estuary was recorded zero in the first survey indicating unusual reading and this may be caused by some factors or details that were overlooked by surveyors during the measurements.

Applying Equation 2.11, the longitudinal salinity distribution curve has been simulated. The Van der Burgh's coefficient K and the dispersion coefficient in term of the mixing number α_0 were calibrated to obtain the best fit between simulated and observed salinity data. The calibrated mixing number α_0 is $12.50\ \mathrm{m}^{-1}$. Another parameter, tidal excursion E was also calibrated based on the horizontal distance between the low water slack (LWS) salinity curve and high water slack (HWS) salinity curve. The value for E in this study is assumed to be constant for both surveys. The salinity lengths at LWS for the first and second survey are 18521m and 19637m respectively. The results of salinity curves for Kuantan estuary for first and second survey are shown in Figure 4.4 and 4.5.

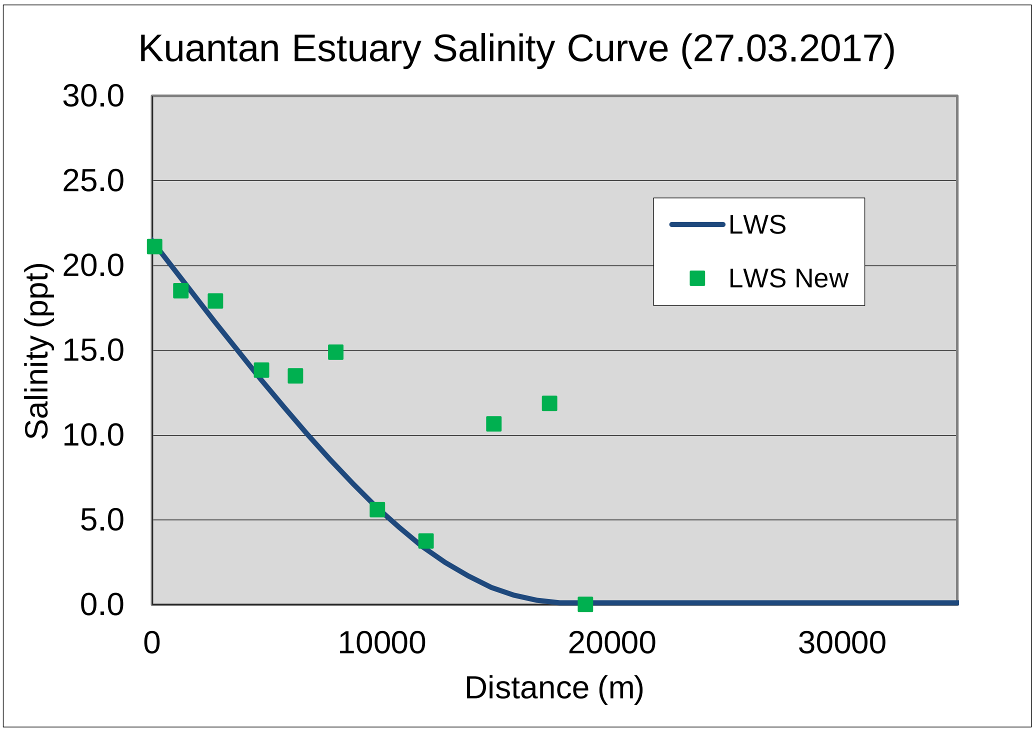

Figure 4.4 Kuantan Estuary Salinity Curve on 27 March 2017

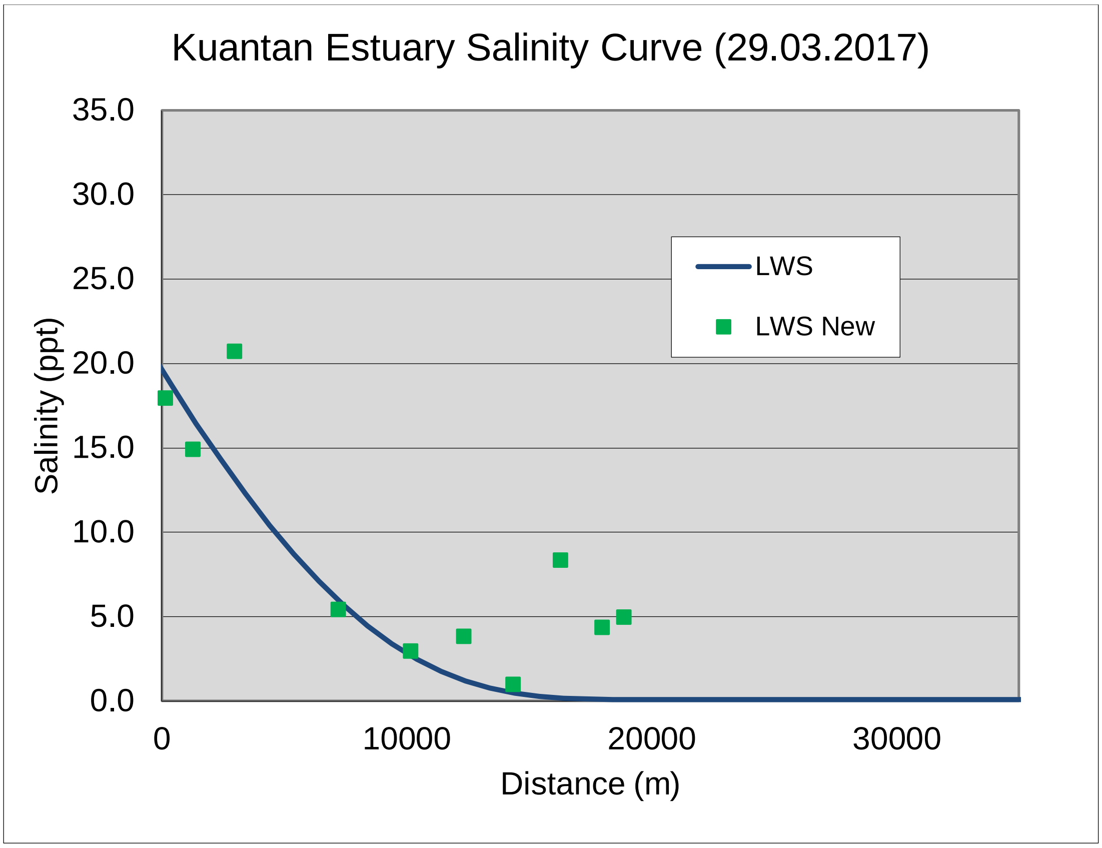

Figure 4.5 Kuantan Estuary Salinity Curve on 29 March 2017

From the calibration the Van der Burgh's coefficient, *K* obtained is 0.40 and this coefficient has been validated based on the results from the second survey. In Figures 4.4 and 4.5, there are some outliers at the distance of 6.50 km from the mouth of the Kuantan Estuary. This can be explained by the existence of a tributary, the Belat River, at this point, thus the saline and fresh water may flow in and out to the Kuantan River from the tributary and affects the salinity data.

4.3 Models Performance

Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) analyses were carried out to evaluate the reliability of the model by comparing the simulated and observed results. The outcome of both error analyses for the survey results conducted on 27 and 29 March 2017 in the Kuantan Estuary are shown in Table 4.2 to 4.5.

Table 4.2 Results of model performance by using Root Mean Square Error (RMSE) for the first measurement

Measurements (27.03.2017)					
$x\ (m)$	Observed Salinity, $O\ (ppt)$	Predicted Salinity, $P\ (ppt)$	$P-O$	$(P-O)^2$	$RMSE$
135	21.13	21.20	0.07	0.00	*5.08*
1273	18.50	19.20	0.70	0.49	
2757	17.91	16.70	-1.21	1.46	
4769	13.83	13.20	-0.63	0.40	
6247	13.50	10.80	-2.70	7.29	
7998	14.88	8.20	-6.68	44.62	
9814	5.60	5.70	0.10	0.01	
11934	3.75	3.20	-0.55	0.30	
14883	10.67	1.00	-9.67	93.51	
17305	11.86	0.20	-11.66	135.96	
18848	0.00	0.10	0.10	0.01	
				284.06	

$$RMSE = \sqrt{\frac{\sum_{i=1}^{11}(284.06)}{11}} = 5.08 \text{ ppt}$$

Table 4.3 Results of model performance by using Root Mean Square Error (RMSE) for the second measurement

Measurements (29.03.2017)					
$x\ (m)$	Observed Salinity, $O\ (ppt)$	Predicted Salinity, $P\ (ppt)$	$P-O$	$(P-O)^2$	$RMSE$
141	17.95	19.30	1.35	1.82	*4.23*
1268	14.90	16.70	1.80	3.24	
2982	20.73	13.10	-7.63	58.22	
7216	5.44	6.00	0.56	0.31	
10153	2.97	2.70	-0.27	0.07	
12327	3.83	1.20	-2.63	6.92	
14347	1.00	0.50	-0.50	0.25	
16289	8.34	0.20	-8.14	66.26	
17975	4.37	0.10	-4.27	18.21	
18871	4.97	0.10	-4.87	23.73	
				179.03	

$$RMSE = \sqrt{\frac{\sum_{i=1}^{10}(179.03)}{10}} = 4.23 \text{ ppt}$$

The RMSE obtained for the first and second measurements are 5.08 ppt and 4.23 ppt respectively. The lower the value for RMSE, the better is the model performance. However, the RMSE that were calculated in both shows higher values. These are due to the outliers at the confluence of Kuantan-Belat River and also at the point where the river bed is deeper contributing to the error of the overall results. Nevertheless, for the rest of the sections, the model still displays good performance.

Table 4.4 Results of model performance by using Nash-Sutcliffe Efficiency (NSE) for the first measurement

Measurements (27.03.2017)					
$x\ (m)$	Observed Salinity, $O\ (ppt)$	Predicted Salinity, $P\ (ppt)$	$P - O$	$(P - O)^2$	NS
135	21.13	21.20	0.07	0.00	*0.98*
1273	18.50	19.20	0.70	0.49	
2757	17.91	16.70	-1.21	1.46	
4769	13.83	13.20	-0.63	0.40	
6247	13.50	10.80	-2.70	7.29	
7998	14.88	8.20	-6.68	44.62	
9814	5.60	5.70	0.10	0.01	
11934	3.75	3.20	-0.55	0.30	
14883	10.67	1.00	-9.67	93.51	
17305	11.86	0.20	-11.66	135.96	
18848	0.00	0.10	0.10	0.01	
	131.63			*284.06*	

$$E = 1 - \frac{\sum_{i=11} 284.06}{\sum_{i=11}\left(131.63 - \frac{131.63}{11}\right)^2} = 0.98$$

Table 4.5 Results of model performance by using Nash-Sutcliffe Efficiency (NSE) for the second measurement

Measurements (29.03.2017)					
$x\ (m)$	Observed Salinity, $O\ (ppt)$	Predicted Salinity, $P\ (ppt)$	$P - O$	$(P - O)^2$	NS
141	17.95	19.30	1.35	1.82	*0.97*
1268	14.90	16.70	1.80	3.24	
2982	20.73	13.10	-7.63	58.22	
7216	5.44	6.00	0.56	0.31	
10153	2.97	2.70	-0.27	0.07	
12327	3.83	1.20	-2.63	6.92	
14347	1.00	0.50	-0.50	0.25	
16289	8.34	0.20	-8.14	66.26	
17975	4.37	0.10	-4.27	18.21	
18871	4.97	0.10	-4.87	23.73	
	84.50			*179.03*	

$$E = 1 - \frac{\sum_{i=10} 179.03}{\sum_{i=10}\left(84.50 - \frac{84.50}{10}\right)^2} = 0.97$$

For the NSE analyses, the values obtained for the first measurement is 0.98 while for the second measurement is 0.97. High NSE values indicate high accuracy in the performance of the model. Nevertheless, the problem faced during the NSE analysis is similar to the RME analysis as outliers are existed at some of the sections. Based on the RMSE and NSE analyses, the overall model performance was good and fit to be used in the salinity study of Kuantan Estuary.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The salinity profile has been simulated successfully and the salinity pattern in the Kuantan Estuary has been developed. This research has verified that 1-D analytical solution is applicable in the Kuantan Estuary. The geometry analysis for the first and second survey showed that the shape of the Kuantan Estuary obeys the exponential function. This study also confirmed that there is a significant change in the downstream cross sectional area after the Kobat Barrage was built. For the tidal mixing mechanism, the salinity pattern in the Kuantan Estuary can be classified as partially-mixed. From the salinity analysis, the Van der Burgh's coefficient, K for the Kuantan estuary was calibrated based on the result of the survey on first survey and was validated based on the second survey giving the values of 0.40. The results from the error analyses also proved the 1-D salt intrusion model is able to simulate the longitudinal salinity distribution in the Kuantan Estuary despite of several explainable outliers. This finding is very useful for water engineer to monitor the salinity condition in the estuary by just using a simple application model.

5.2 Recommendations

There are a few recommendations to improve this research study:

1. More survey should be carried out to obtain higher accuracy of the overall results.

2. More measurements on salinity data should be collected to check the outliers in order to reduce the errors in the model.

3. Discharge measurements should be carried out so that the dispersion coefficient can be validated.

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