RDU160326

# INVESTIGATION OF THE CURRENT SALT INTRUSION CONDITION IN THE KUANTAN ESTUARY AND THE EFFICIENCY OF THE KUANTAN BARRAGE

**(PENYELIDIKAN PENEROBOSAN AIR MASIN SEMASA DI MUARA SUNGAI KUANTAN DAN KEBERKESANAN EMPANGAN KOBAT)**

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# ABSTRACT

Kuantan River has been spotted to have a high potential rate of being affected by salt intrusion issue. A research was conducted to estimate flow discharge in the Kuantan Estuary, to test, calibrate and validate the Van der Burgh coefficient, K and dispersion coefficient, D in the 1-D analytical salt intrusion model, and to verify the salinity condition in the Kuantan Estuary before and after the construction of the barrage. Basin delineation has been done by using GIS approached in collaboration with HEC-GeoHMS. The estimation of flow discharge in the Estuary was carried out by using hydrological modelling, HEC-HMS. Besides that, the study utilised the predictive discharges from the 1-D model for comparison purposes due to data availability issues in the estuary. 1-D analytical salt intrusion model has been adopted in this study to test, calibrate and validate several parameters and the model suitability for the salinity investigation in the estuary. Thus, five field surveys have been conducted in Kuantan Estuary on 27th and 29th March, 3rd October 2017, 7th March, and 15th April 2018. The study for the estuary covered from the mouth of estuary until the reading reached 1ppt but restricted until the Kobat barrage by using moving boat technique. In addition, the study also extended to the Belat Estuary to test the model and study the potential of the tributary. Thus, four surveys in Belat Estuary have been conducted on 26th April, 2nd October 2017, 6th March and 14th April 2018. From the salt intrusion simulation, the Van Der Burgh coefficient, K for Kuantan Estuary and Belat Estuary are 0.45 and 0.5, respectively. The dispersion in Kuantan and Belat Estuary is in the range of 100 to 250 m2/s and 50 to 200 m2/s, respectively. The future low flow in the estuaries was estimated by performing Hydrological Procedure No 12 with 7 days in 50years ARI. The low flow obtained for Kuantan and Belat Estuary is 3 and 61.5m3/s, respectively according to the fraction area. These low flow discharge then utilised in 1-D Salt Model by using the current salinity scheme. The error analyses for HEC-HMS and 1-D Salt Model are performing by using two methods which are NSE and RMSE method. In overall, the 1-D Salt Model demonstrated well in these two estuaries.

# ABSTRAK

Sungai Kuantan didapati mempunyai kadar potensi yang tinggi untuk terjejas oleh isu pencerobohan garam. Satu kajian telah dijalankan untuk menganggarkan aliran keluar di Sungai Kuantan, untuk menguji, menentukur dan mengesahkan pekali Van der Burgh, K dan pekali dispersi, D dalam model analisis pencerobohan garam 1-D, dan untuk mengesahkan keadaan kemasinan di Kuantan Muara sebelum dan selepas pembinaan tambak. Lapisan lintasan telah dilakukan dengan menggunakan GIS mendekati dengan kerjasama HEC-GeoHMS. Pengiraan aliran keluar di Estuary dilakukan dengan menggunakan pemodelan hidrologi, HEC-HMS. Selain itu, kajian ini menggunakan pelepasan ramalan dari model 1-D untuk tujuan perbandingan kerana isu ketersediaan data di muara. Model pencerobohan asid analitik 1-D telah digunakan dalam kajian ini untuk menguji, menentukur dan mengesahkan beberapa parameter dan kesesuaian model untuk penyiasatan kemasinan di muara. Oleh itu, lima tinjauan lapangan telah dijalankan di muara Sungai Kuantan pada 27 Mac, 29 Mac, dan 3 Oktober 2017, kemudian pada tahun berikutnya pada 7 Mac dan 15 April 2018. Kajian untuk muara sungai ini melitupi kawasan dari mulut muara sungai sehingga bacaan mencapai 1ppt tetapi terhad sehingga pintu air Kobat dengan menggunakan teknik perahu bergerak. Di samping itu, kajian ini juga diperluaskan ke Muara Belat untuk menguji model dan mengkaji potensi anak sungai itu. Oleh itu, empat kaji selidik di Muara Belat telah dijalankan pada 26 April, 2 Oktober 2017, serta pada 6 Mac dan 14 April 2018. Daripada simulasi pencerobohan garam, pekali Van Der Burgh, K untuk Muara Kuantan dan Muara Belat adalah 0.45 dan 0.5, masing-masing . Penyebaran di Muara Kuantan dan Belat berada di antara 100 hingga 250 m2 / s dan 50 hingga 200 m2 / s. Aliran rendah masa depan di muara sungai dianggarkan dengan mengaplikasikan Prosedur Hidrologi No 12 dengan anggaran untuk 7 hari aliran rendah dalam 50 tahun ARI. Aliran rendah yang diperolehi untuk Muara Kuantan dan Belat adalah 3 dan 61.5m$^3$ / s, masing-masing mengikut pecahan kawasan. Pelepasan aliran rendah ini kemudian digunakan dalam Model Pencerobohan Garam 1-D dengan menggunakan skim kemasinan semasa sungai-sungai tersebut. Analisis kesilapan antara model hidrologi HEC-HMS dan model pencerobohan garam 1-D dilaksanakan dengan menggunakan dua kaedah iaitu kaedah NSE dan RMSE. Keseluruhannya, Model Garam 1-D telah menunjukkan keputusan yang baik di kedua muara sungai ini.

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| | |
|---|---|
| *A* | *Watershed drainage area, m2* |
| *A* | *Basin area, km²* |
| *A* | *Total watershed area* |
| *A* | *Catchment area, km²* |
| *A* | *Cross-sectional area, m²* |
| $A_0$ | *Cross-sectional area at estuary mouth, m²* |
| $A_1$ | *Cross sectional area at inflection point, m²* |
| $A_t$ | *Cumulative watershed area* |
| $a_1$ | *Cross-sectional convergence length of the seaward reach of estuary, m* |
| $a_2$ | *Cross-sectional convergence length of the landward reach of estuary, m* |
| *B* | *Estuary width, m* |
| $B_0$ | *Width at estuary mouth, m* |
| $B_1$ | *Width at inflection point* $x_1$*,m* |
| $b_1$ | *Width convergence length of the seaward reach of estuary, m* |
| $b_2$ | *Width convergence length of the landward reach of estuary, m* |
| *C* | *Runoff coefficient (dimensionless)* |
| *C* | *Conversion constant ( 2.75 for SI)* |
| $C_p$ | *UH peaking coefficient* |
| $C_u$ | *Unit conversion coefficient* |
| *D* | *Dispersion boundary condition* |
| *D* | *Longitudinal dispersion,* $m^2s^{-1}$ |
| $D_0$ | *Longitudinal dispersion at estuary mouth,* $m^2s^{-1}$ |
| $D_1$ | *Longitudinal dispersion at inflection point* $x_1$*,* $m^2s^{-1}$ |
| *E* | *Tidal excursion* |
| *g* | *gravitational force* |
| *I* | *Design rainfall intensity, m/s* |
| $I_a$ | *Initial abstraction* |
| *K* | *Van der Burgh coefficient (range 0-1)* |
| *L* | *Main stream length, km* |
| *L* | *Salt intrusion length, km* |
| *Nr* | *Richardson number* |
| $O_i$ | *Observed value* |
| $\bar{O}$ | *Average observed value* |
| *P* | *Cumulative rainfall* |
| $P_i$ | *Predicted value* |
| *Q* | *Design discharge, m3/s* |
| *Q* | *Runoff* |
| $Q_B$ | *Baseflow,* $m^3/s$ |
| $Q_f$ | *Freshwater discharge,* $m^3s^{-1}$ |
| *S* | *Maximum of soil water storage potential* |
| *S* | *Weighted slope of main stream, m/km* |
| *S* | *Steady state salinity , kgm⁻³* |
| $S_0$ | *Steady state salinity at estuary mouth,* $kgm^{-3}$ |

| | |
|---|---|
| $S_1$ | *Salinity at inflection point , kgm$^{-3}$* |
| $S_f$ | *Freshwater salinity, kgm$^{-3}$* |
| $T$ | *Tidal period, s* |
| $t_c$ | *Time of concentration of watershed* |
| $v$ | *Velocity amplitude* |
| $x$ | *Distance, m* |
| $x_1$ | *Longitudinal distance, m* |
| $\alpha_1$ | *Mixing number at inflection point $x_1$, m$^{-1}$* |
| $\alpha_0$ | *Mixing number at estuary mouth, m$^{-1}$* |
| $\beta_0$ | *Dispersion reduction rate at the estuary mouth (dimensionless)* |
| $\beta_1$ | *Dispersion reduction rate at the inflection point $x_1$ (dimensionless)* |
| $\rho$ | *Water density, kgm$^{-3}$* |
| $\Delta\rho$ | *Density difference over the intrusion length,ms$^{-2}$* |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| *1-D* | *One-Dimensional* |
| *2-D* | *Two-Dimensional* |
| *3-D* | *Three-Dimensional* |
| *AD* | *Advection Dispersion* |
| *ArcGIS* | *Aeronautical Reconnaissance Coverage Geographic Information System* |
| *CN* | *Curve Number* |
| *DEM* | *Digital Elevation Model* |
| *DID* | *Department of Irrigation and Drainage Malaysia* |
| *GIS* | *Geographic Information System* |
| *HD* | *Hydrodynamic* |
| *HEC* | *Hydrologic Engineering Centre's* |
| *HMS* | *Hydrological Modelling System* |
| *HP-12* | *Hydrological Procedure No. 12* |
| *HP-27* | *Hydrological Procedure No. 27* |
| *HWS* | *High Water Slack* |
| *JUPEM* | *Department of Survey and Mapping Malaysia* |
| *LKIM* | *Lembaga Kemajuan Ikan Malaysia* |
| *LWS* | *Low Water Slack* |
| *MWA* | *Metropolitan Waterworks Authority* |
| *NSE* | *Nash-Sutcliffe Efficiency* |
| *PAIP* | *Pengurusan Air Pahang Berhad* |
| *RMSE* | *Root Mean Square Error* |
| *SCS* | *Soil Conservation Service* |
| *SRTM* | *Shuttle Radar Topography Mission* |
| *SWAT* | *Soil and Water Assessment Tool* |
| *TA* | *Tidal Average* |
| *UH* | *Unit Hydrograph* |
| *USGS* | *United States Geological Survey* |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Estuary connects the ocean and the river system where brackish condition exist. Due to its location, it is generally prone to salt intrusion problem particularly in the arid and semi-arid region. There are many studies have been conducted globally on salt intrusion problem such as along the Bay of Bengal in Bangladesh (Haque, 2006), the Mekong Estuary (A. D. Nguyen, Savenije, Pham, & Tang, 2008), the Pungue Estuary (Graas & Savenije, 2008), the Chao Phraya Estuary (Wongsa, 2015), and the Red River Delta (D. H. Nguyen, Umeyama, & Shintani, 2012). In the 1980s, the agriculture activities in the Mekong River Delta was greatly affected by high salinity during the dry season involving 1.7 to 2.1 million ha out of 3.5 million ha (Ca, 1996). Following to the salt intrusion events, a number of salinity control projects leading to barrage and sluices gates were built in the navigation canals to prevent salt water from entering the delta. However, the salinity has decreased only by 0.8 million ha per year. This phenomenon has caused the fresh water intake activities to be suspended for considerable period of time (varying from several week to months) to prevent the pumping of salty water (A. D. Nguyen et al., 2008). In the Red River Delta, similar problem as the Mekong River Delta was encountered during the dry season. Nevertheless, salt intrusion problem does not occur during the rainy season due to large freshwater discharge from the upstream.

Another significant salt intrusion problem was presented by Wongsa (2015) on the study in the Chao Phraya Estuary, Thailand. Based on previous report from the Metropolitan Waterworks Authority (MWA) Thailand, the salt intrusion issue which affects the raw water supply system in the estuary is mainly caused by uncertain climate change. This phenomenon has severely disturbed the water supply to agriculture area in the lower Chao Phraya River. Besides Thailand and Vietnam, Bangladesh is also greatly affected by salt intrusion during the dry period. Almost 29,000km$^2$ or about 29% of lands in the country are in the coastal region. These coastal areas cover more than 30% of the cultivable lands of the country. Unfortunately, about 53% of them are affected by salinity which consequently causing the normal crop production to be restricted throughout the year (Haque, 2006).

In Malaysia, salt intrusion problem does not give much impacts on agriculture activities but to the commercial and residential water consumptions. Among the earliest studies carried out in the Malaysian Estuaries are the Rompin and Ulu Sedili Besar Estuary. The salt intrusion study in these areas was initiated by The Pahang and Johor State Water Resources Authorities when they discovered the Rompin and Ulu Sedili Besar River as potential water resources points. In 2008, another study was carried out by Breemen (2008) in the Selangor Estuary due to strong demand of fresh water and rapid economic development in Selangor and Kuala Lumpur that weakened the natural state of estuary by salt intrusion. The latest study was conducted by Gisen, Savenije, and Nijzink (2015) which involves six estuaries in Malaysia including the Kurau, Perak, Bernam, Selangor, Muar and Endau Estuary. Similar to the global water supply concern, during the drought season, the fresh water discharge from the upstream of the basin are usually low forcing the water intake stations to be located as downstream as possible to accumulate more water volume. Therefore, the downstream of the rivers are subjected to tidal intrusion and river discharge which promotes saline intrusion further upstream (Breemen, 2008). Other than these three estuaries, another salt intrusion case study that worth highlighted is the Kuantan River Estuary. In the 1970's, the water intake station located at Kg. Kobat, Kuantan was threatened by salt intrusion. As a result, the Malaysia Economic Planning Unit had appointed a study to be carried out to identify the salinity condition in the Kuantan estuaries along with a solution to prevent the pumping of salt water. The study by Farleigh (1978) reported that the salt water from the sea travels about 32 km upstream during the dry period at spring tide, while the Kg. Kobat intake station is located at 17 km from the mouth. Hence, a barrage was built near Kg. Kobat to control the salt water from moving further upstream.

Despite the restriction in water supply, high and rapid changes in salinity concentration also destroy the ecosystem in estuaries. Salinity problem increased with the climate change and its associated dangers such as sea level rise, hurricanes and storms have worsen the saltwater intrusion issue in many coastal areas worldwide. Changes in salinity level is sensitive for some living organisms in the estuarine region especially mangroves and fireflies. Certain species can only survive with a certain level of salinity (Feller & Sitnik, 1996). Fireflies are among the most sensitive species to salinity changes and when this happens the chances for them to live and breed is declined (Breemen, 2008). According to Breemen, changes in salinity may retard the growth of Berembang trees *(sonneratia caseolaris)*, which serve as the natural breeding and displaying grounds for fireflies. There are 11 mangrove species available around the Kuantan Estuary mainly are *Sonneratia alba* and *Rhizophora mucronata* (Shahbudin, Zuhairi, Kamaruzzaman, & Jalal, 2009). Mangroves function as natural shore refuge measure where its roots have the ability to dissipate wave energy, which give sheltered nursery to assorted marine and terrestrial flora and fauna (Jalal, Azfar, John, Kamaruzzaman, & Shahbudin, 2012). Other than mangroves environment, the development of fish is also depends on saltiness changes (Jalal et al., 2012). Dasgupta, Kamal, Khan, Choudhury, and Nishat (2014) found that the productivity of a number of captured fresh water fish and giant freshwater prawn species experienced adverse effect due to salt intrusion problem. Salinity affects the fresh water supply and destroys the spawning ground (Akhter, Hasan, & Khan, 2012).

Since salt intrusion problem is crucial for agriculture activities, fresh water supply, and the flora and fauna in an estuarine region, it is essential to monitor the salinity condition in the downstream or delta areas. This is to ensure the sustainability of the estuarine ecosystem as a whole.

## 1.2 Problem Statement

In Malaysia, salinity problem received very little attention in the past because of the high rainfall climate in this region. However, the global warming phenomenon and uncertain climate change have forced the Malaysian government to identify the estuaries affected by saline intrusion whenever a water supply project is to be started. In the recent years between March 2016 to August 2016, Malaysia has been greatly hit by the El-Nino phenomenon, in which the entire states experienced higher temperature and drier weather compare to the past years. This extreme dry season (El-Nino) has decrease the rainfall frequency drastically in this region. As the consequences in April 2016, the public complained that the water distributed to their premises in the Kuantan City and Pekan Town has a slight salty aftertaste as reported in Figure 1.1. In responds to this matter, the water authority, Pengurusan Air Pahang Berhad (PAIP) issued a circular notice to the public as shown in Figure 1.2 claiming the extreme low flow from the upstream has induced salt water intrusion from the tide causing the pumping of salt water into Kg. Kobat water treatment plant. Additionally, the failure of the embankment that was constructed to limit the intrusion length is another factor contributes to salt water problem at the area. Since the fresh water demand is increasing with the population growth, the study of salt intrusion in the Kuantan River is needed in order to prevent the recurrence of the issue.

36 Sinar Harian • Jumaat 29 April 2016

SENTRAL

HUBUNGI SKUAD SENTRAL:
ASWANY OMAR- 019-9882695

# Bekalan air bersih masin, payau

Adun Teruntum mahu Paip siasat segera masalah yang didakwa melanda tiga kawasan itu

NORAWAZNI YUSOF

KUANTAN - Penduduk di tiga kawasan di daerah ini merungut dan mendakwa bekalan air di rumah mereka masin dan payau akibat cuaca panas yang melanda negara sejak Mac lalu.

Kawasan terlibat ialah Bukit Setongkol, Air Putih dan taman perumahan di sekitar Jalan Haji Ahmad.

Tinjauan *Sinar Harian* ke kawasan terbabit mendapati mendapati dakwaan penduduk itu ada asasnya apabila air yang diminun terasa masin walaupun ditapis terlebih dahulu.

Adun Teruntum, Sim Chon Siang berkata, beliau menyedari masalah itu kelmarin.

Katanya, beliau terkejut apabila air diminumnya terasa masin dan segera bertanya kepada ahli keluarga dan jirannya sama ada mereka mengalami masalah sama.

"Apabila saya tanya jiran, semua kata air ada rasa berbeza berbanding sebelum ini. Mereka kata ada rasa payau dan sedikit masin.

"Ini air yang saya rasa selepas bekalan itu ditapis, bayangkan kalau bekalan air tersebut tak ditapis semestinya rasa payau dan masin itu lebih ketara," katanya.

Beliau berkata demikian kepada pemberita ketika ditemui di Pejabat Pengurusan Air Paip Berhad (Paip), di sini semalam.

Chon Siang berkata, setakat ini beliau menerima enam aduan daripada penduduk di tiga kawasan terbabit mengenai masalah itu.

Menurutnya, aduan telah dibuat kepada Paip kelmarin namun masih tiada maklum balas diterima.

"Saya hanya mahu tahu punca kenapa air ini berubah menjadi payau dan masin. Ini perlu diperjelaskan oleh Paip kerana kesemua pengguna di Pahang menggunakan bekalan air bersih yang disalurkan oleh agensi itu.

"Saya bimbang jika perkara ini berlarutan ia pasti boleh mengundang bahaya kepada pengguna sekiranya bekalan air tersebut tercemar tetapi masih disalurkan," katanya.

Chon Siang berkata, beliau mengunjungi pejabat Paip semalam untuk meminta penjelasan mengenai perkara itu namun pegawai terlibat sedang bermesyuarat.

Katanya, beliau mahu pihak terbabit menyiasat punca masalah itu.

"Kita beri tempoh untuk Paip cari punca masalah ini dan saya akan ambil sampel air untuk mereka rasa serta kaji masalah ini," katanya.

YUEH SOON

Sementara itu, penduduk di kawasan Bukit Setongkol, Chen Yueh Soon, 76, berkata, dia sekeluarga terkejut apabila mendapati bekalan air yang disalurkan ke rumahnya masin.

Katanya, masalah berkenaan disedari sejak seminggu lalu.

"Mula-mula saya ingat rasa itu perkara biasa, tetapi setelah anak-anak mengadu ada terasa berbeza pada air itu saya segera membuat aduan kepada YB Sim. Saya juga tidak menyangka YB Sim juga mengalami masalah yang sama," katanya.

Yueh Soon berkata, dia berharap Paip segera menyelesaikan masalah air itu kerana bimbang kesihatan pengguna terlibat akan terjejas.

Chon Siang mengambil sampel air bersih yang didakwa mempunyai rasa masin untuk diserahkan kepada Paip.

Figure 1.1 Report on public complained

Source: Yusof (2016)

According to the news reported on 29th April 2016, the residents in three areas in the district complained that the water supply at their homes is salty and brackish during the hot weather that hit the country since March. The residential areas involved are Bukit Setongkol, Air Putih and Jalan Haji Ahmad.

**KENYATAAN MEDIA**
**Siaran Segera**

**Air Terawat Masih Selamat Diminum**

Pengurusan Air Pahang Berhad (PAIP) ingin mengesahkan bahawa bekalan air terawat yang dibekalkan masih selamat untuk diminum. Pihak PAIP telah mengesan sedikit kemasukan air masin pada tempoh yang singkat sewaktu air laut pasang ke dalam muka sauk di Kobat. Hal ini disebabkan keadaan paras air sungai Kuantan di muka sauk adalah sangat rendah akibat kesan fenomena *El Nino*.

Bagi mengatasi perkara ini, paras air sungai sedang ditingkatkan dengan pelepasan air dari Empangan Chereh. Di samping itu, paras air sungai di Loji Rawatan Air (LRA) Panching juga berada di paras yang rendah dan menyebabkan kapasiti pengeluaran loji menurun. Gangguan bekalan air akan berlaku kepada pengguna-pengguna di kawasan yang mendapat bekalan air dari loji tersebut.

Pihak PAIP menjangkakan keadaan akan pulih apabila paras air sungai dapat ditingkatkan dan keadaan ini sedang dipantau dari semasa ke semasa.

Pengguna juga dinasihatkan agar menggunakan air secara berhemah dan menyimpan bekalan air secukupnya sepanjang tempoh fenomena *El Nino*. Pengguna yang ada sebarang pertanyaan boleh menghubungi talian Pusat Khidmat Pelanggan (PULAPEL), di talian 09-573 9999.#

**SEKIAN, TERIMA KASIH**

PENGURUSAN AIR PAHANG BERHAD

***'Air Penjana Pembangunan'***

Dikeluarkan oleh :

**Nurul Farhana Binti Abdul Hamid**
**Pegawai Perhubungan Awam dan Komunikasi Korporat**

**Kenyataan Media PAIP, 29 April 2016**

Figure 1.2 Circular notice for public assurance
Source: PAIP (2016)

In responds to the issue, PAIP held a press conference on 29th April 2016 to clarify that there was a slight salt water intrusion detected in the intakes area at Kobat due to impact of El-Nino phenomenon which causing extremely low fresh water discharge. However, PAIP confirmed that the treated water supplied is safe to drink.

## 1.3 Objectives of Study

The objectives of this research are as follows:

1. To estimate flow discharge in the Kuantan Estuary.
2. To test, calibrate and validate the Van der Burgh coefficient, K and dispersion coefficient, D in the 1-D analytical salt intrusion model.
3. To verify the salinity condition in the Kuantan Estuary before and after the construction of the barrage.

## 1.4 Scope of Study

The study area of this research covers the tidal region of Kuantan Estuary from the mouth until the upstream of the barrage at Kobat and also the Belat tributary. Field measurements were carried out during the dry period at spring tide as salt intrusion is most crucial when there is the least of rainfall. It is worth to note that neap tide measurement was not considered in this study because the timing of the slack moment occurred at night time and during the dawn which make the field work impossible to conduct. This research required a considerable amount of data collection activities, including primary and secondary data 1) primary data: field observation data 2) secondary data: readily available topography and hydrological data. The topography map and hydrological data were purchased from the Department of Survey and Mapping, and Department of Irrigation and Drainage Malaysia. Field observations data collected are the cross-sectional area (width and depth) and salinity data. Hydrological Modelling System (HEC-HMS) collaborated with Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS) were used in order to estimate freshwater discharge in the Kuantan River. The digital elevation model (DEM) used in ArcGIS is the shuttle radar topography mission (SRTM) with 30m resolution, while the transformation method used in HEC-HMS is the Muskingam Method for routing hydrographs through stream reaches in HEC-HMS. For the salt intrusion modelling, the geometry and salinity analyses were carried out by adopting the theory developed by Hubert H.G. Savenije (1986) which claimed that the cross-sectional area and width of an estuary can be expressed in an exponential function. Both the geometry and salinity analyses were performed in reference to tidally average condition. The 1D-analytical salt intrusion model and its predictive equations by Hubert H.G. Savenije (1986); H. H. G. Savenije (1989, 1993, 2012) was considered only for the steady state condition.

## 1.5 Significance of Study

Construction of barrage is one of the most efficient approach to solve salt intrusion problem at affected water abstraction station. However, restriction of salt water flow upstream increased the salinity concentration at the downstream area. This condition is worsen with the extreme dry season which increase the surface evaporation, and subsequently induced hyper saline situation. Thus, this research is important to evaluate the current salinity condition. Furthermore, the outcome of this study can become a reference to update the gate opening frequency of the Kuantan Barrage based on current salinity condition. Hence, carrying out new study in the Kuantan Estuary is essential to monitor and evaluate the water quality resulted from the barrage construction in the late 1970's. Moreover, the collection of updated data on the morphology, tidal dynamics and salinity in Kuantan Estuary can contribute to the Malaysian Estuaries management database initiatedhec by  Gisen, Savenije, Nijzink, and Abd. Wahab (2015).

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Estuaries

Estuary is located between the fresh water river system and Open Ocean which is an important coastal environment. The word "estuary' is originated from the Latin word *aestuarium*, which refer to "tidal" (Pinet, 2006). According to Pritchard and Donald (1967), the water salt water in estuaries is quantifiably weakened with flushing freshwater from the land waste. Kjerfve and Magill (1989) claimed that estuaries is a coastal indentation that has a limited connection with the seas, stays open at any rate discontinuously and has a tidal stream zone, a mixing zone, and a nearshore turbid zone. Estuaries have strong salinity gradient zone from land to sea.

Estuaries comes in many shapes and shape with varies distinctive names, for example, lakes, (shallow) harbors lagoons, bays, rivers or inlets. Sydney Harbor and Broken Bay are example of deep harbors which are drowned river valleys. According to H. H. G. Savenije (2012), the banks, flow of water, sediment transport, and sporadic floods are the typical characteristic of riverine of an estuary. Meanwhile, the tides and salinity are the typical characteristics of marine side. Tides, waves, river discharge, littoral sediment transport and difference in density  between the salt water and fresh water are the combination of driving forces around its vicinity are the key to determine the shape of estuary (Gisen, 2014).

### 2.1.1 Mixing Classification

The mixing classification in estuary is considered as the competition between the buoyancy force from stream release and mixing from tidal constrain. The tidal forcing of mixing in estuaries are relative to the amount of seawater volume entering the estuary during each tidal cycle which is known as the tidal prism (Valle-Levinson, 2010). There are three types of mixing classification which are highly stratified or salt wedge, partially mixed and well-mixed estuary as illustrated in Figure 2.1. Highly stratified or salt wedge estuaries are the point in which the fast stream waterway releases water into the sea as the tidal forces are weak. The two water masses will not mix with weak tidal currents in salt wedge estuary as they are separated by a sharp and stable halocline (Pinet, 2006). The Columbia River in Washington and Oregon, Hudson River in New York and Mississippi River in Louisiana are among the salt-wedge estuaries in the world. Partially-mixed estuaries are where the seawater and fresh water are mixed at all depth yet the lower layer remain saltier than the upper layers. The salinity is higher at the mouth of estuaries and decreases when it flows to the upstream. According to Ross (1995), the San Francisco Estuary in California and Puget Sound Estuary in Washington are among the deep estuaries that are slightly stratified. Well-mixed estuary happens when the flow of river is low while tidally created ebbs and floods are moderate to strong (Ross, 1995). In well-mixed condition, the vertical salinity levels at a point are the same from the top to the base of the estuary. The vertical layer that separate the freshwater and seawater are eliminated by the strong tidal currents and the salinity controlled by daily tidal stage. This type of mixing is found in extensive and shallow estuaries, for example, Delaware Bay.

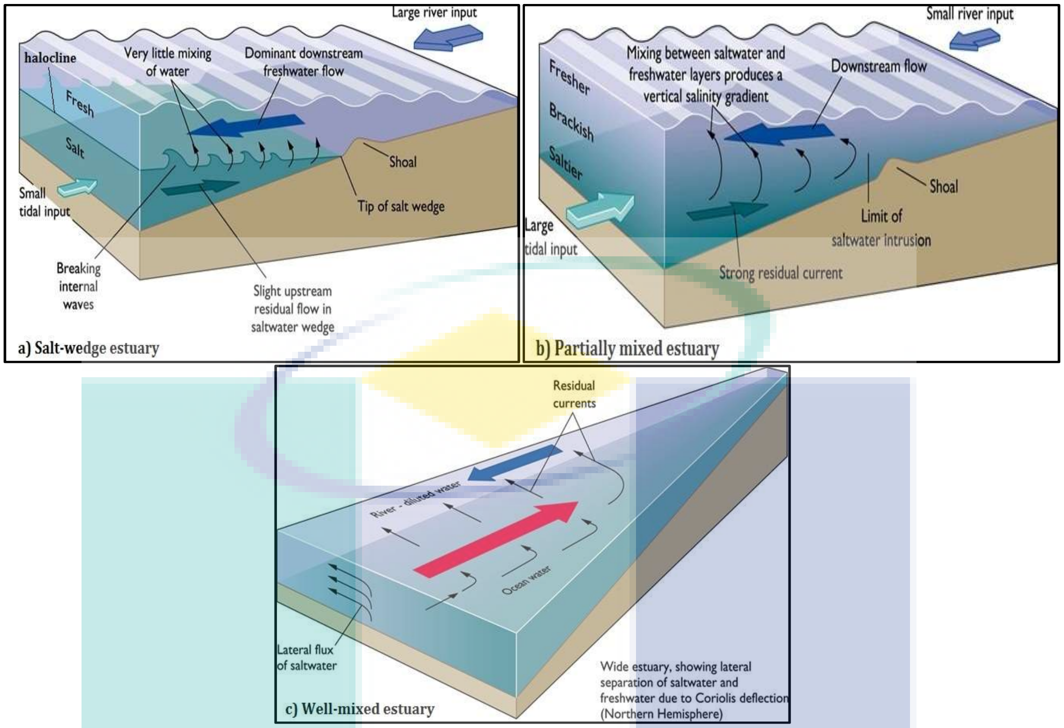



Figure 2.1 The mixing classification in estuary a) Salt-wedge estuary b) Partially mixed estuary c) Well-mixed estuary
Source: Pinet (2006)

### 2.1.2 Salinity

Salinity is a measurement of salt substance in a water. In estuaries, the salinity levels depend on the mixing of the freshwater from the waterway and saltwater from the sea. Generally, the salinity levels will increase along a coastal stream as it gets nearer to the mouth of river because it is influenced by the tide. The density of saltwater is higher than freshwater, thus it will sink to the bottom of the estuary and will cause the bottom become more saline than the surface water. This condition will affect the aquatic life in the estuary because numerous estuarine species can survive within certain range of salinity. The salinity has been conventionally expressed as parts per million or parts per thousand (Morse & Mackenzie, 1990). The salinity index illustrated in Figure 2.2.

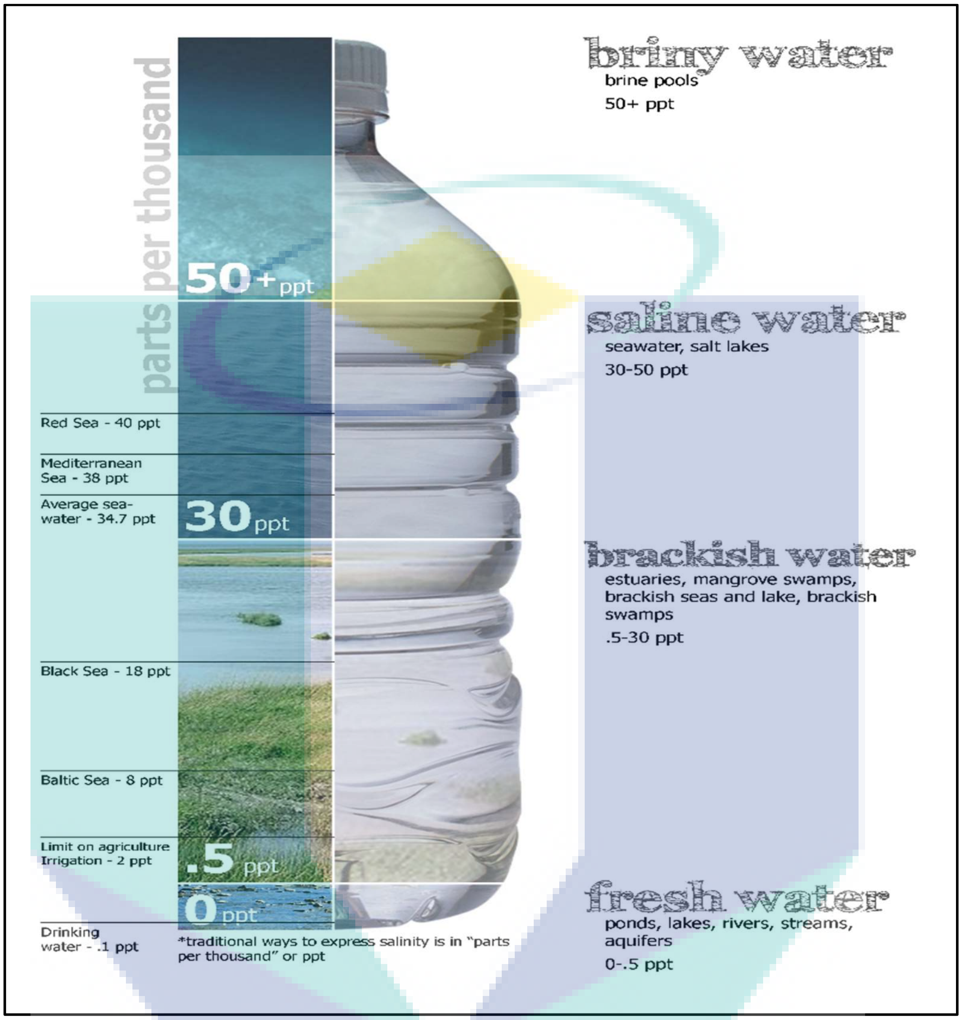



Figure 2.2 Salinity index

Source: Summerlin (2011)

### 2.1.3 Importance of estuaries

The characteristics of estuary are suitable for unique plant and animal communities such as mangroves and brackish water crocodiles. An estuary also provides ecosystem services and functions such as natural filters for runoff and acts as nursery grounds to numerous types of birds, fish and other animals. The estuarine region includes shallow open waters, freshwater and saltwater marshes, swamps, sandy shoreline, mud and sand flats, rocky shores, mangroves forests, river deltas, tidal pools and seagrass beds as shown in Figure 2.3. In the United States, the National Estuarine Research Reserve System were established to manage and monitor 29 estuarine network to provide study areas for long-term research, water quality and habitat monitoring, education, and coastal stewardship (NOAA, 2017). These reserved estuarine give the fundamental natural surroundings to untamed animals life, offer the opportunities for understudies to investigate, and fill in as living research station for researchers.

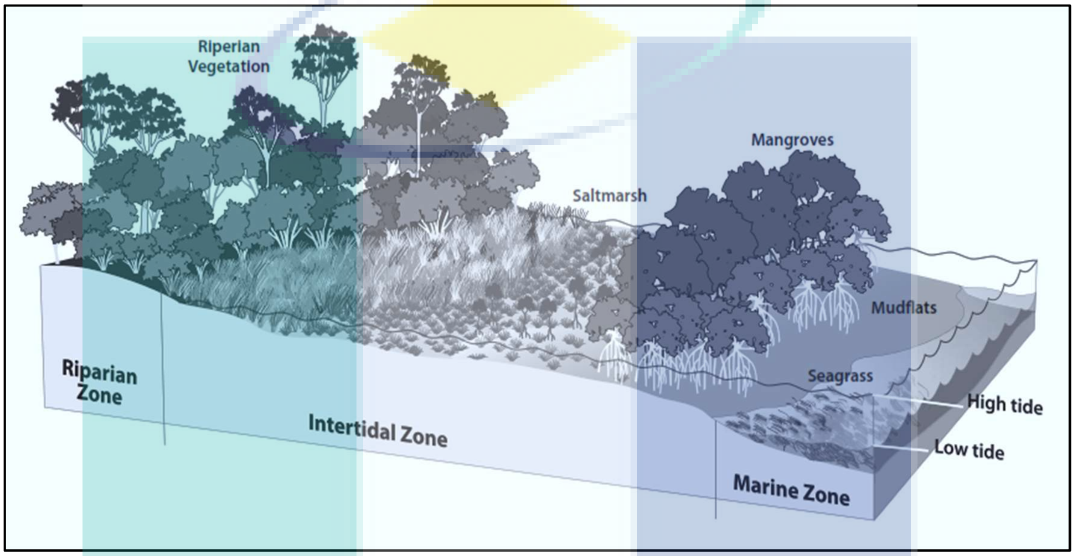



Figure 2.3 Estuarine habitat
Source: Waterwatch (2010)

Seagrass and animal species such as sea slugs, squid, octopus, cuttlefish, prawns, pipe fish, seahorses, weedy seadragons, numerous type of crab and fish usually lives in the marine zone which is open to the ocean. At the upstream of the marine zone, the region is known as the intertidal zone. In this zone, several types of plants such as mangroves and saltmarsh can be found. The sand and mudflats region have become the habitats for several animal species such as snails, cockles, flatworms, ragworms, many types of crabs, little sand-dwelling macroinvertebrates. Estuaries species for example mangrove air breather, snails, whelks, numerous types of crabs, oysters, isopods and fish are living at the mangroves area which is brackish and occasionally dry. In the saltmarsh area, the low salinity condition is suitable for snails, crabs, birds including transitory birds, fish. The distribution of living organisms in different zones of estuary is shown in Figure 2.4.

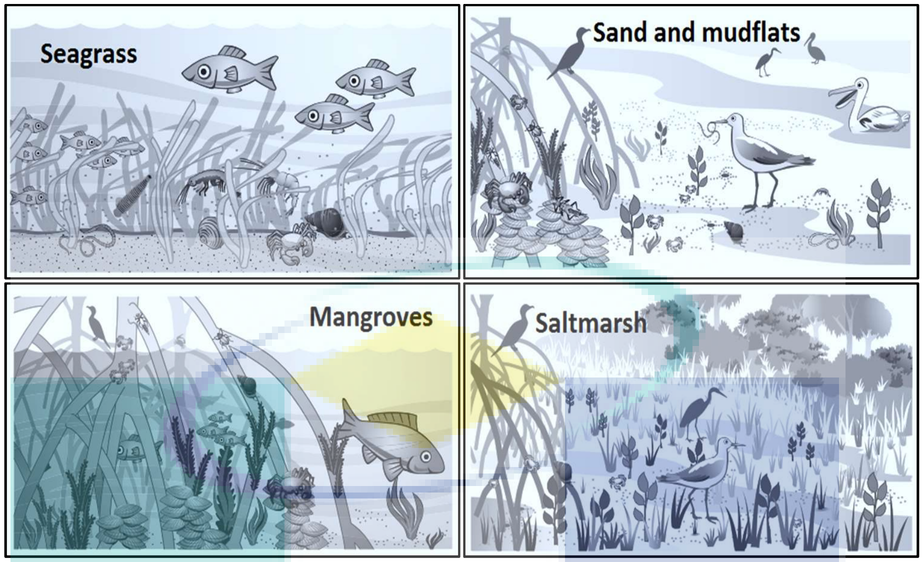



Figure 2.4 Distribution of living organisms in estuaries
Source: Waterwatch (2010)

## 2.2 Tides

Tides are the cyclic rise and fall of seawater that are brought on by the slight variety of the gravitational attraction between the earth and the moon and the geometric relationship with the sun to the locations on Earth's surface (Pidwirny, 2006). The gravitational pull is constantly changing due to earth's rotation which lead to daily tidal cycles. The tidal range in estuary is one of the factors that influence the shoreline condition which explained by (Davies, 1964) and (Dyer, 1997) and illustrated as in Figure 2.5:

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

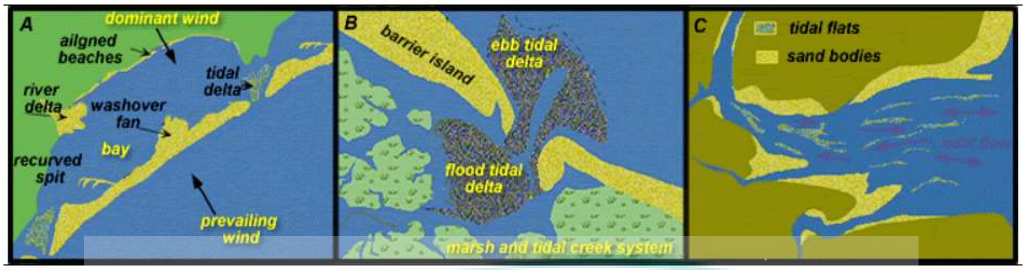



Figure 2.5 Estuary models a) Microtidal b) mesotidal c) macrotidal
Source: Hayes and Kana (1976)

### 2.2.1 Types of tidal

The gravitational forces of sun and moon are maximized during full moon or new moon phases that produced large range of high and low tidal level called spring tides. This phenomenon happens when the earth, sun and moon are in line. On the other hand, neap tides occur when the gravitational forces of sun and moon are at their minimum during the quarter moon phases in which the range of high and low tidal level is small. Neap tides occur twice a month during the first and third quarters of the moon. There are three types of tidal oscillations namely diurnal, semi diurnal and mixed tide. Figure 2.6 shows the tidal oscillations distribution at the coastline around the world.

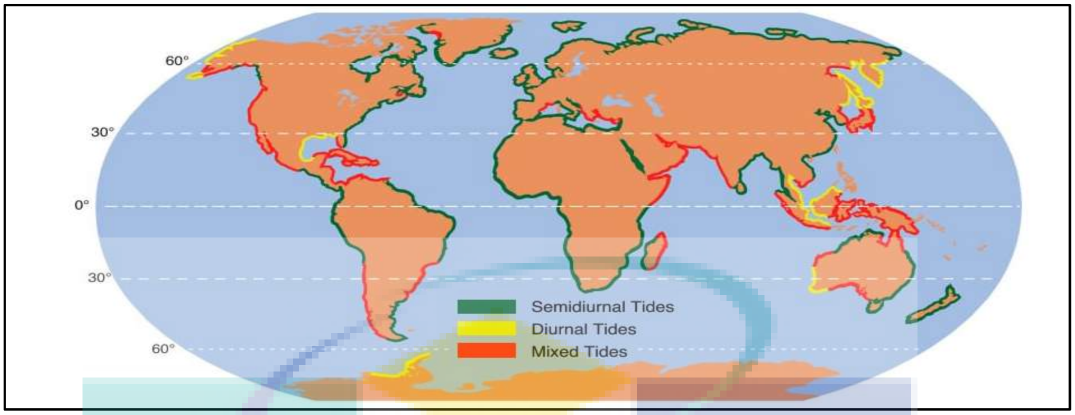



Figure 2.6 Global tidal oscillations map
Source: Pidwirny (2006)

#### 2.2.1.1 Diurnal tide

Diurnal tidal cycle is described by a single high tide and low tide at every 24 hours and 50 minutes. This tide usually occur in partially enclosed basins, such as the Gulf of Mexico and on the East Coast of the Kamchatka Peninsula. Figure 2.7 shows the tidal level over time for a diurnal tidal cycle.

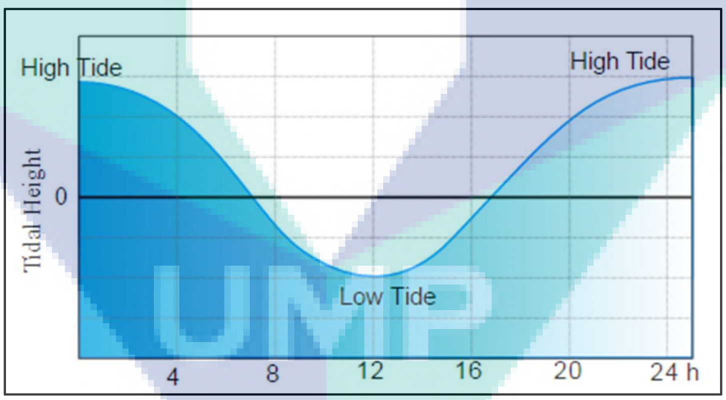



Figure 2.7 Tidal level for a diurnal tidal cycle
Source: Ingo (2016)

#### 2.2.1.2 Semidiurnal tide

A semidiurnal tide occurs in a region that encounter two nearly equivalent high and low tides in each lunar day. The wavelength of this tidal pattern are more than half the circumference of earth with a period of 12 hours and 25 min (NASA, 2005). Referring to Figure 2.8, it can be seen that most places experience semidiurnal tidal cycle. The following diagram shows the sea level change over time for a typical semidiurnal tidal cycle.

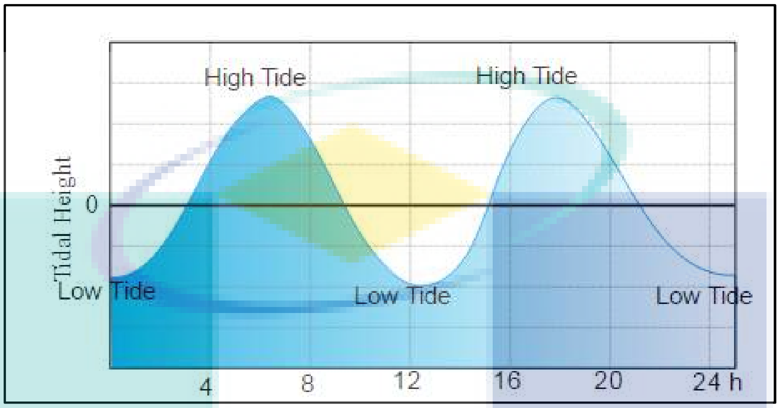



Figure 2.8 Tidal level for a semidiurnal tidal cycle
Source: Ingo (2016)

#### 2.2.1.3 Mixed tide

A mixed tidal cycle can be described by two high tides and two low tides contrast in tidal range within each lunar day. The distinction in height between progressive high (or low) tides is called the diurnal inequality as illustrated in Figure 2.9. Areas with a mixed tidal cycle can be found alongside the Alaska, Hawaii, and West cost of the North America, West cost of the USA, in parts of Australia and in South East Asia.

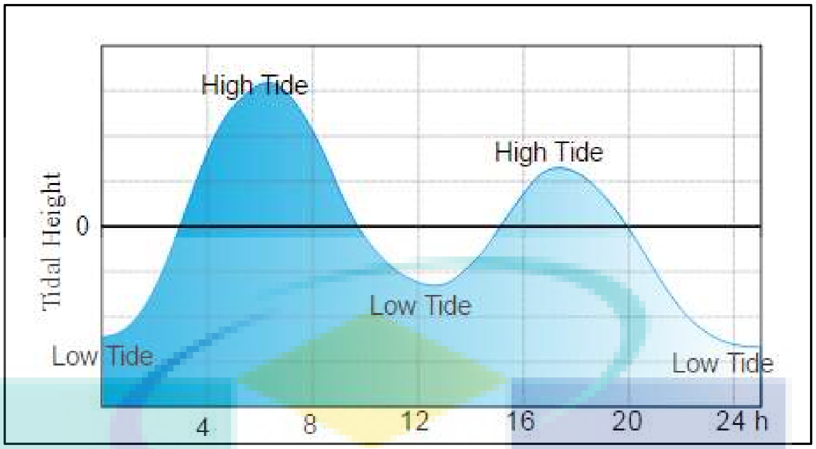



Figure 2.9 Tidal level for a mixed tidal cycle
Source: Ingo (2016)

### 2.2.2 Tidal slack

There are two types of tidal slack in estuary namely the high water slack (HWS) and low water slack (LWS). Slack water usually happens about 30 minutes to an hour after the high and low water just before the tide changes its directions. During the slack moment, the flow velocity is zero and the water is stagnant. The relationship between slack water and tidal stages fluctuates is based on localities. HWS are the situation where the water surface is slightly below the highest level, whereas LWS occur after water level is slightly above the lowest level (Gisen, Savenije, Nijzink, et al., 2015).

## 2.3 Geographical Study

Geography is study on the relationship between the social sciences (human geography) and the natural sciences (physical geography). The historical traditions in geographical research includes spatial analyses of natural and the human phenomena, area studies of places and regions, studies of human-land relationships, and the Earth sciences.

### 2.3.1 Geographic Information System (GIS)

GIS is a system for collecting, storing, analysing and disseminating data of a certain areas. The GIS system can be characterized by the relation:

$$\text{GIS} = \text{Geographic} + \text{Information system} \tag{2.1}$$

In the geographic element, the information needed is such as the satellite data usually presented in DEM format. GIS provide a platform to undertake the task for geographic data management, information arrangement and editing, mapping and representation and geographic analysis.

The collected information stored in GIS is presented in terms of layers. In the geographic analysis, different layers of information is combined and overlap in the GIS platform to interpret and investigate the characteristics of the study area. With GIS, a better conclusion can be obtained from analysing the interaction between different types of data (Terefe, 2010).

#### 2.3.1.1 Function of ArcMap and ArcCatalog

The primary application in ArcGIS Desktop is ArcMap application which work as a platform to display and control geographic information, including mapping, query and selection, and editing. ArcMap can be used to run map documents which composed of information frames, layers, symbols, labels and geographic items. ArcCatalog is an application that helps user to store and manage the information of GIS such as datasets, map documents, and layer files. Additionally, it is also used to sort GIS contents, manage geodatabase schemes, search and add content to ArcGIS server, and manage standard-based metadata. GIS data comes in an assortment of information formats and document types (Elangovan, 2006).

#### 2.3.1.2 Components in GIS

There are three general components of GIS as explained by Shamsi (2009) which are:

i) Geometry

This parts represents the real world areas with geographic components, for example, hydrants and water mains which are presented as points and lines. Information represents the geometry of components are additionally alluded as the geographic, spatial or geospatial information.

ii) Attribute

This parts gives graphic information about the geographic elements, for example, water main diameter.

iii) Behaviour

This parts characterizes the rules that geographic components must follow, for example, hydrant should not exist without a water main.

### 2.3.2 HEC-GeoHMS

HEC-GeoHMS is a public-domain software package that is compatible with the ArcGIS. This software package is collaborated within the Spatial Analyst function in ArcGIS to build up various number of hydrologic modelling inputs. HEC-GeoHMS analysed the digital terrain by changing the drainage paths and watershed boundaries into hydrologic information structure that represents the watershed response to precipitation. Besides hydrologic information structure, HEC-GeoHMS are able to develop a grid-based data for the linear quasi-distributed runoff transformation (ModClark), HEC-HMS basin model, physical watershed and stream attributes, and background map file (Maidment & Djokic, 2000). The latest version of HEC-GeoHMS is able to generate a background map file, lumped basin model, a grid cell parameter file, and a distributed basin model. The background map file contains the stream arrangements and sub basin boundaries. The water movement through drainage system are presented in lumped basin model which contains hydrologic components and its connectivity. The lumped basin file incorporates watershed area, and reserves empty fields for hydrologic parameters. The tables containing physical characteristics of streams and watersheds can be produced to assist in estimating hydrologic parameters. Additional interactive permit user to build a hydrologic schematic of the watershed at stream gages, hydraulic structures, and other control points. Physical characteristics of the river and watershed are processed and used to estimate hydrologic parameters. The hydrologic output from HEC-GeoHMS then imported to HEC-HMS, where simulation are performed.

## 2.4 Hydrological Study

Hydrological study is the scientific investigation on the water movement, distribution, and quality including the water cycle, water resources and nature watershed sustainability. Most of hydrological research nowadays are focused on a modelling approach for a simplified, representative and logical presentation of a hydrological system (Salih & Hamid, 2017). This approach merged a topographical information, site investigations, hydrological data, flow surveys, rainfall data, geological information and historical data to determine the extent of catchment areas contributing runoff, and the flows in a stream and drainage systems.

### 2.4.1 HEC-HMS

HEC-HMS is a software and tool used in analysing, planning and simulating the process of rainfall and runoff. It is a new program of hydrological modelling from Hydrologic Engineering Centre's (HEC) to simulate the hydrological process of the watershed system (Ramli & Harun, 2009). HEC-HMS accompanies with ArcMap extension through the full exploitation of GIS hydrographic delineation capabilities automates the model development info and particularly the averaging the type of soil and land cover properties, topography and local drainage delineation (Pistocchi & Mazzoli, 2002). Hydrological modelling reveals how precipitation responds to natural watershed runoff for example the peak discharge, quantity of runoff and detention (Chu & Steinman, 2009).

#### 2.4.1.1 Methods to analyze rainfall-runoff relationship

There are several methods available in HEC-HMS to perform the transformation of rainfall data to runoff data. The methods are described as follows;

*Peak Discharge Method*

Peak Discharge Method is used to analyse the data of rainfall and runoff and this method also can determine the peak discharge for the watershed, the number of curves, time of concentration and depth and volume of runoff and the area of the watershed. This method only effective for watershed which the area more than 2000 acres in size. Peak Discharge Method is one of the best methods to solve the flooding through hydrograph as the hydrograph can be used as flood prediction which are also called Slope-Area Method. The total volume of runoff is computed from the uniform-flow equation.

*Rational Method*

Rational method are among the simplest methods to minimize, control and estimate runoff from small watershed (Thompson, 2006). This method is only effective for watershed in the urban areas that is less than 200 acres. However, this method is not suitable for constructing discharge hydrograph and routing rainfall through the watershed as it only produces the peak discharge. Basically, rational method is related to design discharge, design rainfall intensity and washed drainage area. The combination of these elements produces simple formula:

$$Q = CuCiA \qquad 2.2$$

| | | | |
|---|---|---|---|
| Where, | Q | = | Design discharge (m3/s) |
| | Cu | = | Unit conversion coefficient |
| | A | = | Watershed drainage area (m2) |
| | I | = | Design rainfall intensity (m/s) |
| | C | = | Runoff coefficient (dimensionless) |

*Synthetic Unit Hydrograph Method*

Synthetic Unit Hydrograph Method can be defined as the parametric Unit Hydrograph (UH) with the characteristic of the watershed. UH can be developed from the condition of the watershed for a certain time period. For example, all synthetic unit hydrograph is related to peak UH of drainage area to watershed hydrograph. Unit Hydrograph can be called as synthetic when total time base of UH is same with time of UH peak. Hence, rainfall and runoff data is very important in deriving a unit hydrograph. There are 3 categories of Synthetic Unit Hydrograph which is Snyder's UH (based on characteristics of UH), SCS UH (relate to dimensionless of UH) and Clark's UH which is related to quasi-conceptual of watershed storage.

i. Snyder's Unit Hydrograph Method

Snyder's Synthetic Unit Hydrograph involves three hydrograph characteristic such as effective rainfall duration, $t_r$ basin lag time, $t_l$ and peak direct runoff rate $Q_p$ (Ramirez, 2000). From the relationship between basin lag and peak flow, effective rainfall duration can be defined. Snyder states that effective rainfall duration, $t_r$ related to basin lag time, $t_l$.

$$t_1 = 5.5t_r \qquad 2.3$$

For the standard unit hydrograph, the peak discharge, $Q_p$ is defined by the relationship;

$$Q_p = C\, C_p\, A/t_1 \qquad 2.4$$

Where, A = Basin area, $km^2$
C = Conversion constant ( 2.75 for SI)
$C_p$ = UH peaking coefficient

ii. Soil Conservation Service (SCS) Unit Hydrograph

Soil Conservation Service Unit Hydrograph Method also known as SCS runoff curve number method is one of the methods utilized as part of Unit Hydrograph. According to United State Department of Agriculture Soil Conservation Service, this method separated into four parts which is runoff (Q), cumulative rainfall(P), initial abstraction ($I_a$) and maximum of soil water storage potential (S) (Cronshey, 1986). The equation of SCS runoff is shown below:

$$Q = (P - I_a)^2 + S \qquad 2.5$$

Where, Q = Runoff
P = Cumulative rainfall
$I_a$ = Initial abstraction
S = Maximum of soil water storage potential

SCS Method has been applied in many fields in hydrology for example in GIS (Engel, 1997) and Soil and Water Assessment Tool (SWAT) (Arnold, Williams, Srinivasan, King, & Griggs, 1994). Total runoff from a small area of watershed and curve number also can be determined.

The value of S is defined by the empirical expression of Equations 2.6 and 2.7 depending on the units being used where CN is curve number.

$$S = \frac{100}{CN - 10}\ (inches) \tag{2.6}$$

$$S = \frac{25400}{CN - 254}\ (milimeters) \tag{2.7}$$

iii. Clark's Unit Hydrograph Method

Clark's Unit Hydrograph Method (1945) is different from the other synthetic UH method because it is an instantaneous unit hydrograph which does not consider time duration. Clark's UH has two procedures in the transformation of excess precipitation to runoff which is translation and attenuation. Translation is a condition where the excess precipitation moves from original drainage to the watershed outlet while attenuation is a condition where the magnitude of discharge is reduced and stored in the watershed.

Parameters used in this method are related to the Muskingum hydrograph routing. Clark stated that the valley storage and flood routing technique are suitable to be use in determining the number of gauge basin. Clark's Method also produces Time-Area Histogram and translation hydrograph. The sub catchment area in this part is determined for each increment. Total volume of runoff also calculated. The time-area relationship in HEC-HMS is represented as:

$$\frac{A_t}{A} = \begin{cases} 1.414\ (\frac{t}{t_c})^{1.5} & \text{for} \quad t \leq \frac{t_c}{2} \\ 1 - 1.414\ \left(1 - \frac{t}{t_c}\right)^{1.5} & \text{for} \quad t \geq \frac{t_c}{2} \end{cases} \tag{2.8}$$

Where,
$A$ = Total watershed area
$A_t$ = Cumulative watershed area
$t_c$ = Time of concentration of watershed

Basin storage is the main factor in the formation of the attenuation of hydrograph. The parameter used to calculate attenuation imposed by storage basin is the Muskingum Storage Coefficient, R.

## 2.5 Hydrological Procedure No.27 (HP-27)

The study practiced the standard published by (DID, 2010) in their Hydrological Procedure No.27 (HP-27) regarding the estimation of design flood hydrograph using Clark method for rural catchments in Peninsular Malaysia. The estimated time of concentration, Tc, storage coefficient, R and baseflow, $Q_B$ equations for ungauged catchment developed in the procedure is used in HEC-HMS simulation in this study. The parameters required in the equations such as catchment area, stream slope, and main stream length are obtained from GIS. The estimation equations of Tc, R and $Q_B$ are presented as in equations 2.9 to 2.11 below.

$$T_C = 2.32A^{-0.1188}L^{0.9573}S^{-0.5074} \quad 2.9$$

$$R = 2.976A^{-0.1943}L^{0.9995}S^{-0.4588} \quad 2.10$$

Where,
A = Catchment area, km$^2$
L = Main stream length, km
S = Weighted slope of main stream, m/km

$$Q_B = 0.11A^{0.85889} \quad 2.11$$

Where,
$Q_B$ = Baseflow, m$^3$/s
A = Catchment area, km$^2$

## 2.6 Hydrological Procedure No. 12 (HP-12)

The standard and guideline by DID (2015) was used in estimating low flows in this rivers. This procedures allowed the design low flow of an ungauged catchment in Peninsular Malaysia. The discharge then used in prediction of the future salinity condition in this estuary. The procedures in obtaining the flows are listed in Equations 2.12 to 2.15.

$$\bar{Q}_1 = 1.675 * 10^{-11} * A^{0.984} * R^{2.600} \tag{2.12}$$

$$\bar{Q}_4 = 2.129 * 10^{-11} * A^{0.982} * R^{2.580} \tag{2.13}$$

$$\bar{Q}_7 = 2.423 * 10^{-11} * A^{0.984} * R^{2.568} \tag{2.14}$$

$$\bar{Q}_{30} = 3.157 * 10^{-11} * A^{0.986} * R^{2562} \tag{2.15}$$

Where, $\bar{Q}_{1,4,7,30}$ = Mean annual minimum 1, 4, 7, 30 days flow
A = Catcment area, $km^2$
R = Mean annual catchment rainfall, mm

## 2.7 Salt Intrusion Study

There are several salt intrusion model readily available including one-dimensional (1-D), two-dimensional (2D) and three-dimensional (3-D) models. These models have been widely tested in simulating salinity distribution in estuaries network. However, this 2-D and 3-D models such as Mike21, Delft3D and Zeedelta are comprehensive salinity model which requires a numerous and substantial amount of funding. Hence, one dimensional modelling develop by Hubert H.G. Savenije (1986); H. H. G. Savenije (1989, 1993, 2012), is a good approach to model salt intrusion due to effective cost and its reliability. Moreover, despite there are many advanced numerical 3-D models are accessible that can adapt the complexity of the physics these days, relatively simple tools for quick-scan actions in an early stage of a project of still needed for instructive purposes (Kuijper & Van Rijn, 2011).

### 2.7.1 1 Dimensional Analytical Salt intrusion Model

There are two parts involves in salt intrusion model which is the geometry and longitudinal salinity distribution analyses. According to A. D. Nguyen and Savenije (2006), Zhang, Savenije, Chen, and Mao (2012), and Gisen, Savenije, Nijzink, et al. (2015), this salt intrusion model can be implemented in single-reach and multi-reaches estuaries. Single reach estuaries is where the estuaries does not encounter strong ocean waves close the mouth and only have one convergence length while multi reach estuaries experience big waves at the mouth which have two convergence length. Figure 2.10 illustrated the single and multi-reaches estuaries.

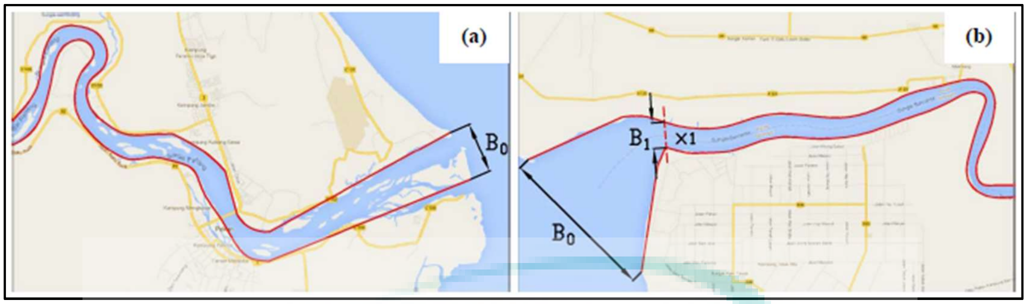



Figure 2.10 Geometry of estuaries a) Single reach estuaries b) Multi-reaches estuaries

Sources: Gisen, Savenije, Nijzink, et al. (2015)

#### 2.7.1.1 Geometry analysis

Geometry analysis part involved several parameters namely the channel cross sectional area, width and depth. The shape analysis of the model are applicable to multi-channel and multi reach estuaries as in Mekong Delta (A. D. Nguyen & Savenije, 2006) and Yangtze Estuary (Zhang et al., 2012). The linear formula that derived from the prismatic channel (laboratory basis) works very poorly in natural estuaries, while 1-D analytical salt intrusion model works very well on the alluvial estuaries based on many studies worldwide conducted by A. D. Nguyen and Savenije (2006), Graas and Savenije (2008), Zhang et al. (2012), and (Gisen, Savenije, Nijzink, et al., 2015). According to H. H. G. Savenije (2012), the geometry of an estuary can be presented in exponential functions as shown in Equations 2.16 to 2.21:

$$A = A_O e^{-\frac{x}{a_1}} \quad \text{for} \quad 0 < x \leq x_1 \qquad 2.16$$

$$A = A_1 e^{-\frac{(x-x_1)}{a_2}} \quad \text{for} \quad x > x_1 \qquad 2.17$$

$$B = B_O e^{-\frac{x}{b_1}} \quad \text{for} \quad 0 < x \leq x_1 \qquad 2.18$$

$$B = B_1 e^{-\frac{(x-x_1)}{b_2}} \quad \text{for} \quad x > x_1 \qquad 2.19$$

$$h = h_O e^{-\frac{x(a_1-b_1)}{a_1 b_1}} \quad \text{for} \quad 0 < x \leq x_1 \qquad 2.20$$

$$h = h_1 e^{-\frac{(x-x_1)(a_2-b_2)}{a_2 b_2}} \quad \text{for} \quad x > x_1 \qquad 2.21$$

Where, $A$ = Cross-sectional area, m$^2$

$A_0$ = Cross-sectional area at estuary mouth, m$^2$

| | | |
|---|---|---|
| $A_1$ | = | Cross sectional area at inflection point, $m^2$ |
| $a_1$ | = | Cross-sectional convergence length of the seaward reach of estuary, m |
| $a_2$ | = | Cross-sectional convergence length of the landward reach of estuary, m |
| $B$ | = | Estuary width, m |
| $B_0$ | = | Width at estuary mouth, m |
| $B_1$ | = | Width at inflection point $x_1$,m |
| $b_1$ | = | Width convergence length of the seaward reach of estuary, m |
| $b_2$ | = | Width convergence length of the landward reach of estuary, m |

#### 2.7.1.2 Longitudinal Salinity Distribution

There are four types of salt intrusion characteristics and occurrence condition which depend on topography, hydrology and tide. Generally, the salt intrusion in estuaries is well-mixed or partially-mixed type when it comes to dry season period. A recession shape occurs in narrow or prismatic channels such as a navigation channel or a riverine estuary with high fresh water discharge. A bell shaped curve occurs in trumpet shaped estuaries where is strongly converged at mouth and slightly converged at the inflection point of upstream. A dome shape curve occurs in strongly funnel shaped estuaries with short convergence lengths. A humpback shape curve occurs if evaporation exceeds rainfall and fresh water inflow in shallow estuaries. Types of well mixed salinity curves are shown in the Figure 2.11.

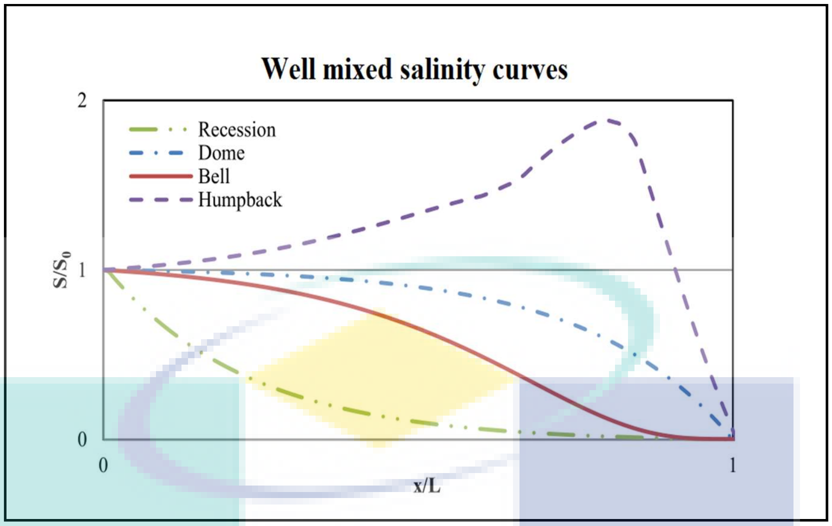



Figure 2.11 Types of well mixed salinity curves
Source: Gisen (2014)

The longitudinal variation of salinity is used to simulate the salinity profile in the estuaries at tidal average (TA) condition and high water slacks (HWS) situation (H. H. G. Savenije, 2006, 2012). The simulated salinity profile then is compared with the existing predictive equation of dispersion. The longitudinal salinity distribution equation for a steady state condition is resulted from the substituting of the Equations 2.22 to 2.27 and integrating the Burgh (1972) equation into the salt balance equation.

$$\frac{S - S_f}{S_0 - S_f} = \left(\frac{D}{D_0}\right)^{\frac{1}{K}} \qquad \text{for} \quad 0 < x \leq x_1 \qquad 2.22$$

$$\frac{S - S_f}{S_0 - S_f} = \left(\frac{D}{D_1}\right)^{\frac{1}{K}} \qquad \text{for} \quad x > x_1 \qquad 2.23$$

Where,

| | | | |
|---|---|---|---|
| | $S$ | = | Steady state salinity , kgm$^{-3}$ |
| | $S_0$ | = | Steady state salinity at estuary mouth, kgm$^{-3}$ |
| | $S_1$ | = | Salinity at inflection point , kgm$^{-3}$ |
| | $S_f$ | = | Freshwater salinity, kgm$^{-3}$ |
| | $D$ | = | Longitudinal dispersion, m$^2$s$^{-1}$ |
| | $D_0$ | = | Longitudinal dispersion at estuary mouth, m$^2$s$^{-1}$ |
| | $D_1$ | = | Longitudinal dispersion at inflection point $x_1$, m$^2$s$^{-1}$ |

The salinity and dispersion equations are considering the exponentially varying geometry then expressed as:

$$\frac{D}{D_0} = 1 - \frac{Ka_1}{\alpha_0 A_0}\left(\exp\left(\frac{x}{a_1}\right) - 1\right) \qquad \text{for} \quad 0 < x \leq x_1 \qquad 2.24$$

$$\frac{D}{D_1} = 1 - \frac{Ka_2}{\alpha_1 A_1}\left(\exp\left(\frac{x - x_1}{a_2}\right) - 1\right) \qquad \text{for} \quad x > x_1 \qquad 2.25$$

With:

$$\alpha_0 = \frac{D_0}{Q_f} \qquad \text{for } 0 < x \leq x_1 \qquad 2.26$$

$$\alpha_1 = \frac{D_1}{Q_f} \qquad \text{for } x > x_1 \qquad 2.27$$

Where,

| | | | |
|---|---|---|---|
| | $A_0$ | = | Cross-sectional area at estuary mouth, $m^2$ |
| | $A_1$ | = | Cross sectional area at inflection point, $m^2$ |
| | $a_1$ | = | Cross-sectional convergence length of the seaward reach of estuary, m |
| | $a_2$ | = | Cross-sectional convergence length of the landward reach of estuary, m |
| | $D$ | = | Longitudinal dispersion, $m^2s^{-1}$ |
| | $D_0$ | = | Longitudinal dispersion at estuary mouth, $m^2s^{-1}$ |
| | $D_1$ | = | Longitudinal dispersion at inflection point $x_1$, $m^2s^{-1}$ |
| | $K$ | = | Van der Burgh coefficient (range 0-1) |
| | $Q_f$ | = | Freshwater discharge, $m^3s^{-1}$ |
| | $x$ | = | Distance, m |
| | $x_1$ | = | Longitudinal distance, m |
| | $\alpha_0$ | = | Mixing number at estuary mouth, $m^{-1}$ |
| | $\alpha_1$ | = | Mixing number at inflection point $x_1$, $m^{-1}$ |

Since the data for freshwater discharge is always not available in the tidal region and the dispersion is not measurable, their ratio is then expressed as the mixing number, $\alpha_0$ [$m^{-1}$] and $\alpha_1$ [$m^{-1}$] in the calibration process. The ultimate objective in the salt intrusion study is to determine the furthest distance the salt water intrudes into the river system.

The salt intrusion length, $L$ is using the Equations 2.28 and 2.29 computed for $D=0$ at tidal average condition.

$$L^{TA} = a_1 ln\left(\frac{1}{\beta_0} + 1\right) \qquad \text{for } 0 < x \leq x_1 \qquad 2.28$$

$$L^{TA} = x_1 + a_2 ln\left(\frac{1}{\beta_1} + 1\right) \qquad \text{for } x > x_1 \qquad 2.29$$

Where,
- $a_1$ = Cross-sectional convergence length of the seaward reach of estuary, m
- $a_2$ = Cross-sectional convergence length of the landward reach of estuary, m
- $x_1$ = Longitudinal distance, m
- $\beta_0$ = Dispersion reduction rate at the estuary mouth (dimensionless)
- $\beta_1$ = Dispersion reduction rate at the inflection point $x_1$ (dimensionless)

Equations 2.30 and 2.31 then shifted for $x = -E/2$ to convert the intrusion length from TA to HWS condition where the salinity length is the most.

$$S^{HWS}(x) = S^{TA}\left(x - \frac{E}{2}\right) \qquad 2.30$$

Hence, the salt intrusion length equation becomes:

$$L^{HWS} = a_1 ln\left(\frac{1}{\beta_0^{HWS}} + 1\right) \qquad 2.31$$

Where,
- $a_1$ = Cross-sectional convergence length of the seaward reach of estuary, m
- $\beta_0$ = Dispersion reduction rate at the estuary mouth (dimensionless)
- $L$ = Salt intrusion length, km

#### 2.7.1.3 Predictive discharge

In the salt intrusion model, it is mentioned that the discharge and dispersion are represented by the calibrated mixing number. If the mixing number is known through simulated longitudinal salinity distribution, the fresh water discharge can be estimated by substituting the dispersion coefficient with the predictive equation developed by A. D. Nguyen and Savenije (2006) which is then improved by Gisen, Savenije, and Nijzink (2015). The improved empirical predictive equations for the dispersion is expressed in Equations 2.32 and 2.33:

$$\frac{D}{vE} = 0.1167 N_r^{0.57} \tag{2.32}$$

With

$$N_r = \frac{\Delta\rho}{\rho}\frac{gh}{v^2}\frac{QT}{DE} \tag{2.33}$$

The mixing number then integrated into Equations 2.29 and 2.30 which yields to Equation 2.34.

$$\frac{\alpha Q}{vE} = 0.1167\left(\frac{\Delta\rho}{\rho}\frac{gh}{v^2}\frac{QT}{DE}\right)^{0.57} \tag{2.34}$$

| Where, | | | |
|---|---|---|---|
| | D | = | Dispersion boundary condition |
| | E | = | Tidal excursion |
| | g | = | gravitational force |
| | Nr | = | Richardson number |
| | T | = | Tidal period, s |
| | v | = | Velocity amplitude |
| | ρ | = | Water density, $kgm^{-3}$ |
| | Δρ | = | Density difference over the intrusion length, $ms^{-2}$ |

## 2.8 Model performance

Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) are the methods that applied to analyse the error performance which is then used to evaluate the applicability and viability of model. RMSE is used to determine the average different between the observed and predicted data. The RMSE value is computed with the Equation 2.35:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad 2.35$$

Where, $O_i$ = Observed value
$P_i$ = Predicted value

Equation 2.36 is the NSE equation which used to determine the overall model performance.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad 2.36$$

Where, $O_i$ = Observed value
$P_i$ = Predicted value
$\bar{O}$ = Average observed value

The range of Nash-Sutcliffe efficiency is -∞ < NSE < 1. Efficiency of 1 shows the perfect match of model discharge to the observed data however efficiency of 0 shows that the accuracy of model predictions to the mean of the observed data. If the efficiency is less than zero, it can be indicate that the observed mean is a better than the model. By comparing the model results with the observed data, higher accuracy of results can be obtained from this model.

## 2.9 Case Study

Study on previous salt intrusion case by other researchers are required to improve the current study and avoid mistakes that are done before. Several cases in oversea and Malaysia have been studied before the research was conducted. Through the case study, it shows that there are several different methods of analysis that can be performed to conduct salt intrusion studies in estuary.

### 2.9.1 Mekong Delta, Vietnam

The Mekong Delta is an alluvial estuary that consists of many branches and that transports a large amount of freshwater to the sea, even during the dry season (in the order of $2000 m^3/s$). This research applied the theory by Hubert H.G. Savenije (1986); H. H. G. Savenije (1989, 1993) to test the theory either it is reliable to a multichannel estuary. River discharge and tidal data are provided by the Vietnamese National Hydrometeorology Services were used in this study. The overall results of salinity computation indicate that the model is acceptable and that the simplified method can produce satisfactory results for a complex system such as the Mekong Delta.

### 2.9.2 Pungue Estuary, Mozambique

Meanwhile, a salt intrusion study in Pungue Estuary was conducted by Graas and Savenije (2008) to determine the minimum discharge required to prevent salt intrudes to the water intake area which located 82km from the estuary mouth. The monthly mean discharge can be as low as $8 m^3/s$ and as high as $893 m^3/s$. The water intake frequently has to be ceased in the dry season to prevent salt intrusion due to high salinity. This research is practicing analytical method and predictive equations developed by Hubert H.G. Savenije (1986); H. H. G. Savenije (1989, 1993) to predict the salinity along the estuary. Estimated river discharge from the nearest gauging station has been used in this study. The good result obtained and the performance of the salt intrusion model for the Pungue estuary is satisfactory.

### 2.9.3 Rompin and Sedili Besar Estuaries

SMHB, Ranhill, and Zaaba (2000) had conducted the salinity study in the Rompin and Sedili Besar Estuary due to its important potential water resources. The locations of water intake need to be situated as close as possible to the saline tidal limit for a maximum catchment runoff and to ensure the salinity level will not interrupt the abstractions. The Mike-11 model was adopted in this study which involved Hydrodynamic (HD) Module and Advection Dispersion (AD) Module. This model required a lot of real-time data to ensure its effectiveness include freshwater discharge which were measured on site.

### 2.9.4 Selangor Estuary

In Malaysia, the study conducted by Breemen (2008) by using a 3-dimensional numerical model of Delft3D to analyse the water extraction effect on salt intrusion in the Selangor Estuary. The behaviour of this estuary is controlled by freshwater discharge and tidal wave from Malacca Strait. This model includes the salinity and long-term freshwater discharge data provided by Department of Irrigation and Drainage Malaysia (DID). However, the freshwater discharge in this model is consumed to be constant from the upstream to the river mouth. (Breemen, 2008) claimed that the method can provide very accurate and promising result, but the time consuming is not suitable for the small-scale estuary. Besides that, sufficient field knowledge and experience are required to simulate the tidal model and waves for the boundary condition.

### 2.9.5 Kurau, Perak, Bernam, Selangor, Muar & Endau Estuary

The latest study were done by (Gisen, Savenije, Nijzink, et al., 2015) in Malaysia which includes the Kurau, the Perak, the Bernam, the Selangor, the Muar and the Endau Estuary by applying 1-Dimensional analytical salt intrusion model. The model was developed by Hubert H.G. Savenije (1986) and have been improved time to time by several researchers include J. I. A. Gisen, Savenije, Nijzink, et al. in 2015 which indicates that 1-dimensional analytical model has a very good fit on all the estuaries and appropriate in poor data environments. Apart from Malaysia, this model has proven to be well implemented in many countries around the world such as Vietnam, Thailand, and China. Due to discharge data constraint in this study, underestimation of discharge from some parts of drainage basin, dispersion ($D_0$), mixing number ($\alpha_0$) and intrusion length ($L^{HWS}$) did not tally to the observed data. Then, the mean monthly stream flow data and yearly maximum discharge frequency were used in order to compensate the problem. Differs from the open space estuary in the previous study, the new model was tested in Kuantan Estuary which is partially open estuary with barrage structure in the downstream.

### 2.9.6 Kuantan Estuary

Farleigh in 1978 conducted a study in Kuantan Estuary due to salt intrusion threat into Kobat water intake station which located about 17km from the mouth. The mathematical model was used in this study to predict the salinity distribution when additional freshwater abstracted from the river. The predictions have been made for river flows associated with 1 in 5, 1 in 20 and 1 in 50-year droughts in conjunction with various abstraction rates both for municipal water supply and agricultural use. This study has led to the construction of Kobat barrage to prevent the salt intrusion into the area. However, the extreme El-Nino phenomenon in April 2016 had affected the water supply system in Kuantan River Basin.

## 2.10 Research Gap

Table 2.1 summarised te case studies mentioned in section 2.7. The table shows the research gap between the previous and current research.

| Research Area | Method | Type of estuary | Source |
|---|---|---|---|
| *Mekong Delta, Vietnam* | *1-D salt analytical model* | *Multi-channel alluvial* | *(A. D. Nguyen & Savenije, 2006)* |
| *Pungue Estuary* | *1-D salt analytical model* | *Multi-channel alluvial* | *(Graas & Savenije, 2008)* |
| *Rompin and Sedili Besar Estuaries* | *Mike-11 Model* | *Rompin- alluvial*<br>*Sedili besar- alluvial* | *(SMHB et al., 2000)* |
| *Selangor Estuary* | *Delft3D Model* | *Alluvial* | *(Breemen, 2008)* |
| *Malaysia estuaries* | *1-D salt analytical model* | *Kurau – alluvial*<br>*Perak- alluvial*<br>*Bernam- alluvial*<br>*Selangor- alluvial*<br>*Muar- alluvial*<br>*Endau- alluvial* | *(Gisen, Savenije, Nijzink, et al., 2015)* |
| *Kuantan Estuary* | *Mathematical model* | *Alluvial* | *(Farleigh, 1978)* |
| *Kuantan Estuary* | *1-D salt analytical model* | *Alluvial* | *Current research* |

Table 2.1 Case studies summary


| Research Area | Method | Type of estuary | Source |
|---|---|---|---|
| *Mekong Delta, Vietnam* | *1-D salt analytical model* | *Multi-channel alluvial* | *(A. D. Nguyen & Savenije, 2006)* |
| *Pungue Estuary* | *1-D salt analytical model* | *Multi-channel alluvial* | *(Graas & Savenije, 2008)* |
| *Rompin and Sedili Besar Estuaries* | *Mike-11 Model* | *Rompin- alluvial*<br>*Sedili besar- alluvial* | *(SMHB et al., 2000)* |
| *Selangor Estuary* | *Delft3D Model* | *Alluvial* | *(Breemen, 2008)* |
| *Malaysia estuaries* | *1-D salt analytical model* | *Kurau – alluvial*<br>*Perak- alluvial*<br>*Bernam- alluvial*<br>*Selangor- alluvial*<br>*Muar- alluvial*<br>*Endau- alluvial* | *(Gisen, Savenije, Nijzink, et al., 2015)* |
| *Kuantan Estuary* | *Mathematical model* | *Alluvial* | *(Farleigh, 1978)* |
| *Kuantan Estuary* | *1-D salt analytical model* | *Alluvial* | *Current research* |

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This research involved a considerable amount of data collection activities, which were divided into two sections: primary data and secondary data. Primary data included all the in-situ studies while secondary data focused on the data obtained from the authorities. The digital elevation data, SRTM 30m was downloaded from the United States Geological Survey (USGS) website, while the topography maps were purchased from the Department of Survey and Mapping Malaysia (JUPEM). For the hydrological data, it was requested from the Department of Irrigation and Drainage Malaysia (DID). The field observations data collected were the cross-sectional area (width and depth), and salinity data.

## 3.2 Study Area

The Kuantan River Basin is located at the North East region of the Pahang State, Malaysia. Its river system started from coordinate 3º55’59” N 103º03’4” E (upstream) to 3º48’10” N 103º20’39” E (downstream). Meanwhile, the Belat Tributary started from the confluence at coordinate 3°46'43.33"N 103°18'22.64"E until 3°47'11.18"N 103° 6'9.80"E in Gambang area. The study area involved is illustrated in Google earth as shown in Figure 3.1. The Kuantan River originates from the Tapis Mountain (+1512 m) at the western border. It flows in a south-east direction through the towns of Lembing River and Kuantan River before discharging into South China Sea. The upper catchment is steep and dominated by natural forest, whereas the middle and downstream portions are occupied by oil palm and rubber plantations with swamps near to the lower reaches. A view along Kuantan River shown in Figure 3.2. The main river has a total length of about 86 km and commands a total basin area of about 1638 km$^2$. Kuantan River Basin is mostly undeveloped except for the downstream (estuary) part where the Kuantan City is located (Jayawardena, Takahasi, Tachikawa, & Takeuchi, 2004). At this are, a riverside of about 4km length have been built for tourist attraction such as cruise activities. Besides that, there is a 500-year-old ancient mangrove forest reserve and swamps near to the confluence of Belat Kuantan River, which covers an area of 340 hectares. This mangroves forest is importance as the habitat for varieties of estuarine plants, birds and fish species. Fishery activity is a major economic activity in the Kuantan River. Since a fishing landing complex belongs to the Lembaga Kemajuan Ikan Malaysia (LKIM) Pahang are among the largest complex in the country, it becomes a stopover for fishermen along the estuary for fishery activities (Jusoh, 2017). Many of the facilities provided at the jetty include boat mooring jetty, input supply jetty, slipway (workshop), trawl shop, cold room (10 tonnes and 20 tonnes) and more (Jusoh, 2017). Other than the big scale fishery activities, there are also several small scale local fishing such as catching shrimps, freshwater fish, and crabs searching.

Kuantan River is the main source of water supply in the Kuantan District. For this reason, Chereh dam was constructed at the upstream of the river and several water intake stations were built along the river as part of the water supply network. The main freshwater abstraction point in the Kuantan Estuary is the Kobat pumping house situated at about 20km from the estuary mouth. In 1977, this pumping station was affected salt intrusion problem in which a barrage gate was built to prevent the inflow of sea water into the Kobat region. Figure 3.3 shows the view of the Kobat water intake station and the barrage.

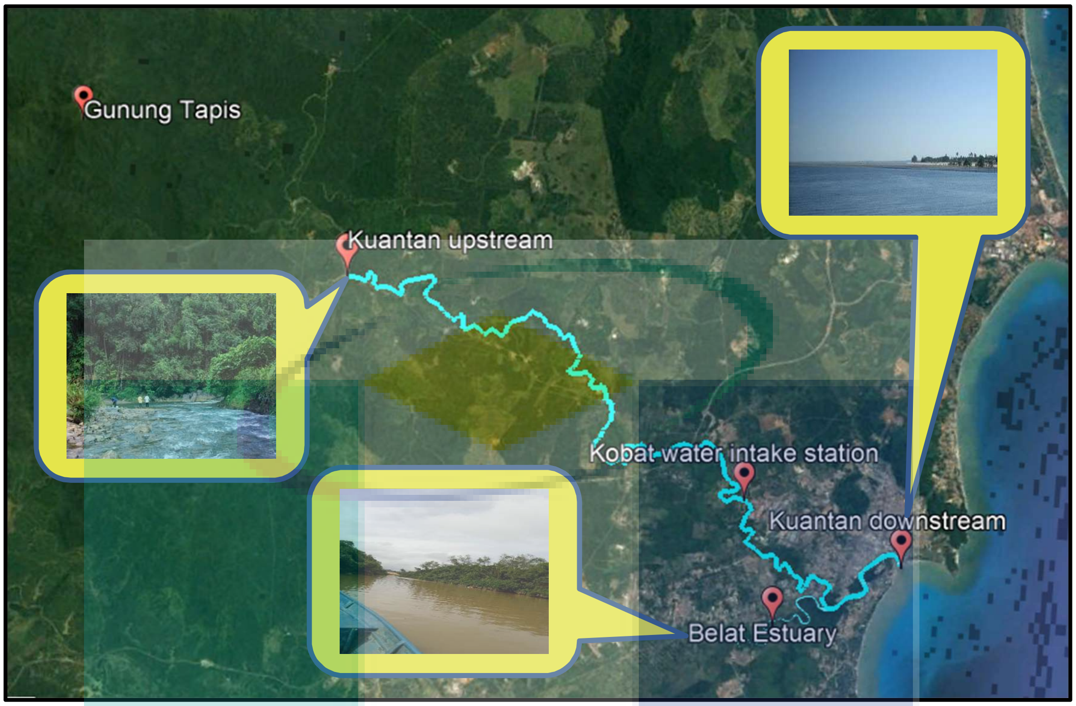



Figure 3.1 Kuantan River


Figure 3.2 Views along Kuantan River

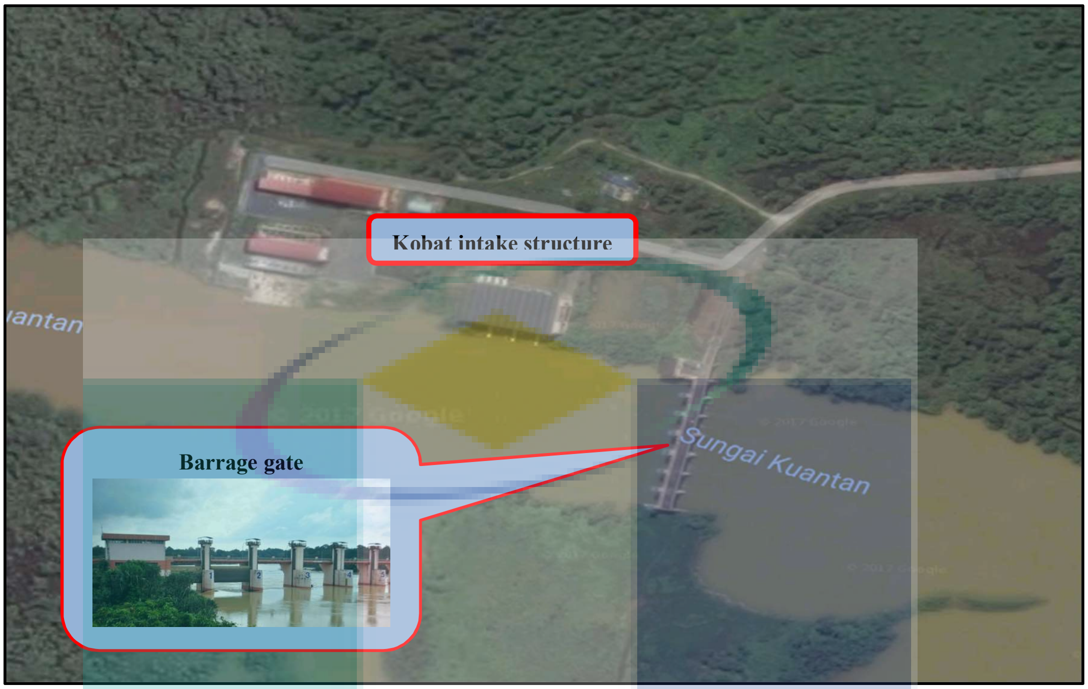



Figure 3.3 A view of Kobat area

## 3.3 Hydrological history

### 3.3.1.1 Rainfall

The historical rainfall patterns were identified from six stations that are available along Kuantan River as presented in Figure 3.4. There are two rainfall stations covered the downstream region, while three stations in the middle region, and one station at the upstream part. Selected data for the year 1976 to 1978 were analysed to observe the historical rainfall patterns, while the data for the year 2015 and 2016 were used to identify the recent rainfall patterns. From the rainfall data patterns in Figure 3.5, the maximum rainfall received by Kuantan River Basin for both the historical and recent years occurred in December with 318mm and 322mm, respectively. Furthermore, the wet season was observed to begin from October to February. The minimum rainfall in the dry season occurred in March with 69mm and 47mm, respectively for the past and recent rainfall patterns. Dry season takes place between March to September. Hence, the salt intrusion measurement were conducted in March, April and October. The annual total rainfall for every stations were plotted in Figure 3.6.

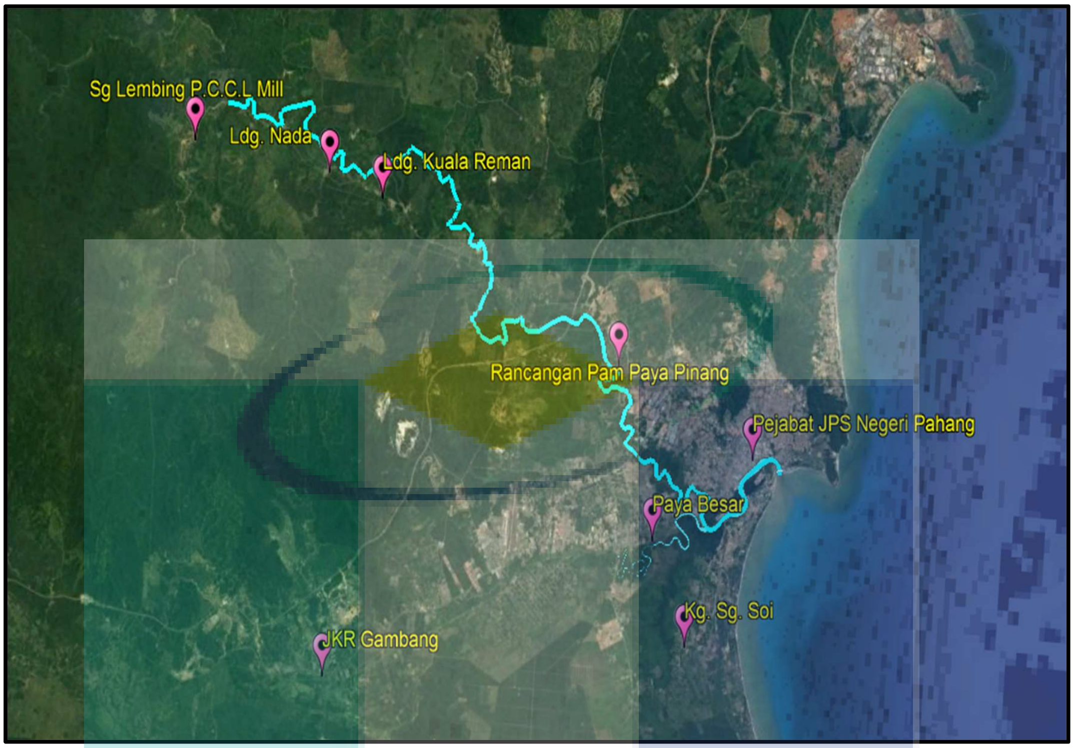
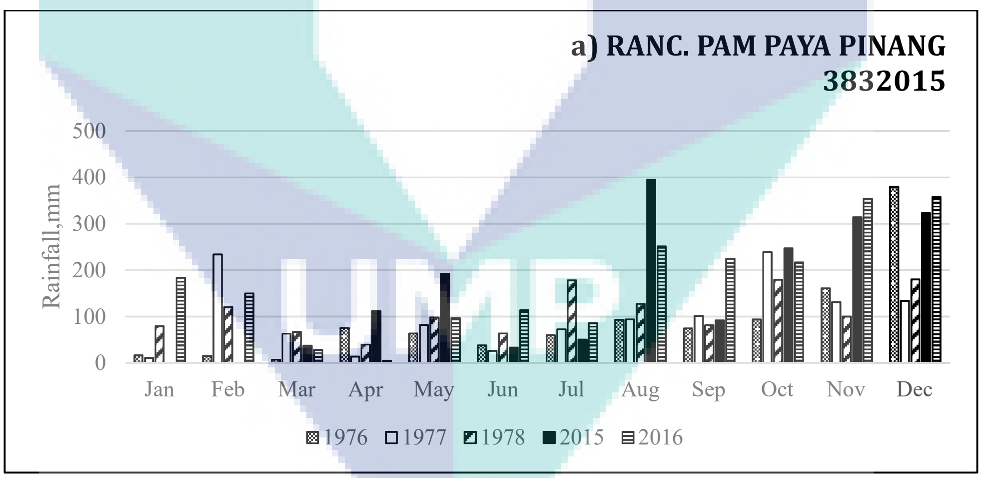
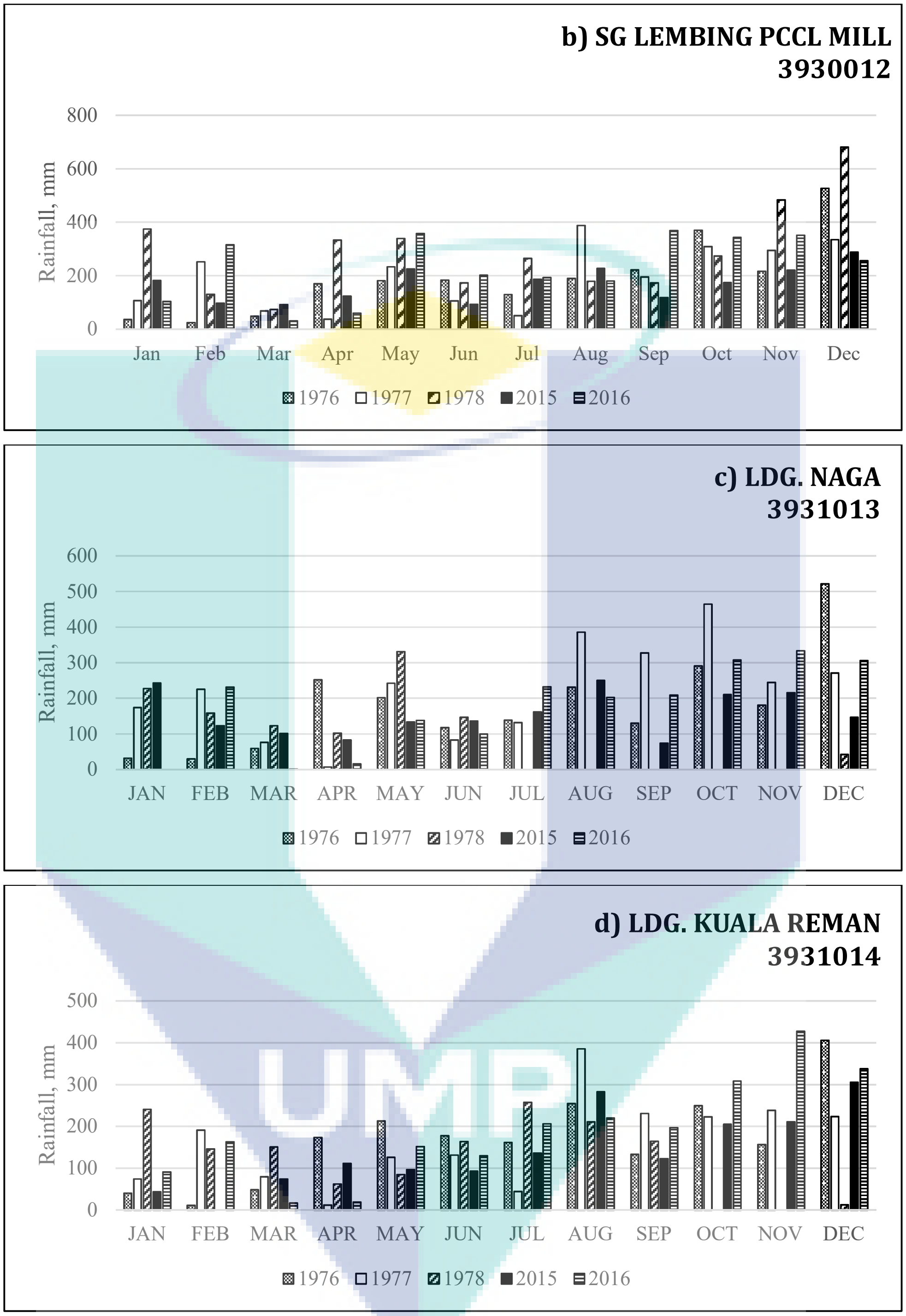
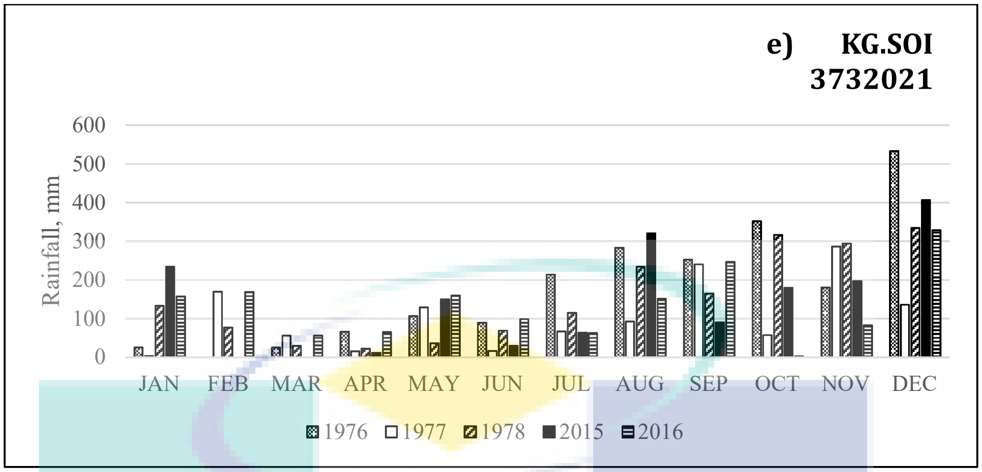



Figure 3.4 The location of rainfall stations




b) SG LEMBING PCCL MILL
3930012
Rainfall, mm
800
600
400
200
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1976 1977 1978 2015 2016
c) LDG. NAGA
3931013
Rainfall, mm
600
500
400
300
200
100
0
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
1976 1977 1978 2015 2016
d) LDG. KUALA REMAN
3931014
Rainfall, mm
500
400
300
200
100
0
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
1976 1977 1978 2015 2016



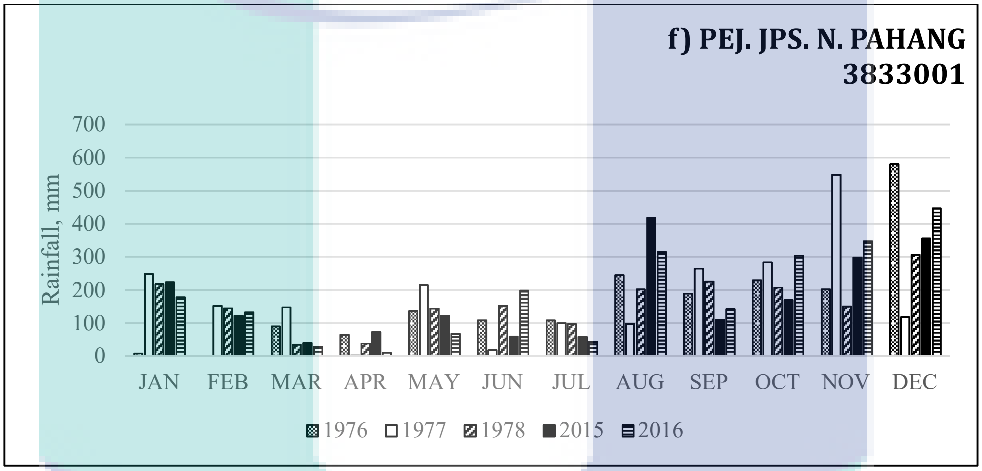
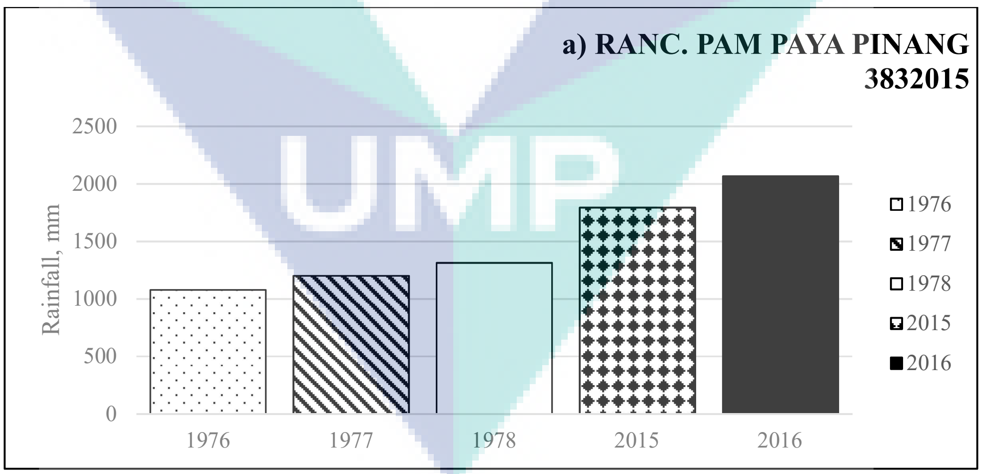
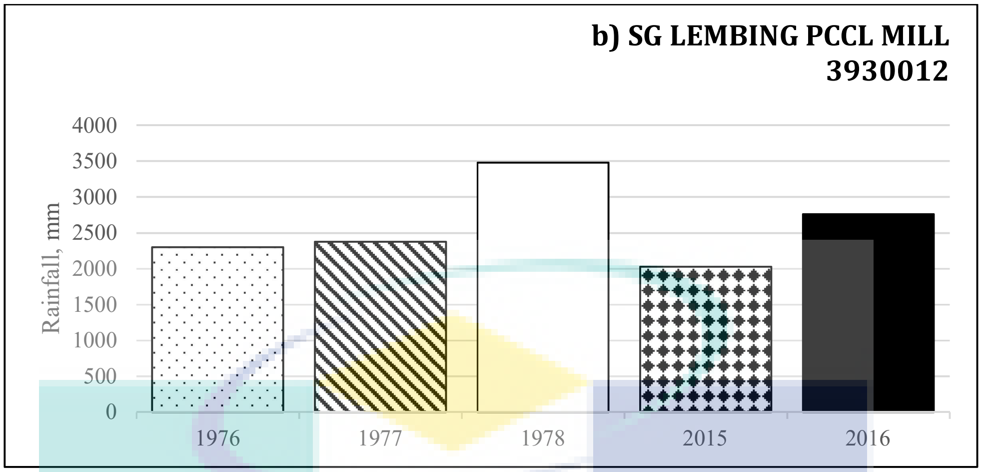
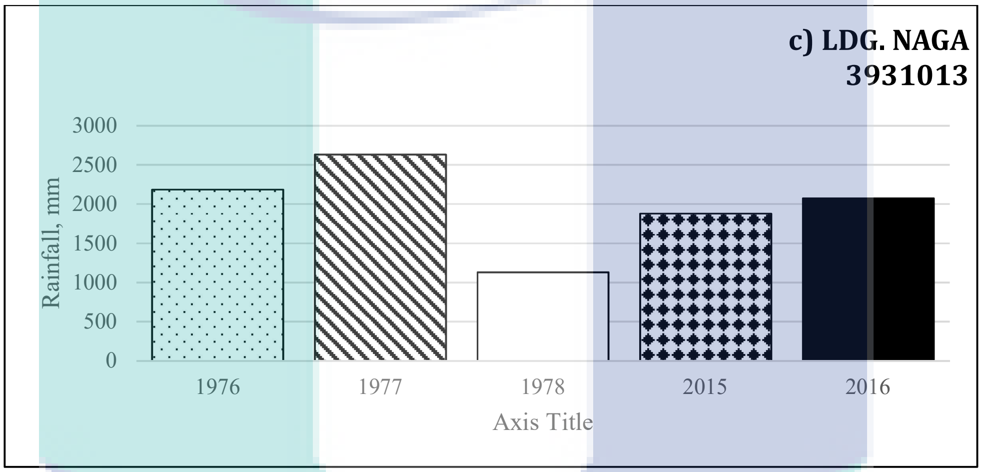
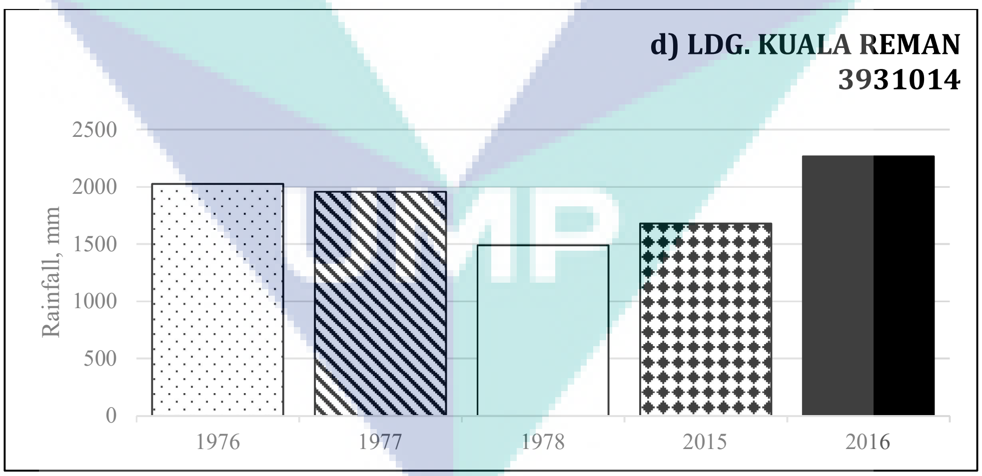




Figure 3.5 Monthly rainfall of six rainfall stations at Kuantan Estuary




b) SG LEMBING PCCL MILL
3930012
Rainfall, mm
4000
3500
3000
2500
2000
1500
1000
500
0
1976
1977
1978
2015
2016


c) LDG. NAGA
3931013
Rainfall, mm
3000
2500
2000
1500
1000
500
0
1976
1977
1978
2015
2016
Axis Title


d) LDG. KUALA REMAN
3931014
Rainfall, mm
2500
2000
1500
1000
500
0
1976
1977
1978
2015
2016

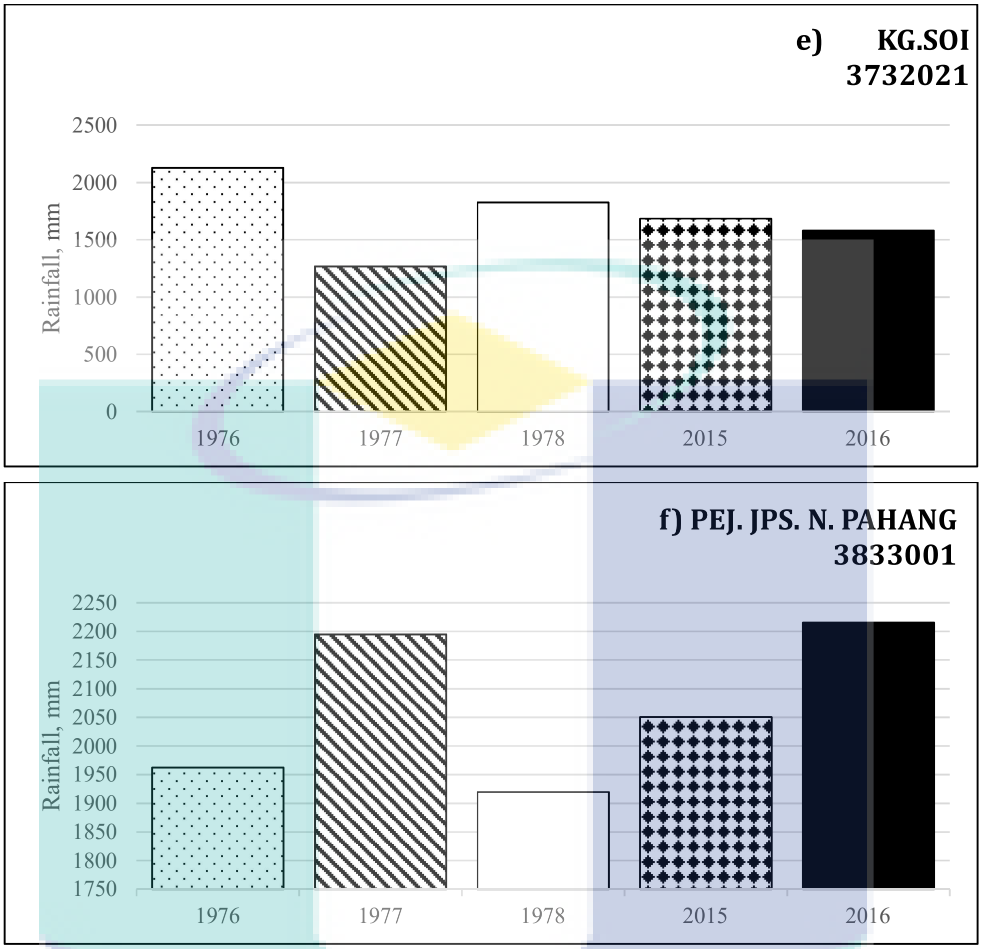



Figure 3.6 Total rainfall of six rainfall stations at Kuantan Estuary

#### 3.3.1.2 Discharge

In Kuantan River Basin, there is only one streamflow station available at the upstream which is the Bukit Kenau gauging station as displayed in Figure 3.7. This station covered a catchment area of 582 $km^2$ .The mean annual discharge recorded is 37.7 $m^3/s$ (DID, 2009).

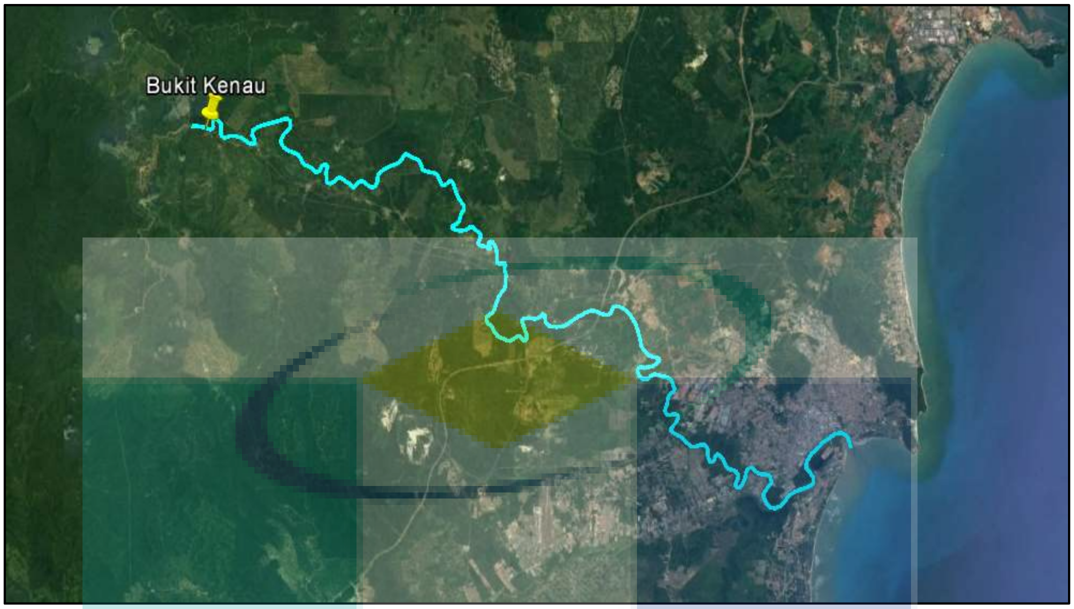



Figure 3.7 The location of Bukit Kenau gauging station

## 3.4 Tidal history

The tidal history in the Kuantan Estuary were identified from the tidal oscillation graph for the year 1977 and 2016 as shown in Figure 3.8. From the observation, this estuary was classified as mixed semidiurnal tide because it experienced two different level of low and high tides.

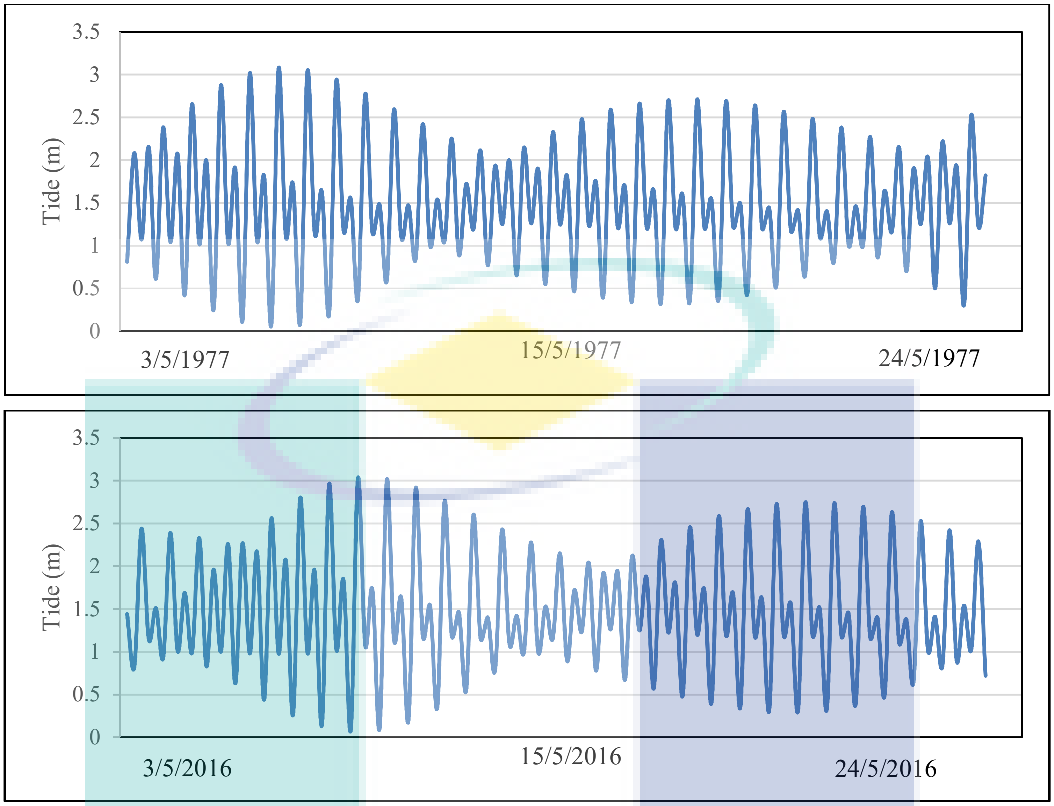



Figure 3.8 Tidal pattern of Kuantan Estuary

## 3.5 Data Collection

Data required in completing the salt intrusion study were collected on-site, obtained from the local authorities in Malaysia, browsed from literature and reports, and downloaded from online databases. The historical data of rainfall, discharge, and cross sectional data were obtained from Department of Irrigation and Drainage Malaysia (DID).While, the tidal data was purchased from the Marine Department Malaysia. The types of data to be collected on-site are water level and salinity data. These data were analysed as described in Figure 3.9.

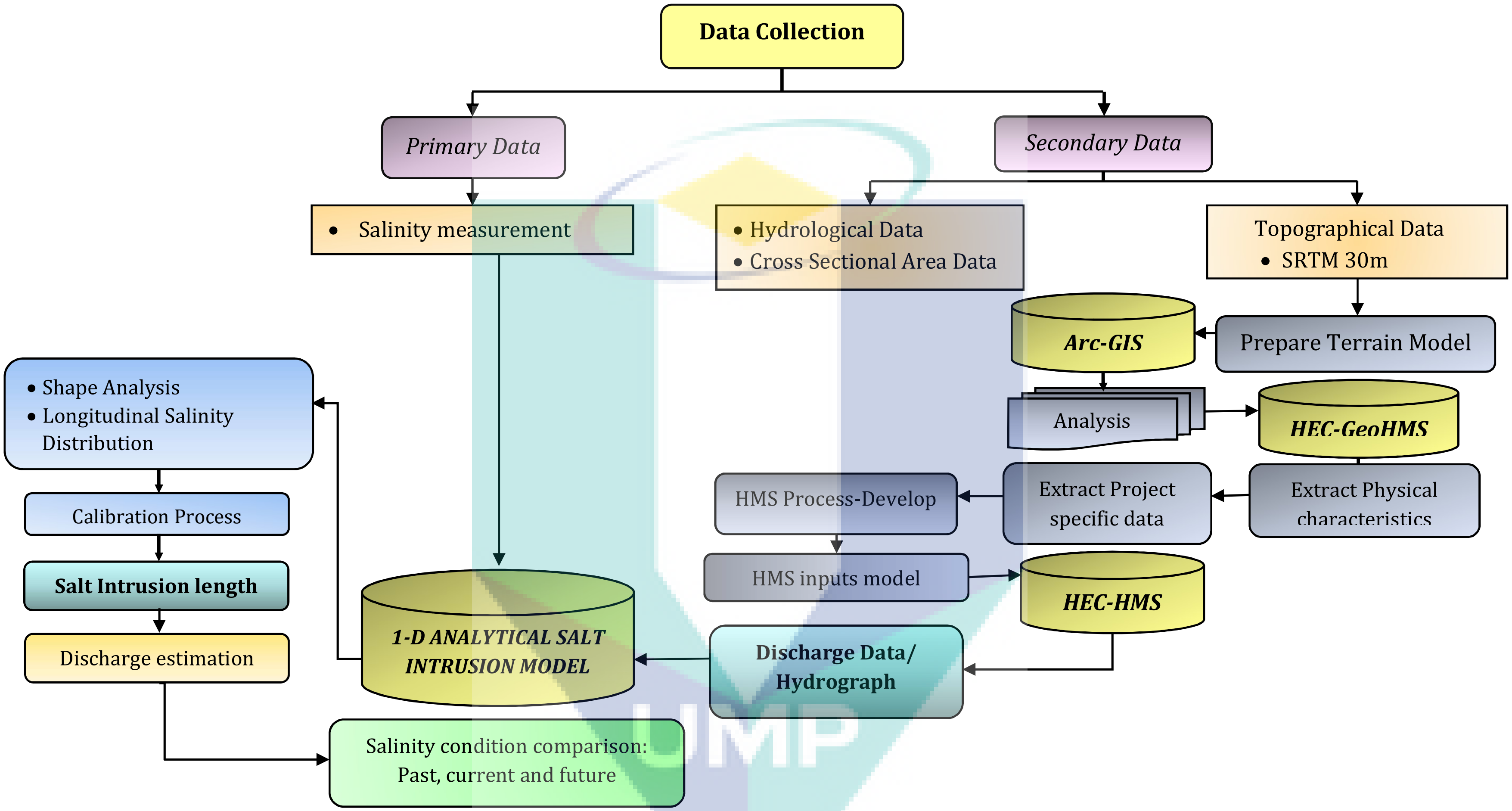



Figure 3.9 Flowchart of methodology

### 3.5.1 Preliminary Survey

Before field measurements, pre-visit to the site is essential to observe and be familiar with the surrounding area, as well as to locate the available stream flow and water level stations. During this visit, some information such as the condition of the river accessibility, and possible danger that requires attention were obtained from the local people living within the study area. Furthermore, the preliminary surveys also observed and noted the land uses along the river basin for hydrological model purposes. Preliminary survey is crucial to minimize errors and unwanted difficulties during the measurement periods.

### 3.5.2 Salinity data

Salinity surveys were carried out throughout the dry season for spring tidal conditions. A moving boat technique was adopted to measure the longitudinal salinity level. This is because salt water intrudes furthest when the fresh water discharge is at minimum and tide is at maximum. Neap tide measurement was not included due to the timing issue. Salinity measurements were conducted during the High Water Slack (HWS) and Low Water Slack (LWS) before the flow changes its direction. Slack moment is represented by stagnant water with zero velocity which occurs after the high water and low water as presented in Figure 3.10.

Figure 3.10 The water condition during slack moment

Before salinity measurement were conducted, the sampling locations were predefined from Google Earth. Based on the predefined locations, the waypoints were marked during the survey by using GPS along the estuary. Time of slacks were noted together with the coordinate. In this measurement, the average water depths were captured by using the handheld depth sounder due to its simplicity of handling. Then, a multi-parameter water quality device attached to a 30cm cable was used to measure the salinity at every meter over the vertical during the moments of slack. The equipment used are shown in Figure 3.11. It is worth to note that appropriate weight was attached to the probe to make sure it was vertically penetrated into the water without adrift. Without the weight, the probe tends to float on the water surface and causes the measurement at the bottom not possible. The salinity measurements began at the mouth, then the boat moved inland to another point following the speed of the wave celerity. This procedure was repeated until salinity level reaches 0.1 ppt. The sketch of the salinity measurement technique are shown in Figure 3.12 and Figure 3.13, respectively.

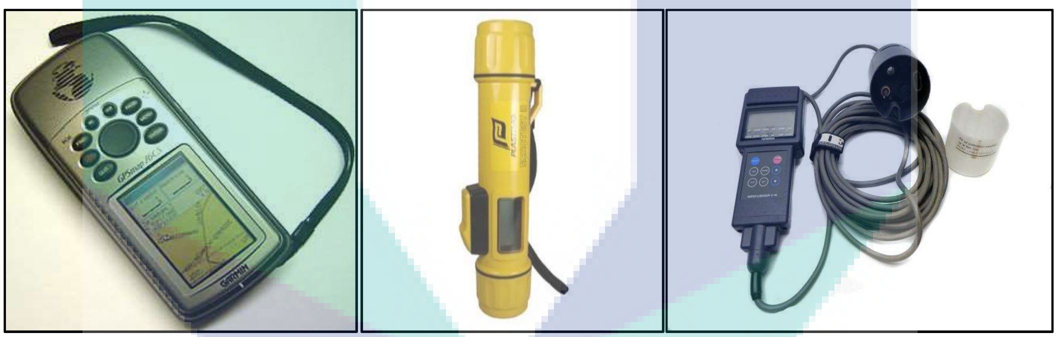


Figure 3.11 Equipment in conducting water salinity measurement

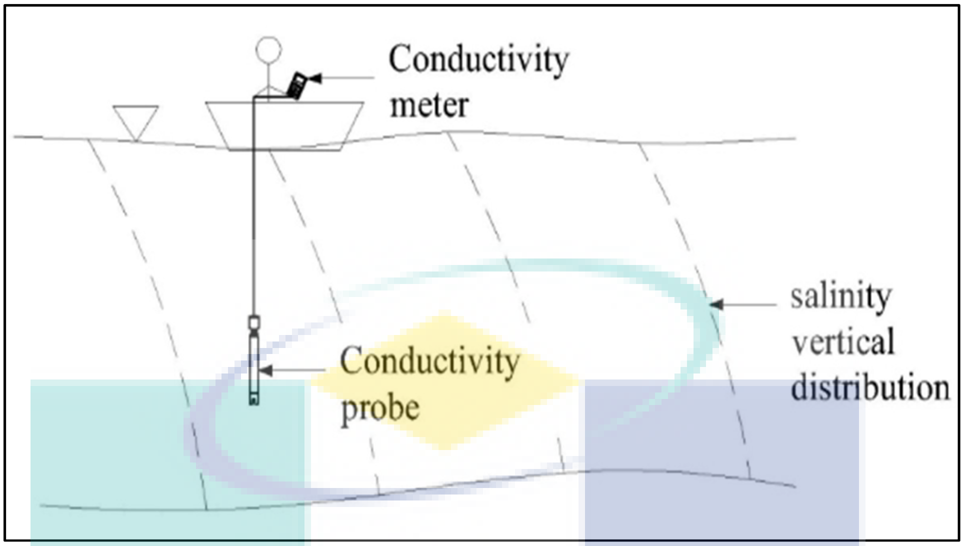



Figure 3.12 The sketch on salinity measurement technique

Figure 3.13 Salinity measurement conducted on site

### 3.5.3 Hydrological data

The amount of fresh water discharge into the estuary was estimated by performing the hydrological modelling, HEC-HMS incorporating with ArcGIS. The low flow estimation obtained from HP-12 then used in a salt model in estimating the probability length of salt intrusion. Secondary data used to accomplish this study are tabulated in Table 3.1.

Table 3.1 Data and the sources

| Data | Source |
|---|---|
| *Rainfall Data* | *The Department of Irrigation and Drainage (DID)* |
| *Streamflow Data* | *The Department of Irrigation and Drainage (DID)* |
| *Topography Data* | *The Department of Survey and Mapping Malaysia (JUPEM)* |

The rainfall data for this study was obtained from the DID covering the starting years of operation until the recent year. There are thirteen rainfall gauging stations have been identified in the Kuantan River Basin but only eight rainfall stations were selected for this study due to the data availability factor. Daily rainfall data was utilised in the HEC-HMS hydrological model to simulate streamflow hydrograph. Other than that, 10 years rainfall data from 2007 to 2017 was utilised in HP-12 which used to find future low flow thus predict a future salt intrusion length in the river. Table 3.2 provides the information of rainfall stations used in this study.

Table 3.2 Rainfall stations information

| Station ID | Station Name | Latitude | Longitude |
|---|---|---|---|
| *3731018* | *JKR Gambang* | *03 42 20* | *103 07 00* |
| *3732020* | *Paya Besar* | *03 46 20* | *103 16 50* |
| *3732021* | *Kg. Sg. Soi* | *03 43 50* | *103 18 00* |
| *3832015* | *Rancangan Pam Paya Pinang* | *03 50 30* | *103 15 30* |
| *3833002* | *Pejabat JPS Negeri Pahang* | *03 48 30* | *103 19 45* |
| *3930012* | *Sg. Lembing P.C.C.L Mill* | *03 55 00* | *103 02 10* |
| *3931013* | *Ldg Nada* | *03 54 30* | *103 06 20* |
| *3931014* | *Ldg Kuala Reman* | *03 54 00* | *103 08 00* |

The streamflow data for this study was also obtained from the DID which covers 10 years period from year 2006 to 2016. There are only one streamflow gauging station available in the Kuantan River Basin which is known as the Kenau station. Table 3.3 below shows the details of the gauging station.

Table 3.3 Streamflow station used in HEC-HMS

| Station ID | Station Name | Latitude | Longitude |
|---|---|---|---|
| *3930401* | *Bukit Kenau* | *03 55 55* | *103 03 30* |

## 3.6 Data Analysis

There were three components involved in this study which are the geometry, salinity and hydrological analysis. Geometry analysis consists of the river depth, width and cross sectional area. Salinity analysis was carried out by analytical solution in accordance to the observed data. Meanwhile, the hydrological analysis involved GIS application and hydrological modelling.

### 3.6.1 Geometry analysis

In the geometry analyses, the cross sectional areas for the Kuantan and Belat Estuary were obtained from the DID. For the Kuantan Estuary, the newly obtained cross sectional area was compared to the historical geometry data captured in the salt intrusion study conducted in 1977. These cross sectional data then were plotted in semi log graph to obtain several parameters such as the length and width at inflection point and the convergence length. The simulated river geometries were then calculated by performing the exponential function developed by H. H. G. Savenije (2012) using Equations 2.16 to 2.21.

### 3.6.2 Salinity Analysis

The salinity analyses were carried out by integrating the geometry equation into the salt balance Equations 2.22 and 2.31. Salinity profile analyses were simulated based on the longitudinal variation at TA and HWS conditions. In these estuaries, the study at HWS is more crucial because the salinity is at maximum during this period. A barrage was built in 1980's at the downstream of the estuary to prevent salt intrusion into the water intake region. Since the previous study was done about forty years ago, it is essential to investigate the current salinity condition up to the barrage at Kobat. For the Belat Estuary, the salinity analysis was performed until the salinity level shows 0.1 ppt. The simulated salinity profiles then were compared to the observed data and the simulated curve was adjusted to fit the observed by calibrating the Van der Burgh's coefficient, K and dispersion coefficients, α.

### 3.6.3 Predictive discharges

From the simulated longitudinal salinity distribution, a mixing number was obtained through calibration process. The fresh water discharge was estimated by integrating the dispersion coefficient with the predictive equation as referred to Equations 2.32 to 2.34. Salinity level in the estuarine environment before and after the barrage construction were evaluated based on the salt intrusion distribution and length obtained from the analyses and the result presented in the 1970's report.

### 3.6.4 Topographical and hydrological analysis

A Shuttle Radar Topography Mission (SRTM) with resolution of 30m of the Kuantan River Basin was used for basin pre-processing under ArcMap platform collaborated with HEC-GeoHMS extension and Spatial Analyst. Basin pre-processing is the platform where the initial analysis of the terrain was performed to produce dataset for river network and river basins. Terrain processing was setup by performing filling the sinks, flow direction, flow accumulation, stream definition, stream segmentation, watershed delineation, watershed polygon processing, stream segment processing, and watershed aggregation in ArcMap. River length extraction, slope calculations, centroid determination, longest flow path and centroid flow path calculations are done according to the basin characteristics. The next step involved the importing of the Kuantan Basin Model generated through HEC-GeoHMS into HEC-HMS hydrological model.

In HEC-HMS, a basin model, meteorological model and control specifications were generated. For the basin model, several parameters including time of concentration, Tc, storage coefficient, R and baseflow, $Q_B$ for the entire catchment were calculated based on HP-27. These parameters were calibrated according to the observed data at Bukit Kenau station for one rainfall event. The calibration result was applied for two different rainfall events for validation purposes. In the meteorological model, selected precipitation and streamflow data were assigned according to the gauging stations. Rainfall pattern distribution chosen in this study was based on thiessen polygon method generated in GIS. Besides that, this study used specified hyetograph method for the precipitation specification. The events duration in control specifications was assigned in monthly basis with 1 day interval. The result of the fresh water discharge generated in HEC-HMS model were then applied in the predictive model as in Equations 2.15 to 2.16 to estimate the predictive dispersion coefficient.

The future salinity prediction analysis was conducted by using HP-12 in estimating the low flow events. 7-day low flow with ARI 50 years was selected as an event for a long-term projection. The resulted flow from the procedure was then utilised in a salt model to find the probability length of salt intrusion during the event.

## 3.7 Error Analyses

Error analyses were carried out to evaluate the reliability and performances of the 1-D analytical salt intrusion model in simulating the salinity distribution in the Kuantan Estuary. The error analyses were also conducted for the validation of the streamflow hydrograph in simulated HEC-HMS. Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) as described in Equations 2.35 and 2.36 and were applied to determine the models performances.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 Introduction

The ArcGIS application in collaborating with HEC-GeoHMS has been successfully delineated for Kuantan River Basin from Digital Elevation Model dataset. HEC-HMS model was developed to obtain the freshwater discharge which was then compared to the predictive discharge estimated by using the method introduced by Gisen, Savenije, and Nijzink (2015) for validation purpose. This study was also extended to the Belat Estuary because it is the main tributary which contributed to the inconsistent salinity distribution to the Kuantan Estuary. Several measurements series were carried out on 27$^{th}$ & 29$^{th}$ March 2017, 3$^{rd}$ October 2017, 7$^{th}$ March 2018 and 15$^{th}$ April 2018 for Kuantan Estuary. Meanwhile, four measurements have been conducted in the Belat Estuary on 26$^{th}$ April 2017, 2$^{nd}$ October 2017, 6$^{th}$ March 2018 and 14$^{th}$ April 2018.

## 4.2 Geographical and hydrological analysis for discharge estimation

### 4.2.1 Basin model generation

The sub-catchments of the Kuantan River Basin have been successfully delineated based on SRTM 30-meters resolution dataset using ArcGIS application integrated with HEC-GeoHMS. Result of the delineated sub-basins are displayed in Figure 4.1. The red, yellow and green sections represent the upstream, middle stream and downstream region of the basin, respectively. There were a total of 69 sub-basins that have been generated with a total catchment area of 1686 km$^2$. Two sub-basins were delineated for the Bukit Kenau station and the Kobat barrage to extract the coverage areas of these two locations. The curve number analysis result obtained from GIS application has a range between 32 to100. This range is also supported by Akbari, Samah, and

Daryabor (2016). Besides that, there were several parameters acquired from GIS such as catchment area, stream slope, and main stream length as tabulated in Appendix 1.

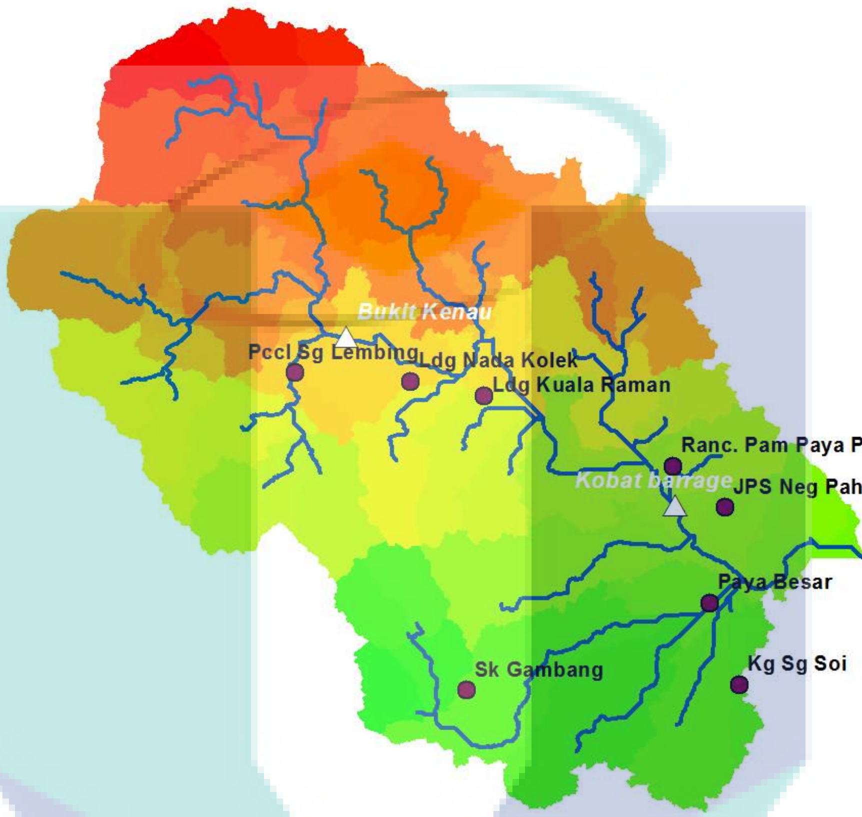



Figure 4.1 Delineated Kuantan River Basin

### 4.2.2 HEC-HMS

HEC-HMS schematic basin model for Kuantan River Basin as presented in Figure 4.2 was imported from GIS application through HEC-GeoHMS hydrological analysis. The simulation processes were facing difficulties in finding the freshwater discharge due to a lot of missing data issues from the authority level. Moreover, there is also no devices found at Kobat barrage gate in monitoring the freshwater released. To overcome the issue of missing data, comparison of the scenarios to determine the range of parameters were considered. The different scenarios with the high (January 2012), moderate (February 2011) and low (August 2011) flow were selected in the calibration and validation process. The Curve Number values used in loss method are generated from GIS. While, other several parameters such as base flow and transform method utilised Clark Unit Hydrograph in the simulation are obtained from the standard procedure practice, Hydrological Procedure No.27 published by (DID, 2010).

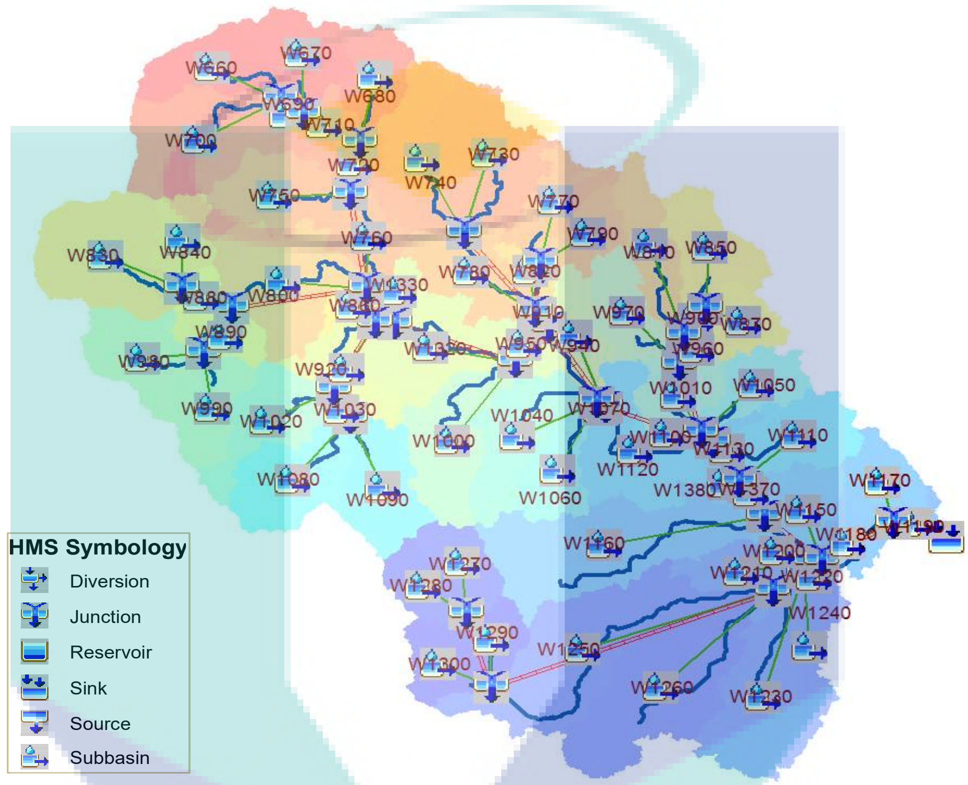



Figure 4.2 The HMS Schematic basin model

The calibrated and validated results for three scenarios as presented in Figure 4.4 are conducted at Bukit Kenau point because it is the only stream flow station available in Kuantan River. On the other hand, the simulation process for the month involved with the site surveys only consider the rainfall gauging stations due to the availability of streamflow data in Kenau station. Three rainfall stations surrounding streamflow station that influence the streamflow reading were used for comparative purposes. The total rainfall for all months involved in the study at Sg Lembing PCCL Mill, Ldg Nada, and Ldg Kuala Reman station were plotted as in Figure 4.5. The total rainfall of historical and current events from three stations around the streamflow station as in Figure 4.4 were then compared in order to get the scenario and range of the baseflow parameter. The range of baseflow parameters obtained from the selected scenarios simulation then used in the current event simulation. The calibration part for current scenarios only considered the downstream rainfall station to represent the barrage restriction and study limitation. The discharge of Kuantan Estuary considered at the lower reach area located near the mouth which covers the lower stream area from the barrage. For Belat Estuary, the discharge were taken from the junction of Belat catchment. The discharge results for all desired date for Kuantan and Belat Estuary are summarised and tabulated in Table 4.1.

#### 4.2.2.1 Calibration analysis

The low flow event in August 2011 was simulated as the calibration dataset with several parameters as shown in Appendix 2. The best simulated hydrograph obtained after several adjustment and trial and error process is presented in Figure 4.3. From the hydrograph, the simulated stream flow patterns show two peaks discharges in this low flow event. The first peak was identified start to increase 3 days earlier from 19th August 2011 before reached the peak on 23rd 2011 with slightly underestimated by 3.5 m3/s. For the second peak, it is also observed the simulated hydrograph start increased 1 day earlier and reached peak on 29th March 2011 with underestimated flow by 50.7 m3/s.

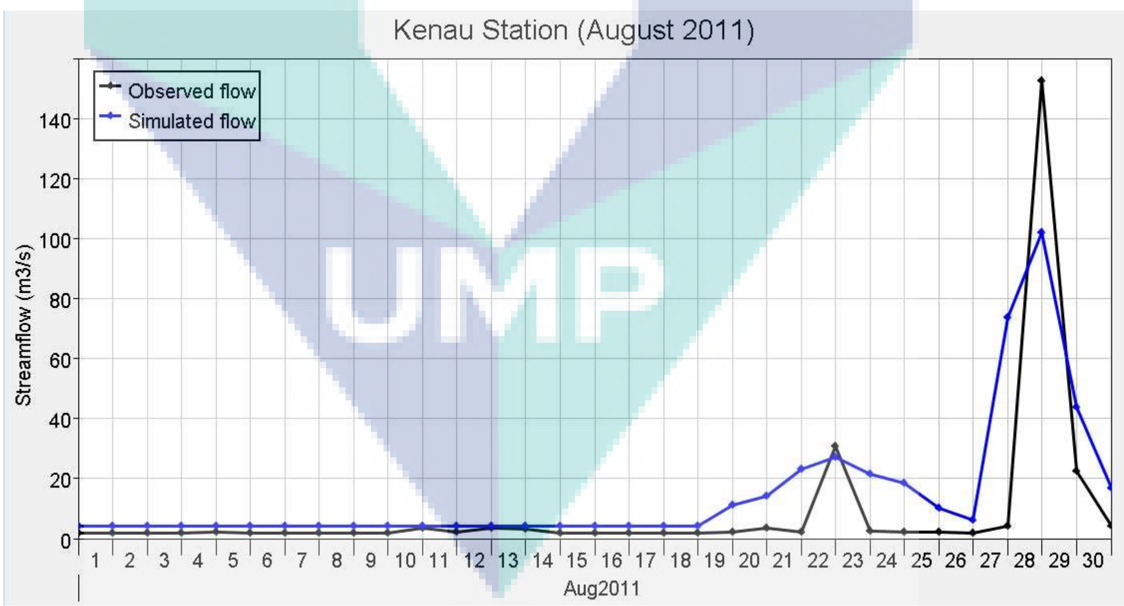
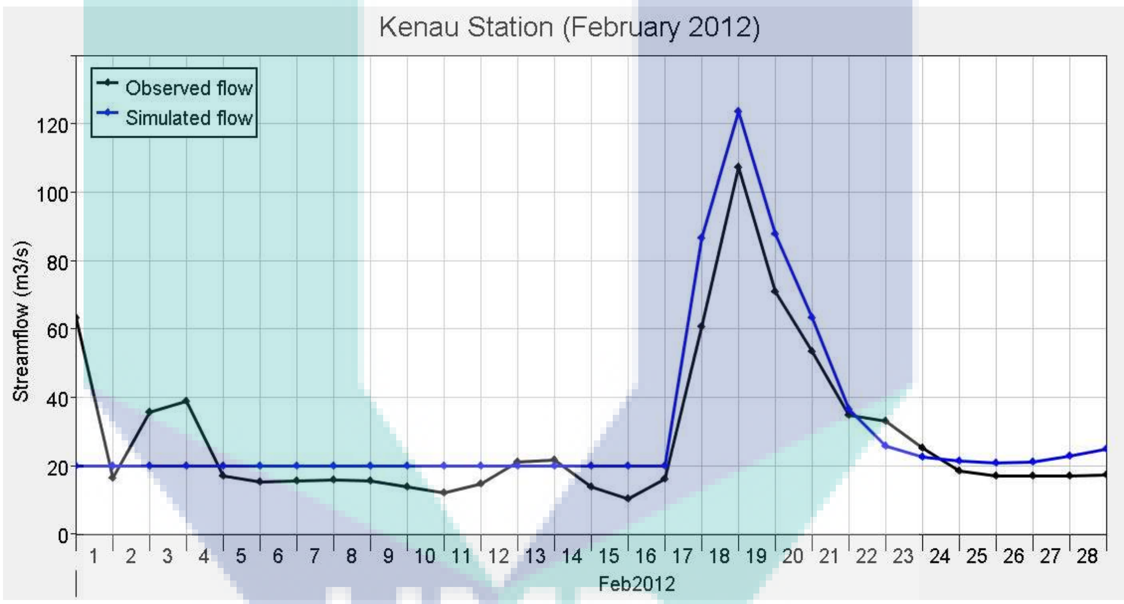



Figure 4.3 Calibrated low flow event in August 2011

#### 4.2.2.2 Validation analysis

For validation part, the study considered two different events, which are medium flow in February 2012 and high flow in March 2011 as presented in Figure 4.4 The simulated hydrograph pattern shows a consistent flow in the early phase of a month while the observed hydrograph indicated a slight fluctuation discharges pattern. There was only 1 peak discharges in the entire event while the observed indicated 3 small peaks discharges through the event. A peak which occurred on 18th February showed that the simulation slightly overestimated the streamflow by 16.3 m3/s.

a) Moderate flow scenario in February 2012




The parameters were validated for second time by using high flow event in January 2012. From the hydrograph, the observed and simulated streamflow showed two peaks of discharges. The first peak which took place on 12th January showed that the simulation underestimated the streamflow by 299.6 m3/s. Meanwhile the second peak showed the overestimated of flow by 19.4 m3/s. It is also observed that the first peak occurred a day late whereas the second peak occurred a day earlier compare to the observed peak.

b) High flow scenario in January 2012

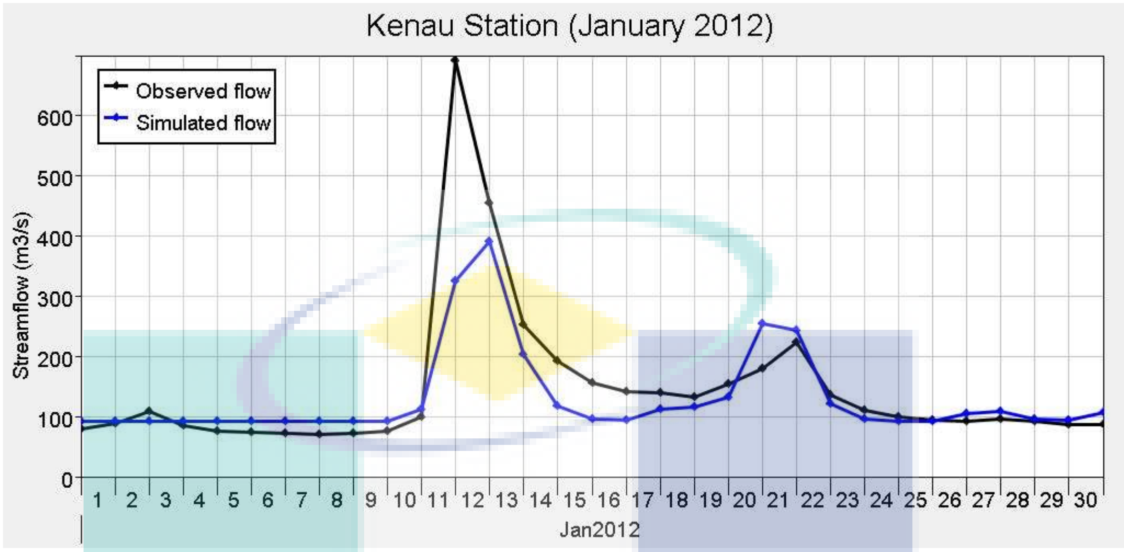



Figure 4.4 The validated hydrograph for two scenarios; a) Moderate flow scenario in February 2011 b) High flow scenario in January 2012

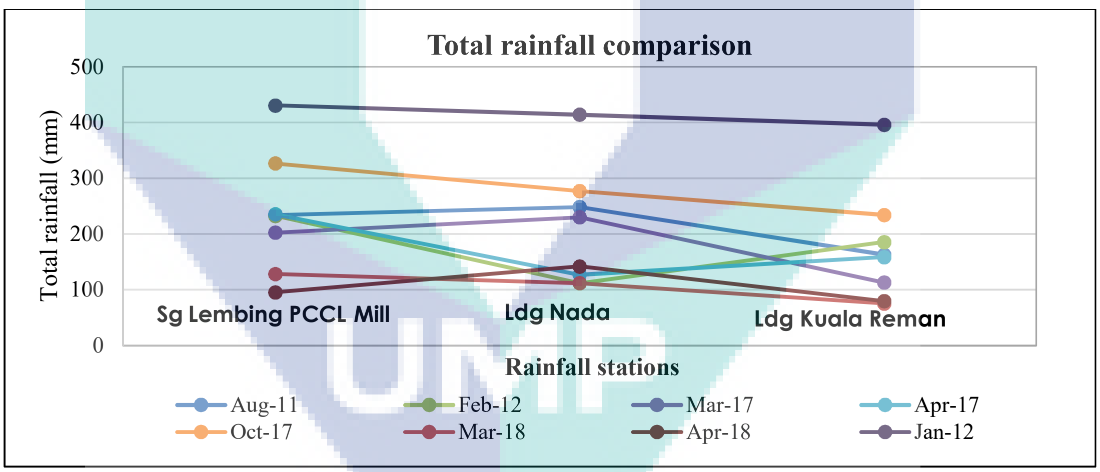



Figure 4.5 Total rainfall comparison at three stations for all months.

Table 4.1 Summary results from HEC-HMS run for desired dates.

| Kuantan Estuary | |
|---|---|
| Date | Discharge [m³/s] |
| *27th March 2017* | *16.7* |
| *29th March 2017* | *20.5* |
| *3rd October 2017* | *22.6* |
| *7th March 2018* | *28.3* |
| *15th April 2018* | *8.3* |

| Belat Estuary | |
|---|---|
| *26th April 2017* | *11.6* |
| *2nd October 2017* | *5.1* |
| *6th March 2018* | *5.3* |
| *14th April 2018* | *2.0* |

#### 4.2.2.3 Error analyses for HEC simulation

| MONTH | RMSE (m3/s) | NSE | Observed Peak discharge, Q (m3/s) | Computed peak discharge, Q (m3/s) |
|---|---|---|---|---|
| | | *CALIBRATION* | | |
| August 2011 | 17.4 | 0.581 | 152.5 | 101.8 |
| | | *VALIDATION* | | |
| February 2012 | 17.4 | 0.691 | 107.2 | 123.5 |
| January 2012 | 72.7 | 0.660 | 691.2 | 391.6 |

## 4.3 Salt Intrusion Analyses

### 4.3.1 Geometry Analyses

The geometry analyses for Kuantan and Belat Estuary were done in three sections which are the cover cross-sectional area, width, and depth. These estuary characteristics were plotted in a semi-logarithmic graph. The simulated geometry characteristics obtained by Equations 2.16 to 2.21 were presented in a regression form.

#### 4.3.1.1 Kuantan Estuary

Figure 4.6 shows the geometry analysis for the Kuantan Estuary based on the cross-sectional area obtained from the most recent (2015) and past survey (1977). The observed cross-sectional area, width, and depth surveyed in 2015 are indicated by blue, red and green markers, respectively, whereas the observed cross-sectional area in 1977 is represented by red markers. The simulated latest geometry characteristics of the Kuantan Estuary are indicated by the blue, green and grey solid lines. The red solid line represents the simulated cross-sectional area for the year 1977. It can be seen that there were good correlations between the simulated and observed cross-sectional area, width and depth. This indicates that the exponential function can well representing the geometry of this estuary.

Comparison between these two geometry analyses demonstrated a significant change near the mouth. However, from the distance of 10km onwards, the patterns were almost the same for both surveys and then slightly changed near to the Kobat barrage. Since the report by Wallingford (1978) has no width and depth information, only the cross-sectional area were compared. Decreasing patterns of the geometry landwards signified that the Kuantan Estuary is an alluvial type of estuary. From the recent survey, the cross sectional area near the mouth is lower compared to the past survey probably caused by the construction of the Kobat Barrage which has disturbed the river flow. On the other hand, the area near the Kobat Barrage is larger for the recent survey. This may be due to the deeper riverbed caused by strong thrust of large discharge during barrage opening. Furthermore, this condition may occurred due to the sediment trapping at the upstream of the barrage when it is closed.

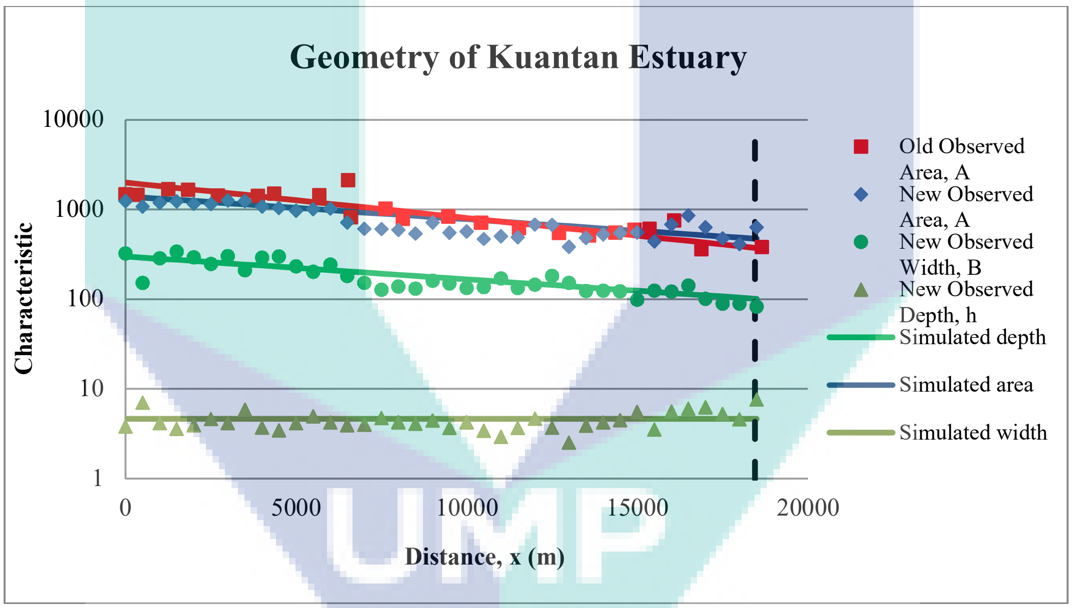



Figure 4.6 Geometry profile of Kuantan Estuary

From the geometry results, the cross-sectional area, $A_0$ and width, $B_0$ at the estuary mouth were found to be 1400 m$^2$ and 300 m, respectively. Meanwhile, for the convergence length for the cross-sectional area, $a_1$ and width, $b_1$ were both 17000 m. The average depth of the estuary, $h$ was 4.5 m. The comparison between is summarized in Table 4.2.

Table 4.2 Geometry characteristics of Kuantan Estuary

| Kuantan Estuary | $A_0$ ($m^2$) | $a_1$(m) | $B_0$ (m) | $b_1$ (m) | $\bar{h}$ (m) |
|---|---|---|---|---|---|
| *New (2017)* | *1400* | *17000* | *300* | *17000* | *4.5* |
| *Old (1977)* | *2000* | *11000* | - | - | - |

#### 4.3.1.2 Belat Estuary

Geometry profile of the Belat Estuary is presented in Figure 4.7. The geometry of the Belat Estuary consist of two reaches in which the downstream part belongs to Kuantan River and the upstream part the Belat River. The inflection point located at 6.5km from the mouth. Survey points available for the Belat River were only up to 20km from the mouth. This is because the accessibility further inland is limited as it is the narrow and shallow area.

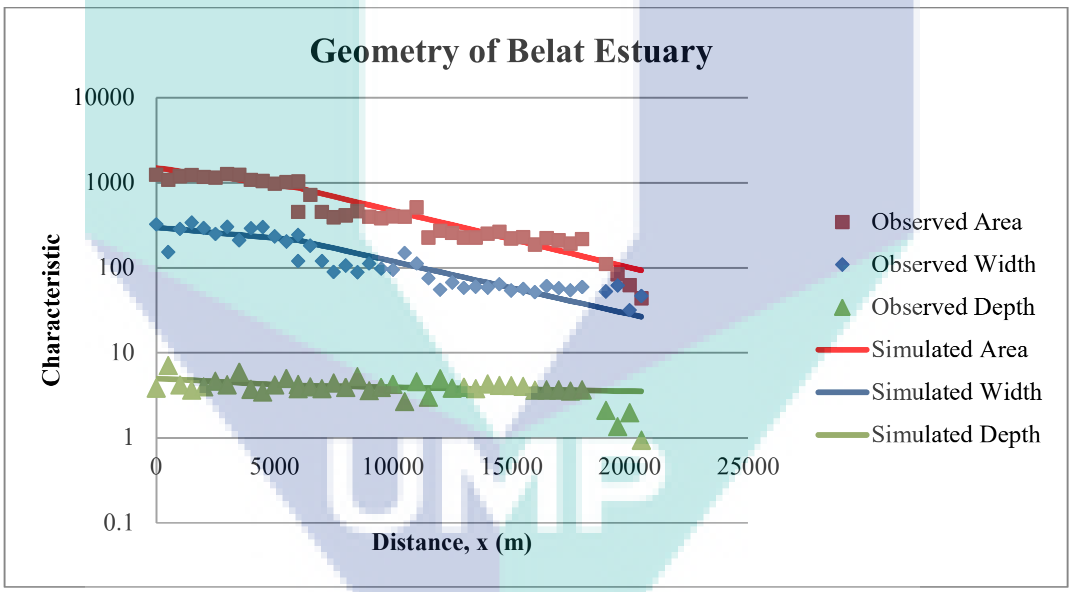



Figure 4.7 Geometry profile of Belat Estuary

Table 4.3 shows the geometry characteristics obtained from the regression analysis. The results confirmed that the exponential function is applicable to be used in the geometry analysis not only for the Kuantan Estuary but also its tributary, the Belat Estuary.

Table 4.3 Geometry characteristics of Belat Estuary

| *Characteristic* | *Mouth, $x_0$* | *Inflection point, $x_1$* |
|---|---|---|
| Area, A ($m^2$) | *1400* | *880* |
| Width, B (m) | *280* | *210* |
| Area convergence, a (m) | *17000* | *6500* |
| Width convergence, b (m) | *17000* | *7000* |
| Average depth, h (m) | *4.5* | *4* |

### 4.3.2 Salinity analyses

Salinity analyses were divided into two sections: vertical and longitudinal salinity distribution. The salinity measurements were conducted in the Kuantan Estuary at HWS and LWS for the measurement date on 27th March 2017, 29th March 2017, 3rd October 2017, 7th March 2018 and 15th April 2018. Meanwhile, another four surveys conducted in the Belat Estuary in 26th April 2017, 2nd October 2017, 6th March 2018 and 14th April 2018.

#### 4.3.2.1 Vertical distribution salinity analyses

*Kuantan Estuary*

The vertical salinity results for Kuantan Estuary dated 27th March 2017, 29th March 2017, and 15th April 2018 as in Figure 4.9 (a), (b) and (e) showed partially mixed patterns along the estuary for both HWS and LWS. The mixing of saltwater and freshwater occurs at all depth but with inconsistent mixing level. There is the existence of fresh water at mouth area were detected near the surface layer more probably due to the freshwater drained from the Galing tributary and other small tributaries from the mangroves area. Moreover, inconsistency of mixing mechanism were also found at kilometres 6 to7 from the mouth which is the confluence of Kuantan-Belat estuary.

From the observation, this area was critically impacted by salinity as there are no small tributaries of drainage point which can contribute to the freshwater discharges along this section. Besides that, the factor contributes to the unstable pattern the restriction of the movement of freshwater and saltwater in and out of the estuary caused by the barrage at

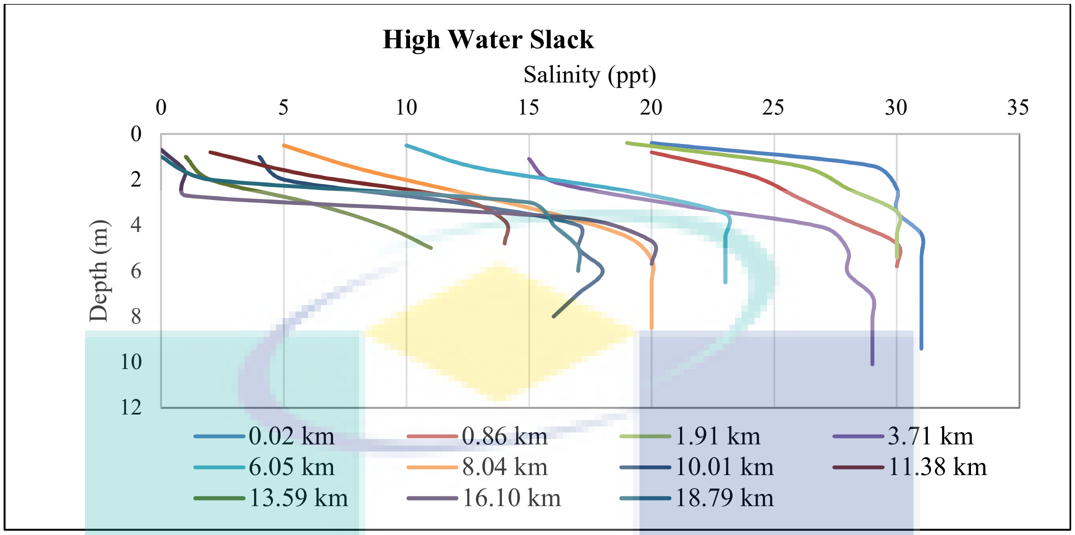
Kobat. In addition, there was a sudden increase in the water depth observed within that distance during measurement conducted. This situation was probably influenced by the change in morphology after the Kobat Barrage was built. This unusual phenomenon may be due to the sediment upstream is being blocked 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 the 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 freshwater 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 condition seems becomes worse reliably effected by uncontrolled human activities along the river such as sand dredging activity. This changes the morphology thus, disturbs the natural flow of water for the area.

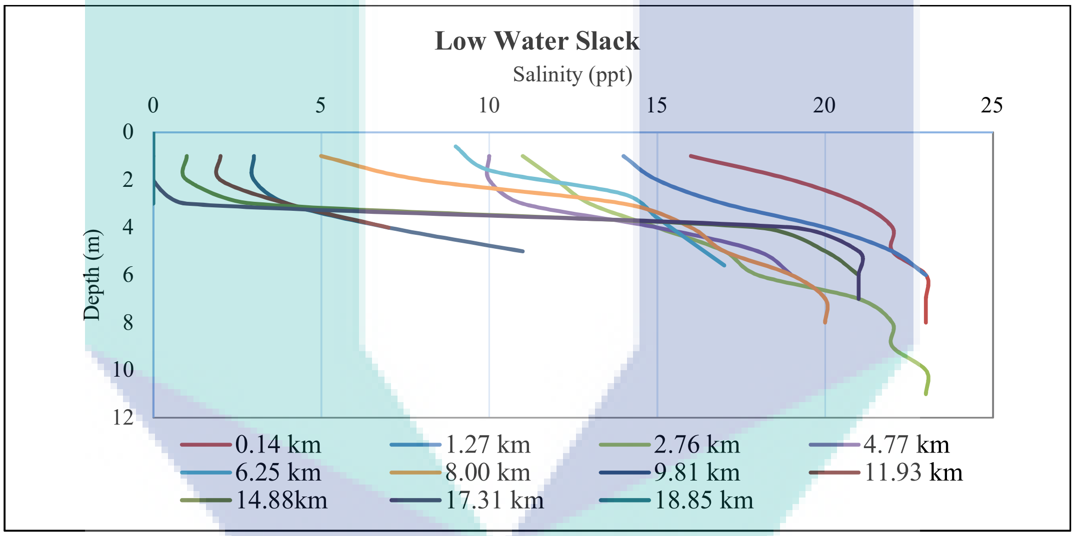
The third survey has been conducted on 3rd October 2017 as in Figure 4.9 (c) to monitor the salinity condition of the Kuantan Estuary. This was the interchanged season from dry period to monsoon period where the estuary began to receive more rainfall. For this period, the pattern does not give much difference from the second measurement. The pattern from the mouth until the confluence of the Belat-Kuantan Estuary presents a partially mixed salinity and become partially stratified from the confluence up to 12km.pattern sama ja From this point, the water started to change its colour, murky than usual. The measurements also demonstrate a well-mixed pattern from this kilometre up till barrage which indicates that the estuary is in stable condition. The murky water and stable condition of salinity reliably were caused by the released of high freshwater discharge from the upstream through one of the Kobat barrage gate. For this set of data measurement, only two point of measurements were taken due to heavy rainfall. A better well-mixed pattern was expected from this LWS measurement due to the released of freshwater discharge from the upstream. The demonstration of first two-point at the mouth area shows a partially mixed condition with salinity less than 20ppt compared to a first and second survey.

The forth measurement was carried out to investigate the salinity condition in the estuary on 7th March 2018 resulted in Figure 4.9(d). This month is the starting month of the dry season according to the historical pattern. There is no barrage opening activity is expected at this time due to the less rainfall in the season. For this time, the patterns seem more stable and fresh for both LWS and HWS compared to the previous surveys. The patterns in HWS shows a well-mixed at the mouth part and stratified in the middle of the estuary and slightly well mixed at the Kobat area. Meanwhile, in LWS only several points show the slightly stratified with most area shows the slightly well mixed. This condition initially gave a bit of hope that the state of the river was getting better. Monitoring were conducted until the barrage and found that the fresher water is due to the big discharge released from the barrage opening. The orientation of the gate seems not closed properly as shown in Figure 4.8.

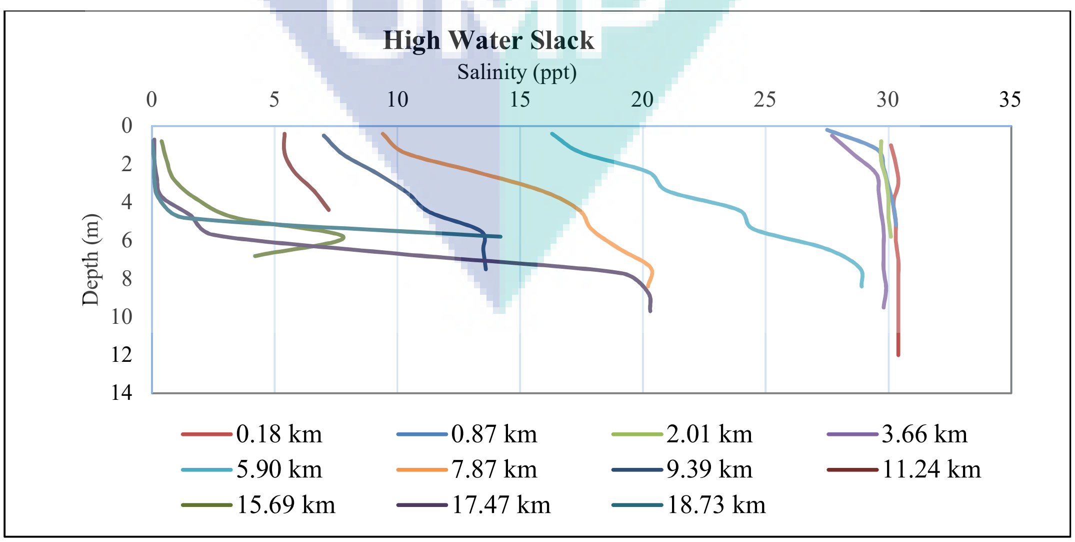
Figure 4.8 Barrage Kobat on 7th March 2018

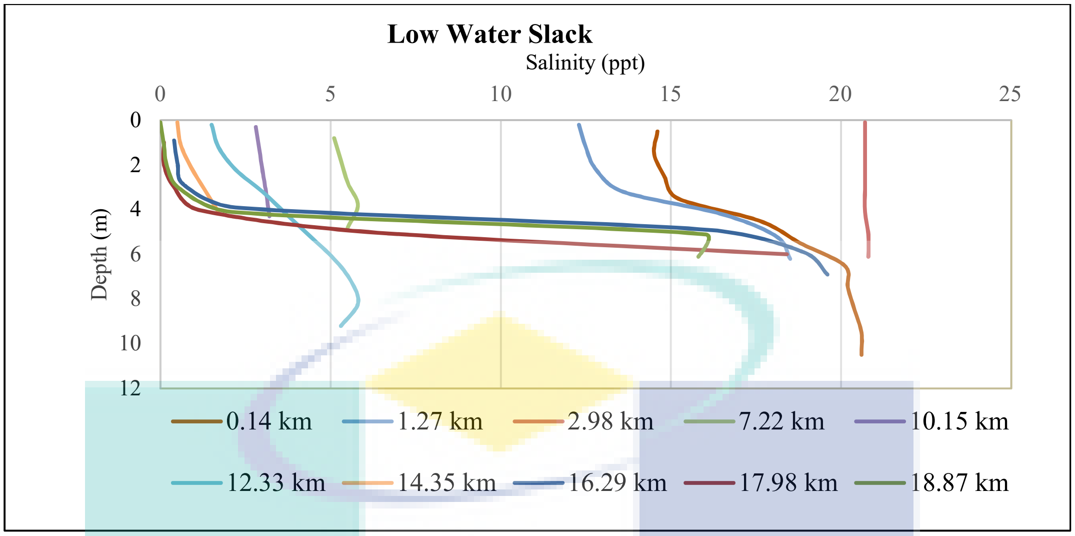
a) 27th March 2017



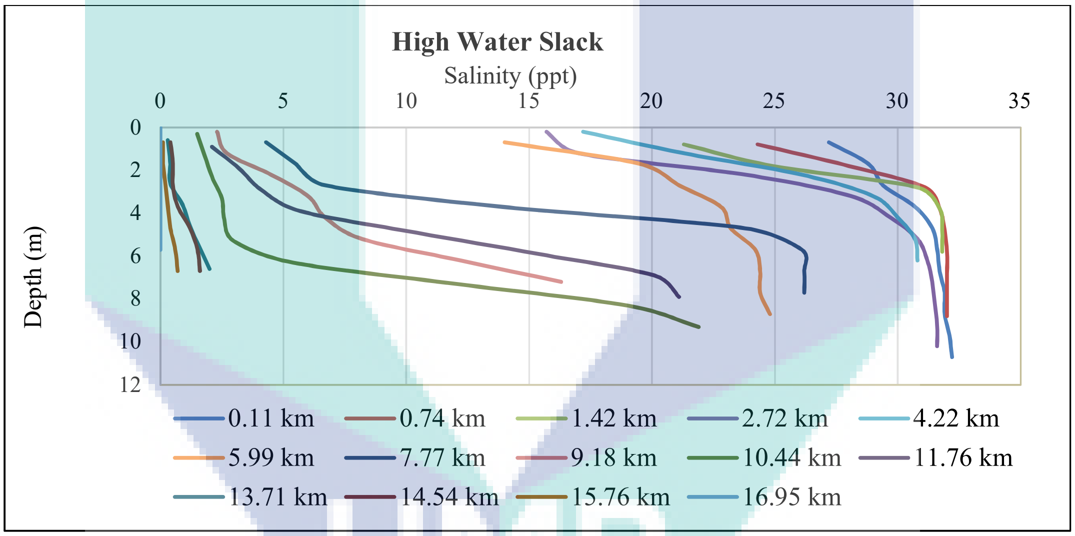



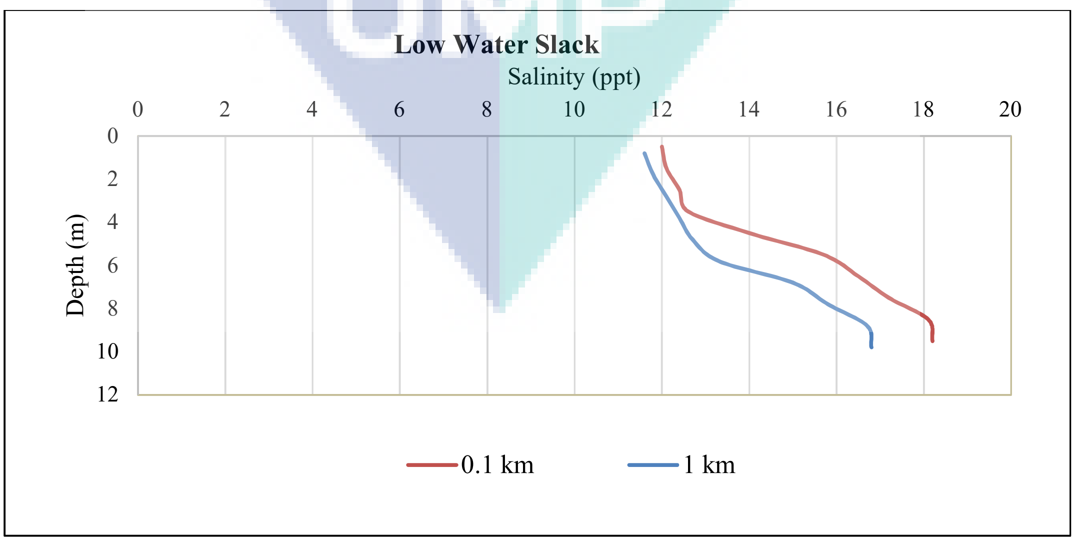

b) 29 March 2017



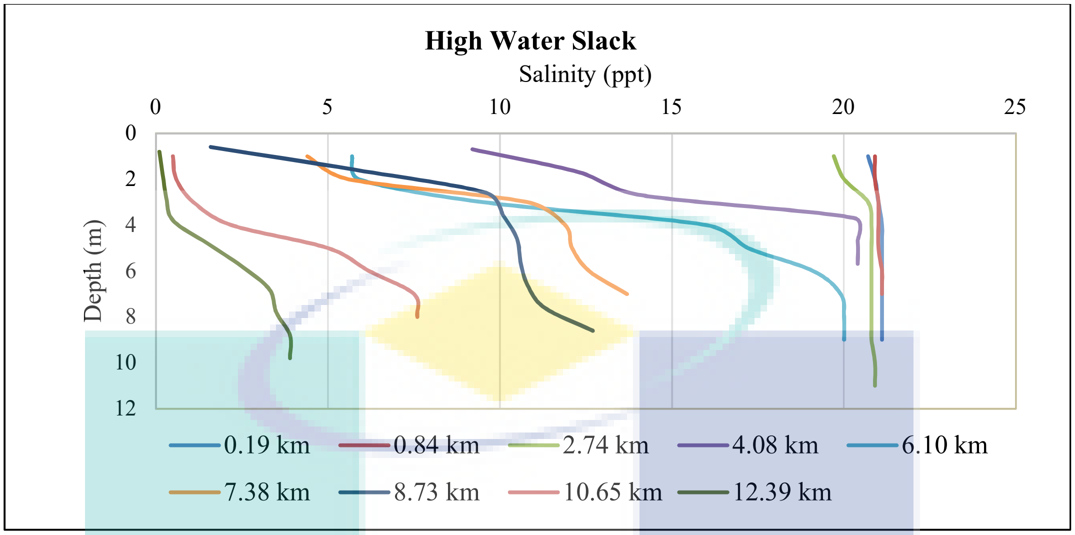


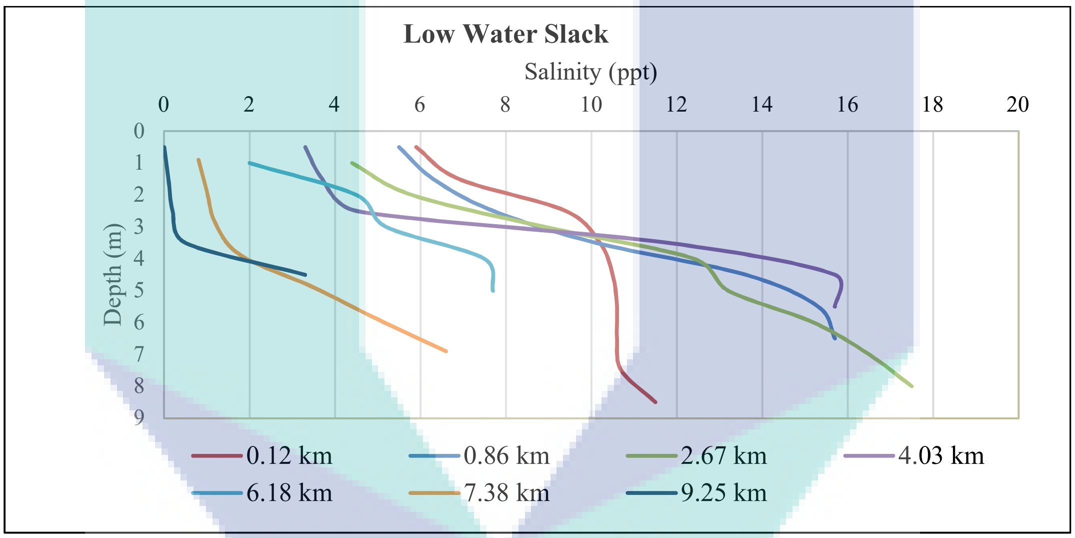

c) 3rd October 2017



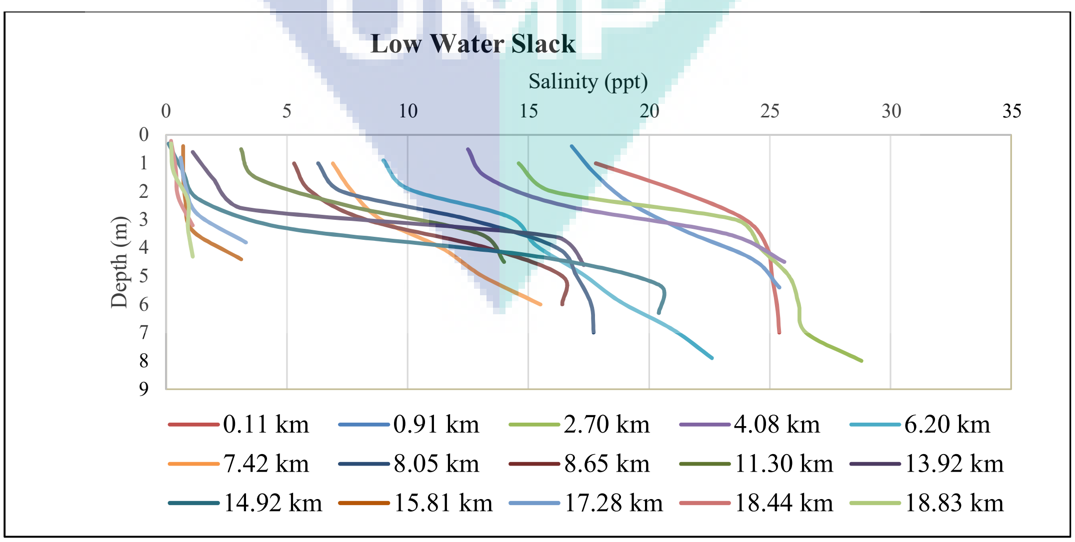



d) 7 March 2018




e) 15 April 2018



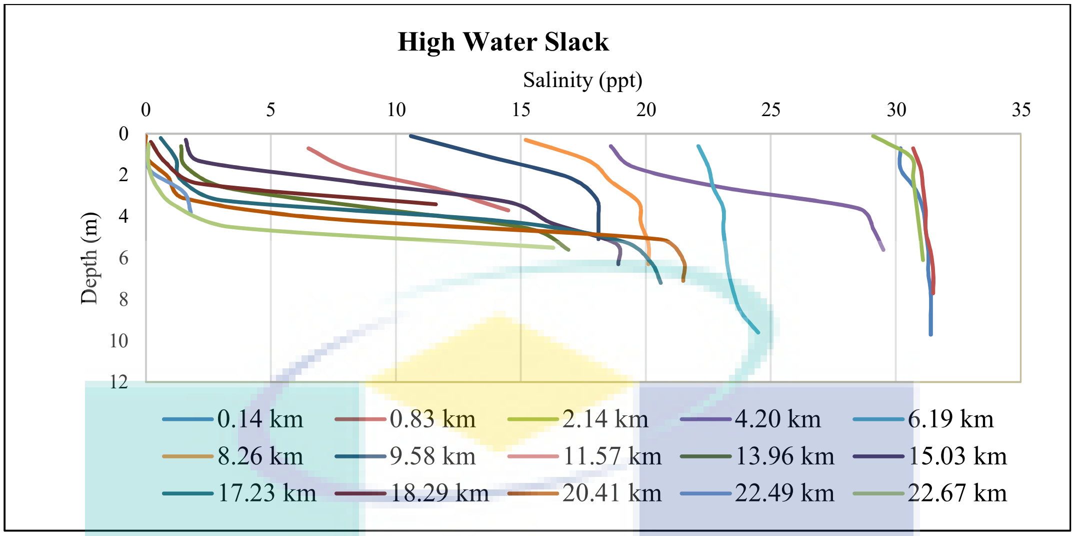



Figure 4.9 Vertical salinity distribution for Kuantan Estuary at HWS and LWS on a) 27th March 2017 b) 29th March 2017 c) 3rd October 2017 d) 7th March 2018 e) 15th April 2018

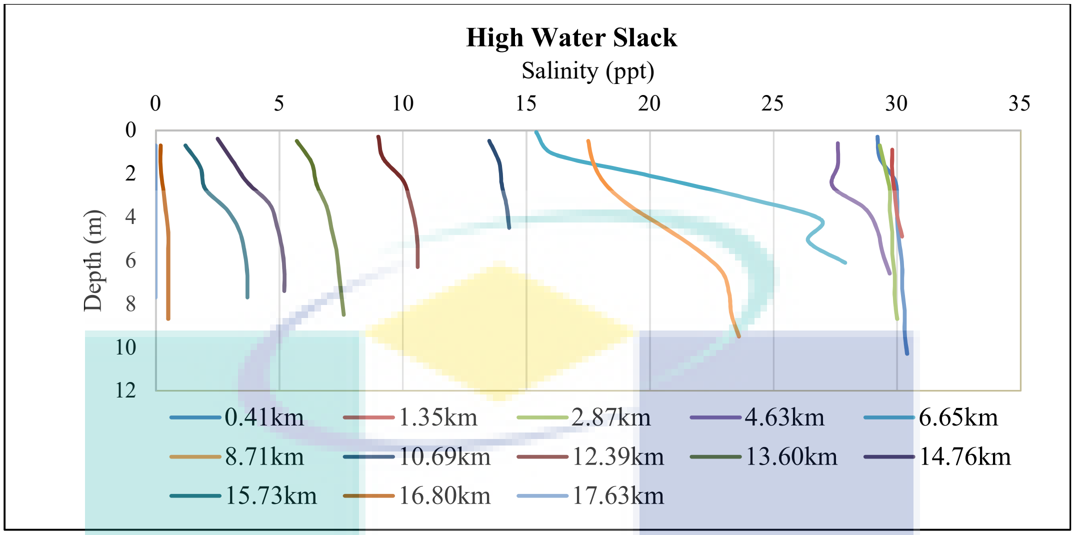
*Belat Estuary*

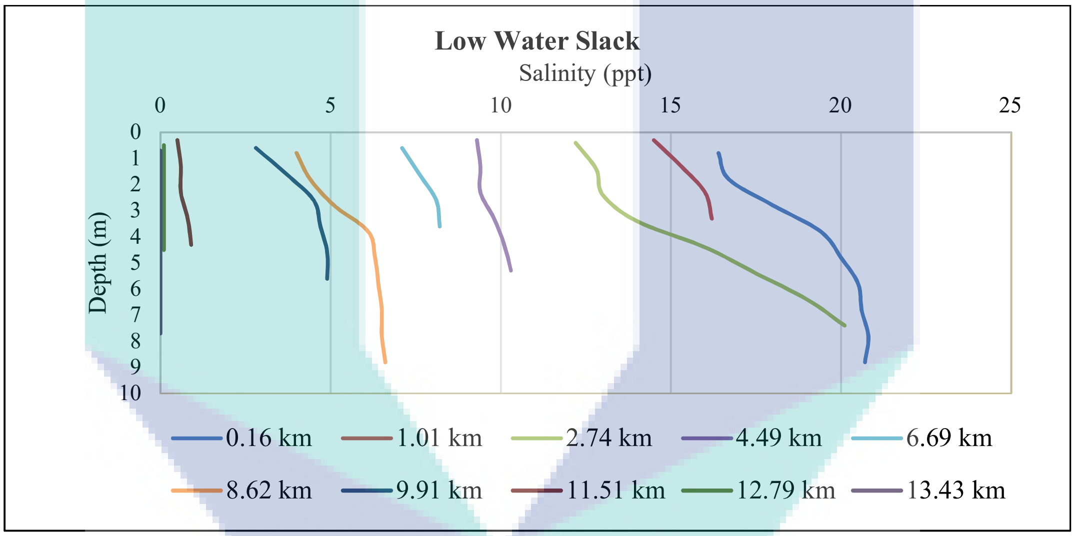
Figure 4.10 shows the vertical salinity distribution of the Belat Estuary during HWS and LWS for four surveys that have been conducted. From the first and third survey dated 26th April 2017 and 6th March 2018, the patterns demonstrated a good patterns which can be classified as well-mixed except for several points. These two measurements presented in Figure 4.10 (a) and (c) indicated that the significant stratification occurred at 4 to 5km from the mouth during the HWS. While, the stratification occurred starting from 2km during LWS. The stratification was due to the split of the river which caused the meeting received freshwater discharge during LWS and the saltwater sharing for both rivers during HWS. However, in 26th April 2017, its stratification in LWS at this kilometres cannot be seen obviously due to the low depth in the moment.

Survey dated on 14th April 2018 illustrated in Figure 4.10 (d) showed some differences in the vertical distribution patterns compared to the 2 surveys discussed earlier. For HWS, the distribution pattern displayed similar well-mixed pattern along the estuary with only minor deviation at the confluence area. However, the depths near to the surface were fresher because the measurements were conducted slightly earlier from the slack moment. At LWS, the pattern demonstrated partially mixed conditions but several stratified distribution at kilometres 2 to 4. The stratification pattern detected might be due to the wind factor effect which fasten the movement of the fresh water on the surface. Besides that, unusual condition was identified during the field survey in which the salt intrusion length has travel up to 19km, 6km further than the previous survey during dry season. This phenomenon indicates there might be water abstraction or diversion activity occurred at the upstream part.

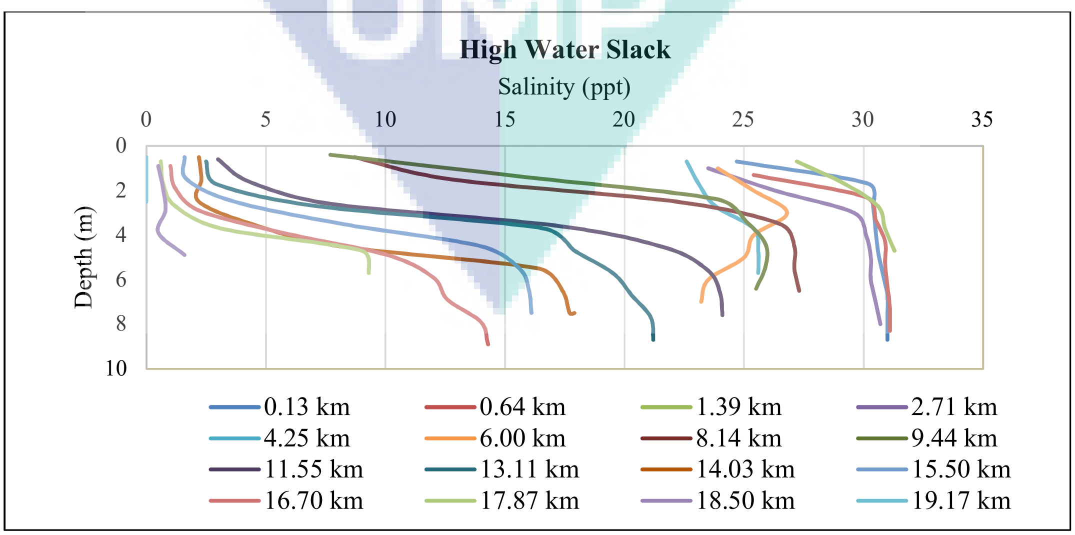
The measurement dated on 2nd October 2017 presented in Figure 4.10 (d) fell in the early monsoon season. At HWS, the vertical salinity distribution demonstrated partially mixed pattern at mouth area but began to become stratified starting from the confluence moving inland. Well-mixed conditions were observed only when the measurements reached the last point at about 18km. For LWS, the distributions obtained can be classified as highly stratified from the mouth up to 14km and began to mix well at kilometres 12km and above. The stratification conditions at both HWS and LWS may be due to the late timing of measurements which were conducted after the slack moment. However, only at the upstream part the measurements were able to be done during the slack moments as shown in Figure 4.10(b). Besides that, the rainfall events that occurred before the field survey also contributed to the stratification condition. It is worth to note that the water level observed at LWS does not differ much from the level at HWS.

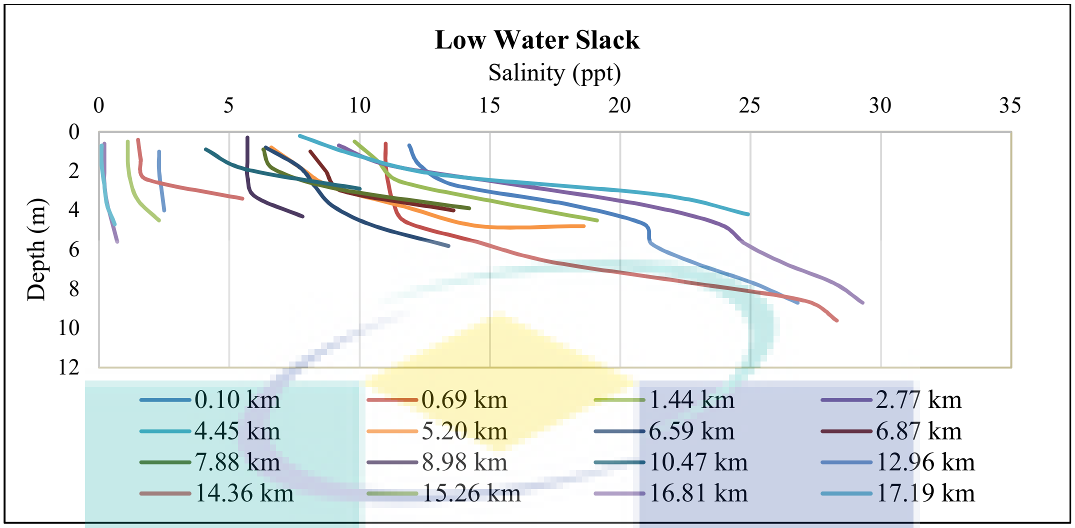
a) 26th April 2017



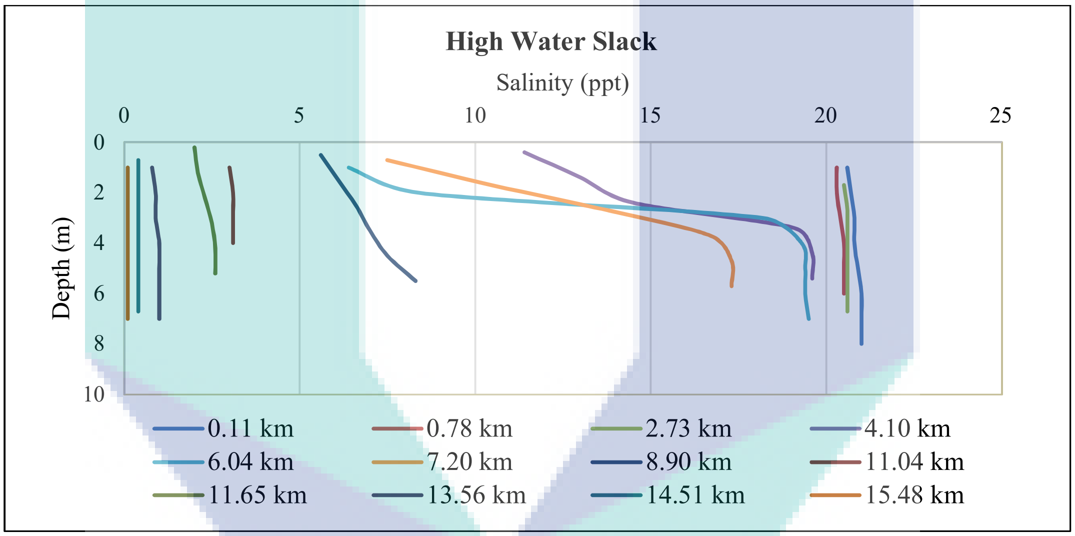



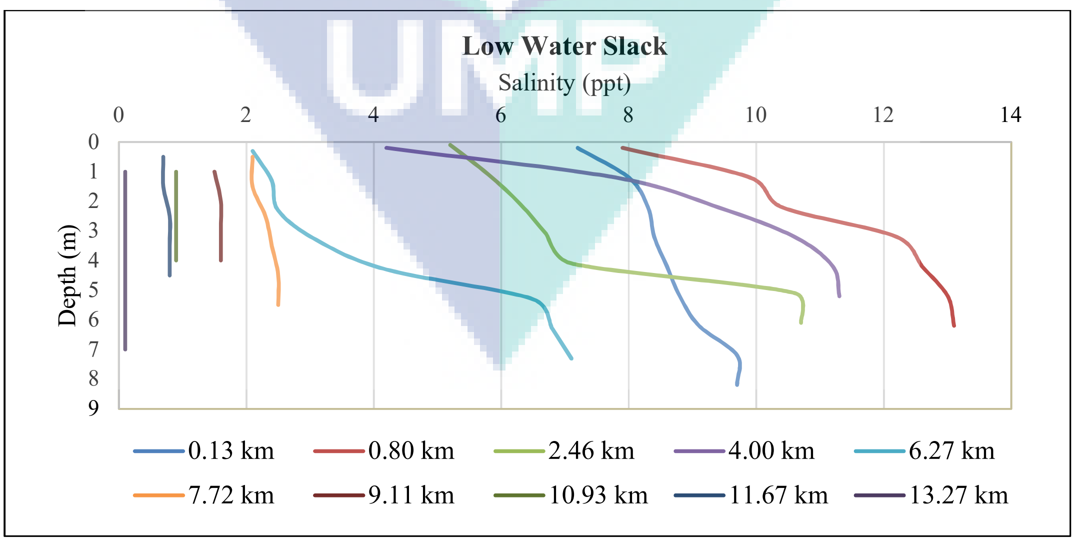

b) 2 October 2017






c) 6 March 2018



d) 14 April 2018

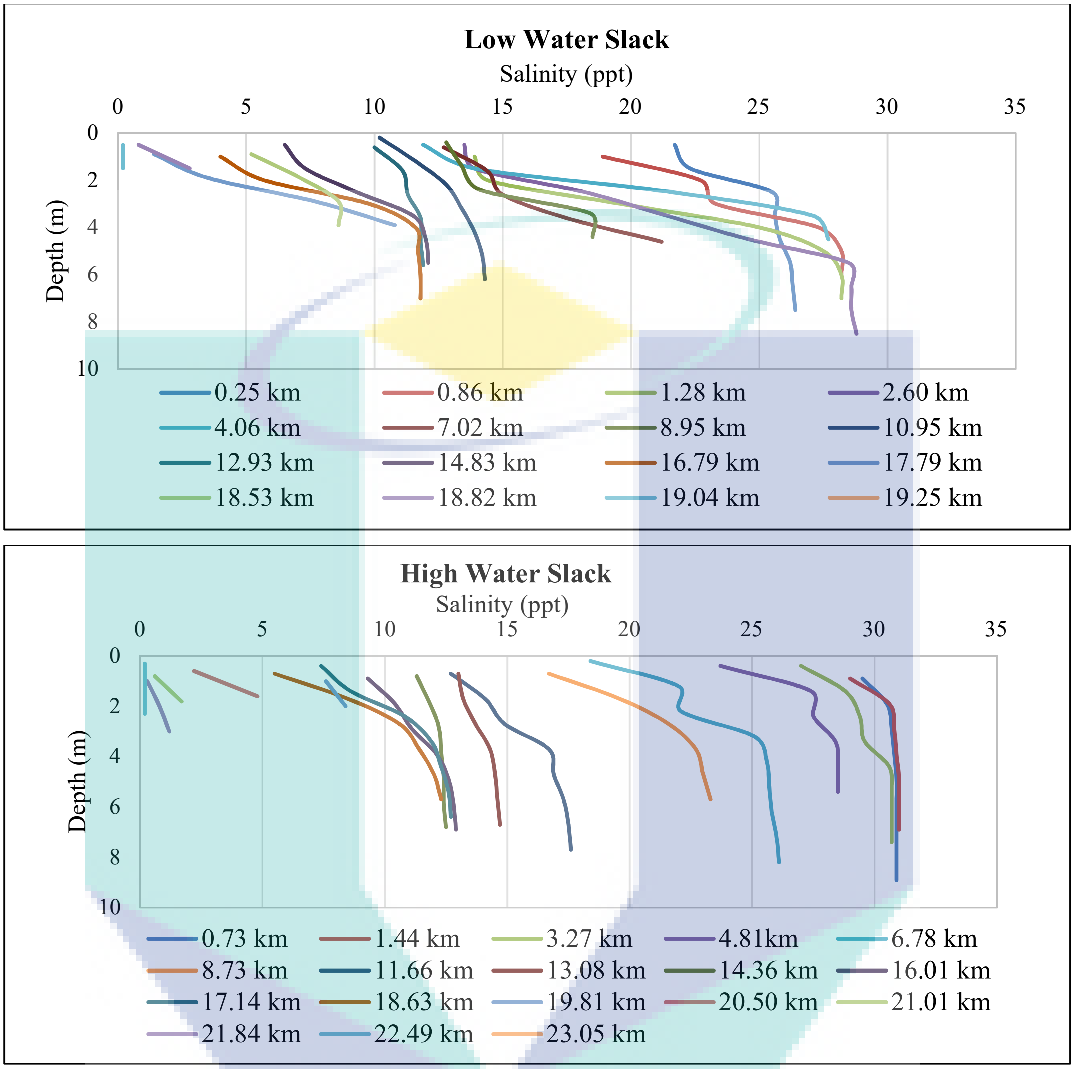



Figure 4.10 Vertical salinity distribution for a) 26th April 2017 b) 2nd October 2017 c) 6th March 2018 d) 14th April 2018

#### 4.3.2.2 Longitudinal salinity distribution

The longitudinal salinity distributions in this study has been successfully simulated by utilising Equations 2.22 and 2.23. For this part, the Van der Burgh coefficient K and dispersion D were calibrated to get the best fit curve between simulated and observed salinity data. Since the velocity amplitude was not measured onsite, the tidal excursion E also was calibrated. The alternative way in solving this problem, the dispersion D was calibrated in terms of the mixing number α0 which indicates the dispersion-discharge ratio.

*Kuantan Estuary*

The calibrated parameters used in salinity curve for Kuantan Estuary are summarized as in Table 4.4. The salinity length for Kuantan estuary was determined by using Equation 2.31. The total salinity length at HWS obtained for 27th &29th March 2017, 3rd October 2017, 7t March 2018 and 15th April 2018 are 21km, 18.82km, 21.05km, 16.24km, and 24km respectively and summarised in Table 4.5.

Table 4.4 Calibrated parameters in Kuantan salinity curve

| | *Van der Burgh coefficient, K* | *Mixing coefficient, $\alpha_0$ [1/m]* | *Tidal excursion, E [m]* | *Dispersion, D [m2/s]* |
|---|---|---|---|---|
| 27th March 2017 | *0.45* | *11* | *4500* | *129.8* |
| 29th March 2017 | *0.45* | *8.6* | *6000* | *176.3* |
| 3rd October 2017 | *0.45* | *9.0* | *9000* | *203.4* |
| 7th March 2018 | *0.45* | *6.8* | *5000* | *192.4* |
| 15th April 2018 | *0.45* | *14* | *4800* | *116.2* |

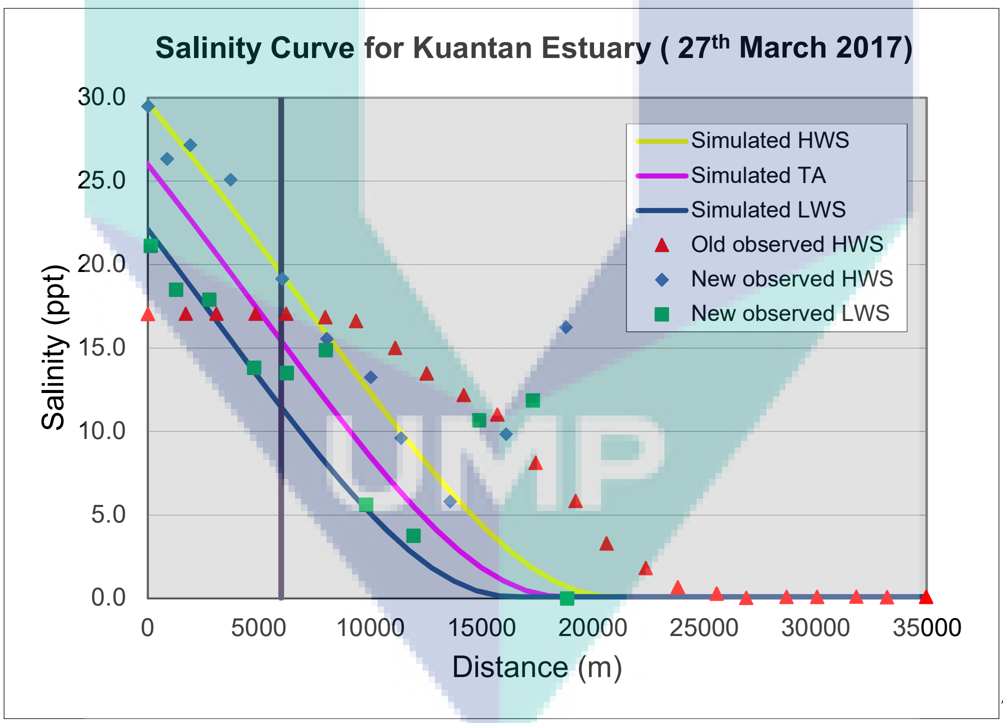
Table 4.5 The total salinity length at HWS results in the Kuantan Estuary.

| *Survey date* | *Total salinity length at HWS ($L_{HWS}$) , km* |
|---|---|
| 27th March 2017 | *21.00* |
| 29th March 2017 | *18.82* |
| 3rd October 2017 | *21.05* |
| 7th March 2018 | *16.24* |
| 15th April 2018 | *24.00* |

The longitudinal salinity profile of the Kuantan Estuary for all the surveys conducted were presented in Figure 4.11 (a) to (e). All the measurements demonstrated slightly lower salinity level at location of about 2km to 4km from the estuary mouth. This was contributed by stratification pattern as discussed in the vertical salinity distribution analyses section. Several outliers were observed at the confluence of the Belat-Kuantan Estuary for the LWS. During the ebb tide, the flows travelled from the upstream to the downstream of the Belat and Kuantan Estuary which carry the saltwater back towards the ocean met at the confluence. This has caused the meeting point to have higher salinity concentration. Besides that, there were several outliers for both LWS and HWS condition at the critical area from 16km to 20km which are near the Kobat barrage area. These outliers were caused by the unequal distribution of salinity and changes in morphology within this area. Hence, the saline water becomes unstable in this area.

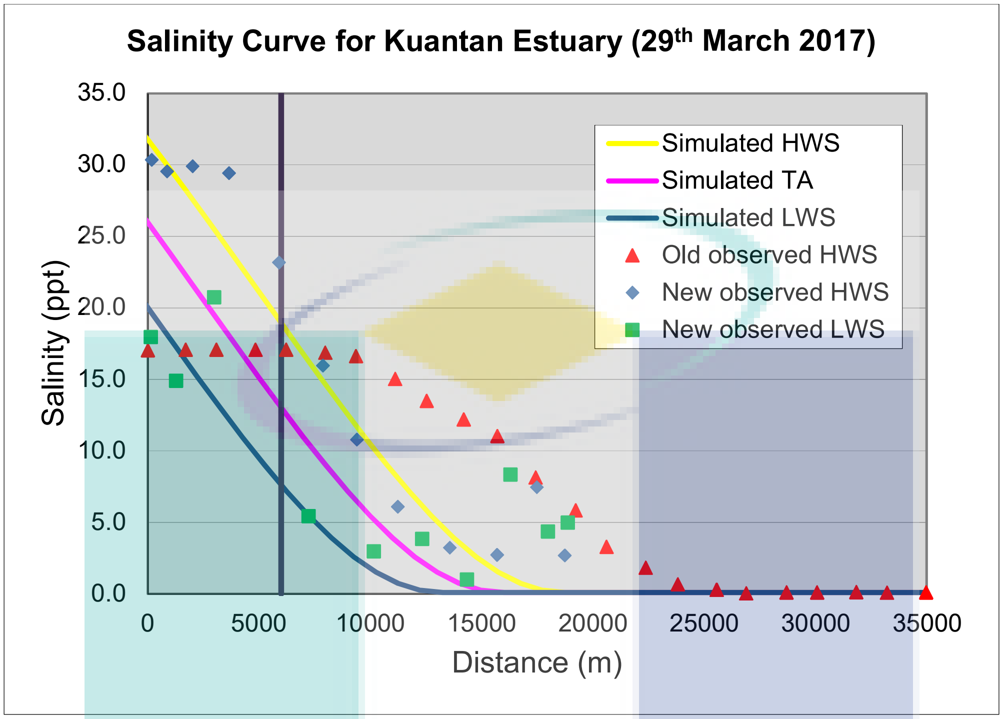
The comparisons of the newly surveyed salinity results with the previous research (red markers) have indicated that the pattern of longitudinal salinity distribution has significantly changed after the construction of the barrage. The new measurements also show that the natural hydrodynamic process in the Kuantan Estuary has no longer in equilibrium condition and is unstable. Hence, these changes required the most attention as they may give serious impact on the ecology.

a) 27th March 2017

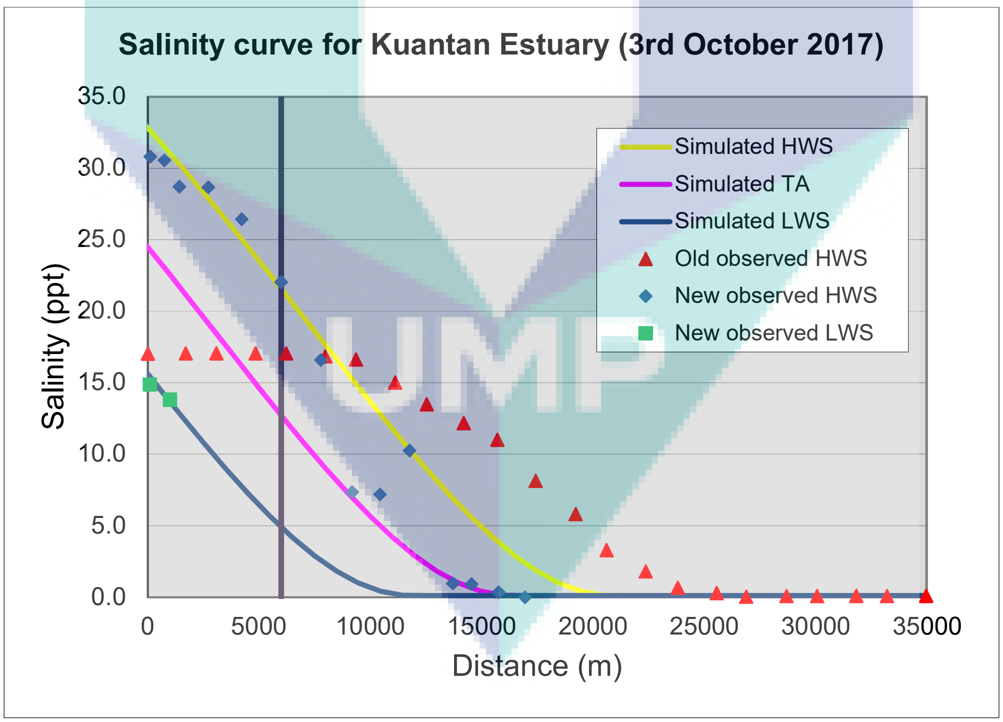



7th

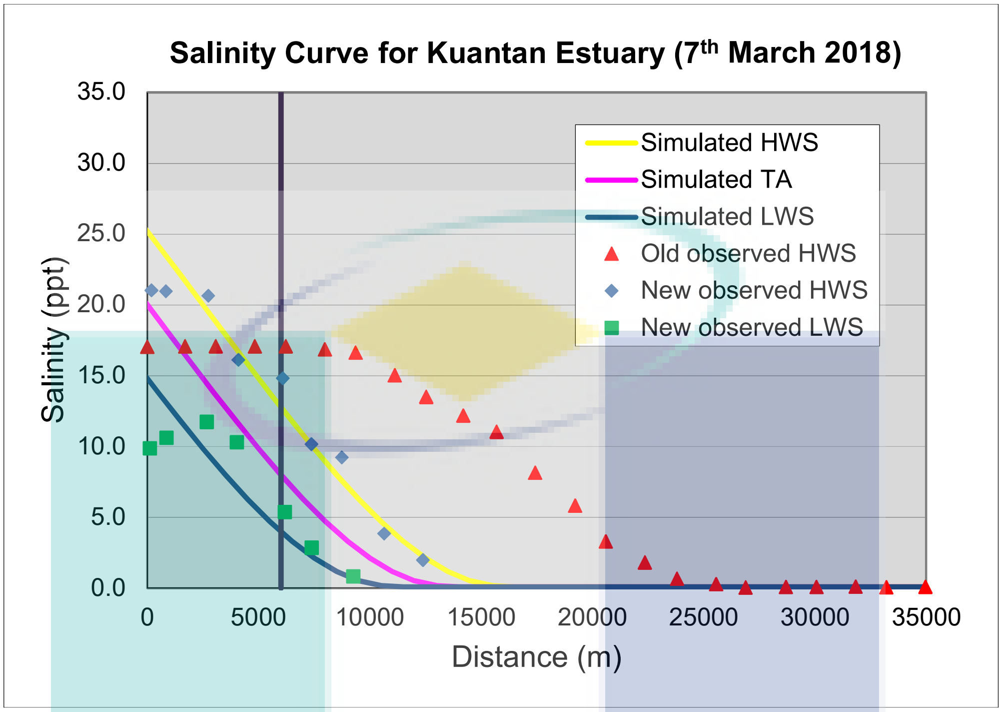
b) 29th March 2017




c) 3rd October 2017



d) 7th March 2018




e) 15th April 2018

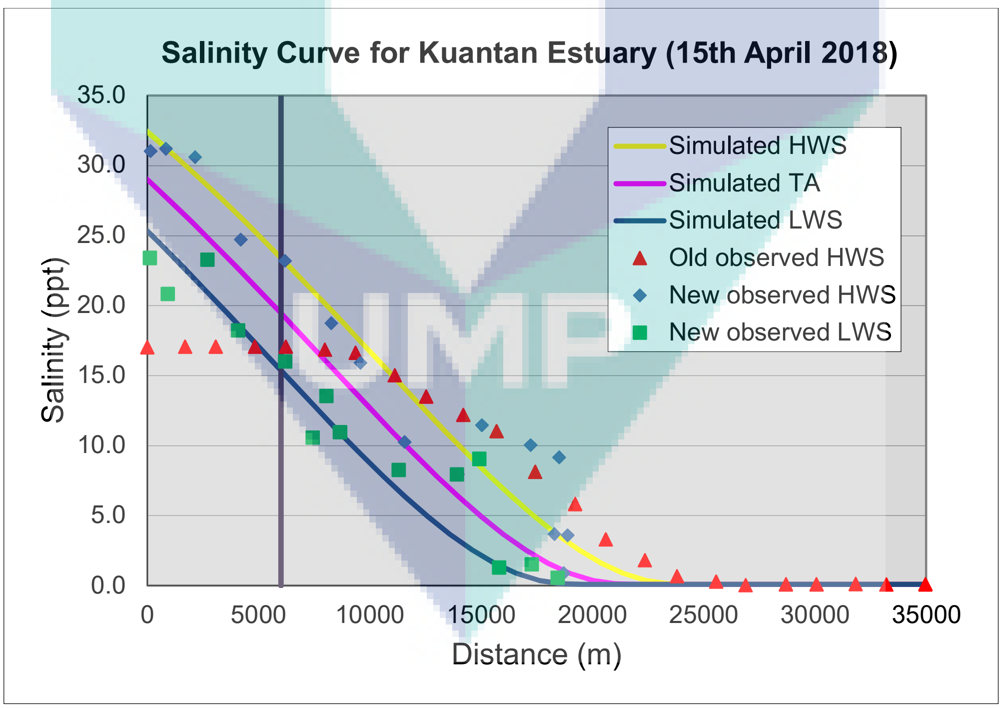
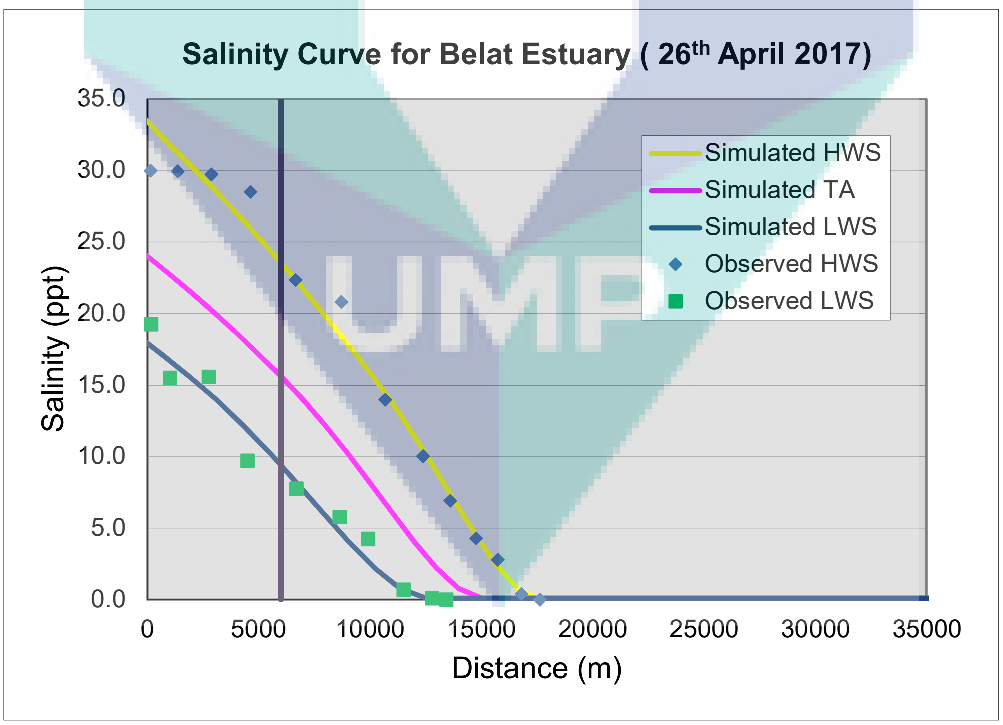



Figure 4.11 The longitudinal salinity distribution on a) 27th March 2017 b) 29th March 2017 c) 3rd October 2017 d) 7th March 2018 e) 15th April 2018

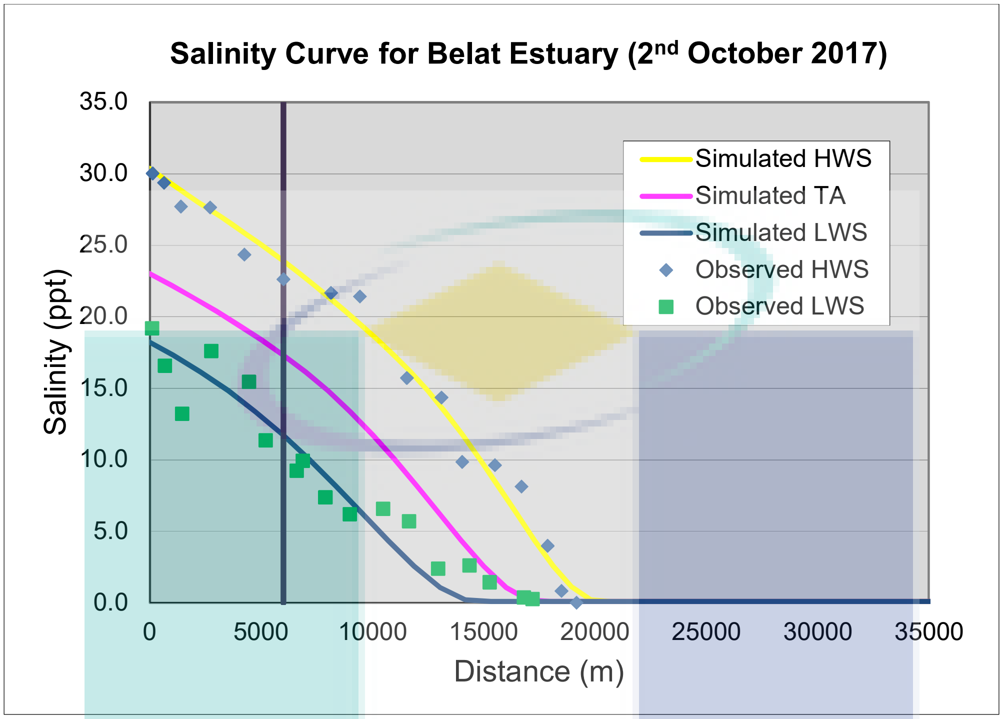
*Belat Estuary*

The simulated longitudinal profile for all Belat Estuary measurements were illustrated in Figure 4.12. Most of the results show good agreement between the simulated and observed data. However, at distance 6.5km, there are still some outliers due to the split in the Kuantan River (Belat – Kuantan). For the downstream part near the mouth, it can be seen that the salinity distributions show some inconsistencies. This was because the downstream part of the Belat Estuary belongs to the Kuantan River which is no longer in an equilibrium condition after the construction of the Kobat Barrage. The measurement dated 2nd October 2017 in Figure 4.12 (b) during the early wet season, the HWS simulation shows a good fit but for the LWS there were many deviations observed along the estuary. This was due to the late timing of measurements. Last survey conducted on 14th April 2018 presents good fit at the downstream part of estuary but show significant outliers starting from 4km after the confluence. The outliers occurred during both LWS and HWS. It was suspected that water abstraction activity at the upstream when the measurements were performed.

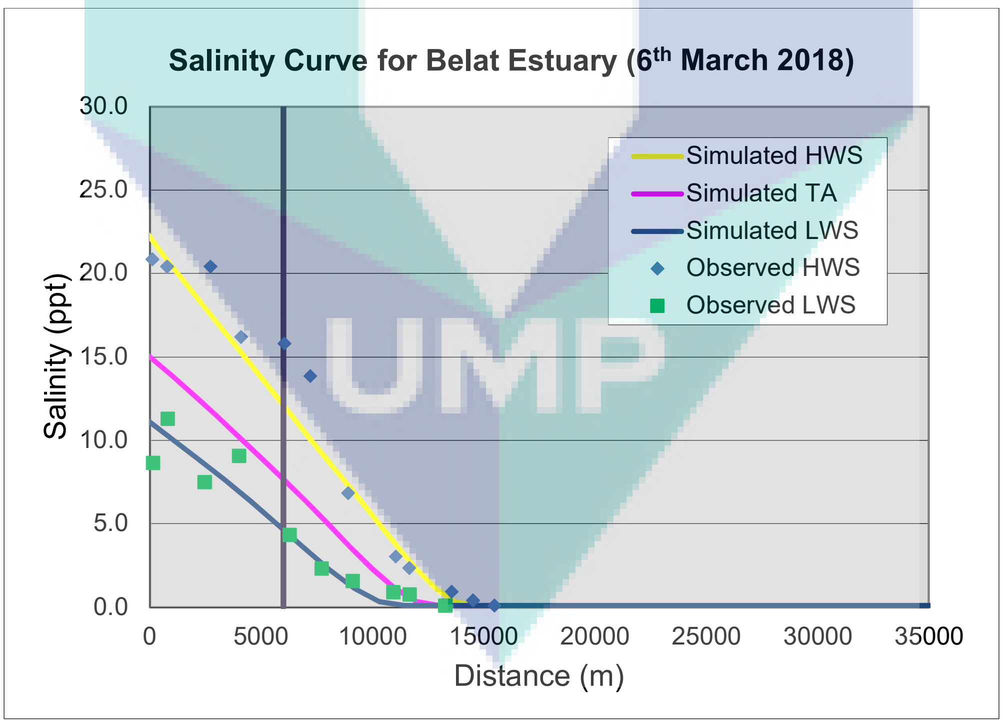
a) 26th April 2017



b) 2nd October 2017




c) 6th March 2018



d) 14th April 2018

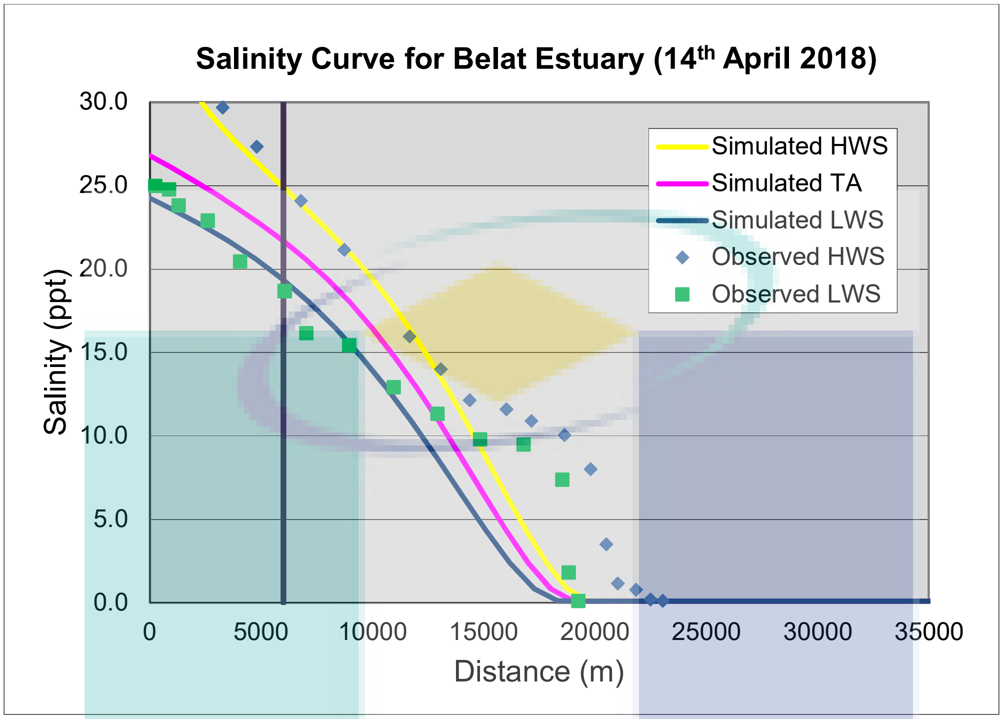



Figure 4.12 Salinity curve for Belat Estuary on a) 26th April 2017 b) 2nd October 2017 c) 6th March 2018 d) 14th April 2018

Table 4.5 Calibration parameters for Belat Estuary salinity curve

| | *26th April 2017* | *2nd October 2017* | *6th March 2018* | *14th April 2018* |
|---|---|---|---|---|
| Van der Burgh coefficient,K | *0.50* | *0.50* | *0.50* | *0.50* |
| Mixing coefficient, α [1/m] | *14* | *20.50* | *9.50* | *27.00* |
| Tidal excursion at mouth, $E_0$ [m] | *11500* | *13500* | *8500* | *9000* |
| Tidal excursion at inflection point, E1 [m] | *8240* | *9924* | *5358* | *4939* |
| Convergence length, e [m] | *18000* | *19500* | *13000* | *10000* |

From the calibration parameters summarised in Table 4.5 above, the Van der Burgh's coefficient K obtained is 0.5 and this coefficient is fit for all surveys. The salinity length for Belat Estuary was determined by using Equation 2.31. The total salinity length at HWS obtained for 26th April 2017, 2nd October 2017, 6th March 2018 and 14th April 2018 are 20.85km, 24.2km, 17km, and 23.66km respectively.

Table 4.6 The total salinity length at HWS results in the Belat Estuary.

| Survey date | Total salinity length at HWS ($L_{HWS}$) , km |
|---|---|
| 26th April 2017 | 20.85 |
| 2nd October 2017 | 24.20 |
| 6th March 2018 | 17.00 |
| 14th April 2018 | 23.66 |

#### 4.3.2.3 Belat-Kuantan Estuary

The surveys conducted in 2nd and 3rd October in Belat and Kuantan Estuary, respectively which falls in early monsoon season. In addition, these dates were identified is in full moon phase. Besides the increase in total rainfall in this season, the surveys also identified the same water level of HWS and LWS due to the longer HWS than LWS in full moon phenomenon phase. Thus, the vertical salinity patterns for both water slack showed the same pattern through all the points along river. It shows a partially mixed pattern from mouth till the middle of river then mixed well at several points before salinity becomes 0.1ppt. The longitudinal distribution salinity patterns, both surveys showed a good results in the lower reach area which from the mouth until the diversion point of the estuary. The middle of Kuantan Estuary shows a good agreement to the predicted salinity before several outliers detected before the Kobat barrage due to the restriction of water flow. However, It differs to the The Belat Estuary which are patterns showed However, Belat Estuary reliably have a good and balance water flow condition thus showed a good agreement for all measurements along the estuary.

Meanwhile, in March, HWS at Belat and Kuantan shows a well-mixed patterns at mouth and becomes partially mixed at the middle and again mixed well at the upper reach. The inconsistency in the mixture at HWS identified starts from 4 to 7 km from the mouth. Besides that, the LWS patterns at these dates shows the partially mixed and inconsistency in its salinity as early as starting from 2km from the mouth. In longitudinal salinity distribution, the deviation signified at the confluence area then seems unite with the prediction salinity until the salinity becomes 0.1 ppt.

In April, which is the dry season, LWS shows stratification at mouth for both measurements on 14th and 15th April 2018. While, salinity mixed well at mouth during HWS. The salinity level shows high salinity reading in both HWS and LWS at mouth due to less discharge at this time. Besides that, in longitudinal salinity distribution, the patterns seems having a good agreement between the observed and predicted salinity from mouth until the confliction point. However, the longitudinal salinity patterns for both estuary at these dates seems experiencing an abstraction of water. This occurrence might be due to the abstraction for vegetation area uses around which effected by dry season.

### 4.3.3 Predictive Discharges

Other than discharges obtained from HEC-HMS simulation, the predictive discharges also calculated by utilising predictive equations in 1-D Salt Intrusion Model. The calculated predictive discharges are tabulated in Table 4.6.

Table 4.6 Summary of calculated predictive discharges

| Kuantan Estuary | |
|---|---|
| Date | Predictive discharge [$m^3/s$] |
| *27 March 2017* | *11.8* |
| *29 March 2017* | *23.5* |
| *3 October 2017* | *27.1* |
| *7 March 2018* | *27.4* |
| *15 April 2018* | *6.5* |
| Belat Estuary | |
| *26th April 2017* | *17.7* |
| *2nd October 2017* | *10.2* |
| *6th March 2018* | *22.5* |
| *14th April 2018* | *3.6* |

In summary, the results show a good agreement between the HEC-HMS results and predictive discharge except for survey in Belat Estuary dated 6th March 2018. It shows the under estimated discharges by HEC-HMS might be caused the by underestimated of CN and base flow at this area.

### 4.3.4 Future salinity condition

The future salinity length was carried out by finding the low flow discharge by using HP-12 procedure. The area chosen in Kuantan and Belat Estuary were based on the area fraction produced in ArcGIS. The low flow information then utilised in 1-D Salt Model for the salinity length prediction for the Estuary. The future salinity result was presented as in Table 4.7 below. The results for Kuantan Estuary was expected to become worse than the current condition. However, the salt intrusion length prediction in Belat Estuary have no significance effect in the future with consistent length compared to the current length. This occurrence may be usually caused by the restriction of the natural flow of the estuary. It is reliably will be getting worse year by year if the barrage is still not function and maintain well.

Table 4.7 Prediction on future salinity intrusion

| | Low flow, $Q_{7,50}$, $m^3/s$ | Salt intrusion length, km |
|---|---|---|
| *Kuantan Estuary* | *3* | *29* |
| *Belat Estuary* | *61.5* | *14* |

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## 4.4 Models performance

| | *Kuantan Estuary* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DATE | 27th March 2017 | | 29th March 2017 | | 3rd October 2017 | | 7th March 2018 | | 15th April 2018 | |
| SLACK | *HWS* | *LWS* | *HWS* | *LWS* | *HWS* | *LWS* | *HWS* | *LWS* | *HWS* | *LWS* |
| RMSE | *5.18* | *4.73* | *3.08* | *4.30* | *3.60* | *0.41* | *1.84* | *2.57* | *2.57* | *2.56* |

| NSE | 0.99 | 0.98 | 1.00 | 0.97 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 |
|---|---|---|---|---|---|---|---|---|---|---|

There are two error measuring tools used in this study which are Root Means Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) in order to evaluate the applicability and reliability of the model. By evaluating the correlation between the observed and predicted results, the error performance of the models in simulating and predicting the salt intrusion in estuaries was determined. The lower the value for RMSE, the better is the model performance. While high NSE values indicate high accuracy in the performance of the model. The outcome of all error analyses for both Kuantan and Belat Estuary are tabulated in Table 4.8 and Table 4.9, respectively.

Table 4.8 Results of model performance by using Root Mean Square Error (RMSE) and Nash-Sutcliffe Error (NSE) for Kuantan Estuary surveys

The RMSE values obtained for all surveys in Kuantan Estuary is in range 0.41 to 5.18 ppt. The outliers at the confluence of Kuantan-Belat River and also at the point in the Kobat area are contributing to the error of the overall results. Most surveys show the RMSE in LWS is higher than in HWS except on 3rd October 2017 which only have 2 measurements in LWS. For the NSE analyses, the values obtained for all surveys shows a good performance in HWS. 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.

Table 4.9 Results of model performance by using Root Mean Square Error (RMSE) and Nash-Sutcliffe Error (NSE) for Belat Estuary surveys

| Belat Estuary | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **DATE** | **26th March 2017** | | **2nd October 2017** | | **6th March 2018** | | **14th April 2018** | |
| **SLACK** | **HWS** | **LWS** | **HWS** | **LWS** | **HWS** | **LWS** | **HWS** | **LWS** |
| **RMSE** | 1.41 | 1.16 | 1.22 | 1.96 | 1.83 | 1.15 | 3.64 | 3.25 |
| **NSE** | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 |

The RMSE values obtained from measurements in Belat estuary are in range 1.15ppt to 3.64ppt. In this tributary, the outliers mostly found from the mouth of estuary up to Belat-Kuantan confluence. On the other hand, the analysis shows high NS efficiency for both survey conditions with the factor of 0.99 and 1 which is very near to unity. Nevertheless, for the rest of the sections, the model still displays good performance. This means that the salt intrusion model is very reliable and efficient.

## 4.5 Kobat Barrage Assessment

The assessment of the barrage have been done by conducting a site visit at barrage control station. However, the data available is only an opening and closing gate time and duration. The barrage also did not have any specified control data either discharge or the velocity of water released. This practised and regulation have affect the estuary system either the changing in water flow, geometry, living organism in the ecosystem and etc. The barrage location, condition and structure need to be restudied again due to the problem facing every dry season.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Introduction

The Kuantan River Basin have been delineated by using ArcGIS and the unit hydrograph generated by using HEC-HMS. Eight rain gauges stations and one streamflow station were considered in this watershed. A one-dimensional analytical salt intrusion model has been successfully applied to the Kuantan Estuary during spring and neap tide with high and low water slack condition. There is two salinity distribution analysed which is vertical and longitudinal distribution profile. The results for this part also shown a good arrangement between the simulated and observed salinity curve. This proves that the 1-D analytical solution is reliable and applicable for the salt intrusion study in the Kuantan Estuary and its tributary. The parameters of the Van der Burgh's coefficient K, Dispersion $D_0$ and tidal excursion E for the Kuantan estuary were calibrated on the first survey and validated by the second and third survey. Meanwhile, in Belat Estuary the parameters were calibrated in the first survey and validated by the second survey.

It is also found that the predictive equation for discharge can be used in this ungauged downstream. The model also applied to the Belat Estuary which is the main tributary of this estuary. In term of geometry, the results show that the shape of the Kuantan and Belat Estuary are well described by the exponential equations. Apart from that, this study also confirmed that there is a significant change in the downstream cross-sectional area after the Kobat Barrage was built. The future salinity length prediction performed by using 1-D Salt Model in collaboration with HP-12 in finding the low flow for 7 days in 50 ARI.

Five field surveys have been conducted in Kuantan Estuary on 27th and 29th March, 3rd October 2017, 7th March, and 15th April 2018. The study for the estuary covered from the mouth of estuary until the reading reached 1ppt but restricted until the Kobat barrage by using moving boat technique. In addition, the study also extended to the Belat Estuary to test the model and study the potential of the tributary. Thus, four surveys in Belat Estuary have been conducted on 26th April, 2nd October 2017, 6th March and 14th April 2018. From the salt intrusion simulation, the Van Der Burgh coefficient, K for Kuantan Estuary and Belat Estuary are 0.45 and 0.5, respectively. The dispersion in Kuantan and Belat Estuary is in the range of 100 to 250 m2/s and 50 to 200 m2/s, respectively. The future low flow in the estuaries was estimated by performing Hydrological Procedure No 12 with 7 days in 50years ARI. The low flow obtained for Kuantan and Belat Estuary is 3 and 61.5m3/s, respectively according to the fraction area. These low flow discharge then utilised in 1-D Salt Model by using the current salinity scheme. The error analyses for HEC-HMS and 1-D Salt Model are performing by using two methods which are NSE and RMSE method.

The tidal mixing mechanism in the Kuantan Estuary and Belat Estuary are not consistent due to the existence of Kobat barrage which it depends on the freshwater discharge at the observation time as mentioned by Gisen (2014). 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 several explainable outliers. The performance of the 1-D analytical salt intrusion model were evaluated and the results showed accuracy.

In overall, the results of this study have provided an insight into the current salinity condition in the Kuantan Estuary after the construction of the barrage in the late 1970's. It is proven that the salinity distribution has no longer fulfil the pattern in a natural alluvial estuary, and the hydrodynamics is unstable and not in an equilibrium state. In short, the application of 1-D salt intrusion model proven to be a good approach for this estuary. Hence, it is can be a useful tool to the water manager in monitoring the current salt condition in this estuary.

## 5.2 Limitations and recommendations

There is a few proposed recommendation has been made to improve on this research as well as to give suggestions for future researchers the Kuantan and Belat Estuary:

1. The salinity data collected are limited to the downstream of the barrage. This is because necessary permission is needed from the water authority to pass through the barrage.

2. The dry season during the research year is late as compared to the previous year. As this study only can be carried out during the dry season in conjunction with the excessive reduction in the freshwater discharge, the field works have been delayed. Hence, more data collection should be carried out in order to validate the calibration parameters gained obtained in this research. This is essential to improve the accuracy of the results. More measurements are recommended be carried out promote higher accuracy.

3. The research found that the duration of a slack moment in this estuary is short in time. Hence, the using of two moving boats are needed which 1 will be conducted at the lower reach and another 1 in the upper reach.

4. Discharge measurements are the crucial part of this study because of absent of gauging station at the downstream. Furthermore, if the freshwater discharge data is available from the water authority (captured at the barrage), a visit to the barrage will be useful in this study.

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# APPENDIX A
## SAMPLE APPENDIX 1

| *Subbasin* | *Stream length, km* | *Shape area, km²* | *Basin Slope* | *Tc* | *R* |
|---|---|---|---|---|---|
| W1380 | 36.61 | 30.31 | 28.12 | 8.93 | 12.13 |
| W1330 | 35.38 | 27.90 | 19.62 | 10.48 | 14.05 |
| W1300 | 33.84 | 23.88 | 18.65 | 10.50 | 14.18 |
| W1290 | 12.82 | 3.17 | 14.63 | 5.96 | 8.89 |
| W1280 | 48.57 | 54.65 | 29.75 | 10.61 | 13.98 |
| W1270 | 22.99 | 12.93 | 16.76 | 8.23 | 11.40 |
| W1260 | 27.43 | 13.23 | 19.67 | 8.96 | 12.58 |
| W1250 | 56.76 | 47.36 | 10.65 | 21.10 | 26.91 |
| W1240 | 57.50 | 44.01 | 17.95 | 16.54 | 21.76 |
| W1230 | 45.67 | 37.28 | 26.40 | 11.12 | 14.96 |
| W1220 | 30.32 | 20.26 | 15.44 | 10.61 | 14.30 |
| W1210 | 41.66 | 23.28 | 10.22 | 17.44 | 23.11 |
| W1200 | 46.22 | 33.41 | 7.38 | 21.77 | 27.76 |
| W1190 | 29.52 | 18.20 | 13.44 | 11.24 | 15.15 |
| W1180 | 52.88 | 55.25 | 25.33 | 12.47 | 16.35 |
| W1170 | 43.45 | 28.35 | 17.67 | 13.43 | 18.04 |
| W1160 | 23.11 | 7.20 | 5.62 | 15.45 | 21.20 |
| W1150 | 43.57 | 57.02 | 46.97 | 7.55 | 10.09 |
| W1370 | 27.06 | 18.73 | 29.60 | 6.90 | 9.61 |
| W1130 | 40.74 | 30.94 | 11.89 | 15.28 | 19.95 |
| W1120 | 18.18 | 8.43 | 13.96 | 7.59 | 10.65 |
| W1110 | 28.84 | 17.85 | 10.88 | 12.26 | 16.37 |
| W1100 | 17.50 | 8.16 | 31.93 | 4.83 | 7.06 |
| W1090 | 23.73 | 14.38 | 28.91 | 6.36 | 8.97 |
| W1080 | 10.85 | 3.43 | 7.62 | 7.01 | 10.00 |
| W1070 | 12.02 | 2.54 | 3.06 | 12.73 | 17.85 |
| W1060 | 37.97 | 22.33 | 28.84 | 9.47 | 13.19 |
| W1050 | 47.52 | 45.33 | 13.11 | 16.10 | 20.66 |
| W1040 | 40.55 | 24.36 | 7.41 | 19.90 | 25.85 |
| W1030 | 21.39 | 7.89 | 3.81 | 17.29 | 23.04 |
| W1020 | 16.58 | 5.86 | 6.25 | 10.91 | 15.07 |
| W1010 | 38.33 | 27.29 | 9.47 | 16.42 | 21.35 |
| W1000 | 38.89 | 36.12 | 24.62 | 9.92 | 13.23 |
| W990 | 32.60 | 24.33 | 21.63 | 9.38 | 12.71 |
| W980 | 50.97 | 42.01 | 20.42 | 13.88 | 18.35 |
| W970 | 30.38 | 21.07 | 6.67 | 16.20 | 20.90 |
| W960 | 46.53 | 33.44 | 28.66 | 11.00 | 14.99 |
| W950 | 13.93 | 3.97 | 16.22 | 5.96 | 8.82 |
| W940 | 49.31 | 38.90 | 12.90 | 17.13 | 22.25 |
| W1320 | 36.05 | 21.89 | 7.37 | 18.05 | 23.51 |

| | | | | | |
|---|---|---|---|---|---|
| W920 | 36.67 | 24.78 | 14.68 | 12.75 | 17.02 |
| W910 | 4.19 | 0.46 | 7.85 | 3.53 | 5.63 |
| W900 | 42.83 | 39.71 | 28.80 | 9.93 | 13.32 |
| W890 | 39.63 | 36.29 | 24.09 | 10.21 | 13.61 |
| W880 | 18.86 | 5.13 | 8.08 | 11.01 | 15.63 |
| W870 | 38.64 | 32.73 | 8.97 | 16.65 | 21.30 |
| W860 | 57.75 | 43.87 | 7.02 | 26.75 | 33.65 |
| W850 | 28.35 | 8.29 | 3.51 | 23.46 | 31.40 |
| W840 | 21.94 | 9.84 | 6.07 | 13.62 | 18.28 |
| W830 | 32.23 | 23.09 | 6.49 | 17.19 | 22.06 |
| W820 | 79.87 | 80.04 | 11.82 | 26.08 | 32.60 |
| W810 | 30.01 | 23.32 | 13.66 | 10.99 | 14.57 |
| W800 | 30.82 | 14.90 | 4.08 | 21.96 | 28.43 |
| W790 | 21.02 | 6.84 | 7.52 | 12.24 | 17.03 |
| W780 | 12.88 | 2.23 | 1.76 | 18.30 | 25.30 |
| W770 | 38.46 | 21.67 | 1.96 | 37.62 | 46.11 |
| W760 | 10.23 | 1.50 | 2.08 | 14.13 | 20.10 |
| W750 | 58.55 | 56.54 | 2.07 | 48.81 | 56.80 |
| W740 | 43.08 | 17.58 | 1.71 | 46.13 | 57.33 |
| W730 | 87.89 | 80.87 | 6.14 | 39.78 | 48.32 |
| W720 | 72.54 | 75.77 | 2.18 | 56.51 | 65.05 |
| W710 | 27.24 | 20.01 | 24.11 | 7.65 | 10.50 |
| W700 | 24.84 | 17.47 | 24.13 | 7.11 | 9.83 |
| W690 | 28.72 | 19.16 | 8.78 | 13.50 | 17.74 |
| W680 | 28.04 | 17.90 | 12.28 | 11.22 | 15.05 |
| W670 | 19.97 | 7.54 | 18.55 | 7.29 | 10.50 |
| W660 | 7.27 | 1.04 | 1.20 | 14.09 | 19.77 |

# APPENDIX B
# SAMPLE APPENDIX 2

| Subbasin | Curve Number | Time of concentration (hr) | Storage Coefficient (hr) | Baseflow (m3/s) |
|---|---|---|---|---|
| W1380 | 39.64 | 8.93 | 12.13 | 0.11 |
| W1330 | 36.61 | 10.48 | 14.05 | 0.62 |
| W1300 | 44.10 | 10.50 | 14.18 | 1.31 |
| W1290 | 45.01 | 5.96 | 8.89 | 1.39 |
| W1280 | 39.63 | 10.61 | 13.98 | 1.28 |
| W1270 | 38.02 | 8.23 | 11.40 | 1.44 |
| W1260 | 45.93 | 8.96 | 12.58 | 4.53 |
| W1250 | 44.06 | 21.10 | 26.91 | 4.79 |
| W1240 | 47.19 | 16.54 | 21.76 | 1.29 |
| W1230 | 48.23 | 11.12 | 14.96 | 3.52 |
| W1220 | 52.60 | 10.61 | 14.30 | 0.16 |
| W1210 | 47.48 | 17.44 | 23.11 | 1.54 |
| W1200 | 58.11 | 21.77 | 27.76 | 0.22 |
| W1190 | 47.43 | 11.24 | 15.15 | 0.57 |
| W1180 | 53.49 | 12.47 | 16.35 | 1.12 |
| W1170 | 53.15 | 13.43 | 18.04 | 1.64 |
| W1160 | 39.30 | 15.45 | 21.20 | 4.74 |
| W1150 | 53.41 | 7.55 | 10.09 | 1.63 |
| W1370 | 45.27 | 6.90 | 9.61 | 0.78 |
| W1130 | 41.26 | 15.28 | 19.95 | 0.68 |
| W1120 | 39.93 | 7.59 | 10.65 | 2.83 |
| W1110 | 46.54 | 12.26 | 16.37 | 2.20 |
| W1100 | 42.09 | 4.83 | 7.06 | 0.45 |
| W1090 | 42.54 | 6.36 | 8.97 | 2.40 |
| W1080 | 44.15 | 7.01 | 10.00 | 2.60 |
| W1070 | 30.75 | 12.73 | 17.85 | 0.06 |
| W1060 | 45.87 | 9.47 | 13.19 | 1.73 |
| W1050 | 46.77 | 16.10 | 20.66 | 1.56 |
| W1040 | 43.67 | 19.90 | 25.85 | 2.55 |
| W1030 | 49.46 | 17.29 | 23.04 | 0.36 |
| W1020 | 41.53 | 10.91 | 15.07 | 2.24 |
| W1010 | 43.93 | 16.42 | 21.35 | 1.51 |
| W1000 | 41.33 | 9.92 | 13.23 | 2.73 |
| W990 | 38.13 | 9.38 | 12.71 | 1.71 |
| W980 | 37.91 | 13.88 | 18.35 | 2.40 |
| W970 | 49.56 | 16.20 | 20.90 | 1.88 |
| W960 | 45.32 | 11.00 | 14.99 | 0.50 |
| W950 | 42.12 | 5.96 | 8.82 | 0.65 |
| W940 | 40.04 | 17.13 | 22.25 | 1.71 |
| W1320 | 41.35 | 18.05 | 23.51 | 2.91 |

| | | | | |
|---|---|---|---|---|
| W920 | 42.70 | 12.75 | 17.02 | 1.58 |
| W910 | 36.89 | 3.53 | 5.63 | 0.25 |
| W900 | 49.57 | 9.93 | 13.32 | 0.32 |
| W890 | 38.27 | 10.21 | 13.61 | 1.09 |
| W880 | 38.47 | 11.01 | 15.63 | 0.67 |
| W870 | 47.62 | 16.65 | 21.30 | 1.31 |
| W860 | 37.01 | 26.75 | 33.65 | 0.69 |
| W850 | 46.65 | 23.46 | 31.40 | 2.10 |
| W840 | 37.82 | 13.62 | 18.28 | 1.36 |
| W830 | 37.99 | 17.19 | 22.06 | 3.55 |
| W820 | 39.31 | 26.08 | 32.60 | 0.60 |
| W810 | 46.07 | 10.99 | 14.57 | 1.95 |
| W800 | 38.11 | 21.96 | 28.43 | 3.45 |
| W790 | 43.59 | 12.24 | 17.03 | 1.33 |
| W780 | 40.73 | 18.30 | 25.30 | 2.24 |
| W770 | 45.19 | 37.62 | 46.11 | 1.64 |
| W760 | 44.22 | 14.13 | 20.10 | 1.46 |
| W750 | 40.25 | 48.81 | 56.80 | 2.46 |
| W740 | 45.41 | 46.13 | 57.33 | 2.84 |
| W730 | 49.27 | 39.78 | 48.32 | 3.02 |
| W720 | 45.03 | 56.51 | 65.05 | 1.01 |
| W710 | 50.85 | 7.65 | 10.50 | 0.99 |
| W700 | 38.04 | 7.11 | 9.83 | 3.42 |
| W690 | 43.51 | 13.50 | 17.74 | 0.30 |
| W680 | 47.78 | 11.22 | 15.05 | 1.68 |
| W670 | 40.14 | 7.29 | 10.50 | 1.92 |
| W660 | 38.17 | 14.09 | 19.77 | 2.06 |