PREDICTION IN UNGAUGED ESTUARIES

by

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NOMENCLATURE

a	Cross-sectional convergence length [L]
a_1	Cross-sectional convergence length of the seaward reach of estuary [L]
a_2	Cross-sectional convergence length of the landward reach of estuary [L]
A	Cross-sectional area [L^2]
A'	Boundary value of the cross-sectional area [L^2]
A_0	Cross-sectional area at estuary mouth [L^2]
A_1	Cross-sectional area at inflection point x_1 [L^2]
b	Width convergence length [L]
b_1	Width convergence length of the seaward reach of estuary [L]
b_2	Width convergence length of the landward reach of estuary [L]
B	Estuary width [L]
B_0	Width at estuary mouth [L]
B_1	Width at inflection point x_1 [L]
B_b	Bankfull stream width [L]
B_e	Effective storage width of estuary [L]
B_f	Stream width [L]
c_0	Classical wave celerity [L/T]
c_x	x-dependent wave celerity [L/T]
C	Coefficient of Chezy [$L^{0.5}$/T]
D	Longitudinal dispersion [L^2/T]
D_0	Longitudinal dispersion at estuary mouth [L^2/T]
D_1	Longitudinal dispersion at inflection point x_1 [L^2/T]

D_i	Dispersion coefficient at HWS, TA and LWS [L^2/T]
D_{50}	Diameter of the bed material that is exceeded by 50% of the sample weight [L]
E	Tidal excursion [L]
E_0	Tidal excursion starting from the estuary mouth [L]
E_1	Tidal excursion starting from the inflection point [L]
f	Friction factor [-]
f_D	Darcy-Weisbach friction factor [-]
F	Froude number [-]
F_d	Densimetric Froude number [-]
g	Acceleration due to gravity [L/T^2]
h	Estuary depth [L]
$\bar{h}$	Averaged estuary depth [L]
$\bar{h}_1$	Averaged estuary depth after the inflection point x_1 [L]
h_0	Estuary depth at the mouth [L]
h_b	Bankfull stream depth [L]
h_e	Effective channel depth [L]
h_f	Stream depth [L]
h_{obs}	Observed depth [L]
h_{hyd}	Hydraulic depth [L]
h_{reg}	Regime depth [L]
h_{ideal}	Ideal depth [L]
H	Tidal range [L]
H_0	Tidal range at estuary mouth [L]
H_1	Tidal range at inflection point x_1 [L]
k	Mixing mechanism [Prandle, 1981] [-]
k_b	Specific discharge ratio [-]
k_s	Sediment material coefficient [$T^{0.5}L^{-0.5}$]
K	Dimensionless Van den Burgh's coefficient [-]
K_m	Dimensionless Manning's coefficient [-]
L	Salt intrusion length [L]

N	Canter-Cremers Estuary number [-]
N_b	Width ratio Canter-Cremers Estuary flood number[-]
N_Q	Discharge ratio Canter-Cremers Estuary flood number [-]
N_r	Estuarine Richardson number [-]
N_{r1}	Estuarine Richardson number with boundary condition at inflection point x_1 [-]
P_b	Bankfull wetted perimeter [L]
P_t	Flood volume [L^3]
Q_b	Bankfull discharge [L^3/T]
Q_f	The freshet or fresh water flushing [L^3/T]
r_s	Storage width ratio [-]
s	Salinity [M/L^3]
S	Steady state salinity [M/L^3]
S_0	Steady state salinity at estuary mouth [M/L^3]
S_1	Steady state salinity at inflection point x_1 [M/L^3]
S_i	Steady state salinity at HWS, TA and LWS [M/L^3]
S_f	Fresh water salinity [M/L^3]
t	Time [T]
T	Tidal period [T]
u_0	Velocity of the fresh water discharge at estuary mouth [L/T]
U_b	Velocity of the bankfull discharge [L/T]
U_f	Velocity of the fresh water discharge [L/T]
x	Distance [L]
x_1	First inflection point [L]
x_2	Second inflection point [L]

HW	High water
TA	Tidal average
LW	Low Water
HWS	High Water Slack
LWS	Low Water Slack

α_0	Mixing number at estuary mouth [L^{-1}]
α_1	Mixing number at inflection point x_1 [L^{-1}]
β	Dispersion reduction rate [-]
β_0	Dispersion reduction rate at estuary mouth [-]
β_1	Dispersion reduction rate at inflection point x_1 [-]
β_{rev}	Dispersion reduction rate for reversed calculation [-]
χ	Friction number [-]
δ	Damping number [-]
δ_H	Damping rate of tidal range [L^{-1}]
ϵ	Phase lag between HW and HWS, or LW and LWS [-]
η	Tidal amplitude [L]
γ	Estuary shape number [-]
λ	Celerity number [-]
λ_1	Length of the tidal wave with boundary condition at inflection point x_1 [L]
μ	Velocity number [-]
ϕ_u	Phase of velocity [-]
ϕ_z	Phase of water level [-]
φ	Natural angle of repose of sediment material characteristics [-]
ρ	Fluid density [ML^{-3}]
$\Delta\rho$	Density difference over the intrusion length [ML^{-3}]
ω	Tidal frequency [T^{-1}]
υ	Tidal velocity amplitude [L/T]
υ_0	Tidal velocity amplitude at estuary mouth [L/T]
υ_1	Tidal velocity amplitude at inflection point x_1 [L/T]

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1

1.1. IMPORTANCE OF ESTUARY

An estuary has the characteristics of both a river and a sea [Savenije, 2005]. The geographic locations of estuaries are often strategic for the aquatic environment and navigation. Estuaries are rich in nutrients due to the natural fertilizers carried by the river flow and from agriculture activities in the upstream area. These fertilizers serve as nutrients to aquatic plants which again become food for aquatic animals and organisms. With the availability of sufficient nutrients and a calm environment, estuaries have become a superb habitat for aquatic life [Savenije, 2012; Chiras, 2013]. Moreover, the existence of mangrove eco-systems in estuaries allows aquatic animals to nest and breed between the mangroves roots [Faridah-Hanum et al., 2013].

Hence, estuaries provide food and transportation for human need. Many people living near estuaries work as fishermen or fish-farmers in small to medium scale aquaculture. Some estuaries, bays and lagoons, serve as marinas and ports for shipping [Dyer, 1997]. People living near the estuaries also use it as their source for agriculture and fresh water supply. However, the area where the water is extracted is sometimes prone to salt water intrusion [Nguyen et al., 2012; Zhang et al., 2011; Savenije, 2012].

Likewise, estuaries are also prone to pollution. The construction of harbours near the coastal area of estuaries may cause critical impact on the pollution in the area. Sediments runoff from upland areas flowing into estuaries often carry polluted substances with them. The sediments settle on the bed of the estuaries primarily in the transition from fresh to saline water [Dyer, 1997]. This phenomenon allows the pollutant to remain in the estuaries for a long time and creates a polluted situation. Recent studies on the biochemical responses have shown the pollutants such as carbon, phosphate, nitrate, metal and among others, are mainly terrestrial origin (industrial, agriculture, deforestation), which subsequently degrades the water quality particularly the oxygen level in estuaries [Bauer et al., 2013; Volta et al., 2014]. Therefore, more attention should be paid to manage the sustainability of the estuarine resources.

1.2. THE IMPORTANCE OF ESTUARIES IN MALAYSIA AND ITS MAIN ISSUES

In Malaysia, the main functions of estuaries are as habitat for mangrove eco-systems and for shipping (harbour development). The mangrove eco-system is very important in Malaysia due to the erosive capacity of monsoon winds (Southwest monsoon and Northeast monsoon) especially on the east coast. Roots of mangroves retain the soil on the banks of the estuaries and protect the coastal area from erosion particularly during the monsoon by attenuating the wave energy when waves pass through them. The reduction in wave energy offers a more stable environment to the estuaries. This protection is essential to keep the land area from flooding by storm surges particularly the areas with agricultural activities such as in the state of Kedah in Malaysia [Ong et al., 1991]. Mangroves also provide home to aquatic life and fireflies. In Kuala Selangor, the fireflies habitation has become a tourist attraction and subsequently contributes to the tourism industry in Malaysia [van Breemen, 2008].

The quiet wave motion in estuaries encourages the construction of harbours and ports for ships and boats to berth. Big ships require a certain depth of channel to navigate, and the sea bed is shallower towards the bank. Thus, a navigation channel is constructed to deepen the bed by dredging the sediments from the estuaries. This action has led to an imbalance in the estuaries where the natural hydrodynamic behaviour between the salt and fresh water has changed [Cai et al., 2012, 2014b].

Due to dredging, saline water intrudes further upstream which may reach irrigation channels in areas where the water is utilized for agricultural purposes. As a result, crops and vegetation die due to salinization. Higher level of salinity in the mangrove swamps may affect the growth of mangroves and subsequently kill the aquatic life. Fireflies are also sensitive to changes in salinity, and this development has declined the chances for them to live and breed [van Breemen, 2008].

Another factor that leads to the depletion in the quality of the estuaries is the increasing population and activities in the developed hinterland [Ibrahim et al., 1996]. For the case of Selangor estuary, the natural condition in the estuary is weakened by the extraction of river discharge upstream to supply water to the residents in Selangor and Kuala Lumpur. Therefore, there will be less discharge of fresh water into the estuary which enhances salt water intrusion further upstream [van Breemen, 2008].

1.3. FORMULATION OF THE PROBLEMS

Managing estuaries can be very troublesome, especially in ungauged basins. Until today, most of the estuary basins worldwide are still ungauged except for some very large estuaries such as the Yangtze, Schelde, Elbe, Thames and others. Conducting field surveys to study an ungauged estuary is always time and energy consuming, and may be very expensive. Without substantial funding, it is almost impossible to collect the data needed to investigate the underlying hydrological processes in an estuary. Although some estuaries have been widely explored, there is still no comprehensive compilation of databases accessible for all the gauged estuaries. The only way to obtain the existing data for these estuaries is from the literature (e.g. Savenije [2005, 2012]; Toffolon and Savenije [2009]).

Information on geometry such as cross-sectional areas of an estuary often requires intensive field surveys: either self-conducted or by professional surveyors and this can sometimes be very difficult. The hydrological data such as fresh water discharge on the other hand, can be collected from the authority of the countries to which the estuaries belong. However, the available streamflow stations are commonly situated further upstream from the upper boundary of the estuaries. This has led to the underestimation of the actual fresh water discharge draining into the estuaries. In salt intrusion models, regardless of being analytical or numerical 1-D, 2-D or 3-D models, at least two (e.g. the Van der Burgh coefficient K and dispersion coefficient D_0) or more parameters have to be calibrated to fit the salinity curve against measured salinity data. This means that the longitudinal salinity distribution can be simulated only with the presence of salinity measurements. Savenije [1993a, 2005] provided predictive equations for K and D_0, but these are subject to improvement.

Realizing the complications in conducting estuary studies, we have taken the initiative to search for possible methods to simplify the investigation process. This is done by searching for new predictive methods to enable a further understanding of the hydrological processes in estuaries of interest. Improving the existing and developing new predictive tools would be very useful for water managers and engineers in managing estuaries.

1.4. OBJECTIVES OF THE THESIS

The objectives of the research in this thesis are to seek for solutions to overcome the problems discussed in Section 1.3 which are listed as follows:

1. To extend the database with consistently surveyed estuaries in Malaysia to test anc expand the theory.
2. To reorganize and homogenize the existing datasets from the literature and include new data from the surveys into a well-organized database. In the database the estuaries are classified based on the reliability of the observations, geometr and type of mixing.
3. To Test the applicability of the existing one dimensional analytical salt intrusion model and its predictive methods for the Malaysian estuaries.
4. To improve and further simplify the predictive equations for the Van der Burgh an dispersion coefficient.
5. Finally, to develop methods to predict the bankfull discharge and estuary depth b relating the hydraulic geometry to the tidal dynamics.

It is worth to note that in establishing the predictive methods, we tried to make use c as much readily available or observable information as possible, which is particularl useful for ungauged estuaries.

1.5. OUTLINES OF THE THESIS

This thesis is organized according to the objectives listed, providing background on th theory and survey methods. In this chapter, we briefly discussed the importance of estuaries mainly to mankind, and the problems faced by water managers and engineers i maintaining a healthy estuarine environment. The objectives of the study were summarized to provide some insight in the possible solutions proposed to solve the difficulti in estuary management. Short descriptions of the rest of the chapters in this thesis a as follows:

Chapter 2 introduces the theories applied in developing predictive methods. They a described according to the estuary classification, shape, tides, mixing processes, salin ity, bankfull discharge and hydraulic geometry. The general equations adopted in th analyses processes of the studies are introduced.

Chapter 3 explains the processes involved in establishing the estuaries database. Her we first illustrate the study area of the newly surveyed estuaries in Malaysia. Next, w explain the equipment and methods used in conducting the cross-sectional area, wat level and salinity measurements. Subsequently, we discuss on the discharge data ar provide the links and references on where to obtain hydrological data either, from readily accessible databases or by request.

In Chapter 4 we test the existing 1-D analytical salt intrusion model and its predictive equations in the 7 newly surveyed Malaysian estuaries. The longitudinal salinity distributions are plotted against measured salinity curves by calibrating the Van der Brugh and dispersion coefficients. These calibrated variables are later compared to calculated values to validate the performance of the predictive equations. In the discussion section, we introduce an approach to adjust the underestimated discharge data, and how it affects the final results.

In Chapter 5 we revisited the existing predictive equations for the Van der Burgh coefficient K and dispersion coefficient D_0. Here, we attempt to improve and simplify the equations by taking into account only the easily measurable independent parameters. The new predictive methods are established on a selection of the most reliable measurements data for calibration. The less reliable data are merely used for verification.

In Chapter 6, we try to find a relation between the regime theory and tidal dynamics processes. We tested the applicability of hydraulic geometry in representing the hydraulic characteristics of an estuary (focusing mainly on the upstream part). Predictive methods are suggested to estimate the averaged estuary depth $\bar{h}$, estuarine flood number N_b, and bankfull discharge Q_b.

Chapter 7 summarizes the conclusions and the results obtained including the limitations of the developed predictive methods. Recommendations are given for future improvements and studies.

2

2.1. INTRODUCTION

THE definition of an estuary is subjective and closely depending on one's opinion [Dyer, 1997]. Over the 60 years, various definitions have been proposed by researchers including Cameron and Pritchard [1963], [Dalrymple et al., 1992], Dionne [1963], Perillo [1995], and others. In short, an estuary can be described as a transition medium between a sea and a river . It has a flat topography and is located most downstream where the river is connected to the ocean environment [Savenije, 2012]. Generally, an estuary consists of a single branch but in some coastal areas such as deltas, it is formed by a multi-network channel. Since an estuary receives water from both the sea and a river, it has characteristics of both storing and transporting water and sediment. Estuaries are naturally calm with little wave action compared to the open sea. However, floods can occur when high river discharge coincides with high tide especially during spring tide and the wet season.

Estuaries are affected by a combination of driving forces around its vicinity, including the tide, waves, river discharge, littoral sediment transport, and density difference between the saline and fresh water. These driving forces are key in determining estuary shape. Estuaries can be classified based on their shape, tidal influence, river influence, geology and salinity properties. Incorporating the different classification of estuary from various sources such as Pritchard [1952b, 1955], Cameron and Pritchard [1963], Pickard [1956, 1961], Fairbridge [1980], Perillo [1995], and Dyer [1997], Savenije [2005] summarized the overall classification as tabulated in Table 2.1.

Table 2.1: Summary of the estuary classification

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

Fresh water discharge is one of the most important factors in determining the estuary type. However, this is the most difficult information to measure. Thus, by examining relationships between the measurable data, it would be an advantage to find some predictive measures to estimate parameters that are not directly obtainable.

2.2. SHAPE

The geometry of estuaries is generally found in two types: funnel and prismatic. For a tide dominated estuary the seaward geometry has a funnel shape, while a discharge dominated estuary has nearly straight banks [Savenije, 2005, 2012]. A trumpet shape formation is caused by wave action near the mouth, and for this type of estuary the geometry is analysed in two sections: seaward and landward. In salt intrusion studies, tide dominated estuaries are more of interest as the minimum discharge during the dry season will exacerbate salt water intrusion. Figure 2.1 illustrates the examples of two types of geometry found in general. The estuary shown in Figure 2.1(a) is a single reach estuary that does not experience strong wave action. Figure 2.1(b) on the other hand is the estuary that is strongly affected by wave action near the mouth and is sectioned into two reaches at the inflection point, x_1.

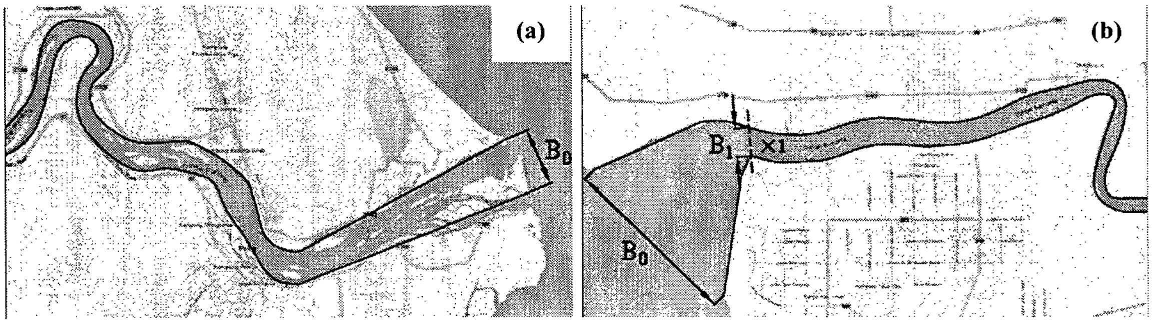

Figure 2.1: Geometry of estuaries in general: a) single reach channel; and b) trumpet or dual reach channel.

Studies to investigate the best representation of estuary shape in a mathematical way has been carried out since decades. As the estuary shape converges gradually towards inland, the relationship between the geometry and distance can no longer be presented in a simple linear function. In the earlier stage, the geometry is analysed with a trapezoidal mesh method. Later, the geometry, particularly the width is presented in exponential function [Friedrichs et al., 1998; Davies and Woodroffe, 2010]. Savenije [1989] suggested that the shape of an estuary generally can be expressed in an exponential function as:

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

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

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

where A, B and h represent the tidally averaged cross-sectional area, width and depth at location x, while a and b are the cross-sectional and width convergence length. Estuaries that do not experience strong ocean waves near the mouth can generally be described by a single reach with only one convergence length, whereas those that experience strong waves near the mouth generally have two reaches with two convergence lengths; a short reach close to the sea with a short convergence length and a long one upstream with a longer convergence length. The geometry analyses proposed in Equations 2.1 to 2.3 have been widely used in many estuaries and the application has been proved to be valid [Nguyen and Savenije, 2006; Zhang et al., 2011; Gisen et al., 2014a].

It is important to note that the shape analysis is performed on tidally averaged geometry data. This implies that the estuary depth is obtained by compensating the measured data in reference to the average tidal level. In tidal dynamics and hydraulic geometry analyses, the second reach of the estuary is more crucial due to the absence of wave action and is most probably in morphological equilibrium. The shape analysis is important to provide boundary conditions for tidal dynamics, salinity and hydraulic geometry analyses.

2.3. Tides

The dynamics of water is strongly interrelated to the geometry of the estuary. Wave action, tide, and fresh water discharge determine the shape of the mouth by forming sand bars, spits or barrier islands, and the funnelling of the estuary (deposition and erosion of sediment process). In return, the water level and velocity of the tide and river flow are strongly influenced by the shape of the estuary [Savenije, 2005, 2012]. In salt intrusion study, the condition of interest is when the river discharge is small and the system is tide dominated. The geometry of estuaries can also be classified according the tides condition as follows [Davies, 1964; Dyer, 1997]:

- Micro tidal estuary: $H < 2$m; 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

Tides are commonly recognized in three types based on the tidal period: diurnal, mixed diurnal, and semi diurnal. A semi-diurnal tide has two nearly identical tidal cycles in a day (two high and two low water), whereas a diurnal tide has only one complete tidal cycle (one low and high water) [Pond and Pickard, 1983]. For the mixed diurnal, the difference of the tidal range between the two tidal cycles in a day is large and the effect of the smaller tidal range is almost insignificant compared to the larger ones [Gisen et al., 2014a]. Figure 2.2 display the water level oscillation during the tidal cycles in 24 hours for the different tides.

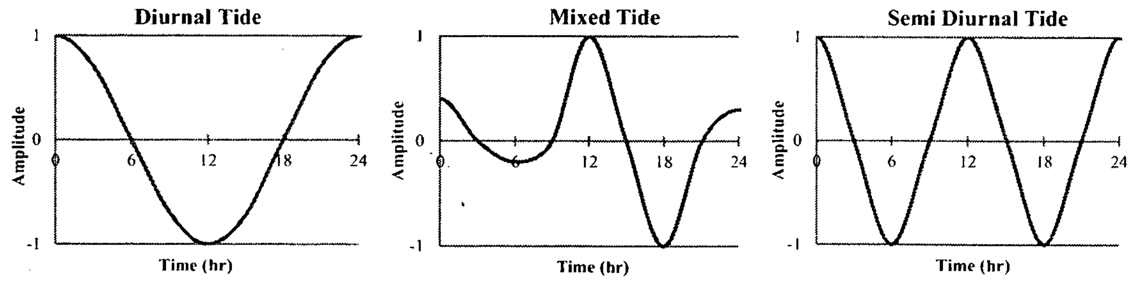

Figure 2.2: The tidal oscillation of the diurnal (left), mixed (middle) and semi diurnal (right) tides.

Other than knowing the tidal period, identifying the types of tidal wave in an estuary is also important. The type of tidal wave in an estuary is strongly influenced by the geometry: semi-enclosed, prismatic or convergent. A fully standing wave only occurs in semi-enclosed body such as lagoon, where the wave can be entirely reflected when it hits the boundary of the closing structure. This type of tidal wave reaches its highest level when the velocity is zero (see Figure 2.3(a)). An example of standing wave in our regular life is when a person is playing on a swing. On the other hand, a progressive wave occurs only in a fully prismatic frictionless channel with infinite length. The velocity and water level amplitude are in phase as shown in Figure 2.3(b) [Dyer, 1997]. However, none of these apply in funnelled shape estuaries [Gisen and Savenije, 2014].

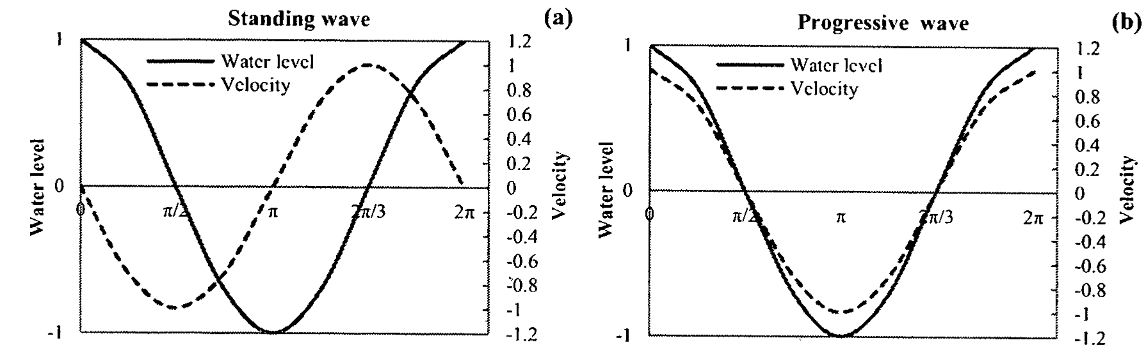

Figure 2.3: Types of tidal waves: a) purely standing wave; b) purely progressive wave.

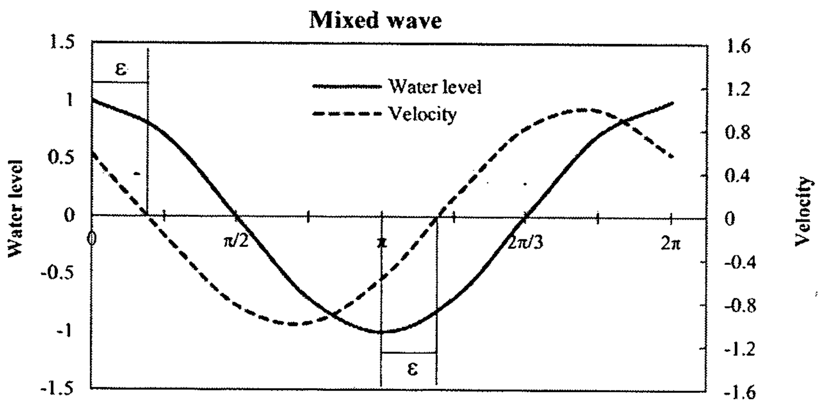

Figure 2.4: A mixed type tidal wave in converging estuary with the phase lag ε between HW and HWS, as well as LW and LWS [Savenije, 2005, 2012].

In convergent estuaries, the water level always reaches the highest or lowest point before the tidal velocity becomes zero (or slack moment). The delay between the high water (HW) or low water (LW) and high water slack (HWS) or low water slack (LWS) is known as the phase lag ϵ, which lies between 0 to $\pi/2$. Figure 2.4 illustrates the mixed type tidal wave which occurs in alluvial estuaries. Knowing the phase lag is crucial in tidal dynamics analysis to understand the tidal wave propagation. Furthermore, it is also an important parameter in predicting the average tidal depth in the case where minimal data are available.

2.4. MIXING

Substantial research has been done to determine the driving force of the mixing mechanism in an estuary which subsequently regulates the longitudinal salinity distribution. Mixing processes have been studied in several ways including turbulent mixing, transverse mixing, mixing due to gravitational circulation, density driven mixing, tidal driven mixing, wind driven mixing and residual circulation [Fischer, 1976]. Savenije [1993a] categorized mixing mechanisms into three types of dispersion: riverine hydraulics riverine dispersion due to the turbulence caused by the interaction between river flow and changes in geometry, where no tidal influence exists; tide driven dispersion caused by tidal circulation when interacted with geometry, channel roughness, wind effect, and tidal trapping; density driven mixing due to the different density of fluids in the estuary (sea and fresh water), causing gravitational circulation.

Smith [1980] in his work which was later confirmed by West and Broyd [1981] found that density driven dispersion is more likely to occur in wide and strongly convergent estuaries. West and Broyd [1981] claimed that tide driven dispersion occurs in prismatic channel with shallow depth and constant cross-section. This usually refers to the upstream part of the saline area in which the system is gradually dominated by the fresh water discharge. Savenije [1993a] found that both tide and density driven dispersion can occurs simultaneously in an estuary. This is true for natural alluvial estuaries which generally have a wide and strong convergent geometry near the mouth, and switch to a less convergent shape upstream as illustrated in Figure 2.5. Near the mouth, where the density gradient is small, the mixing is primarily tide driven, whereas in the region with a strong salinity gradient, the density driven mixing is dominant.

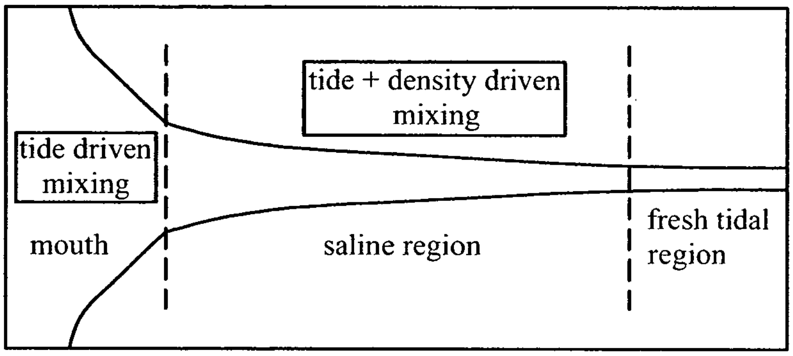

Figure 2.5: Illustration of the regions dominated by the tide and density driven dispersion.

Field observation and laboratory works have been carried out over several decades to find a reasonable description of mixing mechanisms. Making use of 5000 data of velocity and salinity from James River, Pritchard [1954] explained that the salt balance equation can be described by three terms: horizontal advective, vertical- diffusive transport and residual vertical velocity. Bowden and Gilligan [1971] who studied the Mersey Estuary obtained similar findings as Pritchard [1954] and they suggested that the longitudinal velocity can be categorized into net velocity of river flow, tidal variation of tidal cycle, irregularity of estuary shape in lateral direction, and vertical gravitational circulation. Their results showed that the vertical circulation is the main contribution of the net salt transport at one of the central stations, which is about fifty percent of the total.

Three main laboratory observations were carried out to determine the mixing and dispersion in an estuary including the work by the US Army Corps of Engineers [Ippen and Harleman, 1961; Harleman and Ippen, 1967]– WES Flume , van Rees and Rigter [1969] – Delft Flume and Daniels [1974]. All the laboratory experiments were carried out using rectangular prismatic flumes with constant cross-section. The main difference between these experiments lies in the type of roughness applied to the system. The WES flume has vertical strips attached to the sides, Delft flume attached vertical strips to the bottom (standing upward), and Daniels used rocks to create roughness. Apart from that, the Delft flume had varying Chezy roughness, mean depth, and flume length, whereas Daniels [1974] had different width to depth ratio. Daniels [1974] obtained different results from the former two researchers in which he observed the occurrence of continuous stratification in eight experiments conducted. From the comparison, it can be concluded that the roughness plays an important role in mixing processes, which subsequently influences the dispersion distribution.

Analytical techniques have also been widely used to understand the physical processes of mixing as a cause for dispersion. Researchers who worked on analytical solutions to relate longitudinal mixing and dispersion with salinity distribution in estuary included Hansen and Rattray [1965], Fischer [1972], Thatcher [1972], Prandle [1981], Savenije [1993a], and Kuijper and van Rijn [2011]. Zimmerman [1976], de Swart et al. [1997], and Nguyen et al. [2008] developed analytical measures to investigate the important of tidal pumping in a strong ebb-flood channel with shallow depth and small islands within the main channel. Their models have been tested in the Dutch Wadden Sea, Eems Estuary and Western Scheldt Estuary, respectively.

2.5. RELATIONSHIP BETWEEN DISPERSION AND SALINITY DISTRIBUTION

Most researchers focused only on a specific type of mixing mechanism, and only after the 1980's, Prandle [1981], Savenije [1993a], Kuijper and van Rijn [2011] and [Gisen et al., 2014b] lumped the longitudinal mixing mechanism to develop a predictive model to compute the longitudinal distribution of salinity in an estuary. The one dimensional salt balance equation with the effective average tidal and cross-sectional area is written as:

$$A\frac{\partial s}{\partial t} + Q_f\frac{\partial s}{\partial x} - \frac{\partial}{\partial x}\left(AD\frac{\partial s}{\partial x}\right) = 0 \qquad (2.4)$$

where $s = s(x, t)$ is the salinity, Q_f and D represent the fresh water discharge and dispersion, respectively. Note that since the positive x-axis points upstream, that the fresh river discharge has a negative value. In steady state condition, the fresh water discharge remains unchanged over time and hence, the integration of Equation (2.4) yields:

$$Q_f\left(S - S_f\right) - AD\frac{\partial S}{\partial x} = 0 \qquad (2.5)$$

where $S(x)$ is the steady-state mean tidal salinity. At the upstream boundary of salt intrusion limit, the salinity S_f is near to fresh water discharge, and it is often close to zero.

From the integration of the salt balance equations, Prandle [1981] found and teste the followings relationship between dispersion and salinity and obtained reasonab successful results.

2

$$D = D_0 \tag{2.}$$

$$D \propto \frac{\partial S}{\partial x} \tag{2.}$$

$$D \propto \left(\frac{\partial S}{\partial x}\right)^k \tag{2.}$$

Here, k has the value of 0, 1 and 2. D_0 in Equation (2.6) refers to the dispersion at tl estuary mouth. It is worth the attention that Equation (2.7) of Prandle is in agreeme with the assumption made by Thatcher [1972] in his numerical one-dimensional mod The different number of k value represents the type of mixing mechanism of the dispe sion: $k = 0$ means the system is fully tide driven; $k = 1$ indicates that it is fully dens driven; and $k = 2$ means there is also lateral stratification in density gradient. Saven [1993a] reported that the result obtained by Prandle is contradicted by many other ı searchers. Prandle claimed that k value is much larger than unity in a channel or estuε that has constant cross-section, and k is zero in deep, wide and strong convergent est aries. However, others claimed otherwise.

Savenije [1993a] took an effort to investigate and explain the disagreement in t work done by Prandle and others. In his study, he used the ratio of the dispersion a salinity instead of the salinity gradient as proposed by the earlier researchers, so that t relation becomes dimensionless as:

$$\frac{D}{D_0} = \left(\frac{S}{S_0}\right)^K \tag{2}$$

where S_0 is the salinity at the mouth. Using data of 16 estuaries worldwide, and mc ification of the relation between the dispersion and salinity, Savenije found that at ı mouth, the dominant mixing mechanism is contributed by the tide, whereas in the m dle reach of the estuary the mixing is density-driven. In order to explain the changes the mixing mechanism along the estuary, an example is given on the Scheldt Estuary shown in Figure 2.6.

In this plot, it can be seen that the density-driven mixing has a much lower value n the mouth, and only starts to increase to a peak at the middle reach of the estuary. T finding also suggests that the assumption that the dispersion is lower near the moı and increases upstream is incorrect, and should be the reverse. The basic concept Savenije's method has later been verified by other researchers among others Nguyen ε Savenije [2006], Kuijper and van Rijn [2011] and Nguyen et al. [2012].

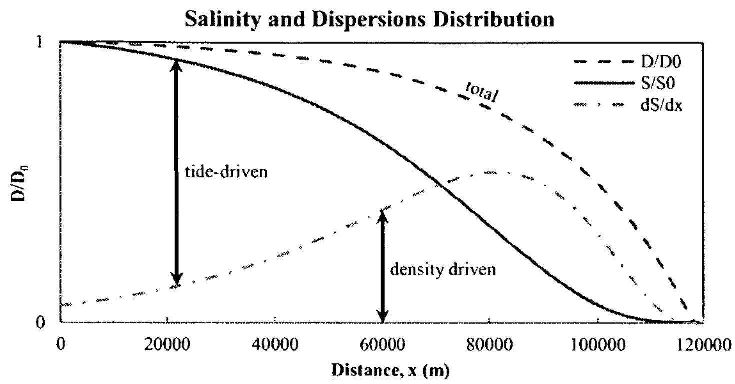

Figure 2.6: Total dispersion, tide-driven dispersion and density-driven dispersion in the Schelde estuary [Savenije, 1993a]

2.6. SALINITY DISTRIBUTION AND ONE DIMENSIONAL SALT INTRUSION MODEL

Depending on the hydrologic condition in the estuary region, the well mixed salinity distribution can be represented in four different curves as shown in Figure 2.7. A recession shape occurs in prismatic channels such as a navigation channel or an estuary that receives very high fresh water discharge. An estuary that has a trumpet shape (strongly converged mouth and then slightly converged upstream) usually has a bell shaped salinity curve. A dome shape curve commonly exists in a strongly funnelled channel. A humpback shape curve occurs in an hypersaline estuary [Pritchard, 1952a] where the evaporation exceeds rainfall and fresh water inflow [Savenije, 2005; Dyer, 1997]. These types of salt intrusion curves are illustrated in Figure 2.7.

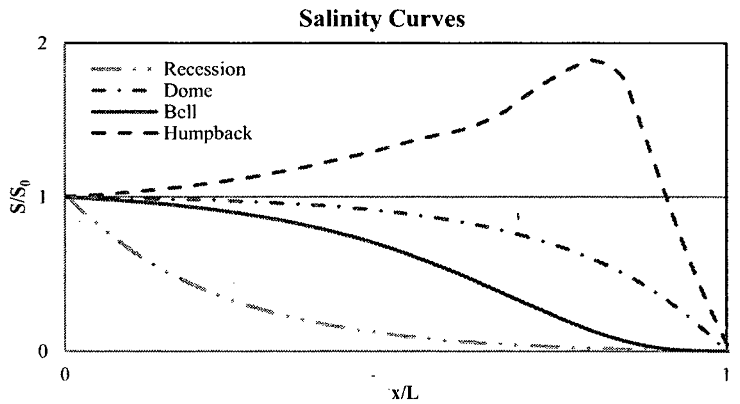

Figure 2.7: Types of well mixed salt intrusion curves.

The analytical one-dimensional salinity model developed by Savenije [1993c, 2005, 2012], presented below, is used to simulate the salinity profile in the estuaries studied. In a steady state situation, the partial temporal derivation in the salt balance equation is zero. Considering a constant fresh water discharge and tidally averaged cross-sectional area, the salt balance equation can be written as:

$$S_i - S_f = -\frac{A}{|Q_f|} D_i \frac{\mathrm{d}S_i}{\mathrm{d}x} \tag{2.10}$$

where $S_i = S_i(x)$ and $D_i = D_i(x)$ are the salinity and dispersion at high water slack (HWS), tidal average (TA) or low water slack (LWS) condition. Since discharge has a negative value, the absolute value of $|Q_f|$ is taken in Equation (2.10). It is worth noting that the changes in the cross-sectional area for different tidal conditions are compensated in the variation of the dispersion coefficient D_i. Making use of the Van der Burgh equation in combination with the salt balance equation, Savenije [2005, 2012] described the relation between dispersion and salinity to be:

$$\frac{\mathrm{d}D_i}{\mathrm{d}x} = -K\frac{|Q_f|}{A} \tag{2.11}$$

in which K is defined as the Van der Burgh coefficient (shape factor). Substituting Equation (2.10) into (2.11), the differential equation for the longitudinal salinity distribution is expressed as:

$$\frac{\mathrm{d}S_i}{S_i - S_f} = \frac{1}{K}\frac{\mathrm{d}D_i}{D_i} \tag{2.12}$$

Integrating Equation (2.12) and removing the subscript i (representation of HWS, TA, and LWS conditions) leads to:

$$\frac{S - S_f}{S_0 - S_f} = \left(\frac{D}{D_0}\right)^{1/K} \tag{2.13}$$

In Section 2.2, it is shown that the geometry parameters vary exponentially over the distance upstream. Substituting the exponential relation into the integration of Equation (2.11) gives:

$$\frac{D}{D_0} = 1 - \beta\left[\exp\left(\frac{x}{a}\right) - 1\right] \tag{2.14}$$

$$\text{where:} \quad \beta = \frac{Ka|Q_f|}{D_0 A_0} \tag{2.15}$$

Here β is the dispersion reduction rate. At the salt intrusion limit (upstream) where only fresh water discharge exist, the salinity is very small, and the dispersion coefficient becomes zero. This means that the distance x is equal to the salt intrusion length L. Hence, the intrusion length is expressed by:

$$L = a\ln\left(\frac{1}{\beta} + 1\right) \tag{2.16}$$

Equation (2.13) to (2.16) are the general equations used to compute the longitudinal salinity distribution based on Savenije [2005, 2012]'s one dimensional analytical solution.

Determining the salt intrusion length is crucial for estuary or delta water resources management, as most of the fresh water supplies in the area originate from pumping or extracting water from the estuary river. In case where pumping stations have to be built within the salt intrusion prone area, the extraction frequency can be precisely arranged by knowing the intrusion length at different period of tidal oscillation (spring and neap tide), HWS and LWS, and the amount of upstream fresh water discharge drained into the system. However, it is also important to notice that water extractions will subsequently induce further salt water intrusion. This makes the salt intrusion model an important instrument for water resources planning.

2.7. Bankfull discharge

Since bankfull discharge is the key variable in downstream hydraulic geometry studies in rivers, it is worth to know the definition of bankfull discharge. From engineering perspective, bankfull stage is important for aquatic habitat design, channel restoration design and other river engineering works [Singh, 2003]. Several studies have been done since the 1970s to determine guidelines for the definition of bankfull flow and the streamflow recurrence interval that is able to define bankfull discharge. Dunne and Leopold [1978] claimed that a bankfull stage is defined as the effective discharge level that is able to provide the most optimal condition for channel self-maintenance by governing its sediment transport, bars forming or reforming actions, formation of bends and meanders, and other dynamic processes that leads to the average morphologic characteristics of the channel. Savenije [2003] stated that it is the discharge whereby the accumulated bed sediment is spilled over the banks, forming natural levees and maintaining stable cross-sections. During field observation, the ability to observe the boundary of the bankfull stage is quite a challenge as this is subjective. However, Dunne and Leopold [1978] proposed guidelines to identify bankfull marks based on their field experience. The guidelines include the followings:

i geometry deviation from vertical bank to flat topography;

ii changes in side slope from steep to gentle;

iii changes in types of vegetation;

iv changes in types of deposited sediment material;

v boundary of the existence (above bankfull stage) and non-existence (below bankfull stage) of fine debris such as corns, needles, leaves and seeds);

vi changes in the roughness and smoothness between cobbles and rocks.

For performing the frequency analysis in determining the appropriate bankfull discharge recurrence interval, Williams [1978] suggested that the datasets used should not vary in the amount of years selected to avoid large variability in the results. Nevertheless, it can be concluded from previous research by Williams [1978], Dury [1976], Castro and Jackson [2001], Savenije [2003] and among others that the recurrence interval of bankfull discharge is approximately 1.5 to 2 years of maximum annual flow. Castro and

Jackson [2001] also suggested that the variation in bankfull discharge recurrence interval (regional) depended on several factors such as climate, vegetation, and annual average precipitation.

2.8. HYDRAULIC GEOMETRY

Regime theory aims to explain relationships between channel characteristics and hydraulic drivers. Channel characteristics involve two sets of parameters including geometric (width, depth and cross-section) and hydraulic (velocity, friction and channel slope) variables. In general, hydraulic geometry studies are categorized into two types: at-a-station and downstream variation. At-a-station hydraulic geometry mainly focuses on the geometric changes in a particular channel cross-section due to a variable discharge over a period of time. The downstream hydraulic geometry considers the variation in the channel form for the entire stream, given a certain discharge frequency generally referred to as bankfull discharge [Lee and Julien, 2006]. Hydraulic geometry is of importance in river engineering because it reflects self-organization of a channel to adjust its cross-section, velocity, and channel slope to the river regime [Lacey, 1930; Singh, 2003].

Over the last century, substantial research has been done on the relations for hydraulic geometry. This work was pioneered by Lindley [1919] in the Indus River Basin. However, it was purely empirical and not well established until it was strengthen by Lacey [1930], who used a large amount of data from the design of irrigation canals in Pakistan. Lacey also formulated the equations for the regime concept empirically, which subsequently were modified by various researchers until today (e.g. Chong [1970]; Leopold and Maddock [1953]; Singh [2003]). Leopold and Maddock [1953] confirmed Lacey's regime theory and expressed the relation between channel geometry (width, depth and velocity) and discharge as power functions. Since then, regime theory has been widely used in river engineering projects to determine the effective dimensions of a channel for transporting a desired amount of discharge and sediment.

The general forms of the power functions are:

$$h_f = cQ_f^y \tag{2.17}$$

$$B_f = dQ_f^z \tag{2.18}$$

$$U_f = mQ_f^n \tag{2.19}$$

where h_f, B_f and U_f are the depth, width, and flow velocity of a channel, respectively. Q_f represents the fresh water discharge in the channel. The symbols c, d and m are the coefficients, while y, z and n are the exponent of each power function. Since,

$$Q_f = B_f \cdot h_f \cdot U_f \tag{2.20}$$

it follows that the product of the coefficients must be equals to 1, the same applies to the sum of the exponents as below:

$$c \times d \times m = 1 \tag{2.21}$$

$$y + z + n = 1 \tag{2.22}$$

The exponent y, z and n commonly have a value of approximately 1/3, 1/2 and 1/6. There are conditions that a channel has to fulfil for the application of the regime theory to be valid. According to most literature, the stream must be in stable condition where it has adjusted its dimensions so as to be able to transport or spill its sediment without introducing significant scouring or deposition. Yu and Wolman [1987] claimed that the flow should be uniform along the channel.

2.9. CONCLUSION

The above contains the general information on the theories applied in this entire study. Some of the information may not directly related to one another such as the hydraulic geometry theory and salinity model, but the new understanding obtained from the hydraulic geometry theory is useful especially in developing the predictive measures for the salinity distribution analysis. Furthermore, information on the shape and tide are adopted in all the analyses performed.