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Spatio-Temporal Patterns of Saltwater Intrusion in A Narrow Meandering Channel

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Abstract: Saltwater intrusion has become a crucial issue for water resources management across the globe. Consequently, this issue leads to problems such as encroachment on water intake zone, loss of freshwater vegetation and also disturbance to aquatic life habitat. Undeniably climate change increases the saline water flow into the river system. The meandering rivers are common, and the hydraulics is more complex than straight rivers. An experimental hydraulic investigation was carried out in the Universiti Teknologi Malaysia to elucidate the hydrodynamic interactions between saline water and freshwater in a narrow meandering channel. The spatio-temporal salinity profiles along the river are discussed in this paper. The findings prevailed a typical characteristic of a salt-wedge estuary and indicated the processes of estuarine mixing. As the saltwater flows upstream, the salinity level drops due to the dilution process. Salinity levels and densimetric Froude number were mainly driven by freshwater discharge in the channel. A variation of dilution rate in a narrow meandering channel were up to 78.9% due to strong velocity forces produced by a high freshwater discharge. Furthermore, the flow resistance induced by the channel boundaries and meander planform itself influenced the salinity intrusion profiles along the channel.

Keywords: Experimental investigation, saltwater intrusion, meandering channel, densimetric Froude number, spatio-temporal patterns, dilution process

1. Introduction

Saltwater intrusion is a common hydrologic process in which saline water invades a river and mixes with freshwater. It is one of the main mechanisms that degrades the consistency of both surface water and groundwater making it unsuitable for drinking and irrigation purpose [1]. Global climate change is predicted to cause an increase in sea level rise, and the frequency and size of storms and storm usage. This will contribute further to shoreline erosion; flood damage, inundation of land, saltwater intrusion into the freshwater lens aquifer, among others [2], [3]. Additionally, an excessive pumping and environmental issues such as sea level rise and tide fluctuations have been highlighted as contributing

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factors to exacerbating the saltwater intrusion crisis [4]- [6]. Salt intrusion in an estuary is subjected to many external forcing factors such as river discharge, tides, and topography [7]- [9].

Saltwater and freshwater tend to mix in estuaries where mixing characteristics can be distinguished as vertically mixed, slightly stratified, highly stratified or saline-wedge [10], [11]. In partially mixed and highly stratified mixed estuaries, the structure of stratified flow is complicated by density gradient and tidal reciprocating flow. The combination of strong density stratification, turbulent diffusion and advection mean velocity led to complex circulation and mixing processes in estuaries [12], [13]. In partially mixed and saltwater wedge estuaries, the water circulation is dominated by the two-layer gravitation circulation (also called estuarine circulation). Freshwater mostly flows out in the surface layer whereas saltwater propagates upstream in the bottom layer. The denser saline water travels inland under the fresh river water and forming a wedge as presented in Fig. 1. Velocity differences between the two layers generate internal waves at the interface or pycnocline, mixing the seawater upward into the freshwater layer. High freshwater discharge led to decreasing in vertical mixing and increasing in gravitational circulation.

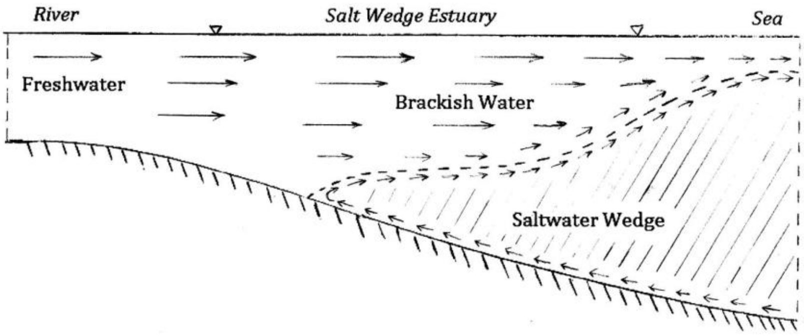


Fig. 1 - Saltwater wedge estuary schematic [14]

Estuarine hydrodynamic processes such as mixing and salinity intrusion have been studied extensively [15]- [17]. It has been revealed that the estuary was well-mixed/partially mixed during the spring tide and stratified during the neap tide, especially in tide-dominated estuaries under low river flow conditions. Saline water intruded more during the dry season than during the wet season due to low river flow conditions. In the meantime, the river discharges hinder saltwater from entering the estuary in the wet season, and the estuary becomes either well-mixed with only freshwater (salinity less than one) or stratified [18], [19]. Apart from that, human activities such as dredging, and shoreline development influence the estuarine dynamics. The salinity intrusion problem is becoming worse due to overexploitation of groundwater resources, intensive farming, industrial waste materials, and natural events caused by climate change [20], [21]. These resulted in salt intrusion problems which directly affect the quality of water resources and give a threat to marine species. Hence, the study of salt intrusion is necessary to ensure water quality is safe and suitable for consumption.

Meandering rivers are a common feature in Malaysia and meander dynamics have been the focus of river engineering for decades. However, it is a challenge for researchers to precisely predict the flow behaviour and its geomorphological processes [22], [23]. The flow structure in a meandering river is highly three dimensional and extremely complicated as compared to a straight river [24]. Meanders can affect the channel flow dynamics by restricting the saltwater intrusion from the downstream as well as river flow from the upstream. The meanders reduce the stratification and increase mixing by restricting the development of two-layer circulation [25], [26]. Channel curvature and meandering can alter both lateral and along channel circulation through centrifugal acceleration and helical lateral flow under adequate curvature [27]. An increase in river discharge combined with the complex curvature geometry results in reduction of salinity intrusion where the saltwater is washed out due to a flushing process. Meanwhile, a reduction in river discharge is mainly a dispersive process that requires a much longer period of time for dilution process. Furthermore, the understanding on the mixing between saltwater and freshwater in a meandering river is not fully understood. Field studies on saltwater-freshwater dispersion study are difficult and costly. Alternatively, a laboratory investigation can be implemented to elucidate the saltwater-freshwater mixing in a meandering river.

The aim of the study was to establish fundamental knowledge on the saline water intrusion in a narrow meandering channel. This study focussed on the spatio-temporal salinity intrusion profiles along the meandering channel. Thus, the objectives of the research were to investigate the freshwater salinisation profiles in a narrow meandering channel due to variation of freshwater discharges. This research output is expected to contribute to a better understanding of saltwater-freshwater interactions in a meandering channel, which will lead to better water resource management and river management practices in the future.

2. Experimental Investigations

A narrow of 10 cm width meandering channel with 690 cm length in Hydraulic Laboratory, Universiti Teknologi Malaysia was utilised to carry out the experimental investigations in this study. The meandering channel bed was set at a gradient of 0.1%. The channel was supported by steel structures and the wall of the channel was built using transparent acrylic sheets. Freshwater was supplied from a sump with a maximum capacity of 15 litres per second (L/s). Freshwater ran from upstream of the flume moving to the downstream and saltwater from a constant head tank with a capacity of 50 gallons was released in the opposite direction. The experiment was carried out with salinity level of 15 ppt. A blue-coloured dye in the saline water was used as a tracer to visualize the mixing in the channel. The experiment was conducted using a constant saline water discharge of 0.32 L/s. Meanwhile, the freshwater discharges were varied at 0.15 L/s and 0.45 L/s. A tailgate placed at the downstream was used to control water level in the channel practically to establish uniform flow condition during the experimental work. The plan view of the meandering channel is illustrated in Fig. 2 (the dimensions are given in millimeters).

The water surface elevations along the channel were checked regularly until an equilibrium flow depth was developed. Freshwater and saltwater discharges were measured using a volumetric approach. The water samples were collected using a siphoning system as shown in Fig. 3. Station 1 to 5 were selected as boundary of measurement station for data collection in this study. Station 1 was the point where saltwater was released (estuary) and Section 5 was the farthest location approaching the upstream (river) as presented in Table 1. The salinity levels were measured using YSI 30 SCT salinometer for a total duration of 180 seconds with a 60 second interval. The total length of the experimental studied area, L was 2620 cm.

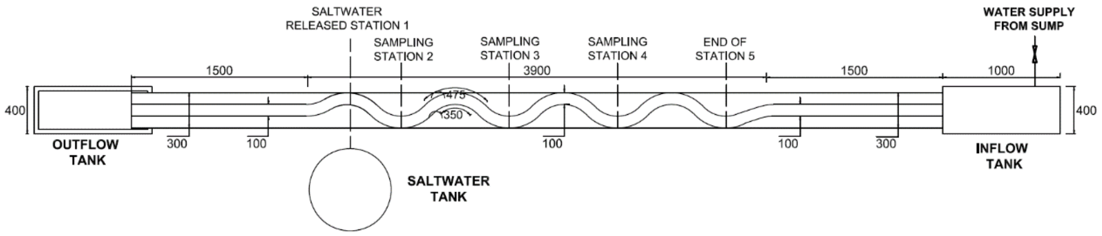


Fig. 2 - Experimental setup in the laboratory study

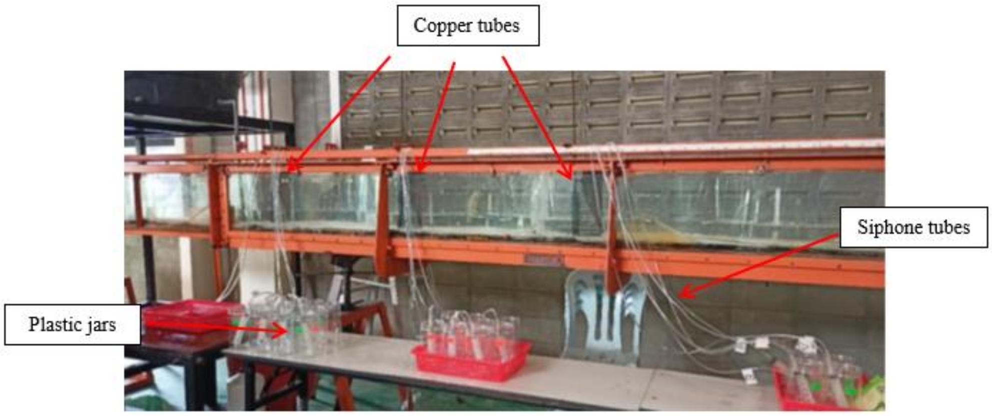


Fig. 3 - Water sampling system in a meandering channel

Table 1 - Sampling stations

Station	x (cm)	x/L
1	0	0.00
2	278	0.11
3	1310	0.50
4	2342	0.89
5	2620	1.00

3. Results and Discussion

The experimental investigations were conducted under uniform flow condition. Meanwhile, the calculated Reynolds and Froude numbers for freshwater and saltwater were greater than 4000 and less than one, respectively. Hence, the regimes of flow were classified as turbulent with sub-critical condition. Q_f, Q_s, H, U_f represent freshwater and saline water discharges, water depth and freshwater velocity, respectively. S is the salinity level at each measurement point, S_i is initial of salinity level (15 ppt), x is longitudinal distance, L is total length of the studied area and z is the sampling elevation measured from the bed channel.

3.1 Densimetric Froude Number

The densimetric Froude number (F_o) represents the ratio of inertial forces to the acting gravitational force due to density differences. The densimetric Froude number (F_o) and the buoyant acceleration (g') were estimated using Eq. (1) and Eq. (2):

$$F_o = \frac{Q_f}{B\sqrt{g'H^3}} = \frac{U}{\sqrt{g'H}} \tag{1}$$

$$g' = \left[\frac{Q_s - Q_f}{Q_f}\right] g \tag{2}$$

where Q_f are the freshwater discharge, B is the channel width, H is flow depth, U is the mean stream-wise velocity, ρ_s and ρ_f are the density of saline and fresh waters and g is the acceleration of gravity. Since the critical theoretical value of F_o is unity, a saline wedge will not form if $F_o > 1$, while the formation of a saline wedge is prevented by values of F_o as low as 0.6 to 0.7. Thus, for the condition $F_o < 0.6$, a salt wedge will form.

The response of the fresh-saline water discharge ratio to the densimetric Froude number is tabulated in Table 2. It was noticed that the densimetric Froude number (F_o) increased by more than 5% as the freshwater discharge rose. Since, all the calculated F_o in the range of 0.32 to 0.40 which were less than 0.6; therefore, salt wedge patterns might be observed in all cases.

Table 2 - Experimental cases

Case	Q_f (L/s)	Q_s (L/s)	H (cm)	U (cm/s)	F_o
A	0.15	0.32	4.5	3.33	0.32
B	0.28	0.32	6.0	4.67	0.38
C	0.40	0.32	7.5	5.33	0.40

3.2 Longitudinal Fresh-Saline Waters Mixing Profiles

Mixing in estuaries is generally being driven by several factors such as river discharge, tides, topography, and wind. Naturally, mixing in an open channel occurs in two directions: vertical and transverse. Density stratification affects transverse mixing more than vertical mixing [22]. Fig. 4 shows the longitudinal distribution of fresh-saline waters mixing in a narrow meandering channel for different cases. The variation of dilution rate (D_R) along the relative distance (x/L) in meandering channels were plotted at a duration of 180 seconds.

The finding prevailed that the D_R at the bottom layer was lower compared to the middle and top layers in all cases. This indicates that the freshwater lies on top flow layer due to its lower density while the saltwater remained in the mid-depth and bottom of the channel. As the freshwater discharge (Q_f) increased, the D_R rose. The D_R values increased in the range of 12.1% to 90.2% from bottom to top layers. The difference in pressures created by densities of fresh and saline waters lead to saltwater wedges continuously intruding into upstream of the flume until the pressure equalizes [28].

The D_R values in Case C were higher compared to Case A and B. It shows that saline water having difficulty to intruded into upstream where strong velocity forces of ambient freshwater flow speed up the occurrence of the dilution process in the channel. Similar results on the salinity distribution were reported by Ibrahim et al. [22], Haron [29] and Harun et al. [30]. These phenomena took place when the river discharge was very much larger than the saltwater discharge. For Case A and Case B, it can be seen the variation of D_R values along the channel. It is proven that the saltwater can intrude more further into upstream due to lower freshwater discharge in the channel and vice versa. It has been highlighted by Gubash et al. [18] that the salinity intrusion during the wet season was low compared to that of the dry season which can be attributed to the dominance of river flow during the wet season where there is higher control of river flow over the tidal flow.

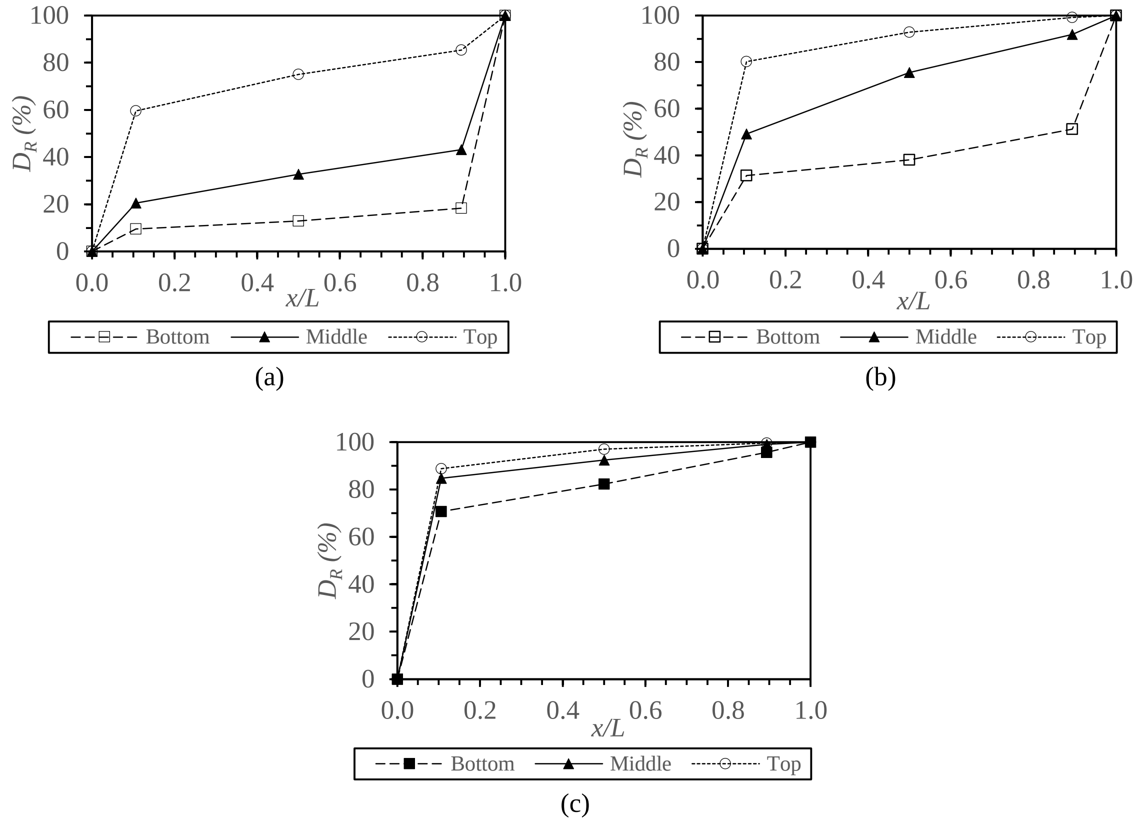
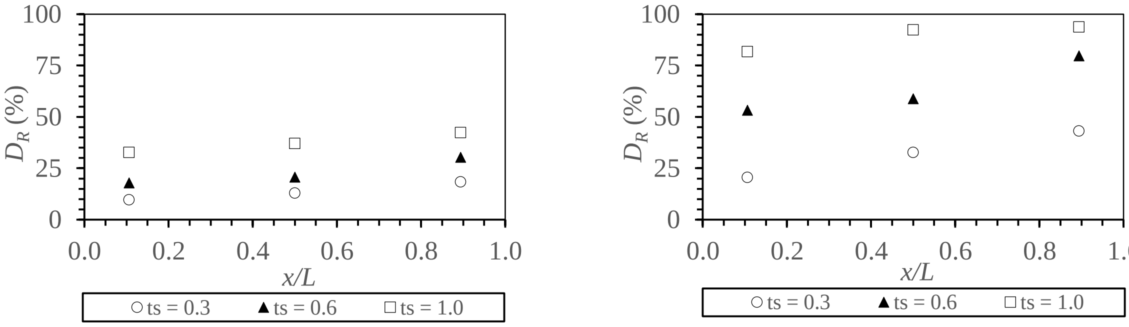


Fig. 3 - Longitudinal distribution of dilution rates for (a) Case A; (b) Case B, and; (c) Case C

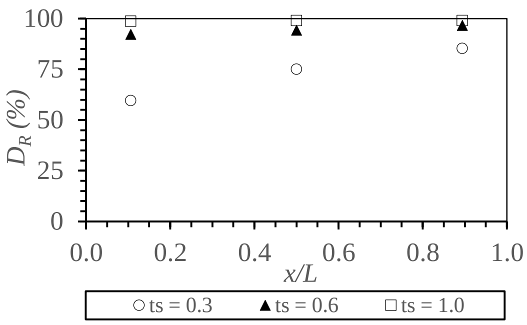
3.3 Temporal Patterns of Dilution Rate

Saline water intrusion in the estuary is primarily regulated by river discharge and tide. The river discharge is the most important element influencing salinity intrusion in the estuarine system, with higher river discharge resulting in less salt intrusion and vice versa. Fig. 4 exhibits the various temporal patterns of dilution rate in a narrow meandering channel at a total duration of 180 seconds for Case A.

The finding prevailed that the D_R along the channel increases as t_s increase. This provides evidence to the occurrence of dilution processes occurs when the saltwater is washed away by ambient freshwater. The D_R at bottom elevation z/D of 0.44 was lower compared to the intermediate z/D of 0.67 and water surface elevations z/D of 0.89. This shows that the presence of deep channel has led to the substantial movement of saline wedge toe towards the upstream direction. Moreover, the highest percentage difference of salinity level S/S_o can be observed at a relative depth (z/D) of 0.67 compared to the bottom and water surface elevations. The percentage difference was up to 78.9%. This suggests that the effects of the channel planform itself on the mixing processes and freshwater-saline water interactions in a narrow meandering river. This phenomenon occurs due to the influence of meanders on the channel flow dynamics by reducing the stratification and increasing the mixing process by restricting the development of two-layer circulation [25], [26]. The findings proven that an increase in river discharge combined with the complex curvature geometry results in reduction of salinity intrusion where the saltwater is washed out due to a flushing process. Meanwhile, a reduction in river discharge is mainly a dispersive process that requires a much longer period of time for dilution process. Similar results on the temporal salinity distribution were reported by McKeon [31].



(a) (b)



(c)

Fig. 4 - Temporal dilution rate profiles at different layers of (a) bottom; (b) middle, and; (c) top of the channel

4. Conclusion

The spatio-temporal patterns of saline-fresh water in a narrow meandering channel have been experimentally investigated. The conclusion can be drawn from the findings are:

- Freshwater discharge influences the D_R in a narrow meandering channel. Since all the calculated F_o were less than 0.6; therefore, salt wedge patterns might be observed in all cases and can be classified as a typical characteristic of a salt-wedge estuary,
- Salinity level is greater at the bottom surface compared to the water surface layer, due to the high density of saline water as compared to freshwater. The dilution rate D_R increased from 12.1% to 90.2% as the measurement depth was close to the water surface in the channel. The dilution rate and process occurred in short time when the freshwater discharge increased,
- The variation of dilution rate D_R in a narrow meandering channel were up to 78.9%. This provides evidence to the occurrence of dilution processes occurs when the saltwater is washed away by ambient freshwater. In addition, the dilution rate and processes might be influenced by the flow resistance induced by the channel boundaries and meander planform itself.

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