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EXPERIMENTAL STUDIES ON MIXING IN A SALT WEDGE ESTUARY

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Abstract: Estuaries, which are rich in nutrient, act as a habitat to some aquatic lives, including mangroves. Human-induced activities such as dredging and shoreline development influence estuarine dynamics which includes mixing process. This will further affect estuarine salinity and adversely affect the aquatic life. A laboratory investigation was conducted in a flume to observe the mixing in a salt-wedge estuary. Three conditions were studied, i.e. mixing in ordinary estuary, mixing in an estuary with a presence of smaller deep channel and mixing in an estuary with a presence of resisting structures along the channel banks. Freshwater was run from one end of the channel, overflowing a weir at the other end, while salt water was introduced at the base of the weir and intruded upstream as gravity current. Mixing in open channel occurs in longitudinal, vertical and transverse directions. The spatial and temporal salt-water intrusions were studied where the mixing patterns were visualized using red dye tracer. To have better understanding on the mixing process, salinity patterns are studied through the plotted isohalines. The spatial and temporal salinity profiles in the flume are also studied through plotted graphs. The results show that salinity differences occurred due to the interfacial mixing between saline and freshwater.

Keywords: *Salt wedge estuary, salinity, mixing, experiment*

1 Introduction

Estuaries are places where seawater is measurably diluted by inflow freshwater. Estuaries are among the most biologically productive ecosystems in this planet. Estuaries serve as habitats for many species of plants and animals. They provide protection, food and space for them. These ecosystems also provide many other important ecological functions. They act as filters for terrestrial pollutants and provide protection from flooding. Estuaries also have economic importance such as fishery and recreation.

Freshwater and saltwater are tend to mix in all estuaries to some extents. Based on mixing characteristics, estuaries can be classified as vertically-mixed, slightly-stratified, highly-stratified or saline-wedge (Fischer *et al*., 1979; Scarlatos, 1996). Estuaries, which are rich in nutrient, act as a habitat to some aquatic lives, including mangroves. Human-induced activities such as dredging and shoreline development influence estuarine dynamics including mixing process (Scarlatos, 1996). For example, in Pulai River estuary in the state of Johor, an 18 m deep channel has been dredged in the middle of river to serve as a navigation channel for Tanjung Pelepas Port (PTP). The dredging work might contribute to salinity changes and further adversely affect the estuarine ecosystem. The presence of resisting structures in the estuary or along its banks might also affect the salinity patterns.

Computer and physical modeling can provide a clear picture of mixing process in different estuarine conditions. Grigg and Ivey (1997) conducted laboratory experiment on the role of changing cross-section on stratified shear-generated internal mixing. Meanwhile, Komatsu and Adachi (1996) carried out experimental study on salinity intrusion in a tidal estuary. In this study, laboratory investigation has been carried out to visualize the mixing pattern and salinity characteristics in a salt-wedge estuary with and without the presence of a deep channel. Another laboratory investigation also has been carried out to study salinity characteristics in a salt-wedge estuary with the presence of resisting structures along the channel banks (e.g. mangroves). The objective of these studies was to obtain better understanding on how salinity distribution would respond to the physical variation of estuarine condition.

2.0 Experimental Setup

Laboratory experiments were conducted using a flume (open channel model) with effective length of 460 cm, 30 cm wide and 40 cm deep. Freshwater runs from one end of the flume overflowing a moveable weir at the other end. Saltwater from a constant head tank with a capacity of 50 liters was introduced at the base of the weir in opposite direction of fresh water flow. A red colored dye was mixed into the saltwater as a tracer to visualize the mixing process in the flume. The first study was conducted with total ambient flow depth of 0.16 m for the ordinary estuary (case 1) and 0.21 m total flow depth for the estuary with a deep channel (case 2). In the third experiment, the flume was modified where concrete slabs with the embedment of steel wires spacing 3 cm apart as resisting structures were provided along portion of the flume (case 3).

Table 1: Location of the sampling stations

Station	Distance from moveable weir, *x* (cm)	x/L (L = 420 cm)
1	20	0.05
2	120	0.29
3	220	0.52
4	320	0.76
5	420	1.00

Five sampling stations were established. Salinity at each station was then measured using YSI 30 SCT equipment, for a total duration of 180 seconds with a 60 seconds interval. The locations of the sampling station are given in Table 1. The constant fresh water and saltwater flow rates used were 3.6 l/s and 2.0 l/s, respectively. Figure 1 illustrates the experimental setup for both cases of the studies.

Figure 2 illustrates the experimental setup for case 3. x, y and z represent longitudinal, transverse and vertical directions, respectively. The resisting structures were placed at point between x/L = 0.33 and x/L = 0.83.

3.0 Estuarine Salinity Profiles

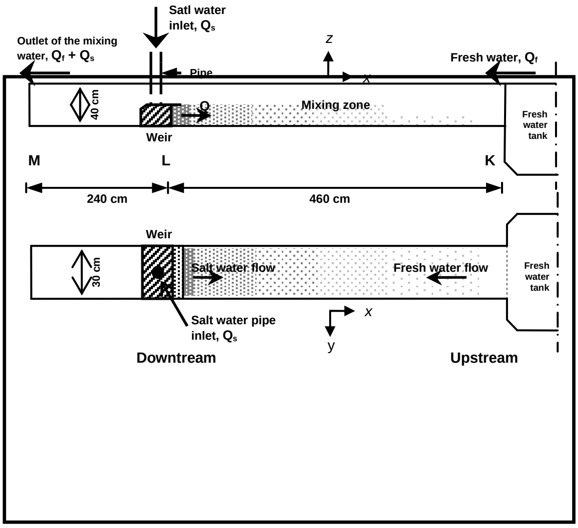
Initially, the saltwater flow enters bottom of the open channel as a typical gravity current. As it moved into the channel, the saltwater that mixed vertically across the interface was pushed back to the downstream by freshwater flow, thus creating a mixing layer between the saltwater and freshwater. The rest of the saltwater traveled upstream and mixed at the bottom of the flume. It took approximately 170 seconds for the saltwater to reach the most upstream, station 5.

Salinity levels (S) were analyzed as relative salinity S/S_o where S_o is the initial salinity value. For discussion purposes, case 1 is referring to ordinary estuary condition and case 2 is referring to estuary with a deep channel. Judging from the densimetric Froude number, Fr_D of 0.5 and Reynolds number, R_e of 36000, the flow condition in the channel was classified as sub-critical and turbulent. Three important features studied in this experiment are cross-sectional salinity patterns, longitudinal salinity profile and temporal salinity profile in the channel.

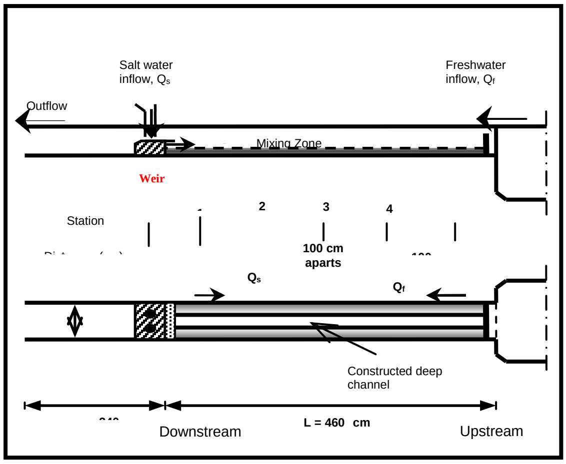
3.1 Cross-sectional Salinity Pattern

(a) Cases 1 and 2

Cross-sectional salinity pattern was observed through isohalines at different locations. Figure 3a and Figure 3b show the salinity patterns at the most downstream station 1 (x/L = 0.05), located 0.2 m from the weir for case 1 and case 2, respectively. This station is the most downstream of the channel and receives the highest volume of salt water. Salt-water intrusion occurs at the bottom of the channel because it is denser than fresh water.



(a) Case 1: Ordinary Estuary



(b) Case 2: Estuary with Deep Channel

Figure 1: Side and plan views of experimental set-up for (a) ordinary estuary (b) estuary with deep channel

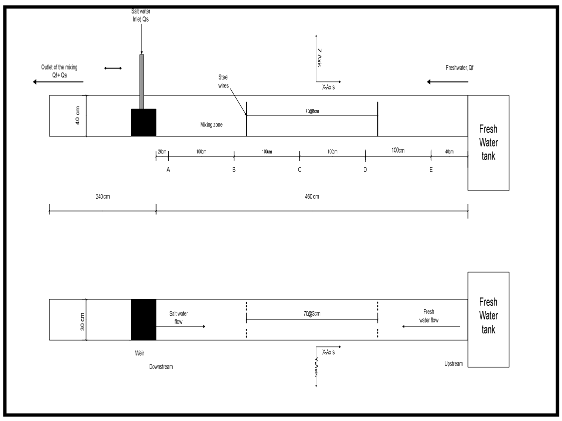
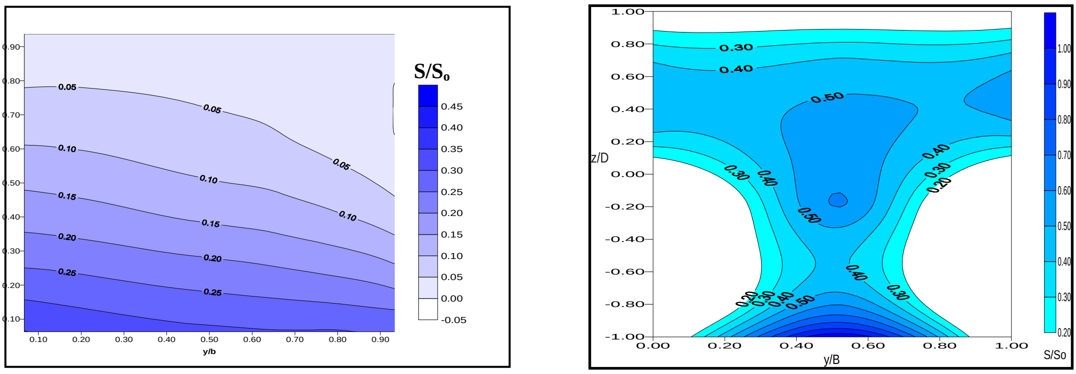


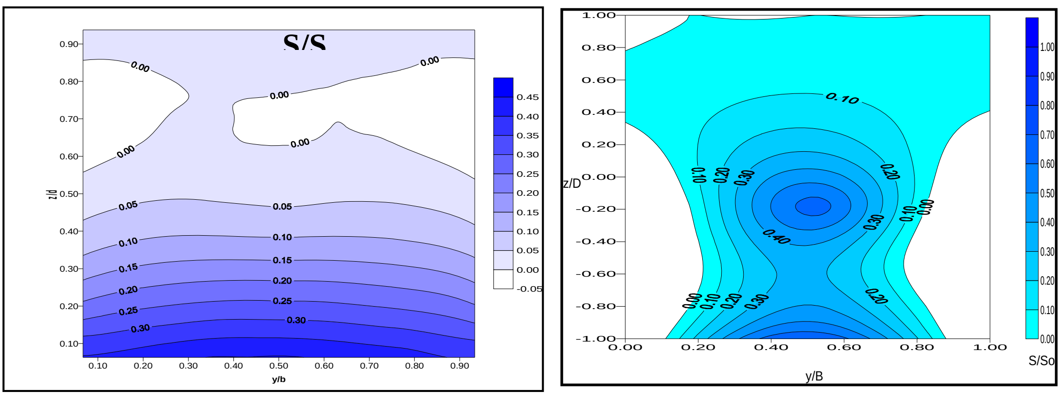
Figure 2: Side and plan views of experimental set-up for estuary with resisting structures (case 3). Concrete slabs with the embedment of steel wires acting as resisting structures (shown on the left)

Figure 3a shows the observed salinity profile in case 1. The salinity profile was uniformly distributed across the channel. However in case 2, the high salinity level was observed to form in the deep channel. Negative values of z/D ratio (z is the depth measured from channel bed and D is the total flow depth) indicate the position of deep channel.



(a) (b)

Figure 3: Isohalines, S/S_o at x/L = 0.05 for (a) case 1 and (b) case 2

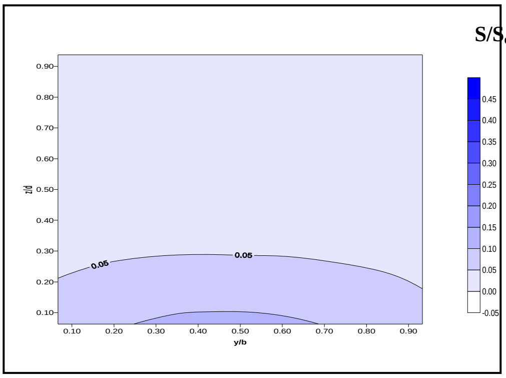


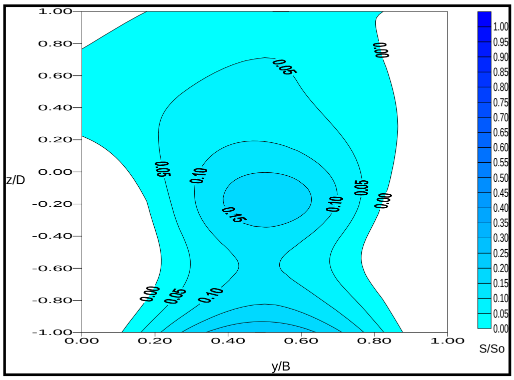
(a) **(b)**

Figure 4: (a) Isohalines, S/So at x/L = 0.52 for case 1; (b) Isohalines, S/So at x/L = 0.52 for case 2

For case 2, saltwater tends to flow upstream in the region of deep channel. This phenomenon was observed visually during the experiment. As salt water intrudes fresh water, turbulent mixing generated at solid boundaries. This process causes the salt water to move vertically to the surface. The salt water then further dispersed and diluted as it flows to the upstream of the channel. The results show the effects of vertical and transverse mixing. Figures 4a and 4b show the isohalines pattern of station 3 located at x/L = 0.52.

Figures 5a and 5b illustrate the isohalines pattern at station 5 (x/L =1.0) located most upstream, near to the fresh water tank. High volume of fresh water and vertical mixing process that occurs in the channel has contributed to the dilution of salt water. It can be seen that, the salinity gradient is small and almost uniform throughout the water column, from the channel bottom up to the water surface. Generally, as the salt water flows to the upstream, mixing occurs and salt water diluted by the fresh water.





(a) **(b)**

Figure 5 (a): Isohalines, S/So at x/L = 1.0 for case 1 (b): Isohalines, S/So at x/L = 1.0 for case 2

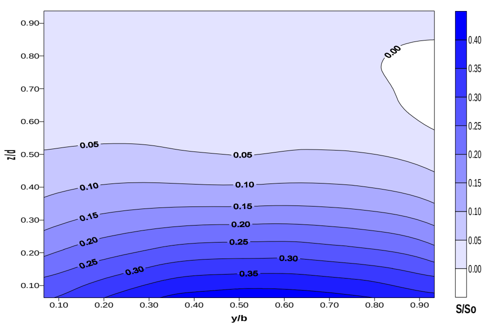


Figure 6: Relative salinity for case 3 at x/L =0.05

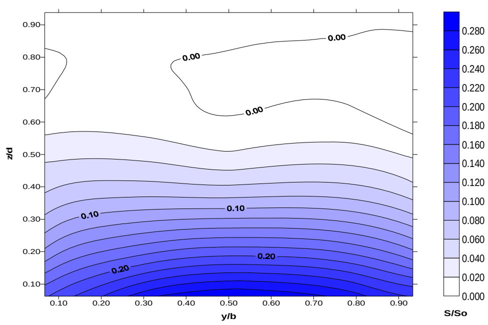


Figure 7: Relative salinity for case 3 at x/L = 0.29 (downstream of structures)

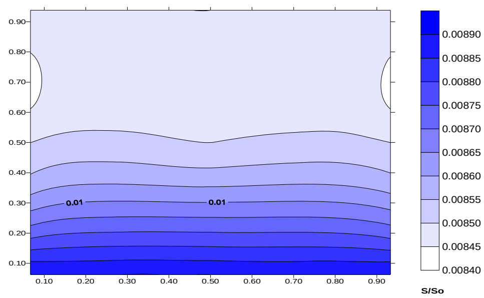


Figure 8: Relative salinity for case 3 at x/L = 1.0

(b) Case 3

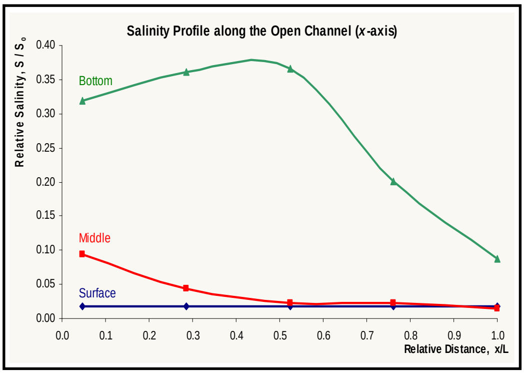
Cross-sectional relative salinity, S/So at various locations along the channel is presented as isohalines shown in Figures 6 to 8. Figure 6 presents the isohalines at x/L = 0.05, i.e. the most downstream station. The pattern is very similar to case 1. As the saltwater moves upstream approaching the resisting structures (case 3), the salinity increases abruptly. These resisting structures constraints the intrusion of saltwater and gets trapped right before the steel wires. The maximum S/S_o at channel bed (case 3) increases from 0.06 at x/L = 0.05 to 0.3 at x/L = 0.29 as shown in Figure 7. At the same time, the freshwater tended to wash out the saltwater by its higher volume and velocity force. After the saltwater passed through the resisting structures, the salinity drops drastically as shown in Figure 8. The maximum relative salinity in case 1 is 0.1 whereas in case 3 is only 0.01. Generally, as the salt water flows to the upstream, mixing occurs and salt water is diluted by the fresh water.

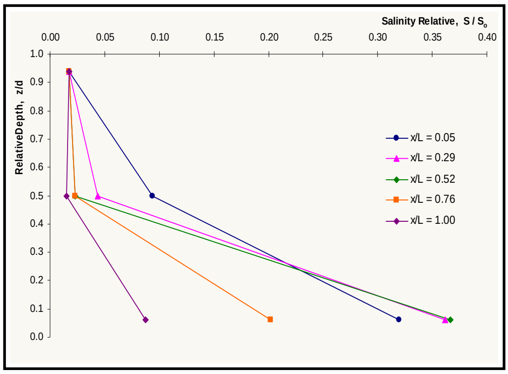
3.2 Longitudinal Salinity Profile

(a) Cases 1 and 2

Figures 9a and 9b present the salinity profiles along the effective channel length, observed at different depths. In general the graphs show that salinity at the bottom of the channel is higher than at the intermediate depth and water surface, due to high density of salt water. AS expected, freshwater lies on top flow layer due to of its lower density while the saltwater accumulate in the mid-depth and bottom of the flume. This represents the formation of salt-wedge in the channel. Downstream part of the channel experience higher salinity compared to the upstream part. Such phenomenon occurs as a result of high saltwater volume at the downstream end, and high fresh water volume at the upstream end. It is also possibly caused by the vertical and longitudinal mixing processes.

Turbulence, which is initiated at the channel bed would breaks into saline- freshwater stratification before interface mixing is created.





(a) (b)

Figure 9: Relative salinity along the channel length for (a) case 1 and (b) case 2

(b) Case 3

As shown in Figure 9a, in general the salinity values were decreasing from downstream to upstream. While the maximum salinity was recorded at station 3 (x/L = 0.52) for case 1, in case 3, maximum salinity is recorded at station 2 (x/L = 0.29). The presence of steel wires (resistance) decelerates and traps saltwater movement in the salt wedge estuary. Such phenomenon is illustrated Figure 10.

Salinity decreases as it moves upstream (x/L = 1.0). A drastic drop in salinity takes place in case 3. Surface salinity is the lowest due to the effect of density difference (stratification) and high freshwater inflow. Most of the saltwater is washed away to downstream by ambient freshwater flow. For cases 1 and 3, saline intrusion still takes place along the channel at the bottom and mid-depth flow as shown in Figures 9a and 10.

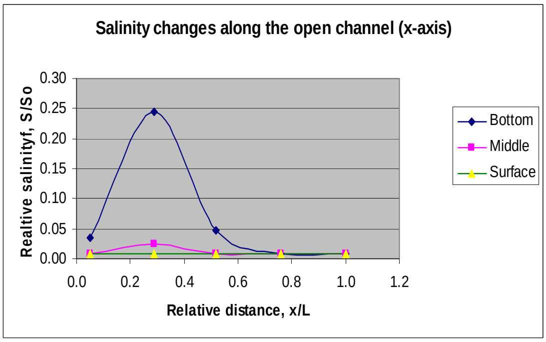
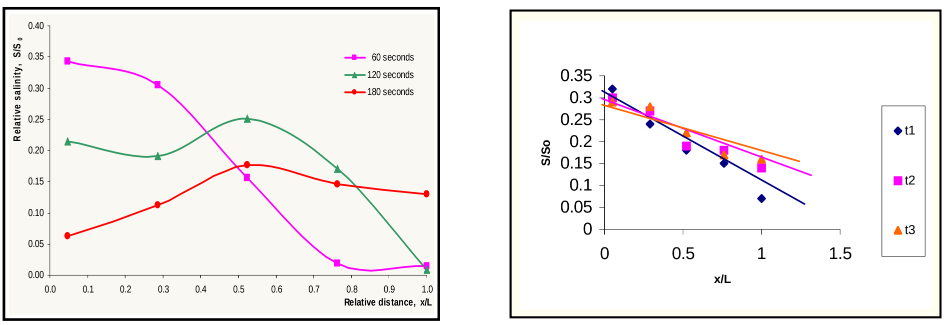


Figure 10: Relative salinity at different flow depths along the channel for case 3

3.3 Temporal Salinity Profile

(a) Cases 1 and 2

The experiments were carried out for a total duration of 180 seconds. Salinity levels were measured at 60 (t_1), 120 (t_2) and 180 (t_3) seconds after saline water is introduced. As shown in Figures 11a and 11b, the salinity at the upstream increases from t_1 to t_3. This provides evidence to the occurrence of salinity intrusion in the channel. Looking at location x/L = 1.0 (upstream) at t_3 (180 sec), the value of relative salinity (S/S_o) for the case 2 is higher than case 1.



(a) (b)

Figure 11: Temporal relative salinity for (a) case 1 and (b) case 2

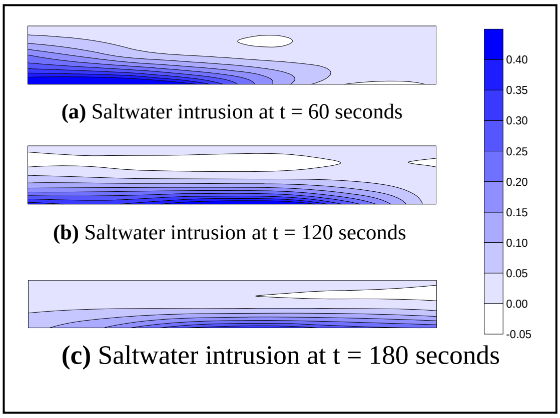
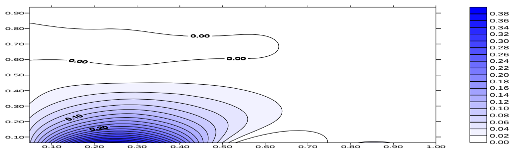


Figure 12: Temporal isohalines pattern along the channel length

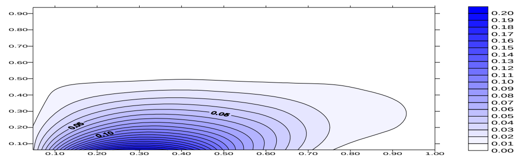
As supported by Scarlatos (1996), this shows that the presence of deep channel has lead to substantial movement of saline wedge toe towards the upstream direction. Meanwhile, at the downstream section, salinity decreases with time. This is due to the turbulent condition which leads to circulation and mixing process. Figure 12 shows the temporal isohalines pattern along the channel. It can be seen that the salt water tends to accumulate at the bottom of the channel and mixing (or dilution) takes place as it moves to the upstream section of the channel.

(b) Case 3

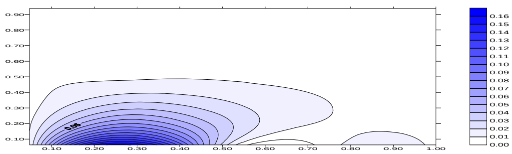
Figure 13 presents the temporal isohalines patterns along the channel length for case 3. The results show that salinity at the upstream increases from t_1 to t_3. This illustrates the occurrence of salinity intrusion in the channel. Looking at location x/L = 1.0 (upstream) at t_3 (180 sec), the value of relative salinity (S/S_o) for the case 3 is lower than in case 1. Also, the length of intrusion for case 3 is shorter than case 1. This shows that saltwater is being trapped as it approaches the resisting structures in the channel. Meanwhile, at the downstream section, salinity decreases with time. This is due to the turbulent condition which leads to circulation and mixing process as mentioned in 3.3(a) earlier.



(a) Saltwater intrusion at t = 60 seconds



(b) Saltwater intrusion at t = 120 seconds



(c) Saltwater intrusion at t = 180 seconds

Figure 13 Temporal isohalines pattern along the channel length in case 3

4 Conclusions

The study aims at understanding the possible behavior of salt wedge estuary acts on the human-induced like activities such as the deepening of channel bed for navigational waterway and natural resisting structures along its banks such as mangroves. Several conclusions can be drawn from the study.

i. Stratification occurrence in the channel is obvious. The salinity profiles show the bottom salinity was higher than water surface. It indicates a typical salt wedge estuary. As the saltwater current flows upstream, the mixing and dilution occurs. Salinity is high at downstream (near to the sea) and decreasing gradually towards upstream (river flow).

ii. Mixing in an estuary takes place in three-dimensional, longitudinal, transverse and vertical directions and turbulence contributes significantly to the mixing process.

iii. The presence of deep channel affects the salinity level. High density of salt water remains in the deep channel, resulted to high salinity concentration at the base of the channel.

iv. The resisting structures such as mangroves and other aquatic trees are capable to constraint the intrusion of saltwater to the upstream of estuary.

More studies should be carried out for different estuary conditions to understand the effect on mixing due to physical estuarine changes. The study of mixing in estuary remains a complex process.

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References

Bowden, K.F. (1978) Estuary Circulation and Diffusion Problems. *Thirtieth Symposium of the Colston Research Society*. Great Britain: Henry Ling Ltd, 141-150.

Chanson, H. (2004) *Environmental Hydraulics of Open Channel Flows.* Oxford: Elsevier Butterworth-Heinemann, 144 – 165.

Chow, V.T. (1959) *Open Channel Hydraulics*. Tokyo: McGraw-Hill. 7-14.

Daugherty, R.L., Franzini, J.B. and Finnemore, E.J. (1989) Fluid Mechanics with Engineering Applications. Singapore, McGraw-Hill.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J.and Brooks, N.H. (1979) *Mixing in Inland and Coastal Waters*. San Diego, California: Academic Press. 229 – 276.

French, R.H. (1986) *Open Channel Hydraulics*, Singapore, McGraw-Hill.

Grigg, N.J. and G.N. Ivey. (1997) A Laboratory Investigation into Shear-Generated in a Salt Wedge Estuary, *Geophys, Astrophys, Fluid Dynamics*. 85: 65-95.

Komatsu, T. and T. Adachi. (1996) Experimental Study On Salinity Intrusion In A Tidal Estuary. *Proc. 10th Congress of the Asian and Pacific Division of the International Association for Hydraulic Research. IAHR*, 1: 392-399.

Martin, J.L. and McCutcheon, S.C. (1999) *Hydrodynamics and Transport for Water Quality Modeling.* Boca Raton: CRC Press, Inc. 91-92.

Mott, R.L. (1990) *Applied Fluid Mechanics, Third Edition*. University of Dayton,Ohio: Merrill Publishing Company.

Scarlatos, P.D. (1996) *Estuarine Hydraulics, Environmental Hydraulics.* V.P. Singh and W.H. Hager (eds.) Kluwer Academic Publishers. 289-348.

Thomann, R.V. and J.A. Mueller. (1987) *Principles of Surface Water Quality Modeling and Control*. New York: Harper & Row Publisher. 91-103.