Journal of Advanced Research Design 144, Issue 1 (2026) 177-190

Journal of Advanced Research Design

Journal homepage: https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Kuala Selangor Estuary Salinity Intrusion Modeling During Extreme Flood Events

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ARTICLE INFO

Article history:
Received 25 February 2025
Received in revised form 23 July 2025
Accepted 4 August 2025
Available online 10 September 2025

Keywords:
Shallow water model (SWM); transverse flow; salinity intrusion; extreme flood event; Kuala Selangor

ABSTRACT

The occurrence of extreme flood events causes flood plain inundation and sedimentation. In the estuary, these processes lead to salinity changes, which adversely affect the estuarine ecosystem. A shallow water model (SWM) had been used for the Selangor River estuary up to Kg. Asahan station, the limit of saline water intrusion. The performance of the model has been verified using two decades of observed data. The model was used to simulate flood events in Kuala Selangor to investigate salinity intrusion attributed to transverse flow during extreme flood events. Analysis shows that as the annual recurrence interval increases, the flood depth increases, but the salinity level reduces due to the dilution effect from the riverine fresh water inflow.

1. Introduction

The occurrence of extreme flood events has an impact on the estuarine system due to the freshwater level rise, sedimentation problems, and fluctuation of salinity intrusion. The phenomenon of extreme flood events that occurred in Johor, Malaysia at the end of 2006 and in early 2007 had impacted the estuaries such as the Pulai River estuary, where the salinity level in the estuary was depleted severely. When it occurred, the dissolved oxygen (DO) level also changed as described by [1] who found that the DO level decreases when the rate of salinity level increases, and vice versa. The extreme flood events in the estuary do not only affect the changes along the estuary but also on the land specifically in the floodplain area due to transverse flow from the flood peak discharge. The extreme flood events and salinity intrusion in transverse flow have affected the estuarine ecosystem where the production of marine life will be reduced and the mangrove areas will be affected. Consequently, the aquaculture industry such as mussels' production may suffer significantly due to high freshwater inflow [2].

Various numerical modelling has been developed to predict the effects of salinity intrusion around the estuary and its flood plain during extreme flood events. Many previous studies use a variety of modelling tools such as the Princeton Ocean Model (POM), Regional Ocean Modeling

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System (ROMS) and to study the estuarine characteristics [3-5]. Most studies on estuarine characteristics aim to evaluate the changes in estuarine salinity [6-18], secondary flow [19,20], tides [21-24], mixing mechanism [25,26], sediment transport [22-23], the effect of wind [27], and also runoff [28-30]. Literature search shows that there is a lack of numerical modelling and experimental studies to investigate the mechanism of mixing between saltwater and freshwater during extreme flood events and under the influence of transverse flow.

A study Lee *et al.,* [31] developed a two-dimensional two-layer shallow water model for two types of fluid with different densities using shallow water equations (SWEs). Other than that, previous studies have built models using SWEs for solving problems such as wetting-drying fronts [32-34], dam breaks [35], one-layer flows [36], two-layer flows [31], and mudflow intrusions [36]. It is applied to the various conditions in many rivers, lakes, and seas, but lack of studies have used these SWEs in estuary studies.

In summary, numerical modelling can be a part of the solution to analyse the mixing process of the salt water and contaminants from the estuary of the river or around the estuary during normal river flow conditions and during extreme flood events. In order to develop an accurate and presentable numerical model, the calibration and validation process should be carried out. Finally, the model will be applied to real cases in any estuarine system either during normal flow conditions or during extreme flood events to analyse the changes in salinity intrusion along the estuarine system. This paper presents a hydrodynamic model development of transverse flow salinity intrusion using SWEs for the Selangor River Estuary to investigate the extent of salinity intrusion during extreme flood events.

2. Study Area

Selangor River estuary located in the Selangor River catchment discharges into the Malacca Strait (Figure 1). The catchment area of the Selangor River covers up an area of about 1960 km^2. Selangor river estuary is hard to classify in which category of the estuarine system either partial mixed, stratified, or well-mixed estuary as the behaviour changes with the conditions. When the discharge is low and the tidal range is high, the Selangor Estuary behaves as a mixed estuary. When the discharge is high and tidal range low, stratification will occur and the Selangor Estuary can be classified as a partial mixed or even a stratified estuary [37]. The location of the turbidity maximum in the Selangor River Estuary extends from 8 to 14 kilometers upstream from the mouth [37].

Fig. 1. Aerial view of the Selangor River Estuary from Google Earth (not to scale) with a map of the Selangor River Estuary study area

3. Shallow Water Equations
3.1 Governing Equations

Shallow Water Equations (SWEs) is a system of hyperbolic partial differential equations (PDEs) governing fluid flow in the oceans, coastal regions, estuaries, rivers, and channels. The most significant hydrodynamic equations are listed in a simplified version below. The Shallow Water Model (SWM) computes the momentum (Eqs. (1) and (2)) and continuity equation (Eqs. (3) and (4)) in the *x*- and *y*-direction. For 3D computations, the vertical velocities are calculated from the continuity equation. Assuming negligible vertical accelerations, the vertical momentum (Eqs. (5) and (6)) leads to the hydrostatic pressure equation.

Horizontal momentum:

$$\frac{\delta u}{\delta t}+u\frac{\delta u}{\delta x}+v\frac{\delta u}{\delta y}+\frac{\omega}{(d+\zeta)}\frac{\delta u}{\delta \sigma}-fv=-\frac{1}{\rho_0}P_x+F_x+\frac{1}{(d+\zeta)^2}\frac{\delta}{\delta \sigma}(\upsilon_V\frac{\delta u}{\delta \sigma}) \quad (1)$$

$$\frac{\delta v}{\delta t}+u\frac{\delta v}{\delta x}+v\frac{\delta v}{\delta y}+\frac{\omega}{(d+\zeta)}\frac{\delta v}{\delta \sigma}-fu=-\frac{1}{\rho_0}P_y+F_y+\frac{1}{(d+\zeta)^2}\frac{\delta}{\delta \sigma}(\upsilon_V\frac{\delta v}{\delta \sigma}) \quad (2)$$

in which:
u, *v* = flow velocities in the *x*- and *y*-direction (m/s)
ω = flow velocity relative to the horizontal plane (m/s)
d = water depth (m)
ζ = free surface elevation (m)
z = vertical co-ordinate in physical space
σ = vertical co-ordinate defined by $(z-\zeta)/(d+\zeta)$
f = Coriolis parameter (1/s)
ρ_0 = reference density of water (kg/m^3)
P_x = hydrostatic pressure gradient (kg/m^{2}s^2)
F_x = turbulent momentum flux (Reynold's stresses) (m/s^2)
υ_V = vertical eddy viscosity (m^2/s)

Continuity:

$$\frac{\delta \zeta}{\delta t}+\frac{\delta[(d+\zeta)U]}{\delta x}+\frac{\delta[(d+\zeta)V]}{\delta y}=0 \quad (3)$$

$$\frac{\delta \omega}{\delta t}=-\frac{\delta \zeta}{\delta t}-\frac{\delta[(d+\zeta)u]}{\delta x}-\frac{\delta[(d+\zeta)v]}{\delta y} \quad (4)$$

in which *U*, *V* is depth-averaged flow velocities in the *x*- and *y*-direction (m/s).

Vertical momentum:

$$\frac{1}{\rho_0}P_x=g\frac{\delta \zeta}{\delta x}+g\frac{\delta+\zeta}{\rho_0}\int_\sigma^0(\frac{\delta \rho}{\delta x}+\frac{\delta \sigma\prime}{\delta x}\frac{\delta \rho}{\delta \sigma\prime})\delta \sigma' \quad (5)$$

$$\frac{1}{\rho_0}P_y=g\frac{\delta \zeta}{\delta y}+g\frac{\delta+\zeta}{\rho_0}\int_\sigma^0(\frac{\delta \rho}{\delta y}+\frac{\delta \sigma\prime}{\delta y}\frac{\delta \rho}{\delta \sigma\prime})\delta \sigma' \quad (6)$$

in which is g = gravitational acceleration (m/s^2) and ρ is density of water (including the effect of salt) (kg/m^3).

3.2 Salinity

In SWM, the salinity transport is modelled by an advection-diffusion equation (Eq. (7)). For each grid cell, the mass balance equation is solved. A simplified version of the formula is given as:

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} - \frac{\partial}{\partial x}\left(\varepsilon_{s,x}\frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon_{s,y}\frac{\partial C}{\partial y}\right) = 0 \quad (7)$$

where C is concentration of the salinity (ppt) and $\varepsilon_s$is eddy diffusivity (m^2/s).

4. Methodology

4.1 Data Collection

Field data collection was carried out to obtain the required data at FDAM Jetty, Kuala Selangor on the 12th and 18th November 2016. From field observation, the soil type at the river mouths up to Kg. Kuantan is identified as mostly clay and mud. The soil type corresponds to Manning's *n* value in the range of 0.02 to 0.04. Data for the five (5) sampling locations is summarised in Figure 2. Secondary data of river cross sections, bathymetry, tidal data, and hydrological data are obtained from government and private agencies.

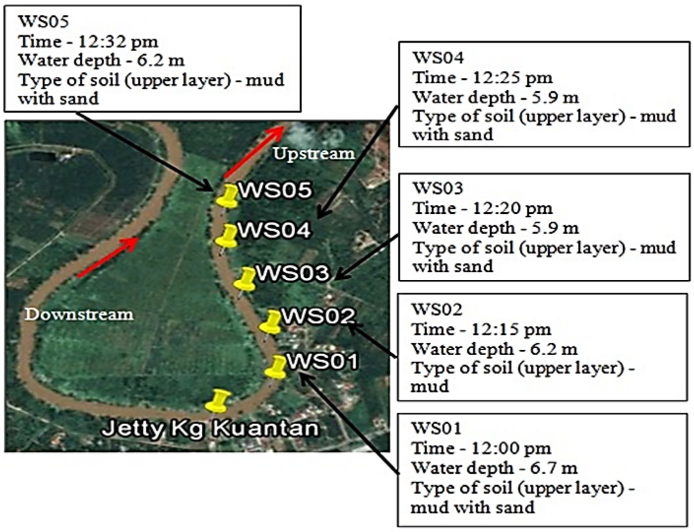

Fig. 2. Locations of the field measurement in November 2016 along the Selangor River Estuary

4.2 Model Development

Domain boundaries must be sufficiently far away from the area of interest so that boundary disturbances do not affect the local conditions. In this study, the model domain of the Selangor River Estuary covers from the river mouth to Kg. Asahan at the upstream of the limit of saline water intrusion (Figure 3). Malaysian Rectified Skew Orthomorphic (RSO) system and Kertau 1948 geodetic datum are used for geographical referencing. A curvilinear grid is generated and optimised using RGFGRID. Depth schematisation is processed from marine charts and survey data using QUICKIN and combined with river cross sections to reproduce the domain bathymetry. Owing to the spatial variability of the raw data sets, interpolation is carried out using grid cell averaging, triangulation, internal diffusion, and smoothing, where applicable. Finally, QUICKPLOT in MATLAB is used to visualise and animate the model results produced by the Selangor River Estuary SWM.

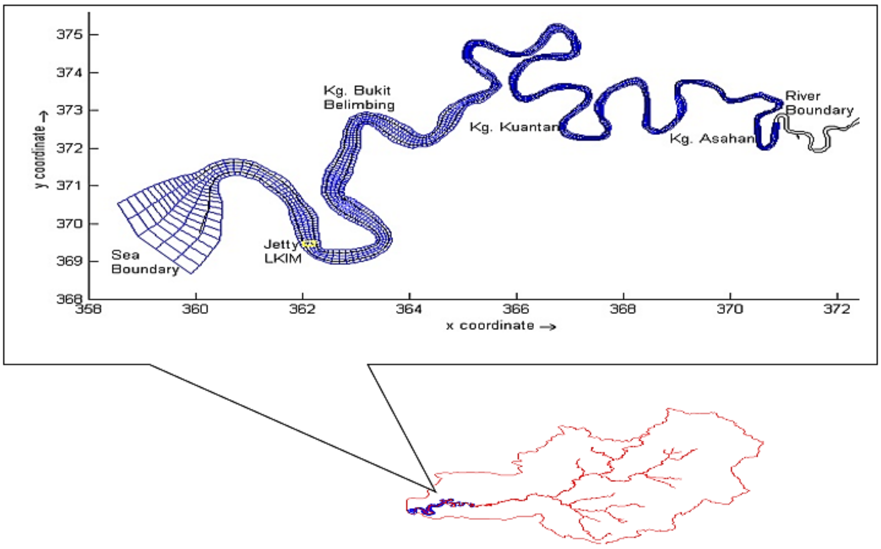

Fig. 3. Boundary of Selangor River Estuary SWM study area

Figure 4 shows the two-dimensional (2D) grid of the Selangor River Estuary SWM. The initial conditions of water level and salinity are defined for the Selangor River Estuary. There are two (2) open boundaries in the model: the upstream limit is defined by constant freshwater discharge, and the seaside is defined by the tidal effects.

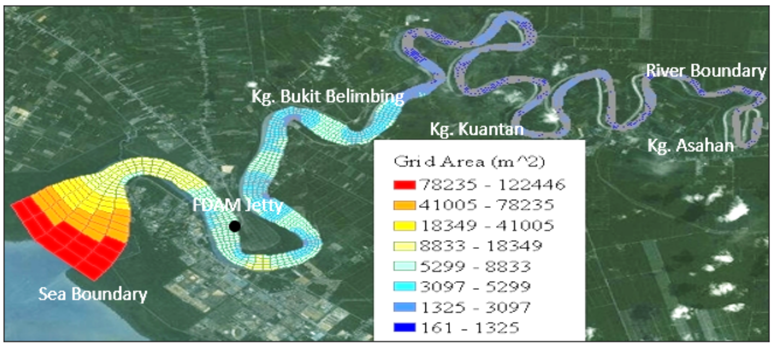

Fig. 4. Selangor River Estuary model grid

4.3 Model Calibration

For model calibration, a comparison between the simulated water depth and observed water depth at FDAM Jetty, Kuala Selangor on 12 November 2016 is assessed (Figure 5). Table 1 shows the *MAE*, *RMSE*, and R^2 values for different Manning's roughness *n*. Results show that $n = 0.02$ is the best value for the model overall.

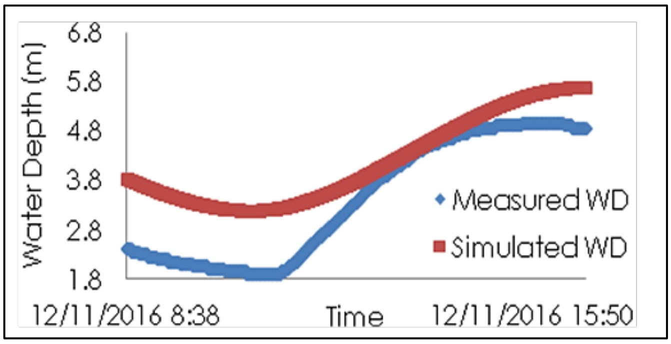

Fig. 5. Comparison of observed and simulated water depth for Manning's *n* value of 0.02 at FDAM Jetty, Kuala Selangor station on 12 November 2016

Table 1
Statistical tests for water depth calibration using different *n* values

n	0.02	0.025	0.03	0.04
MAE (m)	0.771	0.789	0.808	0.842
RMSE (m)	0.898	0.934	0.970	1.034
R^2	0.91	0.89	0.87	0.84

Figure 6 shows the simulated and observed salinity with an *n* value of 0.02. Based on the statistical results (Table 2), we conclude again that the *n* value of 0.02 is the most optimum for the present model.

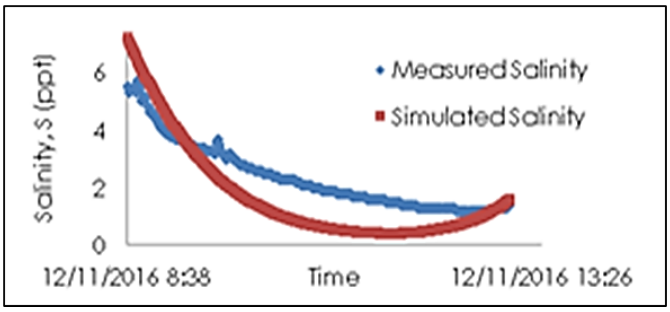

Fig. 6. Comparison of observed and simulated salinity for Manning's *n* value of 0.02 at FDAM Jetty, Kuala Selangor station on 12 November 2016

Table 2
Statistical tests for salinity calibration using different *n* values

n	0.02	0.025	0.03	0.04
MAE (ppt)	0.926	0.993	1.047	1.246
RMSE (ppt)	1.033	1.071	1.131	1.297
R^2	0.90	0.93	0.95	0.95

4.4 Model Validation

Model validation is carried out using the measured data on October 2000 (water level), July 2012 (water level), November 2016 (water depth), and August 2017 (water depth) at FDAM Jetty, Kuala

Selangor. Table shows the statistical analysis of the results for n = 0.02. Overall, the R^2 values are in exceedance of 0.90, whereas the *MAE* and *RMSE* values are well below 0.5 m, except for 18 Nov 2016.

Table 3
Statistical tests for water level or water depth validation (n = 0.02)

	2/10/'00 (WL)	24/7/'12 (WL)	18/11/'16 (WD)	17/8/'17 (WD)
MAE (m)	0.326	0.179	1.351	0.439
RMSE (m)	0.369	0.241	1.434	0.464
R^2	0.90	0.98	0.90	0.90

Table presents the results of statistical tests on the observed and simulated salinity at the FDAM Jetty, Kuala Selangor for October 2000, November 2016, and August 2017. Again, the R^2 values are found to equal or exceed 0.90. For the 18 Nov 2016 data, the MAE and RMSE values are found to be the lowest but much higher in the other two test cases but no more than 2.6 ppt.

Table 4
Statistical Tests for salinity validation (n = 0.02)

	2/10/2000	18/11/2016	17/8/2017
MAE (ppt)	2.608	0.448	2.334
RMSE (ppt)	4.006	0.550	2.515
R^2	0.91	0.91	0.90

4.5 Input Hydrograph

In order to analyse the effect of the flood events on the transverse flow salinity intrusion and the changes in the water level along the estuary, the simulation process for the Selangor River Estuary Model during flood events have been done using flood peak discharge for different 50- (represent minor flood event), 100- (represent a major/large flood event), and 2000- (represents Probable Maximum Flood, PMF condition as extreme flood event) year's Annual Recurrence Interval (ARI). All the different ARIs are selected to represent different flood peak discharge condition, where a 50-year ARI represent a minor flood event, a 100-year ARI represent a major/large flood event, and finally 2000-year ARI represent Probable Maximum Flood (PMF). The details about PMF and other different flood events have been illustrated by previous researchers [38,39]. The historical annual flood peak discharge was obtained from the Department of Irrigation and Drainage Malaysia (DID) for Rantau Panjang station (Table 5). The Rantau Panjang station is located at a distance of 57 km from the river mouth. This area is free from the influence of the tide. The data from the station is used as an approximation input of the flood peak discharge for the Selangor River Estuary SWM as the station is the nearest available gauging station to the model region.

From the historical data of the flood peak discharge at the Rantau Panjang station, the flood peak discharge for 50-, 100-year, and PMF return periods have been estimated using the Frequency Analysis Method based on Gumbel's Extreme Value Type I distribution. The flood peak discharges for different return periods are shown in Table 6. This data is used as input data for the Selangor River Estuary model during flood events.

Table 5
Historical annual flood peak discharge at Rantau Panjang station from 1961 to 2014

Year	Gauging station (m^3/s) of Rantau Panjang (3414421)	Year	Gauging station (m^3/s) of Rantau Panjang (3414421)
1961	166.34	1988	212.15
1962	217.01	1989	245.99
1963	261.12	1990	160.29
1964	160.49	1991	222.45
1965	231.60	1992	170.19
1966	211.48	1993	253.75
1967	267.34	1994	154.63
968	212.28	1995	203.98
1969	221.10	1996	201.63
1970	225.83	1997	140.17
1971	383.39	1998	97.51
1972	215.00	1999	176.92
1973	274.96	2000	313.93
1974	131.19	2001	209.6
1975	186.36	2002	196.28
1976	175.47	2003	213.88
1977	192.35	2004	276.03
1978	136.76	2005	194.35
1979	180.42	2006	308.01
1980	172.62	2007	374.94
1981	156.34	2008	371.74
1982	184.32	2009	287.35
1983	241.25	2010	218.60
1984	168.08	2011	272.18
1985	189.20	2012	288.25
1986	169.69	2013	286.69
1987	198.38	2014	208.08

Table 6
The flood peak discharge for different ARI or return period

Return period (year)	Flood peak discharge (m^3/s)
50	414
100	460
PMF	659

The 50-, 100-year and PMF synthetic flood hydrographs have been generated for modelling and analysis purposes. It must be noted that there is no stream flow near the Selangor River Estuary, specifically at Kg. Asahan station (river boundary), and the nearest station (Rantau Panjang) are approximately 57 km from the mouth of the river. A synthetic flood hydrograph is generated using the historically most severe flood hydrograph from the nearest upstream gauging station located at Rantau Panjang flow into the Selangor River Estuary.

The procedures for generating the synthetic 50-, 100-year and PMF flood hydrographs are as follows:

i. Historical flood hydrograph: Historical flood hydrographs were analysed. The most historical daily flood hydrograph for Rantau Panjang station have been used. Figure 7 shows the historical flood hydrograph at Rantau Panjang station.

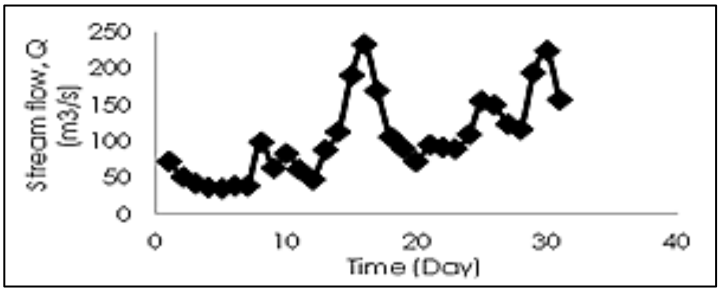

Fig. 7. Flood hydrograph at Rantau Panjang station

ii. Normalised flood hydrographs: The flood hydrograph is normalised by dividing its peak discharge for the respective hydrograph. Figure 8 shows the normalised flood hydrograph at Rantau Panjang station.

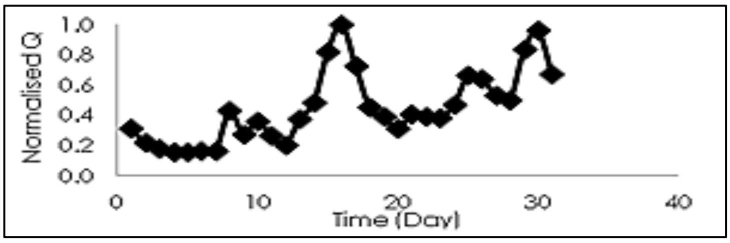

Fig. 8. Normalised flood peak hydrograph at Rantau Panjang station

iii. Regional flood hydrograph: The regional flood hydrograph was obtained by multiplying the estimated flood peak at the Selangor River Estuary by the normalised flood hydrograph. Figure 9 shows the synthetic flood hydrographs for the Selangor River Estuary.

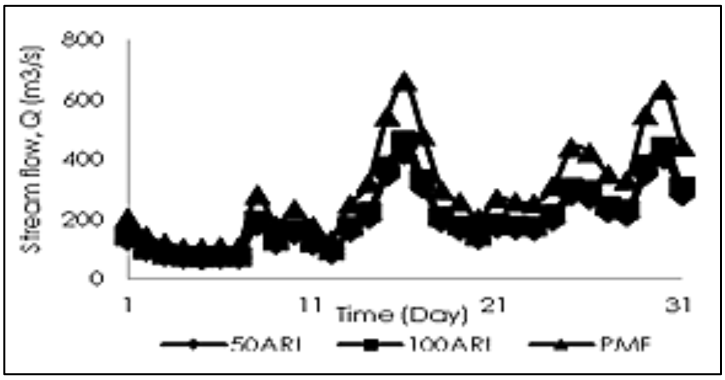

Fig. 9. Selangor River Estuary synthetic flood hydrographs

5. Results and Discussion

In order to analyse the effect of flood events on water depth and transverse flow salinity intrusion along the estuary, a simulation for Selangor River Estuary is carried out using flood peak discharge for different annual recurrence intervals (ARI), namely 50-y which represents minor flood event (Figure 10(a) and (b)), 100-y which represents a major flood event (Figure 11(a) and (b)), and extreme Probable Maximum Flood (PMF) condition taken as 2000-y ARI, as shown in Figure 12(a) and (b).

Results show that the salinity level reduces from the range of 15-18 ppt for 50-year ARI at the LKIM Jetty station, to the range of 9-12 ppt for 100-year ARI, and as low as 0.6-2.1 ppt under PMF condition. This phenomenon occurs due to the dilution effect of freshwater discharge from the catchment runoff. The flood water depth, meanwhile, increases slightly from the range of 4.37 to 4.59 m for 50-year ARI (Figure 13) to the range of 4.40 to 4.62 m for 100-year ARI (Figure 14) and more pronouncedly to the range of 4.59 to 4.83 m under PMF (Figure 15).

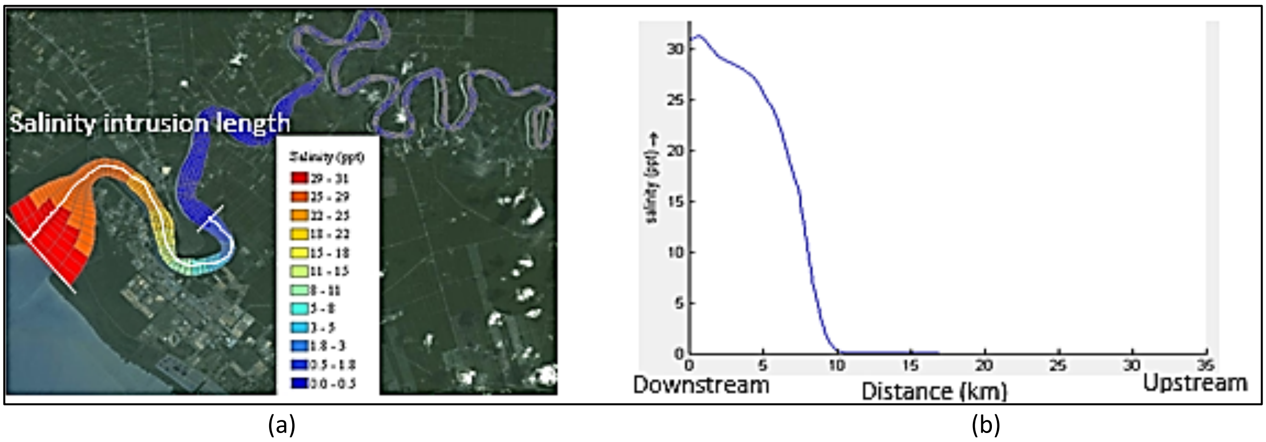

Fig. 10. (a) Salinity contour (b) Intrusion length for a 50-year return period along Selangor River Estuary

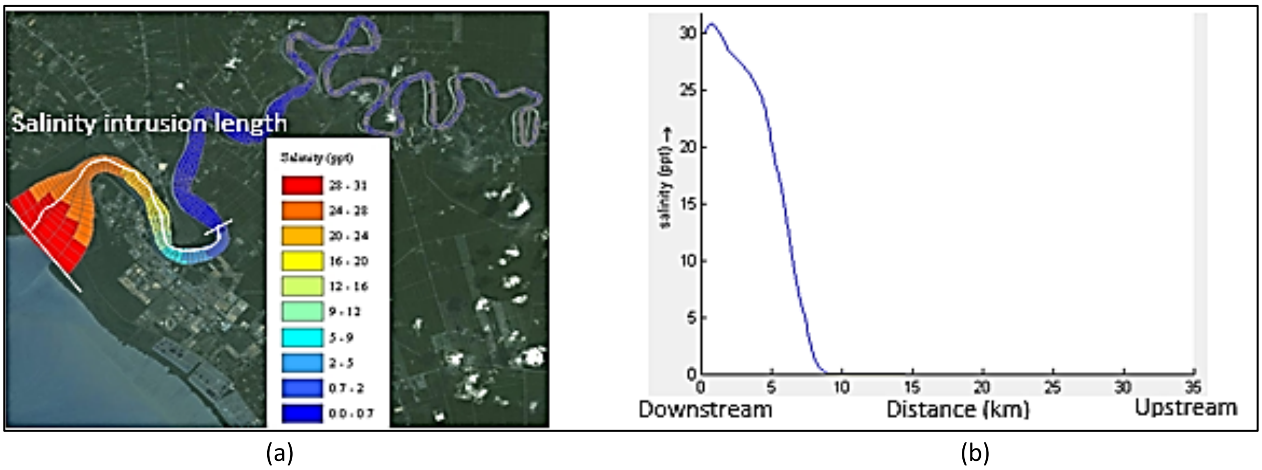

Fig. 11. (a) Salinity contour (b) Intrusion length for 100-year return period along Selangor River Estuary

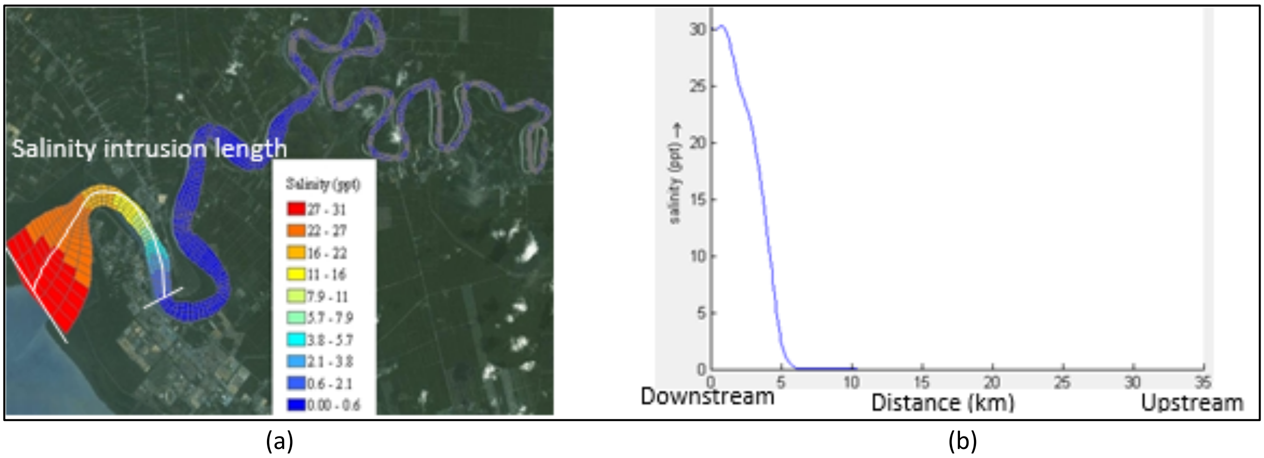

Fig. 12. (a) Salinity contour (b) Intrusion length for PMF along Selangor River Estuary

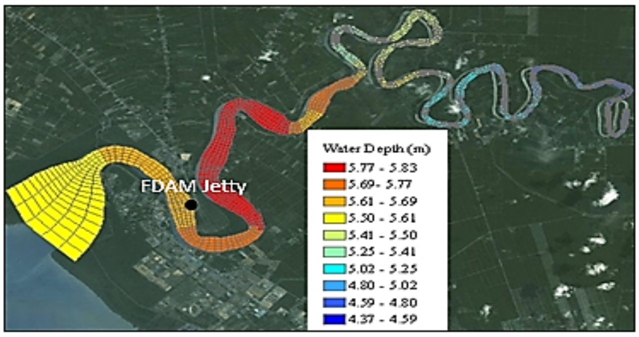

Fig. 13. Water depth for a 50-year return period along Selangor River Estuary

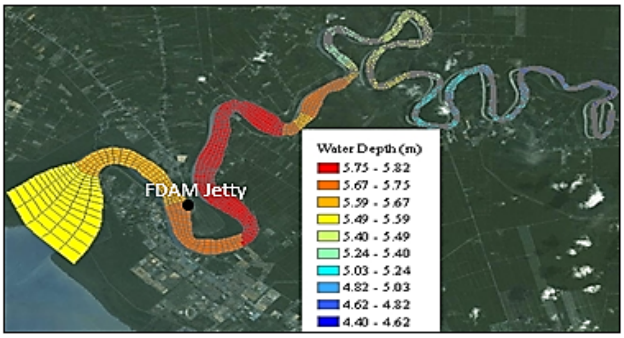

Fig. 14. Water depth for 100-year return period along Selangor River Estuary

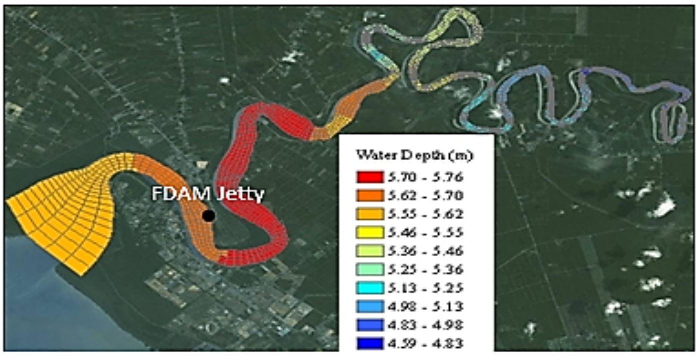

Fig. 15. Water depth for PMF along Selangor River Estuary

5.1 Salinity Intrusion Pattern During Extreme Flood Event

Figure 16 indicates the salinity-upstream flood discharge pattern at FDAM Jetty, Kuala Selangor Station for different return periods (50, 100, and PMF) by using the upstream flood discharges obtained from the synthetic flood hydrographs of the Selangor River Estuary in November 2016. As the upstream flood discharge increases, it affects to salinity level that drops dramatically as higher freshwater flow rate is during flood events. Besides, the movement of fresh water is faster than salt water due to the high velocity and current surface, thus, the mixing occurs so that the concentration of salt water has been disturbed in all directions, either in the longitudinal, transverse, and vertical direction, where the river discharge is one of the mixing factors between salt water and fresh water in an estuarine system.

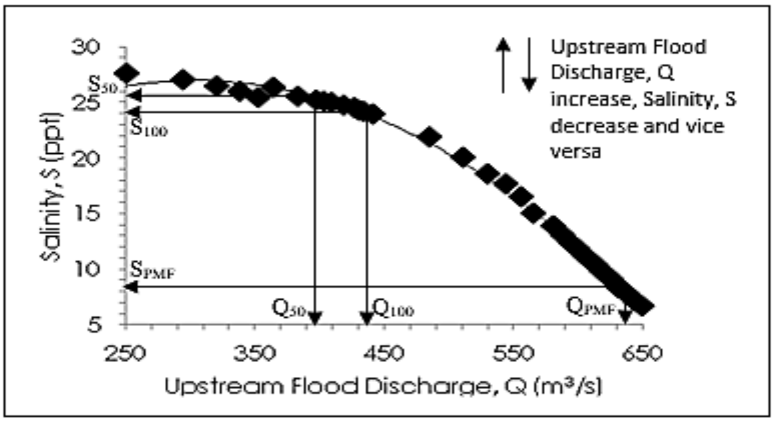

Fig. 16. Salinity-upstream flood discharge pattern at FDAM Jetty, Kuala Selangor station

6. Conclusions

An SWM for Selangor River Estuary was developed, calibrated, and validated using measured water depth/ water level and salinity data at FDAM Jetty, Kuala Selangor for selected events between the years 2000 to 2017. The SWM was applied for different flood-discharge ARIs of 50-y, 100-y, and the PMF. The results show that the upstream region is more affected by water depth rising along the estuary due to the high flood discharge, thus, the distance of salinity intrusion becomes shorter from 50-, 100-year return periods, to PMP. In conclusion, the Selangor River Estuary SWM is capable of predicting the transverse flow salinity intrusion along the estuarine system during extreme flood events. The findings indicated that the SWM model is able to offer a support system to help managers and planners in matters related to the rivers and estuaries and identify the impact of floods on the changes in salinity and water level/water depth, either horizontally, in the transverse direction, or vertically, that affect the environment and wildlife in rivers and estuaries. Thus, integrated river basin management can be carried out more efficiently.

Acknowledgement
This research was funded by a grant and Fundamental Research Grant Scheme (FRGS) and UiTM grant reference FRGS No. 600-RMC/FRGS 5/3 (160/2021) and (SRC Grant 600-RMC/SRC/5/3 (044/2020)).

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