Extreme Estuarine Flooding Leading to Estuary Transverse Flow Salinity Intrusion

Nuryazmeen Farhan Haron, Wardah Tahir, Lee Wei Koon

Abstract—The objective of this paper is to explain the extent of estuarine flooding to estuary transverse flow salinity intrusion. Water quality along the estuary is influenced by salinity intrusion during normal flow condition. However, during the extreme estuarine flooding, the water quality will deteriorate, due to the effect of the transverse flow salinity intrusion. This will reduce the productions of aquatic life. Animals, humans, and plants will also be affected. This paper also discusses a preliminary study on transverse flow salinity intrusion model in estuarine systems due to estuarine flooding. This paper is part of water quality aspects and flood risk management to keep water clean, especially in estuaries.

Index Term- estuarine flooding, transverse flow, salinity intrusion, estuary

I. INTRODUCTION

Estuary is defined as an area where two waters namely semi-enclosed seawater or freshwater (river) and open sea or saltwater (ocean) meet [1]. During the process, distribution of salinity in the estuary changes gradually depending on various factors such as space, time, movement of tides in the estuarine system, fresh water discharge from river, difference in fluid density, shape of estuary, wind effect, and Coriolis effects.

Since long time ago, the estuary has been the main focus of human as a route of communication and trade, especially for people in rural areas far from the coast. Recently, in Malaysia, there has been rapid development of industrial and power generation activities taking place in the estuarine system. These have brought great changes to the natural balance in the estuarine topography due to the dredging of shipping lanes along the bottom estuarine, and the disposal of industrial wastes into the water system.

Furthermore, the pollution in the estuary and the surrounding area will become more serious during flood. Flood events involve areas where there is changing of wet and dry conditions, which are a common situation in the estuaries, lagoons and rivers, or floods resulting from dam breaks and prolonged rainfall, or any flows of shallow water exposed to large changes of its free surface [2]. Extreme flood events in Malaysia, specifically in Johor at the end of the year 2006 that lasted until early 2007 as well as in Pahang in 2001 and 2007, had impacted the estuaries; the salinity level in the areas had decreased dramatically.

When such phenomenon occurs, aquatic life along the estuaries and river area will be affected due to the decline of water quality level. Eventually, low water quality can cause many adverse effects to animals, plants, and especially to humans. For example, when a person takes or uses contaminated water, various kinds of diseases can be transmitted from the contaminated water, such as hepatitis A, blue baby syndrome, and food poisoning.

This paper presents the preliminary study on extreme estuarine flooding and the estuary transverse flow salinity intrusion caused by it.

II. EXTREME ESTUARINE FLOODING AND TRANSVERSE FLOW SALINITY INTRUSION

A. Extreme Estuarine Flooding

The extreme flood events in Johor at the end of the year 2006, which lasted until early 2007, had impacted the Pulai River estuary; the salinity level in the estuary decreased dramatically. When the salinity level decreased, the dissolved oxygen (DO) level increased, as also reported in the study by [3] at Neuse River estuary, North Carolina, USA. This phenomenon had eventually impacted Johor’s economy. The centre of shellfish and aquaculture industry in Western Johor Strait suffered significantly from the storm-driven low salinity event [4]. In addition, the production of mussels in the Johor Straits declined due to high fresh water inflow (Fig. 1). The mussel production must meet a minimum quality requirement or standard in order to get a certificate for export purposes.

Fig. 1. The decline in mussels production on Johor Straits due to flood event (Source: Berita Harian, Feb. 2007).

B. Transverse Flow Salinity Intrusion

Many studies have been done to evaluate the estuarine characteristics such as changes in estuarine salinity [5-13], sediment from various aspects of the shear effect [14-22], influence of wind [23-28], tidal effects [29-34], and runoff...
effects [7, 8, 28, 35], using numerical modelling. However, there is a lack of research to see the mixing process between saltwater and freshwater in estuaries during the normal flow and high flow in a transverse flow.

The extreme estuarine flooding does not only affect the area along the estuary (longitudinal or x-direction), but it also affects the land due to the transverse flow (y-direction) (Fig. 2). The salinity distribution and salinity intrusion length may be considered as major environmental factors affecting the existence and distribution of organisms in estuaries. The extreme estuarine flooding and transverse flow salinity intrusion affect the water quality and the environment—the productions of aquatic life will eventually decline, and humans, animals, and mangrove areas will also be affected.

Fig. 2. An example of transverse flow (y-direction) in estuary due to extreme flood event.

III. THE EXAMPLE OF ESTUARINE FLOODING AT SUNGAI PAHANG ESTUARINE SYSTEM

Sungai Pahang, which flows for a length of 440 km, is the longest river in Peninsular Malaysia (Fig. 3). It has a catchment area of 29,300 km² with an average annual rainfall of between 2000 and 3000 mm. The tidal influence of this river extends about 25 km upstream from the estuary. Severe flood occurred in 1967, 1971, 1999, 2001 and 2007, where houses at the estuarine and coastal areas were hit by the combined effect of high tides and flood discharge (Fig. 4 and 5). The joint occurrence of severe flood discharge from upstream of the river with high seawater level caused the historical major flood in Pekan town and areas close to the estuary. The estuary area was flooded even though there was no rain before or during the flood occurrence.

Siltations at the river mouth also contribute to the flooding especially during the northeast monsoon season. Other than that, salinity level in estuarine system also changes during flood. Salinity level declines dramatically during monsoon season, for examples, in 2001 and 2007. Fig. 6 and Fig. 7 show the locations of water quality monitoring stations at Sungai Pahang estuary, and the graph of salinity level near Sungai Pahang estuary at eight river stations from 2001 until 2011 respectively. Meanwhile, Fig. 8 and 9 show hydrological stations in Pahang, and the hydrograph near Sungai Pahang basin from 2000 to 2012, respectively.

Fig. 3. View of Sungai Pahang estuary.

Fig. 4. View of flooding in Pekan Town near Sungai Pahang Estuary.

Fig. 5. View of inundation of Sungai Pahang at Pekan Town near Sungai Pahang Estuary.
IV. MODELLING THE ESTUARINE FLOODING WITH SALINITY INTRUSION IN TRANSVERSE FLOW

Estuarine flooding and transverse flow salinity intrusion in estuarine systems can be modelled using the Shallow Water Equations (SWEs). Most previous studies only develop 1-Dimensional (1D) \[36, 37\] or 2-Dimensional (2D) \[20, 38-44\] model using SWEs for several cases such as improving the grid-based, studying the general fluid density differences, and studying the sediment transport. Other than that, previous studies have built models using SWEs for solving problems such as wetting-drying fronts \[39, 45, 46\], dam breaks \[45, 47, 48\], one-layer flows \[48, 49\], two-layer flows \[43, 50-52\], and mud flow intrusions \[49, 52, 53\]. It is applied to the various conditions in many rivers, lakes, and the sea. However, these previous studies do not investigate the problem of salinity intrusion in the estuary during flood. Therefore, the use of SWEs to develop Shallow Water Modelling (SWM) is expected to reveal the flood hydrodynamics and salinity intrusion in the estuary and their impact on the water quality and the environment.

The Shallow Water Equations (SWEs) are a model of hyperbolic partial differential equations (PDEs) governing fluid flow in the oceans, coastal regions, estuaries, rivers, and channels. The SWEs can be used to predict tides, storm surge levels, and coastline changes from hurricanes, as well as ocean currents. This model can also be used to study the dredging feasibility. The principles of conservation of mass and conservation of momentum have been used in deriving the Navier-Stokes equations. Vertical integration allows the vertical velocity to be removed from the SWEs because the value of the parameter in \(z\)-direction is much smaller than the value of the parameter in \(y\)-direction.

The SWEs consist of three independent variables, which are time, \(t\), and two spatial coordinates, \(x\) and \(y\) ((1), (2) and (3)). The dependent variables are the fluid depth, \(h\), and the fluid velocity, \(u\) and \(v\). From the equations below ((2) and (3)), \(g\) represents for acceleration of gravity. With the selection of the correct unit, mass conserved quantity, which is proportional to \(h\), and momentum, which is proportional to \(uh\).
and vh, the PDEs in case of no Coriolis, frictional or viscous forces are:

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]

(1)

\[
\frac{\partial (uh)}{\partial t} + \frac{\partial ((uh^2 + \lambda h^2))}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]

(2)

\[
\frac{\partial (vh)}{\partial t} + \frac{\partial ((uh^2 + \lambda h^2))}{\partial x} + \frac{\partial ((vh^2 + \lambda h^2))}{\partial y} = 0
\]

(3)

V. CONCLUSION

In this ongoing research, a Shallow Water Modelling (SWM) for salinity intrusion in estuarine system will be developed in order to see the impact of flood and salinity intrusion in transverse flow model on the water quality of the estuary and on the surrounding area. A relationship between salinity intrusion and various flow parameters can be established using the model. The model simulation of SWM using real-time data in any estuarine system can be used to analyze the process of transverse flow salinity intrusion and the impacts on the water quality and the surrounding area when the fresh water flow varies. The model will be useful in predicting the affected area by measuring the transverse flow salinity intrusion during an extreme flood event. SWEs will be used in order to develop the flood and salinity intrusion model accurately and efficiently for the Government and private use in the future.

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