Advection and Dispersion of Water Quality Constituents in Batu Ferringhi Penang

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ABSTRACT

The incident of beach pollution in Batu Ferringhi in year 2014 has created a major concern over water quality at the tourists’ haven. In order to understand advection and dispersion of pollutants in the area, a coastal hydrodynamic model of Batu Ferringhi beach was developed in this study by taking into consideration its wind, tide, coastal current and riverine runoff. The model was calibrated and validated through observations from adjacent coastal monitoring stations. Simulation was then carried out to investigate scenario of the constituent water quality which originates from the three rivers in the vicinity. Results showed high concentrations of water quality parameters observed near the headland towards the northeast of the study area, with intermittent patchy escape which may retain more than one-third the initial concentrations, weighted by the river discharge. Even more worrying is that localised trapping of up to three-quarter the initial weighted concentrations also occurs at the beach, owing to the interactions between river flow and longshore current.

Keywords: Advection/dispersion, Batu Ferringhi, MIKE21, water quality

INTRODUCTION

In 2014, reports on beach pollution have tarnished the image of Batu Ferringhi beach, a popular tourist destination to both the locals and international travellers. Site visits by the officials of Penang Island Municipal Council (MPPP) found that the river mouth of Batu Ferringhi was heavily contaminated with black-coloured odorous substance. The issue garnered much public attention, with complaints lodged by hotel operators, and local non-governmental organisations, such as Sahabat Alam Malaysia (SAM) and Consumers Association of Penang (CAP) voicing their concerns.
Based on the tests conducted by Department of Environment (DOE), the substance is found to contain *Escherichia coli* (*E. coli*) (Shankar, 2014). It was suspected that the contamination originated from a faulty sewage system (PEG073) some 300 m upstream of the coast. Other possible sources of contamination have since been touted, from river sedimentation, failed toilet connections, illegal food outlets, laundry and car wash services, etc.

Anthropogenic sources of nitrogen and phosphorous into the marine environment have greatly modified the coastal nutrient cycling (Voss, 2011). In particular, discharge of inadequately treated wastes with significant organic contents into the coastal sea can potential cause eutrophication, red tide events, and increased fish mortality such as reported in the southwest coast of India (Babu, Das, & Vethamony, 2006). Mapping the pollutants and studying their transport and ultimate fate are thus important to monitor the well-being of marine water quality. Recently, satellite remote sensing and synthetic aperture radar (SAR) have been used to map coastal water quality (e.g., DiGiacomo et al., 2004; Su et al., 2008). However, the method is only applicable to physical qualities such as total suspended solids (TSS), oil slick, etc., and its extension to other water quality constituents is not straightforward.

Triggered by observations of high fecal coliform count in the coastal water, Babu et al. (2006) used MIKE21 to model assimilation of biological oxygen demand (BOD) from a wastewater outfall off Kochi, the west coast of India. Their study showed that region of high BOD persists in an elliptical zone near the outfall. In addition to BOD, chemical oxygen demand (COD) has also been shown to affect marine water quality and its concentration can be correlated to salinity of the receiving water (Li et al., 2015). Meanwhile, ammonical nitrogen (AN) is known to affect the acidity (pH level) of sea water (Voss, 2011).

The generally assumption which points out discharges into the sea are promptly mixed and hence their concentrations tend to reduce uniformly over time and distance is frequently flawed. Depending on the dynamical interactions between the various forcing at work such as coastal current, wave, tide, and wind, pollutant plumes may remain patchy with well-defined structure. In some cases, they may be stretched to exhibit fractal-like behaviour with localised high concentration (Zimmerman, 1986; Lee, Borthwick, & Taylor, 2014b), or washed ashore (Lee & Zaharuddin, 2015). In addition, the escape time of pollutants from the coastal domain into open sea is also highly dependent on the local geometry, bathymetry and hydrodynamics, and may further be complicated if the coastal water is stratified (Snyder 1985; Lee, Borthwick & Taylor, 2014a).

Koh, Lim and Lee (1997) evaluated the impacts of relocating the discharge outfall from Georgetown, Penang, to different locations within the strait between Penang Island and Peninsular Malaysia. Their study showed that degradation of coastal water quality is evident from raw sewage discharge. There is however a lack of similar study in the northern part of Penang Island, where Batu Ferringhi beach is located (Owens, 1978). In this paper, our purpose is to investigate the spatial and temporal changes of water quality constituents, namely BOD, COD, TSS and AN, in the coastal region of Batu Ferringhi. We present a preliminary two-dimensional model of Batu Ferringhi beach, which considers the riverine discharge from its upstream catchment, tidal fluctuation and coastal wave climate. Using observed river water quality parameters from the study area, the advection and dispersion of these pollutant...
Advection and Dispersion of Water Quality Constituents were simulated over a typical tidal cycle, and the results were determined and analysed.

METHOD

Study Area

The study area is located in the north of Penang Island (Pulau Pinang), off the coast of Peninsular Malaysia in the Straits of Melaka (Selat Melaka) (see Figure 1). Batu Ferringhi beach is located in the Bukit Bendera district. The study area includes three rivers, namely, Sg. Batu Ferringhi River, Sg. Satu and Sg. Mas, all of which discharge into the sea in the northwest direction. Among the three rivers, Sg. Batu Ferringhi has the largest catchment area with 1135 ha. Meanwhile, Sg. Satu and Sg. Mas have less than a quarter the size, with areas of 244 ha and 211 ha, respectively.

The Penang island experiences tropical climate with the average mean daily temperature of 27ºC, while the minimum and maximum temperature recorded ranges from 23.5ºC and 31.4ºC, respectively (Ahmad, Yahaya, & Farooqi, 2006). The humidity in the island ranges from 60.9% to 96.8%. Generally, the study area experiences uniform temperature, high humidity and heavy rainfall with two major monsoon seasons, namely, the southeast and northeast monsoons. It receives varying monthly rainfalls with an annual average of 267 cm, and up to 624 cm.

The seabed in the study area mostly consists of marine deposits of sand and clay layers, which combined can extend up to 100 m thick (DID, 2010). The geographical properties of residual soils are characterised by medium to coarse grained biotite granite layer, with predominant orthoclase and subordinate microcline (Ahmad et al., 2006). The colour of rocks along the beach vary from light grey to dark grey, depending on the amount of biotite present.

Figure 1. Location of the study (DID, 2010)
The coastline along Batu Ferringhi beach experiences semi-diurnal tidal condition. Tidal data were recorded at a jetty station (5°27'44.52"N, 100°12'27.15"E) at Teluk Bahang by Fisheries Development Authority of Malaysia (Lembaga Kemajuan Ikan Malaysia, LKIM), as shown in Table 1. At the worst astronomical condition, the tidal range is about 3.2m. The wave heights at the study area are generally low and seldom exceed 1.5 m (DID, 2010). During the northeast monsoon (Oct-Mar), waves are locally generated between the mainland and Penang Island with a north easterly direction and rarely exceed 0.5 m. During the southwest monsoon (Apr-Sep), wave direction is between northwest and west-north-west. These waves are influenced by the waves generated in the Andaman Sea and the largest wave height usually occurs during this period. Figure 2 shows the wave roses in the study area.

Table 1
Tidal observations at LKIM Teluk Bahang station (DID, 2010)

<table>
<thead>
<tr>
<th>Tide</th>
<th>Tidal level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACD</td>
</tr>
<tr>
<td>Lowest Astronomical Tide (LAT)</td>
<td>+0.0</td>
</tr>
<tr>
<td>Mean Low Water Spring (MLWS)</td>
<td>+0.6</td>
</tr>
<tr>
<td>Mean Low Water Neaps (MLWN)</td>
<td>+1.3</td>
</tr>
<tr>
<td>Mean Sea Level (MSL)</td>
<td>+1.6</td>
</tr>
<tr>
<td>Mean High Water Neaps (MHWN)</td>
<td>+1.8</td>
</tr>
<tr>
<td>Mean High Water Spring (MHWS)</td>
<td>+2.6</td>
</tr>
<tr>
<td>Highest Astronomical Tide (HAT)</td>
<td>+3.2</td>
</tr>
</tbody>
</table>

Figure 2. Wave rose in the study area (DID, 2010)
Model Description

MIKE21 by Danish Hydraulic Institute (DHI) is a popular modelling software used for advanced numerical modelling for shallow water bodies, incorporating the effects of irregular coastline, complex bathymetry and open boundaries. The model solves the two-dimensional incompressible Reynolds averaged Navier-Stokes equations using Boussinesq approximation and assuming hydrostatic pressure distribution. The governing equations are discretised using Cartesian coordinates using cell-centred finite volume method. The model was vigorously tested and validated on a number of key numerical test cases with analytical solution, as well as numerous natural geophysical conditions.

The hydrodynamic (HD) module simulates water level variation, current speed, and current direction incorporating the tidal condition and river discharges. In the present study, tidal boundary condition taken from Global Tide Model (GTM) was applied along the open boundary, and then calibrated and validated against local observations. Fixed discharge boundary condition was applied at river outflow; land boundary was applied along the coastline.

Nearshore wave was analysed to assess the distribution of wave height and wave direction using MIKE21 SW (Spectral Wave). The model takes into account the effects of wave-current interaction, shoaling and refraction due to varying depth, local wind generation and energy dissipation due to bottom friction and wave breaking. Input wind data obtained from British Meteomarine Office (BMO), and the wave climate data derived are as shown in Figure 3(a) and (b).

![Figure 3. (a) Offshore wind rose from BMO wind data; and (b) wave rose derived using spectral analysis](image-url)
The model domain chosen extends 30 km to the north, the south and the west of the study area in order to incorporate the regional circulation. Staggered flexible mesh is adopted, where the grid sizes vary from 10,000 m$^2$ (M1), to 10,000,000 m$^2$ (M4) (Figure 4). Model bathymetry was developed from secondary bathymetric survey data (Figure 5).

MIKE21 AD (Advection/Dispersion) module models the advection and dispersion process using the simulated flow field. In this study, the basic water quality parameter, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solid (TSS), and ammonical nitrogen (AN), are considered. The inputs constitute pollutant loading rates, which are the products of the observed river discharge and the concentrations of the respective parameters at each of the river source obtained from DID.

RESULTS AND DISCUSSION

Calibration and Validation

Simulation was carried out from 2$^{nd}$ – 19$^{th}$ Sep 2007, which includes a 3-day ramp up period, followed by a 14-day semi-diurnal cycle. The neap and spring tidal conditions fall on 6$^{th}$-7$^{th}$ and 13$^{th}$-14$^{th}$ respectively. Average river outflow condition is considered where the magnitude for Sg. Batu Ferringhi, Sg. Satu and Sg. Mas are 1.88 m$^3$/s, 1.15 m$^3$/s, 0.47 m$^3$/s respectively (DID, 2010). The dominant wind speed is 7.5 m/s coming from 288°N, and the resulting wave height ranges between 0.18 to 0.21 m above MSL.

Figures 6(a) to (c) show the calibration of the simulated results using the observation data from station LKIM in Teluk Bahang, which is located to the west of the study area. Both the water level fluctuation and current direction compared well with the observations. Meanwhile, for the current speed, the phase was well captured but the simulated troughs were generally
much higher. The values of the coefficient of determinant are shown in Table 2. Overall, the result is satisfactory.

Table 2

\[ R^2 \text{-values for model calibration and validation} \]

<table>
<thead>
<tr>
<th>Location</th>
<th>Water level</th>
<th>Current speed</th>
<th>Current direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teluk Bahang</td>
<td>0.97</td>
<td>0.92</td>
<td>0.82</td>
</tr>
<tr>
<td>Pantai Keracut</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Next, validation was carried out for the period 27-29\(^{th}\) May 2014 by comparing the results with observations in Pantai Keracut (5°27’43.88”N, 100°10’7.21”E), which is located further west from Teluk Bahang. The water level, current speed, and current direction (Figures 7(a) to (c)) were all well captured in terms of the phase and magnitude, and \( R^2 \) values, as shown in Table 2. These suggest that the model is able to reproduce the local circulation and tidal conditions accurately.

**Simulation of Water Quality Constituents**

The simulated flow field for the period 2\(^{nd}\) – 19\(^{th}\) Sep 2007 showed that the water levels in Batu Ferringhi beach ranged from 0.45 m to –0.45 m during neap tide, and 1.0 m to –1.1 m during spring tide. The current speed ranged from 0.04 m/s to 0.2 m/s, while current direction varied from north easterly to south westerly direction. For the advection/dispersion simulation, the observed water quality parameters in Sg Batu Ferringhi, Sg. Satu and Sg. Mas (Table 3) are used as point source input. The averaged initial concentration is weighted by the discharge in the rivers and used as a comparison to the observed concentration at sea.

Table 3

\[ Initial \text{ and weighted concentration of water quality parameters (DID, 2010)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial concentration (mg/L)</th>
<th>Weighted concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sg. Batu Ferringhi</td>
<td>Sg. Satu</td>
</tr>
<tr>
<td>BOD</td>
<td>8.32</td>
<td>9.00</td>
</tr>
<tr>
<td>COD</td>
<td>30.42</td>
<td>10.13</td>
</tr>
<tr>
<td>TSS</td>
<td>23.63</td>
<td>31.50</td>
</tr>
<tr>
<td>AN</td>
<td>1.20</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Figures 8(a) to (d) show the simulation results for the transport of BOD, COD, TSS and AN along Batu Ferringhi beach. The plots show the distribution scenario at noon time (12:00 p.m.) on 13 September 2007, which was during spring tide condition. In general, a net transport in the north easterly direction was observed, driven primarily by the coastal tidal current, coupled with a predominantly landward wave action.

It can be observed that high localised concentration of the four water quality constituents are trapped mainly at the headland at the northeast. Patchy escape from the headland occurs on a time scale corresponding to the tidal cycle. The highest observed concentrations for BOD, COD, TSS and AN beyond the headland were found to average at 26.8%, 33.7%, 43.5%, and 5.4%, respectively, compared to the weighted initial concentration (see Table 3). This suggests that, other than AN, the dispersion process is relatively slow along the shore in a typical tidal cycle.

Figure 6. Model calibration using the observations from Teluk Bahang: (a) water level; (b) current speed; and (c) current direction
In addition, localised trapping can also be observed towards the west of Sg. Mas. This is likely attributed to the orientation of Sg. Mas river mouth, which approaches the coastline at an oblique angle such that its discharge opposes the northeasterly longshore current, hence prohibits crossing of the constituents at the water front. More specifically, it was found that the concentrations trapped in this location is much higher, at up to 41.8%, 74.1%, 76.1% and 59.5%, respectively, compared to the weighted initial concentration from the three rivers. This suggests that both advection and dispersion are stalled at this location, and pollutants may potentially cause severe beach pollution.

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*Figure 7. Model validation using the observations from Teluk Bahang: (a) water level; (b) current speed; and (c) current direction*
CONCLUSIONS

Hydrodynamic modelling of Batu Ferringhi beach is conducted in the present study using MIKE21 Hydrodynamic Module (HD), Spectral Wave Module (SW), and Advection/Dispersion Module (AD). Calibration and validation results show that the model is capable of reproducing the local hydrodynamics. Using water quality observations in Sg. Batu Ferringhi, Sg. Satu and Sg. Mas as the input, the transport of BOD, COD, TSS and AN in the study area was examined. The results showed that localised trapping occurred at the shoreline between Sg. Satu and Sg. Mas, as well as the headland located to the northeast of the study area, suggesting inadequate mixing, and thus dispersion, in the nearshore region.

In summary, there is a potential threat of beach pollution along Batu Ferringhi, as observed in the incident in 2014 if there is a sudden spike of pollutant discharge from the upstream catchment. Thus, proper care must be taken to monitor and regulate point and non-point sources in the upriver system of this popular beach. In the event of similar occurrences, the stretch of beach front adjacent to Sg. Mas and the headland must be closed to public access on the grounds of health and safety.

Figure 8. Distribution of: (a) BOD; (b) COD; (c) TSS; and (d) AN concentrations along Batu Ferringhi beach
ACKNOWLEDGEMENTS

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REFERENCES


