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# The response of the river plume to the flooding in Moreton Bay, Australia

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**ABSTRACT**

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Coastal zones are important ecological regions and popular areas for human recreational activities. The regions also act as receiving environments for contaminants and sediment discharged from coastal rivers. In Australia, the Brisbane River, and more particularly its estuary (Costanzo *et al.*), is an example of one such environment as it is a complex coastal system with ecological and commercial significance. While Moreton Bay has been the focus of recent intense scientific research, little is known about its physical processes, such as the behaviour of the Brisbane River plume that enters the bay following storm events. In this study, a three-dimensional hydrodynamic model with an unstructured mesh is employed to simulate the generation and development of the flood-driven plume near the mouth of the Brisbane River. The model results are verified by field measurements and satellite observations. The results show that the river discharge is the determinant effect on the plume extension alongshore and offshore. A high correlation coefficient of 0.87 demonstrates that the plume size typically increases with the growth of the river discharge. Following 3 days extension of flood-driven plume, both the salinity and temperature, within the region that 1 km wide and 3.5 km long off the river mouth, decreased by approximately 3.6%.

**ADDITIONAL INDEX WORDS:** *Plume size, Temperature, Salinity*

## INTRODUCTION

Coastal rivers that discharge freshwater, with sediment and nutrients, into the ocean often generate a buoyant river plume in the vicinity of the river mouth. In recent years, some studies (Day *et al.*, 2007; King *et al.*, 2001; Ou *et al.*, 2007; Shi and Wang, 2009) have found that the river plume, driven by river floods, has become a significant environmental issue, which may be increasing in occurrence and severity as a consequence of climate change. The excess runoff created by floods has the capacity to carry a large amount of sediment and contaminants from land-based human activities into the coastal and shelf waters. Consequently, a thorough understanding of flood-driven plumes is a critical question for the management of coastal regions.

The behavioural characteristics of river-forced plumes have been well documented over the years. Cameron (1951) and Pritchard (1956) realized the role of the Coriolis force playing on the asymmetric movement of the plumes near the river mouth. That is, the plume moves right on the coast in the Northern Hemisphere and left in the Southern Hemisphere (Boicourt, 1973). The effect of the river discharge on the river plumes has been examined in previous studies (Chao, 1988a, 1988b; Chao and Boicourt, 1986; Fong and Geyer, 2002; Ou *et al.*, 2009). It can be concluded that the river runoff is one of the most important environmental factors leading to the seaward expansion of the plume and the entire plume size itself. Further, the winds exacerbate the mixing of the plume with coastal waters and this has been discussed in numerous studies (Chao, 1988b; Fong and Geyer, 2001; Ou *et al.*, 2009; Whitney and Garvine, 2005; Yu *et al.*, 2010; Zhang *et al.*, 2004). It has been found that the downwelling favourable wind compresses the plume towards the coast. In contrast, the plume is pushed offshore under the upwelling favourable wind conditions. When flooding occurs, it is expected that the effects of these environmental parameters, including the river discharge, precipitation and winds are more significant on the plume (King *et al.*, 2001) than in normal weather conditions. Shi and Wang (2009) observed that the extent of the Mississippi River plume was two times as great as the six-year mean value following the intensive rainfall and massive flooding during the spring of 2008. It has also been documented that the suspended matter concentration discharged by flooding plumes was very high and it had been moved offshore with the plume transport from the inner shelf to the mid-shelf (Geyer *et al.*, 2000; King *et al.*, 2001; Naudin *et al.*, 1997; Zhang and Chan, 2003).

This paper examines the discharge of the highly developed Brisbane River as it flows into the large and shallow Moreton Bay, Queensland, Australia. Although Moreton Bay has been recognized as a vital marine system, little is known about its physical processes, such as the behaviour of the Brisbane River plume that enters the bay following storm events within its catchment. The Brisbane River is the largest river emptying into Moreton Bay. The variability in its freshwater discharge has the potential to change the hydrographical structure of the bay which in turn may impact on the marine ecosystem

## STUDY SITE

Moreton Bay is located in sub-tropical southeast Queensland, Australia, extending from $153.1^0$ E to $153.5^0$ E longitude and from $27.05^0$ S to $27.75^0$ S latitude as in Figure 1. It covers an approximate area of 1523 $km^2$ with an average depth of 6.8 m (EHMP, 2007). Moreton Bay is the largest confined body of ocean water adjacent to the urban region of Brisbane (to its west). Many of Southeast Queensland's major rivers and creeks flow into Moreton Bay. Compared with other catchments around the bay, Moreton Bay is mainly dominated by the Brisbane River catchment with an area of 13,560 $km^2$ (Dennison and Abal, 1999). A mean annual river water volume of approximately 1400×106 $m^3$ is discharged through the river mouth from the Brisbane River catchment into the coast (Stock, 1999). The Brisbane River, is tide-dominated, with an average tidal range of 1.2 m near the river mouth and tidal range of about 2 m in the bay (Eyre et al., 1998). In the north, east and south of the bay, there are openings which allow the oceanic exchanges between coastal water and ocean water to take place.

## METHODS

### Field Measurements and Satellite Observations

Hourly measurements of surface elevation on the Brisbane Bar (Figure 1) during the whole of May 2009 were provided by the Bureau of Meteorology, Australia. The Brisbane Bar is located near the mouth of the Brisbane River and therefore, the water level at this point is expected to have an instant and effective response to a flood-driven plume. Sea surface temperature data used in this study were derived from the NASA MODIS sensor in 36 spectral bands, from 400 to 14000mm (Nezlin *et al.*, 2008). All the sea surface temperature (TEMP) images covering the region of Moreton Bay were acquired during May 2009 to observe the development of the plume, of which some images are useless because the position of the satellite swath changes day by day resulting in a data gap on some days. The water elevation data were utilized for calibration and the sea surface temperature was employed in model verification.

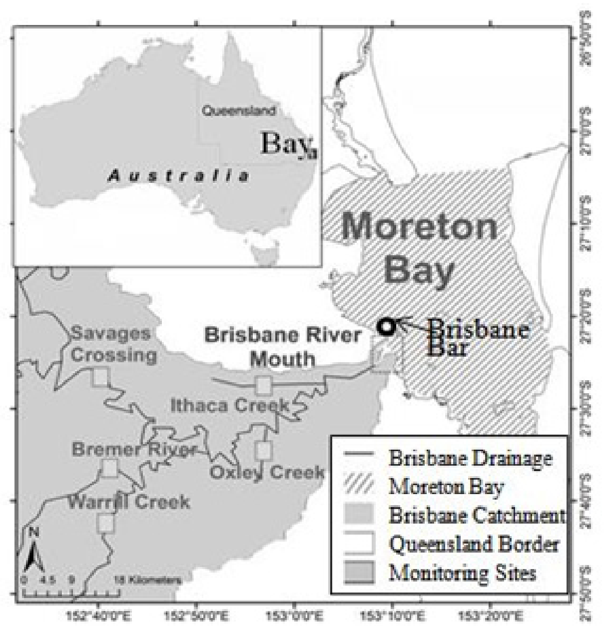


Figure 1. Location map of study site (Source: Geoscience Australia)

### Numerical Model

This numerically based study used a 3D hydrodynamic model MIKE3 FM (DANISH HYDRAULIC INSTITUTE, 2008) to simulate the generation and development of the Brisbane River plume near the river mouth (average depth of 1.2 m below Lowest Astronomical Tide (LAT)) during the time of a large river discharge and precipitation event within Moreton Bay (average depth of 10 m below LAT). An unstructured mesh was applied to this model with a fine resolution (average cell size of 2.5 $km^2$) in the near coastal region and coarse resolution (average cell size of 7.5 $km^2$) in the far field. A vertically structured bottom sigma grid is applied with five layers of variable thickness. One boundary is located at the Brisbane River mouth to represent the river flow from the Brisbane Catchment. The inflow is estimated from the total measured discharge at the monitoring sites which are marked in Figure 1 with green rectangles. Other dynamic parameters, such as the Coriolis force, winds and tides, are taken into account to successfully generate a more realistic simulation environment. King *et al*. (2001) used 35 psu within the model representing the coastal water in the Great Barrier Reef, which is very close to Moreton Bay. Therefore, the 35 psu is defined within the model as the background salinity in Moreton Bay. A salinity of 30 psu is the river water discharged from the river mouth and a salinity of 32.5 psu is an even mix of river water and coastal water, and hence the salinity isohaline of 32.5 psu is determined to be the offshore boundary of the river plume (Ou *et al.*, 2009; Tularam and Singh, 2009).

## RESULTS AND DISCUSSION

### Field and Satellite Data

The Brisbane River catchment experienced storms from the 18th to 24th May, 2009 (Australia Department of Natural Resources and Water Staff, 2009). On the morning of Wednesday 20th May, very heavy rain fell over much of the southeast coast district as a low pressure system moved offshore. With the joint effects of higher runoff (peak value of 874 $m^3$/s), heavy rainfall (peak value of 100 mm) and a strong south wind (the mean speed of 24 m/s), the peak tide at the Brisbane Bar reached a height of 2.7 m above LAT, which exceeded the Highest Astronomical Tide of the year, for 3 consecutive days. In addition, the sea surface temperature (SST) at 14:00 hrs on the 22nd May 2009 decreased from a maximum of about 22 $^0$C to a value of less than 17.1 $^0$C at the mouth of the Brisbane River.

### Model Calibration

The bed roughness height was estimated to be from 1.92 cm to 0.07 cm in Moreton Bay by You (2005), and hence, a range of roughness heights from 2 cm to 0.05 cm, constant over the entire model domain, have been applied in the calibration process in this study. It has been found that the roughness height of 0.05 cm

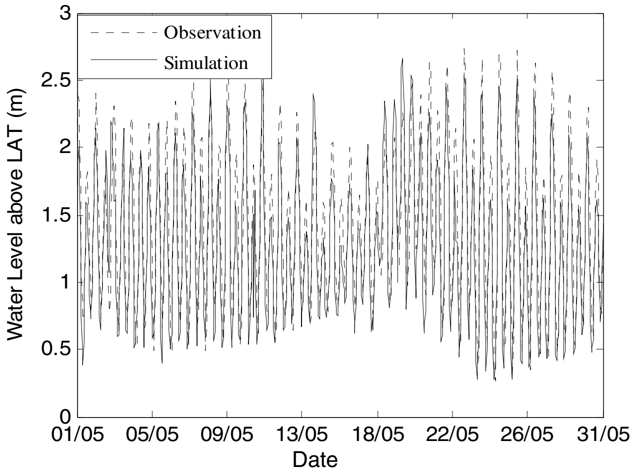


Figure 2. Comparison of the surface elevation at the Brisbane Bar, in May 2009

provided the best SST results. The simulated water levels at the Brisbane Bar are compared with the observed data in Figure 2. The correlation coefficient of 0.9 shows a quite good agreement between observed and simulated water levels. The simulated water level is slightly lower at high tide than the observed, possibly because the realistic conditions in the vicinity of the river mouth are much more complicated than the simulation in terms of topography and hydrodynamic systems. In addition to the comparison between the simulated and satellite observed on sea surface temperature, the correlation coefficient of 0.7 indicates that the simulated temperature basically matched the satellite observations. In the light of these adjustments, the model essentially reproduced the prototype and it was used to investigate plume properties.

## Simulation Results

### Plume Size

The numerical model simulated the evolution of the Brisbane River plume in Moreton Bay during the period of flooding. FIGURE 4 displays the river discharge and simulated plume size in May 2009. Under normal weather conditions, the plume typically covered an area of less than 10 km$^2$ near the river mouth. However, it reached a maximum of 2551 km$^2$ on the 23$^{rd}$ May, which is 250 times greater than the normal value. A high correlation coefficient of 0.87 demonstrates that the plume size typically increases with the growth of the river discharge. The lag between the plume size and the river discharge is very small (approximately 30 minutes). With the termination of the flooding, the Brisbane River plume, particularly along the north-west coast, progressively disappeared. The offshore spreading of the plume also became weak and slow; however, along the south-west coast remnants of the plume existed much longer in the absence of the strong ambient ocean current, and eventually the plume size went down to 434 km$^2$.

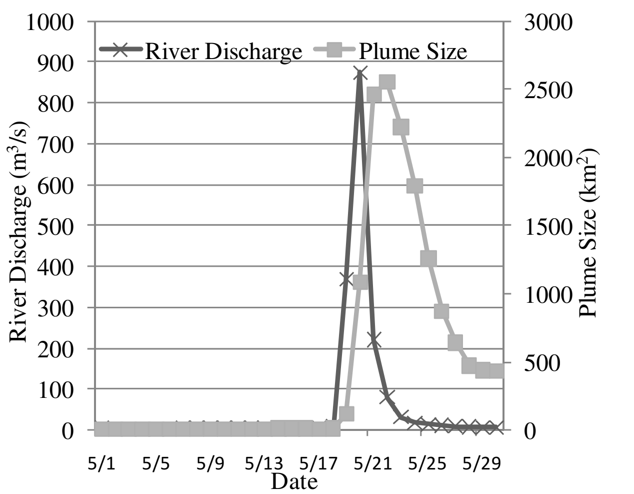


Figure 4. The river discharge and the river plume in May 2009

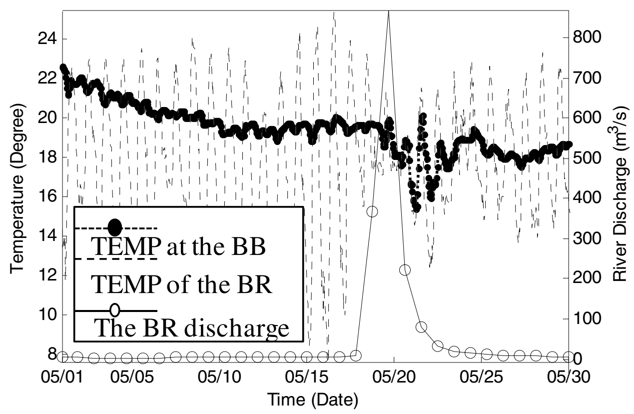


Figure 3. The temperature of the river water and at the Brisbane Bar in May 2009

### Salinity and Temperature Distributions

The temperature variations at the Brisbane Bar (BB) are displayed in Figure 3, which clearly show the effects of the plume extension and the temperature variations in the coastal region. The most striking features in Figure 3 are that the temperature at the Brisbane Bar is less affected by the Brisbane River (BR) water when the river discharge was lower, while significant fluctuations occurred following three peak discharges. The cooler flood water, with a minimum temperature of 13 $^0$C rushed through the Brisbane River mouth from 20$^{th}$ to 23$^{rd}$ May. It led a flood-driven plume extension which in turn induced a decrease in the temperature from 20.1 to 15.5 $^0$C at the Brisbane Bar.

The change in salinity and temperature are presented in during flood events are presented in Figure 5 and Figure 6. With the first flooding discharge beginning on the 20$^{th}$ May, the plume, carrying cooler flood water with an average temperature of 18 $^0$C, moved along the north-west coast as a result of the Coriolis force and ambient ocean current. After 12 hours, the surface salinity and temperature in an area of 3.6 km$^2$ in the vicinity of the river mouth decreased from 33.5 to 29.5 psu and 19 to 17.5 $^0$C respectively. As the second peak in the flood occurred on the 21$^{st}$ May, the plume was driven seawards up to 5.5 km east of the river mouth. As a consequence of the plume offshore extension, both the salinity and temperature within the plume region declined from 30 to 27.6 psu and 18.5 to 15.6 $^0$C respectively. On the 22$^{nd}$ May, a portion of the plume changed to spreading south alongshore, which resulted from upwelling favourable winds and a stronger ambient current. This extension of the plume led to reduced salinity along the

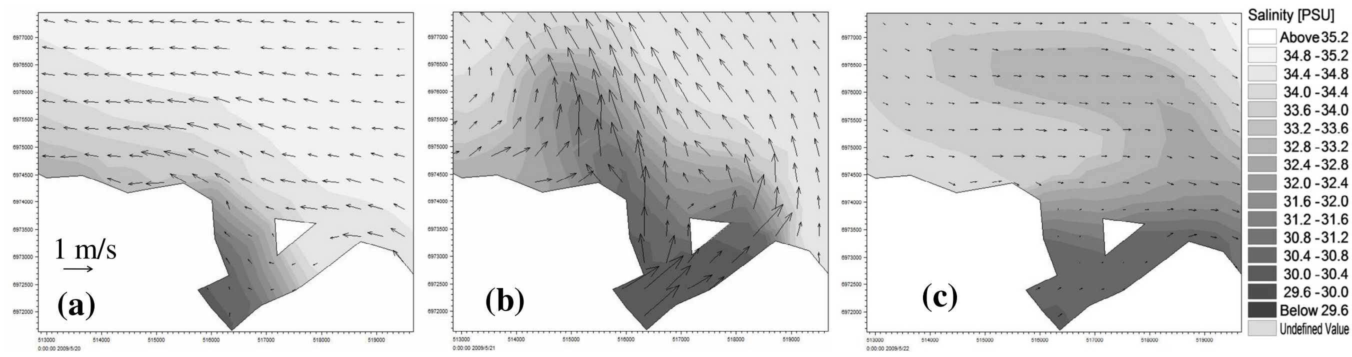


Figure 5. The salinity and velocity fields near the river mouth at midnight on the (a) 20th, (b) 21st, (c) 22nd May 2009

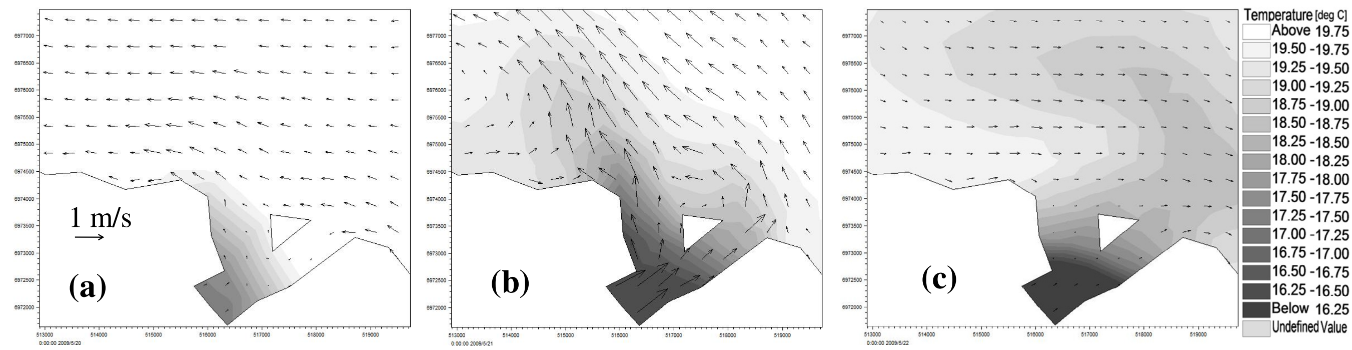


Figure 6. The temperature and velocity fields near the river mouth at midnight on the (a) 20th, (b) 21st, (c) 22nd May 2009

south-west coast, from 34 to 31 psu. Similarly, the temperature decreased from 19.6 to 17.6 $^0$C. On the whole, during this storm, the values of the salinity declined 4.6% along the north-west coast, 4.1% offshore and 2.9% along the south-west coast, with the affected distance of 9.5 km, 5.5 km and 3.2 km respectively. Similarly, the temperature in the coastal region also experienced a decrease, 4.2% along the north-west coast, 3.5% offshore and 3.1% along the south-west coast. The plume extension along the north-west coast was dominated in this storm event due to higher river discharge and the Coriolis force and therefore, the greatest variations in salinity (4.6%) and temperature (4.2%) both occurred in this direction.

## CONCLUSIONS

The simulated results, verified by field measurements and satellite observations, revealed that, expectedly, the magnitude of the river discharge plays a crucial role in fate of the plume. This study showed that the Brisbane River plume usually expands along the south-west coast due to a strong ambient ocean current; however, it turns to spread offshore and along the north-west coast under higher river discharge. The correlation coefficient of 0.87 between the plume size and the river discharge indicates river discharge is the dominant factor influencing plume dynamics. As a consequence of the plume extension, values of the salinity and temperature decreased 4.6% and 4.2% along the north-west coast (9.5 km north of the river mouth), 4.1% and 3.5% offshore (5.5 km east of the river mouth) and 2.9% and 2.6% along the south-west coast (3.2 km south of the river mouth), respectively. It has been demonstrated that the nutrients, sediment and the variations of the temperature and salinity within the Brisbane River plume have the potential to affect the fertilization in Moreton bay and even the navigation conditions (Eyre *et al.*, 1998). Thus, a good understanding of the complex plume trajectories and natural variability is required to investigate the evolution, duration and frequency of plume impacts on the coastal water of the bay. Overall, the impact of the plume appears highly significant to the region. Its behaviour is complex, as it is modified by the varying offshore currents and volumetric flow rate as well as the receiving water bathymetry. The effects of the winds, ambient currents, periodic tide and bathymetry require further study.

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