Numerical analysis on the Brisbane River plume in Moreton Bay due to Queensland floods 2010-2011

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Abstract

During the Queensland floods in the Summer of 2010-2011, a flood-driven Brisbane River plume extended into Moreton Bay, Queensland, Australia, and then seaward, travelling in a northward direction. It covered approximately 500 km². This paper presents a three dimensional hydrodynamic numerical model investigation into the behaviour of the Brisbane River plume. The model was verified by using satellite observations and field measurement data. The present study concludes that the high river discharge was the primary factor determining the plume size and its seaward extensions. A notable finding was that the plume was a bottom-trapped type rather than a buoyant type. Further, the southerly winds were found to have moderately confined the alongshore extension of the plume and caused the plume to mix thoroughly with the ocean water.

Keywords: River discharge, Wind, DHI MIKE3, Hydrodynamic model, Satellite image, Australia, Queensland, Moreton Bay

1 Introduction

The biological systems of coastal oceans are sensitive to pollution. For this reason, the storm runoff associated with urban activities has been increasingly recognised as a major source of coastal pollution. It is predicted that extreme flooding events will increase in occurrence and severity due to climate change (World Meteorological Organization, 2010). As a consequence, flood-driven plumes will carry an increasing amount of sediment and contaminants, causing further deterioration of coastal systems. In recent years, a number of studies (King et al., 2001; Day et al., 2007; Ou et al., 2009; Shi and Wang, 2009; Yu et al., 2010) have found that river flood-driven plumes have become a significant environmental issue. Therefore, an improved understanding of the dynamic characteristics the flood-driven plume would enhance the predictions for flood impacts on coastal systems and, subsequently, assist with designing and implementing coastal zone management options.

The characteristics of river-forced plumes on Northern Hemisphere coasts have been studied over the last four decades. Garvine (1982), O'Donnell (1986) and Garvine (1987) applied a layer model when investigating river plumes with regard to the Coriolis force in the Northern Hemisphere. They found that the lower and the upper layers tended to flow landward and seaward, respectively. The seaward upper layer flowed to the right of the river mouth, while the landward bottom layer flowed to the left. Avicola and Huq (2002; 2003) found that, in addition to the effect of the earth's rotation, river plume development was also impacted by bay geometry and bottom friction. Specifically, in their 2002 study, they observed that a slower and wider river plume tended to occur as the coastal current underwent lateral expansion when the bottom was flat. Conversely, on a sloping bottom, the coastal current might be compressed laterally, in turn, leading to a relatively faster and narrower plume. In the case of deep oceans, however, the bottom friction no longer played a vital role in the dynamic balances (Huq, 2009). An investigation into the effects of the

1 dimensions of the bay mouth on flow dynamics, by Avicola and Huq (2003) and (Huq, 2009),
2 determined that the Kelvin number, K , was the important scaling factor, where K was the
3 ratio of the bay mouth width to the deformation radius of the river plume. The authors found
4 that, for narrow estuaries ($K \leq 1$), the river plume expanded across the entire width of an
5 estuary. In contrast, for wide estuaries ($K > 1$), dense oceanic water flowed landward on the
6 upshelf side, while the plume water flowed seaward on the downshelf side.

7 As plumes in nature are rarely unforced, (Fong and Geyer, 2002) were convinced that
8 plume behaviour might be determined by external forces. Further, the joint effects of river
9 discharge and wind on the spatial structure variations of the river plume was discovered
10 earlier by Lentz and Limeburner (1995). The Froude number ($F = V_m / \sqrt{gh_b}$, the ratio of the
11 river discharge rate V_m , to the speed of internal gravity waves $\sqrt{gh_b}$ in which g and h_b
12 represent the gravity acceleration and trapped depth of the plume) was utilised by Chao
13 (1988a) in order to classify different types of river plumes formed under various conditions.
14 The plume was determined to be a bulge shape (supercritical), if the bulge width was less
15 than approximately 1.7 times the width of the alongshore component of the plume (i.e. $F >$
16 1.7). In contrast, the seaward extent of the bulge for the subcritical plume (i.e. $F < 1.7$) was
17 very minor in comparison to the supercritical plume.

18 It is also hypothesised that the effects of river discharge are more significant on a river
19 plume during flooding than under normal discharge conditions (King et al., 2001), compared
20 to other external forces. Indeed, Marques (2009) emphasised that the amount of fresh water
21 was the principal quantity controlling plume formation and development. The variation of the
22 Eel River (United States) plume's structure during the floods of 1997 and 1998 was reported
23 by Geyer et al. (2000). The flood conditions, which persisted for three days, had peak
24 discharges ranging from 4000 to 12000 m³/s. They were also accompanied by strong winds

1 from the southern quadrant. As a result, the plume was restricted to inside the 50-m isobaths;
2 within 7 km of shore, with northward velocities of 0.5-1 m/s. Occasional northerly winds
3 attenuated the northward motion of the plume and caused it to spread across the shelf. An
4 investigation of the Mississippi River plume following the intensive rainfall and subsequent
5 flooding, during the spring of 2008, was undertaken by Shi and Wang (2009). They found
6 that the extent of the Mississippi River plume was two times as great as the six-year mean
7 value, due to the greatly increased river discharge flows. The plume area coverage reached a
8 maximum size of 5984 km² in May 2008. As a consequence of the generation and evolution
9 of the plumes, the concentration of the suspended matter increased from the approximately 20
10 mg/l (mega litres) six-year mean value to over 30 mg/l. This 10 mg/l was expected to have a
11 long-term adverse impact on the coastal ecosystem, although the storm events only lasted a
12 few weeks.

13 Compared to extent of studies on flood-driven plumes on Northern Hemisphere coasts,
14 very limited investigations into river plumes in response to flood events on Southern
15 Hemisphere coasts have been conducted. Among them, a majority of studies have focused on
16 the river plume in the Great Barrier Reef (GBR), Australia. O'Neill et al. (1992) mapped the
17 12-day travel of a river plume in the Southern GBR, using a combination of salinity
18 measurements and aerial observations of water colour. King et al. (2001) utilized a survey
19 conducted by Wolanski and Jones (1981) to calibrate and verify a three-dimensional
20 hydrodynamic model of the Burdekin River in flood. Their model results showed some of the
21 flood events that led to an intrusion of the river plume into Reef waters. King et al. (2001)
22 applied this model to investigate the plume into GBR in detail. They found that the plume
23 often touched the bottom in the shallow coastal region depending on wind and discharge rate.
24 As the plume extended offshore, its freshwater content would make it more buoyant than the
25 deeper offshore waters. As a result, the plume would float and generate a stratified water

column in deeper coastal waters. They also concluded that the main driving influences on the fate of the plume water were the discharge volume of the river and the local wind forcing in the far field.

As with the GBR, the Brisbane River, which is the largest river emptying into Moreton Bay, also plays a vital role in ecosystem health (Dennison and Abal, 1999). The variability in its freshwater discharge has the potential to change the hydrographical structure of the Bay, which, in turn, impacts on the marine ecosystem (Eyre et al., 1998; Dennison and Abal, 1999; Ecosystem Health Monitoring Program, 2007). However, the only investigation into the Brisbane River flood-driven plume was conducted by Yu et al. (2011). Their results show that the Brisbane River plume driven by the moderate flood (an average flow rate of 487 m³/s) mainly spread offshore in May 2009. As a consequence of the plume extension, values of the salinity and temperature decreased 4.1% and 3.5% offshore (5.5 km east of the river mouth). The correlation coefficient of 0.87 between the plume size and river discharge indicated the river discharge was the dominant factor influencing plume dynamics. (Note that since the current study was restricted to examination of the plume condition in Moreton Bay, the term, Brisbane River plume herewithin refers only to the plume region inside the Bay and correspondingly, the estimation of the plume size only considered the plume area inside the Bay.) Although Yu et al. (2011)'s study investigated the surface extension of the Brisbane River plume following the moderate flood event in 2009, not only the vertical characteristics of the plume but also the behaviour of the Brisbane River plume under severe flood conditions are still unknown. Therefore, to obtain better understanding, a three-dimensional verified hydrodynamic model was used in the present study to identify the behaviour of the Brisbane River plume in Moreton Bay after extreme flooding in January 2011. The simulation results provide accurate information and assessments on the fate of the flood-

driven plume water that will prove to be a valuable aid in the management of this coastal system.

2 Numerical Model

2.1 Research domain

Moreton Bay is located in sub-tropical southeast Queensland; it receives freshwater input from the Brisbane River. The bay extends from 153.1° E to 153.5° E and from 27.05° S to 27.5° S, (see Fig. 1), which covers an area of 1523 km², with the water depth ranging from 2 to 27 m. For the years 1889 to 2006, the mean annual discharge volume was approximately 1.65×10⁶ mg/l, the majority of which was river water from the Brisbane River's estuary in the west of Moreton Bay (Queensland Department of Natural Resources Mines and Water, 2006). Within the estuary, the Brisbane River discharges fresh water into Moreton Bay's coastal water to form the Brisbane River plume. Additionally two large sewage plants, one located at Oxley Creek (32 km upstream from the river mouth) and the another at Luggage Point (near the river mouth), discharge approximately 900 tonnes of nitrogen into the river per year (Costanzo et al., 2005). As a consequence, during flood events, great volumes of sewage are discharged into the Brisbane River estuary, along with the storm water inputs and agriculture runoff. This input leads to extremely high nutrient concentrations that spread within the plume in Moreton Bay.

2.2 Model setup

From late November 2010 to mid-January 2011 the eastern Australian coast experienced an extremely wet period. In south east Queensland, there were six major rain events, leading to widespread flooding of many rivers, and culminating in severe flooding in Brisbane and nearby areas. It is estimated that this flooding event was amongst the most

significant in Australia's recorded history, especially in terms of its extent, damage and severity (National Climate Centre, 2011). One event took place from January 10th to 12th, with the heaviest falls in the areas north and west of Brisbane. Further, the majority of the Brisbane River catchment received in excess of 286 mm of precipitation in three days.

Following this heavy rainfall, the most devastating floods occurred during the second week of January 2011. Consequently, enormous amounts of flood water flowed down the Brisbane River (Fig. 2, a), bringing with it thousands of tonnes of silt and various contaminants, which settled in Moreton Bay. The satellite image from November 2010 shows that waters in the Brisbane River and Moreton Bay were clean (low turbidity), as shown in Fig. 2 (a). However, as the flooding water passed through the mouth of the Brisbane River and into Moreton Bay, in December 2010, the river and bay both displayed elevated turbidity levels (becoming browner in colour) as shown in Fig. 2 (b). To illustrate this further, the observation data show that the salinity at Site 516 (see Fig. 1) was 32.2 psu on 4th Nov and 32.3 psu on 3rd Dec 2010 (before the flood); it then decreased to 19.2 psu on 19th Jan 2011 (7 days after the flood peak discharge). The large reduction in the salinity was therefore attributed to the flood water from the Brisbane River upstream. It also implied that the flood water produced the fresh river plume in the bay. Thus, the Brisbane River plume appeared on the 30th December 2010, then spread significantly on 15 January 2011, and finally virtually disappeared on the 5th February 2011, respectively.

A 3-D hydrodynamic model, DHI MIKE 3 (DHI Water and Environment, 2011b), was used to simulate the Brisbane river plume evolution over Moreton Bay from the 1st November 2010 to the 31st January 2011. The hydrodynamic module of MIKE 3 is a general numerical modelling system for coastal flows, bathymetry, wind field, bed resistance, and hydrographical boundary conditions.

2.3 Bathymetry and mesh structure

The origin of the bathymetry was located at 153.03° E and 27.52° S. The domain to be modelled is presented as a network of three-dimensional elements. The coastline data was provided from the National Oceanic and Atmospheric Administration, while the water depth data was provided by the Marine Safety Queensland. The bathymetry for Moreton Bay shows average depths of 4 m and 16 m in the near coast and far shore regions, respectively (Fig. 2, c). In the horizontal domain, the hydrodynamic model geometry consists of a mesh with 1577 elements; the spatial resolution ranges from 200 to 2500 m, as shown in Fig. 2 (c). The fine meshes (ranging from 200 to 500 m) were applied in the vicinity of the river mouth and near coastal region to simulate the plume's behaviour. The coarse meshes (ranging from 500 to 2500 m) were used in the far-field to save simulation time. In the vertical domain, the variable sigma co-ordinates, formulated by Song and Haidvogel (1994), were applied in the current study (DHI Water and Environment, 2011a). The model was found to be sensitive to the vertical grid resolution. Further, the simulated salinities started to converge when the model had 8 layers. However, to ensure a high resolution at both the surface and the bottom of the bay, the water column was separated into 10 vertical layers. The vertical distribution is given as an example in Fig. 2 (d). The variable sigma coordinate, with 10 layers for the water column, had a depth of 20 m (as shown in Fig. 2, d) and consequently, permitted high resolutions (0.5 m) near the surface and bottom. Additionally, the coordinate also maintained a reasonable resolution (2~3 m) at mid-depth. In the case of the even shallower region, for instance, the area near the coast (depth < 5 m) in Moreton Bay, the resolution at the surface, mid-depth and bottom were approximately 0.5, 1~2 and 0.5 m, respectively.

Additionally, four open boundaries are highlighted in Fig. 2 (c). The northern and eastern boundaries of the model are marked by NB and EB lines representing the North Passage and South Passage of Moreton Bay, respectively. The southern open boundary starts

at the Cleveland Station (153.29° E, 27.52° S) and ends at the west border of North Stradbroke Island (153.41° E, 27.52° S). The fourth open boundary, set at the west of the model mesh, is indicated by a circle (Fig. 2, c) to represent the Brisbane River mouth. In addition to the Brisbane River, the river systems flowing into Moreton Bay include the North and South Pine Rivers, and the Caboolture River. However, in the current study, these have been ignored because of their much smaller discharge compared to the discharge from the Brisbane River.

2.4 Initial and boundary conditions

The present study focuses on the flood-driven plume following the 2010-2011 flood events in the Brisbane area, south east Queensland, Australia. The severe floods occurred from December 2010 (National Climate Centre, 2011); hence, a one month spin-up period was added to the model to allow it to reach a dynamic steady state (Overgaard, 2005; Yu et al., 2010). The simulation began on 1st November 2010 and ended on 31 January 2011. The monthly average temperature and salinity data for October 2010 were obtained from WOA98, NOAA (Antonov et al., 2010; Locarnini et al., 2010), and were used for the initial conditions. The predicted tidal heights from the Danish Hydraulic Institute (DHI Water and Environment, 2011a), were applied to three other open boundaries (Northern, Eastern and Southern boundaries).

An hourly river discharge was used at the west open boundary (i.e. Brisbane River mouth); it was provided and derived from field observations by the Department of Environment and Resource Management, Queensland, Australia. The river water discharge was used as the western boundary condition (river inflow). Due to the lack of the bathymetry data on the Brisbane River, the upstream region was excluded from the simulation. Under the

severe flood condition, the flood water rapidly collected sediment, flowed through the river and was well mixed.

2.5 Calibration and verification

The time-step of the model was set to a 30-second interval, due to the stability restriction using an explicit scheme. The Smagorinsky formulation, with a constant coefficient of 0.28, and the log law formulation were applied for the eddy viscosity in horizontal and vertical directions, respectively (DHI Water and Environment, 2011b). The model was calibrated in terms of the hydrodynamic perspective. The bed roughness heights were estimated as 0.07 cm at the middle of the northern opening (153.263° E, 27.010° S), 0.52 cm at the centre of the bay (153.222° E, 27.215° S) and 1.92 cm at Deception Bay (153.096° E, 27.153° S) in Moreton Bay, based on the mean velocities measured for 5 days by You (2005). Hence, a reasonable range of roughness heights from 0.05 to 2 cm, constantly distributed over the entire model domain, were applied in the current calibration process. A uniform roughness height of 0.05 cm was found to provide the best results in the simulation of this flood event, especially in terms of simulated sea surface temperature, water elevations, and salinity stratifications.

The satellite observations of the sea surface temperatures from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), at 4-km spatial resolutions, were used for the model verification. The day of flooding, the 20th January 2011, was chosen for the availability of reliable temperature records. The r-squared of 0.9, between the simulated and satellite observed sea surface temperatures, indicates that the simulated temperature closely matched the satellite observations (Fig. 3, a).

The field measurements of the water level at the Brisbane Bar were obtained from Maritime Safety Queensland; the measurements were compared with the simulated data in

Fig. 3 (b). The r-squared of 0.73 shows agreement between the observed and simulated water levels. As seen in Fig. 3 (b), the simulated water level was slightly lower at high tide rather than was the observed level. These differences may be attributed to the fact that the actual topography of the river mouth was more complicated than the available one. In addition to the sea surface temperature and the surface elevation, the *in-situ* salinity data, provided by the Ecosystem Health Monitoring Program (EHMP), were available to model verification. The salinity was measured between 9 am and 1 pm (approximately) on the 19th January 2011, at two sites (see Fig. 1). The model properly produced the salinity stratification, as clearly indicated in Fig. 3 (c). The relatively larger differences of salinity between the simulation and the observation near the surface (for example at site 501) may have been due to the local rainfall, which led to a significant reduction in the surface salinity¹. Based upon the agreements between the simulated and measured data (surface temperature, surface elevation, and salinity along the depth), the model was verified.

The simulated plume had a similar shape to that of the satellite's observed silt plume, with an area of approximately 460 km² (Fig. 3, d). In the region 20 km away from the Brisbane River mouth, the patterns of the simulated sediment-plume appear to be the same as the satellite observations. The shape difference between the simulated and remotely observed plume occurred in the northern bay. This difference can be attributed mainly to the flood water inputs from other coastal rivers, such as the North and South Pine Rivers and the Caboolture River. As the contributions of these rivers to the sediment plume development were not taken into account in the current study, the simulated plume was smaller than the satellite observed plume, as shown in Fig. 3 (d).

¹ The local rainfall measurements were not included as an input to the model.

3 Dynamics of the Brisbane River Plume

The salinity isohaline of 34.5 (in Practical Salinity Units) was determined to be the front of the Brisbane River plume (referencing the standards applied in Ou et al. (2009)). The measurement was equivalent to the boundary salinity isohaline used in the Great Barrier Reef study by King et al. (2001). Additionally, to investigate the effects of the river discharge and the winds on the evolution of the Brisbane River plume, numerical simulations, with and without the wind forcing, were used.

3.1 Influence of river discharge

The investigation took into account the Brisbane River discharge, the Coriolis force, and tide. The discharge data from December 2010 to January 2011 (Fig. 2, a) show that three separate flood events occurred. During this time, the total volume of freshwater discharged into Moreton Bay from the Brisbane River catchment area was 10.5 km^3 . The tidal heights obtained from Maritime Safety Queensland were applied at the oceanic open boundaries, to represent the effect of the tidal periodic forcing.

In order to evaluate the effects of a river's discharge and the Coriolis force on the plume, the Rossby number, $R_o = V_m / (f L_m)$, is commonly employed, where V_m is the velocity of the river outflow, f is the Coriolis parameter and L_m represents the width of the river mouth (Fong and Geyer, 2002). However, as Fong and Geyer (2002) pointed out, the original Rossby number is prognostic since it relies only on the river condition. Hence, to investigate a river plume responding to actual coastal conditions, the original Rossby number was modified for the current study. Therefore, to give due consideration to the effect of the background current V_c on the plume development, a modified Rossby number, $R_{mo} = |V_m / (f L_m + V_c)|$, was proposed, where V_c is perpendicular to V_m , and defined as positive if V_c is oriented in the north direction.

1 The first peak discharge ($3134 \text{ m}^3/\text{s}$) in the flood event took place on 21 December
2 2010; it resulted in the plume forming and turning left (north) at the mouth. This left turning
3 was due to the effects of the Coriolis force in the Southern Hemisphere. The plume water,
4 driven by the strength of the river's discharge, flowed towards the North Passage at an
5 average rate of 0.3 m/s and, as a consequence, the plume moved northward along the coast. It
6 filled all of Bramble Bay, and stretched 21.2 km to reach Deception Bay (as shown in Fig. 4,
7 a). In addition, the river plume also extended seawards, travelling 4.9 km to the east of the
8 mouth of the Brisbane River, propagating slightly downstream a distance of 1.6 km . The
9 behaviour of the river water in the vicinity of the river mouth is shown in Fig. 4 (b). A
10 striking feature of the plume's behaviour was that, although the majority of the inflow river
11 water turned left after it was discharged from the mouth, a minority of the flooding water
12 initially flowed straight out into the bay, due to the force of the river discharge, and then
13 turned left.

14 At the end of the first discharge event, the Brisbane River plume covered approximated
15 384 km^2 in Moreton Bay. Afterwards, the plume water gradually mixed with the coastal
16 water and was diluted to a size of 298 km^2 with the decreasing river inflow. The second
17 discharge peak, with an average rate of $5104 \text{ m}^3/\text{s}$, occurred on 29 December 2010. This
18 flood event subsided after two days, and the plume size increased back to 327 km^2 .

19 The third peak river inflow with the highest flood discharge ($17933 \text{ m}^3/\text{s}$) occurred on
20 the 12th January 2011. The salinity contour and surface velocity fields at midnight that day
21 are presented in Fig. 4 (c) and (d). As can be seen in these two figures, the plume water to the
22 north had already passed through the North Passage. Due to the estimation of plume size in
23 this study only considered the plume region inside Moreton Bay, therefore, the plume size
24 after 12 January was underestimated to some extent.

Following the flood runoff, the plume spread over Moreton Bay and covered an area of 519 km². Clearly the inflow river water divided into two branches after it was discharged from the mouth. One branch of the plume water extended north at 1.4 m/s due to the effect of the Coriolis force; the other branch went in a north easterly direction (seawards), at a rate of 2 m/s, being perpendicular to the line of the river mouth. The comparison of the plume behaviour, following these three peak discharges, implies that the third peak discharge was strong enough to produce the significant seawards movement of the Brisbane River plume.

Further, the plume evolution was estimated using the deformation radius of the river plume, R , and the internal Kelvin number, K , which were used in previous studies (Avicola and Huq, 2002; Huq, 2009), as follows:

$$R = (2Qg_r')^{1/4} / f^{3/4} \quad (1)$$

$$K = \frac{L_m}{R} \quad (2)$$

where Q is the river discharge; g_r' represents the reduction gravity calculated from the value of the maximum density anomaly at the source; and L_m is the width of the river mouth.

The variation of the deformation radius of the plume with the river discharge (Fig. 5, a) shows the effects of the river discharge (along with the Coriolis force) on the plume deformation. The larger value of R , arising from the higher river discharge, and the relatively smaller value of L_m , due to the narrow Brisbane River mouth, generally resulted in K values of less than 0.8. For $K < 1$ outflows, the buoyant water flowed out over the entire width of the river mouth; similar results were found by Avicola and Huq (2002). Also, the modified Rossby number and the background current during the flood period, shown in Fig. 5 (b), clearly shows that the R_{mo} , with the $fL_m \approx 0.053$ m/s at the Brisbane River mouth, was closer to 10 after the first peak discharges, and increased to 35 after the second peak discharges. The

1 higher R_{mo} indicates that a strong outflow was created by the momentum of the river
2 discharge.

3 In addition to the effect of the river discharge, the Rossby number also depends on the
4 background current. Thus, if the river discharge is relatively low, then the larger background
5 currents (>0.2 m/s) lead to a smaller R_{mo} ($<=1$). When the three largest R_{mo} occurred after
6 peak discharges, the background current was negative (towards the south), which was in the
7 opposite direction to that of the plume's alongshore transport (i.e. towards the north). As a
8 consequence, the alongshore transport of the plume became relatively smaller and weaker,
9 while the bulge component of the plume developed circularly near the river mouth. These
10 results are in accord with Fong and Geyer (2002) conclusions. Although the model presented
11 here did not include the influence of the wind, the ratio $|V_c / f L_m|$ can be as large as 5,
12 suggesting the variation of the R_{mo} was highly sensitive to the condition of the background
13 current; that is, the background current was expected to strongly affect plume development
14 when the river is located at a low-latitude with a narrow entrance.

15 Four specific points (P1, P2, P3 and P4, as marked in Fig. 1) were selected to
16 investigate the vertical distribution, and the temporal evolution, of the plume. Transect 1 (T1)
17 was located 3 km north of the river mouth, starting at P1 and ending at P2; and Transect 2
18 (T2) was located between P3 and P4, in front of the Brisbane River mouth. Fig. 6 (a) and (b)
19 display typical salinity profiles along the two transects, which show that the plume water,
20 both the seawards and alongshore components, were completely mixed without stratification.
21 As shown in Fig. 6 (a), the denser water was on the landward side, while the lighter water
22 was on the offshore side, across Transect 1. This separation occurred, chiefly, from the
23 northward expansion of the plume bulge (as shown in Fig. 4, c). Thus, the freshest plume
24 bulge off the river mouth, with a salinity isohaline of 25.5 psu , expanded towards the north
25 and passed through P2. As a result, the salinity around P2 continually decreased. In contrast,

1 the salinity in P1 was not affected by the freshest bulge, as the areas were much closer to the
2 coast and was away from the freshest plume bulge. Consequently, at the Transect 1, the
3 heavier water was on the landward side and the lighter water was on the seaward side.

4 In addition to the vertical salinity distribution, the velocity profiles can also be seen in
5 Fig. 6 (c) and (d). In terms of the velocity field for Transect 1, as the plume water flowed
6 northward in a horizontal direction, the plume water moved onshore in a vertical direction,
7 with slower velocities occurring with the high tide. In the presence of the flood tide, the
8 velocities of the outside and inside layers were 0.04 m/s and 0.048 m/s, respectively. The
9 velocity field of Transect 2, as shown in Fig. 6 (d), had different conditions from those of
10 Transect 1. There were two distinct sets of velocity contours across Transect 2 (T2). The left
11 set of the velocity contours (Fig. 6 d, T2) arose from the branch of the river discharge, which
12 was towards the north (Fig. 4, b and c). Hence, its velocity was at the higher rate of 1 m/s and
13 the plume water tended to lift up in the vertical direction. At the right, the flow was
14 augmented by another branch of the river discharge, which was moved seawards (Fig. 4, b
15 and c).

16 Tides also impacted upon the plume (Fig. 6, e), with variations of the Brisbane River
17 water level and velocity being influenced at P4 throughout the tidal cycle. During the ebb tide,
18 the cross-shore velocity at P4 increased, while it decreased during the flood tide. As a result,
19 the tidal wave and the cross-shore velocity were principally in quadrature. In contrast, the
20 alongshore velocity at P4 did not experience large fluctuations, except when it had a higher
21 velocity, due to the peak river discharge in the first six hours. As described above, the
22 flooding flow at the river mouth generated significant northward and seaward velocity fields.
23 Therefore, the tidal influence was significant over the seaward expansion of the plume, but
24 less so on the northward component.

From the above analysis it can be seen that the river discharge plays a vital role in the behaviour of the plume water. Importantly, the higher river discharge was the primary factor determining the size, evolution and dynamic of the river plume. Further, the tidal forces weakened the seawards movement of the plume and provided energy for the plume water to mix with the oceanic water.

3.2 Influence of wind

Various studies (e.g. Chao, 1988b; Cheng and Casulli, 2003; Fong and Geyer, 1997; King et al., 2001; Ou et al., 2009) have shown that plume development is highly correlated to wind conditions. In their studies, Whitney and Garvine (2005), and Ou et al. (2009) applied the wind strength index to estimate the wind impact on plume development. The wind strength index, I_w , is defined as:

$$I_w = \frac{u_{wind}}{u_{ds}} \quad (3)$$

$$where, \quad u_{wind} = \sqrt{\frac{\rho_a}{\rho} \frac{C_{10}}{C_{Da}}} u_{10} \quad (4)$$

$$u_{ds} = \frac{1}{K} (2g_r Qf)^{1/4} \quad (5)$$

where u_{wind} is the alongshore current velocity generated by the wind, and u_{ds} is the alongshore current velocity driven by the river runoff. Thus, u_{wind} and u_{ds} can be estimated using Equations (4) and (5), where U_{10} is the wind velocity at 10 m height; $C_{10} = 1.2 \times 10^{-3}$ is the surface drag coefficient; $C_{Da} = 2 \times 10^{-3}$ is the depth averaged drag coefficient; and ρ_a , and ρ are the densities of the air and the coastal water, respectively. When $|I_w| > 1$, the wind force is dominant. If taking the southward flow direction as positive, then I_w is positive during the north wind flow, or negative during the south wind.

Using the above specifications, the actual wind conditions were introduced into the simulation to closely represent the actual coastal conditions. The wind data were collected at

the Brisbane Bar (as marked in Fig. 1). This time-dependent wind data were applied in the model over the entire study area. Fig. 7 (a) shows the wind speed and its direction. As can be seen Fig. 7 (a), during the flooding event from December 2010 to January 2011, the south-south-easterly (SSE) winds dominated Moreton Bay most of the time, with an average speed of 18 m/s. When the peak discharge occurred on 12 January, the easterly wind blew over Moreton Bay at a maximum speed of 25 m/s.

Further, it was found that the relative size of the Brisbane River plume during the flood was influenced by the winds. Fig. 7 (b) shows the variations in the plume size with and without wind blowing. Generally, the plume with the influence of the wind covered a smaller region of Moreton Bay than the plume developed without wind impacts. A similar result was observed by Fong and Geyer (1997; 2001), Zhang and Chan (2003), and Whitney and Garvine (2005). In addition, the effects of the southerly winds on the plume were present in the vertical direction. Fig. 7 (c) shows the vertical distribution of the velocity across the two transects on the 12th January, 2011. These winds moved the surface water towards the coast, while the subsurface water sank along Transect 1 (Fig. 7, c, T1). Although the pattern of the velocity of T2 in Fig. 7 (c) was similar to that in Fig. 6 (e), the plume water flowed seawards at a slower rate. It is likely that this occurred because of the positive effect of the river discharge on the seawards movement of the plume, which was more dominant than the negative effect of the southerly winds. The wind strength index, I_w , equalled -0.49, -0.75 and -0.31 on January 11th, 12th and 13th, 2011, respectively. The values of $|I_w|$ approach $O(1)$; thus, although the winds were less dominant than the river discharge during this period of flooding, the effects of the wind were potentially still significant.

Simple momentum balances have also been used for the dynamic interpretation of the numerical model solutions (Masse and Murthy, 1992). Applying the Boussinesq

approximation, the horizontal momentum for the cross-shore (x -) and alongshore (y -) components at four specific points, P1, P2, P3 and P4, as marked in Fig. 1, were estimated. These four sites were selected for two reasons: (1) They were within the plume region during the entire period of plume development in Moreton Bay; (2) The four points were located at four different characteristic sites. In detail, P1 is close to the coast but away from the river mouth; P2 is not only away from the river mouth also away from the coast; P3 is close to the river mouth and also near the coast; but P4 is further seaward. Therefore, the momentum conditions at these four points would clearly quantify the influences of river discharge, the Coriolis force and wind on the plume at different characteristic sites. Fig. 8 and 9 illustrate the convection, Coriolis and wind stress terms in the horizontal momentum balance on 12 January 2011. Further, Fig. 8 shows that the Coriolis acceleration dominated the cross-shore balance at P2, P3 and P4; however, the wind stress was more significant in the region near the coast at P1.

Similar results were found for the alongshore momentum balances at P1 and P2 (in Fig. 9); that is, the Coriolis acceleration and the wind stress were the principal influences at P1 and P2, respectively. In relation to P3 and P4, which were closer to the river mouth, their alongshore convections were clearly dominant over the other two factors of Coriolis and wind. Additionally, the wind stresses were negative along the shore, but were positive across the shore, as shown in Fig. 8 and Fig. 9. This result confirmed that the southerly wind that prevailed on the 12th January restricted the seaward extension of the river plume, but drove the northward spread component. In summary, the developments of the river plume were determined by the joint contributions of the wind stress, the Coriolis force, and the river discharge. When the plume formed near the river mouth, the river discharge strongly drove it towards the north. The Coriolis force then became the main influencing factor once the plume

1 moved north from the river mouth. As the plume approached the coast, its movement
2 depended more upon the wind conditions.

3 **4 The Evolution of the Brisbane River Plume**

4 Within this study, it is important to understand the evolution and characteristics of the
5 flood-driven plume. The evolution of the Brisbane River plume, during the period of the
6 largest flood peak, is exhibited below.

7 **4.1 Horizontal characteristics**

8 Following previous studies (Chao, 1988a; 1988b; Fong and Geyer, 2002; Ou et al.,
9 2009), the non-dimensional parameters, λ and λ_i were also used to classify the river plume
10 structure:

$$\lambda = \frac{L}{L_n} \quad (6)$$

$$\lambda_i = \frac{L_u}{L_d} \quad (7)$$

11 where L and L_n represent the width of the bulge area and upstream component of the plume,
12 respectively, and L_u is defined as the length of the upper part of the bulge, while L_d describes
13 the length of the lower part of the bulge, as shown in Fig. 10 (a). For Cases with $\lambda < 1.7$, the
14 river plumes were typically subcritical, and spread in the alongshore direction more than
15 seawards direction (Chao, 1988a; 1988b). Similarly to the findings in Ou et al. (2009), the
16 river plumes were classified as upstream seawards plumes when $\lambda_i > 1$, and as downstream
17 seawards plumes when $\lambda_i < 1$.

18 Fig. 10 (b) depicts the variations of these two non-dimensional parameters of the
19 plume in January 2011. The λ_i , which was larger than 10 at all times, indicated that the
20 northward component of the Brisbane River plume was more dominated than the southward
21 component during the period of the flood event. By the 31st January, the plume stretched

1 more than 20 km northward away from the river mouth, while it travelled only 1.6 km along
 2 the southward coast. A significant decrease of λ_i occurred from the 12th to 17th January.
 3 Further, the simulation results indicated that the plume continuously extended northward and
 4 passed through the North Passage, while the length of the component of the plume along the
 5 southward coast experienced an increase from 1.5 km to 2.3 km, which resulted in a marked
 6 decrease of λ_i . Such variation may be related to occurrence of the severe flood on the 12th
 7 January. Additionally, a large amount of the river water gathered around the river mouth,
 8 with a fraction of the river water propagating along the south coast (see λ_i , Fig. 10, b for a
 9 display in the variation of λ). As suggested by previous study (Yu et al., 2011), the river
 10 runoff through the Brisbane River mouth always formed a bulge plume at the entrance of the
 11 estuary, with the $\lambda > 1.7$ during the moderate flood event (at an average rate of 487 m³/s) in
 12 May 2009. However, following the flooding in January 2011, the λ was generally less than 1.7,
 13 which indicates that the plume mainly spread in the alongshore direction more than the
 14 seawards direction, and the plume bulge in front of the river mouth was not dominant during
 15 the period of the entire evolution of the plume. The λ was greater than 1.7 only on January 12,
 16 13 and 14, when the highest flood discharge (17933 m³/s) occurred. Although the plume
 17 retained a similar shape before and after this peak discharge occurrence, the width of the
 18 bulge component of the plume increased by 91%, from 5.5 km to 10.5 km. In contrast, the
 19 width of the northern component of the plume only increased by 23%, from 5 km to 6.15 km.
 20 The significant increase of the bulge component might be attributed to extremely large
 21 amount of flooding water that entered the bay area and accumulated in the vicinity of the
 22 river mouth over a short period. Overall, the Brisbane River plume in January 2011 was
 23 generally defined as a diffusive-subcritical plume, characterised by high eddy diffuse
 24 viscosity, according to the classification of the river plume proposed by Chao (1988a), and
 25 Kourafalou and Lee (1999). That is, the width of the alongshore component of the plume was

greater than the width of the plume bulge, while the plume was development in a shallow area and driven by high flood discharge.

4.2 Vertical characteristics

Fig. 11 (a, b, c and d) show the vertical profiles of the salinity along Transect 2 on December 1, 2, and 3, 2010, and January 13, 2011. The figures clearly indicate that the water was visibly stratified, with the low-salinity water floating on top of the high salinity water, along Transect 2, on 1 December 2010. However, due to the growth of the river discharge, the salinity stratification became weak, as shown, for example, in the plume in Fig. 11 (d). These findings are consistent with those of King et al. (2001) who found that the plume often touched the bottom in the shallow coastal regions where the depth was less than 15 m. The buoyant layer scaling $h_b = (2Qf / g_r')^{1/2}$ provided by Yankovsky and Chapman (1997) was used to estimate the depth of the Brisbane river plumes in the current study. It yielded a trapping depth of the Brisbane River plume that ranged from 8 m to 24 m, which was larger than the water depth at the Brisbane River mouth of 4.5 m. The study also confirmed that a pure surface-advected plume was difficult to achieve in the vicinity of the Brisbane River mouth, due to the shallow water depth (< 15 m).

Further, the small-scale stratification only took place at the outmost plume layer in the deeper water area. The plume at the cross-section, which was 5 km seaward from the Transect 2, was weakly stratified, as shown in Fig. 11 (e) and (f). Thus, it appears that the less saline water floated above the more saline water. Note that water depth for this cross-section was greater than 15 m; hence, it can be inferred that the bathymetry was another factor influencing the stratification within the plume.

4.3 Plume development and dispersion

According to the simulations and satellite observations of the 2010-2011 Brisbane River flood event, the bulge of the plume was, typically, 5-6 km wide, and reached a maximum width of 14 km after the third peak discharge. The extremely large river discharge resulted directly in the plume's extension seawards in front of the river mouth, as well as along the northward coast. The plume reached the northernmost side of the study area (see Fig. 3, d and Fig. 4, c), where it met the Coral Sea and, thereby, threatened the oceanic environment. As a consequence of the flood-driven plume, the salinity of the coastal water decreased significantly. The values of the depth-average salinity were estimated to decline by 29.4% (from 32.3 to 22.8 psu) along the north-west coast, with an affected distance of 24 km north of the river mouth.

A clear correlation of the plume area and river discharge can be seen in Fig. 7 (b); thus, a lag existed between them. Using cross-correlation analysis, the lag between the plume region and river discharge was estimated at 2 days. To set these results in context, the characteristics of the several extreme flood-driven plumes of recent years are listed in Table 1. It can be concluded, therefore, that the river discharge in January 2011 was 10 times as great as in May 2009, resulting in a 27 times larger plume region. Further, when the flood ceased in May 2009, the plume coverage immediately became smaller (Yu et al., 2011). In contrast, in January 2011, there was a substantial delay in the occurrence of the river plume dissipation after the decline of the river discharge. This effect was due to the extreme flooding event in which the discharge was an enormous amount of river water flowing into the coastal region; hence, it took a much longer time to disperse such large volumes. In January 1981, when there was a major flood event, the plume on the Great Barrier Reef (King et al., 2001) also did not disappear immediately after the flooding.

The dispersion time of a plume can be defined as:

$$T = \frac{\int_{t_1}^{t_2} Q dt}{L_{avg} \times D_{avg} \times V_{depth}} \quad (8)$$

where t is the time, t_1 and t_2 are the starting and finishing times of the flooding event, L_{avg} indicates the average width of the plume, D_{avg} is the average depth of the plume, and V_{depth} represents the depth-average velocity at the front boundary of the plume, while Q is the river discharge.

After the last peak discharge occurred on the 12th January 2011, the outermost edge of the Brisbane River plume (represented by a salinity isohaline of 34.5 psu, as shown in Fig. 4, c) was located in the Central Bay and extended to the North Passage. With a large reduction in the flood discharge from 17 January, the plume began to fade away. Using Equation (8), the Brisbane River plume, in the 2010-2011 flood event, was determined to take approximately 20 days to become completely diluted after the peak discharge. Also, as shown in the Fig. 2 (b), the sediment plume was generally diminished, and Moreton Bay was almost clear again, by 5 February 2011. This finding is in accord with the prediction of Equation (8).

5 Conclusions

The dynamics of the flood-driven Brisbane River plume, resulting from the Queensland floods of 2010-2011, was studied using a three-dimensional numerical model. Both the river discharge and the winds were progressively introduced into the model in order to determine the respective influence of each on the plume and its dynamic characteristics.

The Brisbane River plume covered more than 500 km² in Moreton Bay due to its extremely large discharge strength. The model simulations demonstrate that the Brisbane River plume flowed along the northward coast (upstream) for a distance of about 30 km, and flowed seawards for a maximum width of approximately 14 km. The Brisbane River plume, typically, reached the bottom in shallower coastal waters. Also, there was a typical estuarine

1 circulation with the seaward current in the upper layer and the landward current in the lower
2 layer. In deeper water, the outmost layer of the Brisbane River plume tended to be less dense
3 than the surrounding coastal waters. The plume was observed to be 15 to 25 m thick. The
4 results also show that the river discharge was the dominant factor in determining the
5 development of the Brisbane River plume. It drove the river plume along the north coast and
6 seawards against the south winds.

7 The analysis, using the modified Rossby number R_{mo} , suggests that the river plume was
8 more likely to be affected by the background current when the river is located at a lower
9 latitude, with narrower river outflows. In addition to the effects of the background current,
10 the developments in the river plume were determined by the joint contributions of wind stress,
11 the Coriolis force, and the river discharge. Near the river mouth, the momentum of the river
12 discharge drove it strongly towards the north (the Southern Hemisphere), particularly during
13 large flood events. The Coriolis force then became the main influencing factor once the
14 plume moved north from the river mouth. As the plume approached the coast, its movement
15 depended more upon the wind conditions.

16 While plume trajectories can be said to be complex and event-driven, the present study
17 has clarified a number of aspects related to the dynamics of flood-driven plumes, specifically
18 the river discharge and the wind. Importantly, it has shown that there is a significant decline
19 in the quality of coastal waters following severe flooding.

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Fig. 1. Location map of study site (Data Source: Geoscience Australia). Within Moreton Bay are the smaller bays of Eastern Bay, Deception Bay, Bramble Bay, Central Bay and Waterloo Bay. Brisbane Bar, Brisbane Aero Station and observation sites of Healthy Waterways Organisation are all marked out. There are two transects: Transect 1 starts at P1 and ends at P2, Transect 2 starts at P3 and ends at P4. P1, P2, P3 and P4 are located at (51000, 6980000), (51500, 6980000), (51500, 6975000), and (52000, 6975000) in the Map Projection, respectively.

b

Fig. 2. (a) The Brisbane River 15-minutes discharge from December 2010 to January 2011 (Data Source: DERM Australia). (b) Satellite images of the Brisbane River and Moreton Bay (Source: MODIS Rapid Response System, NASA). The model meshes structure of Moreton Bay in (c) horizontal mesh and (d) vertical σ layers, produced by DHI MIKE. Different color indicates the different water depths.

a **b** **c**

d

Fig. 3. Comparison of the simulated and satellite observed (a) sea surface temperatures on the 15th January 2011 and (b) surface elevation at the Brisbane Bar in January 2011. (c) Simulated and observed salinity and temperature at different sites on the 19th January 2011. (d) [Left panel] Satellite image of the Brisbane River flood plume in Moreton Bay on the 15th January 2011 (Source: MODIS Rapid Response System, NASA) and [right panel] that simulated by MIKE3. The edge of the satellite observed plume has been outlined by using a blue dash-dot line, while the edge of the simulated plume has been outlined by using a pink dash line.

The plume on 21 December 2010

The plume on 12 January 2011

Fig. 4. Simulated the flood-driven plume water ($<$ salinity of 34.5) in Moreton Bay on the 21st December 2010 and the 12th January 2011 respectively: (a) and (c) are the entire plume, and (b) and (d) are the plume near the river mouth. The contour lines are surface salinity and the vectors are surface current (m/s).

Fig. 5. (a) Deformation Radius of the river plume and the river discharge, and (b) Rossby number R_{mo} and background current during the period of Queensland 2010-2011 flood event.

Fig. 6. Vertical distributions of salinity (in a and b) and velocity (in c and d) across Transect 1 (T1) and Transect 2 (T2) on the 12th January 2011 respectively. The contour lines are salinity distribution (in a and b) and velocity condition in m/s (in c and d). (e) Tidal elevation, cross-shore and along shore velocities at P4 during a tidal cycle on 12 Jan. 2011.

Fig. 7. (a) The wind speed and direction over Moreton Bay during this flood event (Data source: BOM Australia). (b) The Brisbane River daily discharge and its plume size with/without blowing wind in Queensland flood event in 2010-2011. (c) Vertical distributions of velocity across Transect 1 (T1) and Transect 2 (T2) on the 12th January 2011 in Case 2. The contour lines and vectors are velocity condition in m/s.

Fig. 8. Estimation of the individual terms of cross-shore momentum at P1, P2 P3 and P4 (as marked in Fig. 1) on the 12th January 2011.

Fig. 9. Estimation of the individual terms of alongshore momentum at P1, P2 P3 and P4 (as marked in Fig 1) on the 12th January 2011.

Fig. 10. (a) Four dimension parameters to characterise the plume. (b) The variations of two non-dimensional parameters, λ_i and λ , from 1 to 25 January.

Fig. 11. Vertical profiles of the salinity distribution at Transect 2 on (a) 1, (b) 2, (c) 3 December 2010 and (d) 13 January 2011. Vertical profiles of the salinity distribution far away from the river mouth on (e) the 13th and (f) the 18th January, 2011. The contour lines are salinity distribution.

Table 1 Comparisons of several extreme flood-driven plumes

		The Eel River plume (Geyer et al., 2000)	River plume on the GBR (King et al., 2001)	The Brisbane River plumes (Yu et al., 2011)	The Brisbane River plumes
Hemispheres		Northern	Southern	Southern	Southern
Flooding Date		Jan 1998	Jan 1981	May 2009	Dec 2010- Jan 2011
Peak Discharge (m ³ /s)		2000-3800	8000-12000	300-880	5100-17000
Wind conditions	Speed (m/s)	10	18	10	18
	Direction	S	SE	S	SSE
Dimensions of the Plume	Width (km)	5	20	3.6	10
	Length (km)	7	150	5.2	29
	Depth (m)	50	30	11	15
Estimated residual time of the plume (days)		-	-	0.4	20