Salinity and turbidity distributions in the Brisbane River estuary, Australia

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Abstract

The Brisbane River estuary (BRE) in Australia not only plays a vital role in ecosystem health, but is also of importance for people who live nearby. Comprehensive investigations, both in the short- and long-term, into the salinity and turbidity distributions in the BRE were conducted. Firstly, the analysis of numerical results revealed that the longitudinal salinity varied at approximately 0.45 and 0.61 psu/hour during neap and spring tides, respectively. The turbidity stayed at a higher level and was less impacted by tide in the upper estuary, however, the water cleared up while the tide changed from flood to ebb in the mid and lower estuary. The second investigation into the seasonal variations of salinity and turbidity in the BRE was conducted, using ten-year field measurement data. A fourth-order polynomial equation was proposed, describing the longitudinal variation in salinity dilution changes as the upstream distance in the BRE during the wet and dry seasons. From the observation, the mid and upper estuaries were vertically well-mixed during both seasons, but the lower BRE was stratified, particularly during the wet season. The estuary turbidity maximum (ETM) zone was about 10 km longer during the wet season than the dry season. Particular emphasis was given to the third investigation into the use of satellite remote sensing techniques for estimation of the turbidity level in the BRE. A linear relationship between satellite observed water reflectance and surface turbidity level in the BRE was validated with an R^2 of 0.75. The application of satellite-observed water reflectance therefore provided a practical solution for estimating surface turbidity levels of estuarine rivers not only under normal weather conditions, but also during flood events. The results acquired from this study are valuable for further hydrological research in the BRE and particularly prominent for immediate assessment of flood impacts.

Keywords: Seasons; Tides; Floods; Numerical model; Satellite surface reflectance

1. Introduction

An estuary is an interaction and transition area between rivers and oceans, and the health status of an estuary significantly affects both the river and ocean environments. Two important characteristics, salinity and turbidity, directly determine the health condition of an estuary. An estuary, in general, brings coastal conditions into the waterway as far as the tidal limit, which raises two particular issues, namely salinity intrusion, and the existence of the turbidity maximum zone (ETM) in the estuary (Peck and Hatton, 2003). The salinity intrusion from the river mouth to the upstream estuary may change the hydrological structure of the estuary and probably lead to contamination of other water resources along the estuary (Uncles and Stephens, 1996). The existence and variation of turbidity not only affects the water quality, but also results in strong spatial and temporal gradients in physical processes, which further influences the flow dynamics (Hughes et al., 1998; Massei et al., 2003). Therefore, a more comprehensive knowledge of salinity and turbidity distribution under a variety of river flow and tidal conditions in an estuary is vital for further hydrological research and also provides coastal zone management options, particularly in relation to increasing demand for flood damage assessment (Yu et al., 2013a).

In recent years, a large number of studies have examined the characteristics of salinity intrusion and turbidity maximum development in estuaries during different seasons. Shetye and Murty (1987) measured the salinity distribution in the Zuari estuary, India, at monthly intervals from 1977 to 1978. Their results revealed that the Zuari estuary was vertically well-mixed during the dry season but partially stratified during the wet season. They demonstrated two processes determining the behaviour of salinity intrusion in the Zuari estuary: i) runoff drove advective transport out of the estuary during the wet season; and ii) tides induced diffusive transport into the estuary during the dry season. Uncles et al. (2006) measured the turbidity over one year throughout the length of the Humber estuary, UK. They found that a strong ETM formed and settled in the lower estuary during the wet season but moved to the upper estuary during the dry season.

Within hourly time scales, for a tide-dominated estuary, the saltwater intrusion and sediment transport including resuspension, deposition, and bed erosion, are essentially determined by tide (Lentz and Limeburner, 1995; Ataie-Ashtiani et al., 1999; Zhang and Chan, 2003; Zhang et al., 2004; Werner and Lockington, 2006). Uncles and Stephens (1996) found that salinity intrusion in the Tweed estuary, UK, was a strong function of spring-neap tidal currents and a

weaker function of freshwater inflow. The saltwater intruded up to 7.6 km into the estuary at flood tides and receded to 4.7 km from the river mouth at ebb tides (Uncles and Stephens, 1996). Ataie-Ashtiani et al. (1999) further illustrated that the tidal fluctuation did not have a large effect on how far the saltwater intruded into the estuary; however, it caused remarkable variations in the configuration of salinity concentration contours, particularly at the water surface. Additionally, the tidal influences on turbidity distribution in estuaries were usually classified into three categories according to different tidal ranges, from micro-tidal, in which the tidal range is not more than 2 m, through to meso-tidal, with a tidal range from 2 to 4 m, and macro-tidal, in which the tidal range is greater than 4 m (Hughes et al., 1998). Compared to the ETM zone within the micro-tidal estuary, which is always triggered by flood events and tide, the ETM zone in meso- and macro-tidal estuaries heavily relies on tidal conditions (Hunt et al., 2006). Two mechanisms were proposed for the development and maintenance of the ETM zone in higher tidal ranges (Hughes et al., 1998). In the first mechanism, the ETM zone is caused by fine sediment accumulation and tidal resuspension, as a result of combined effects of tidal-induced residual currents and gravitational circulation (Hughes et al., 1998); in the second mechanism, the propagation and maintenance of the ETM zone are attributed to the distortion of tidal waves, associated with non-linear interactions between the tide and channel morphology (Dyer, 1986).

Under non-significant flood event conditions, the distribution of salinity and turbidity in estuaries varies between wet and dry seasons; the distribution generally experiences regular variations during a tidal cycle. Following severe flood events, saltwater is usually washed out of estuaries; however, flood inflow carries a large amount of sediment and particles, which would be transported, and then settled in estuaries, resulting in extreme high turbidity levels. To conduct an investigation into the high level turbidity after floods, field measurement is one of the main approaches. In recent years, satellite remote sensing technology also has been widely applied for detection of coastal and oceanic conditions. In comparison with time-consuming, expensive and weather dependent *in-situ* measurement, the main advantages of satellite remote sensing are the capability of covering large areas with spatially continuous records, and the ability to obtain instant information about water colour (Yates et al., 1993). Various visible and near infrared bands were proposed as water turbidity level indicators in previous studies (Tang et al., 2003; Wang and Lu, 2010). For instance, Shi and Wang (2009) used the satellite images to observe the flood-driven Mississippi River sediment plume development. Wang et al. (2009) retrieved water reflectance at Band 4 (with a wavelength

range of 770 to 860 nm) from The Enhanced Thematic Mapper Plus (ETM+) images to estimate the suspended sediment concentration in the large, turbid Yangtze River. A similar investigation was conducted by Wang and Lu (2010), which retrieved water reflectance at Band 2 (with wavelength range of 841 to 876 nm) from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA'S Terra satellite to estimate the suspended sediment concentration in the Lower Yangtze River. It can be seen in previous studies (Wang et al., 2009; Wang and Lu, 2010) that the band selection for turbidity estimation generally depends on the wavelengths of bands and other geographically correlated factors, such as the particle properties.

Studies (Eyre et al., 1998; Dennison and Abal, 1999; Howes et al., 2002; Schacht and Lemckert, 2003; Yu et al., 2013b) on the salinity intrusion and suspended sediment condition within the Brisbane River estuary (BRE) indicated that the saltwater intruded approximately 80 km upstream from the river mouth, and the ETM zone usually extended from about 20 to 60 km upstream from the river mouth under non-significant flood conditions. Additionally, Howes et al. (2002) observed the salinity and turbidity at a single site in the BRE over a period of thirteen months. They proposed a non-linear best-fit curve to describe the relationship between the average turbidity level in the BRE and the tidal range. Yu et al. (2011) conducted the investigation into the flood-driven plume in the BRE. They reported the extension of the sediment plume in Moreton Bay after the flood event in May 2009; A more significant flood event which occurred in the Brisbane River catchment in 2011 was also investigated by Yu et al. (2013a). It was observed that the severe flood event generated approximately 500 km² sediment plume in Moreton Bay and it was estimated that this plume would take about 20 days to become completely diluted. However, due to the lack of field measurement turbidity data, the turbidity level, distribution and variation have not yet been discussed in any subsequent study.

The Brisbane River flows through the large city of Brisbane, Queensland, Australia, and enters into Moreton Bay (see Fig. 1); as such, the condition of the river significantly affects the quality of surrounding water resources, public perceptions of river water quality, and the health of the entire region's ecosystem. The motivation for this study is therefore not only driven by the lack of comprehensive knowledge of the salinity and turbidity distribution of the BRE in the short- (under tides) and long-term (during the wet and dry seasons), but also by the increasing demand for the efficient and immediate estimation of turbidity state after

flood events. This study will further incorporate numerical investigations of sediment transport in coastal areas under non-flood and flood conditions.

2. Study area

The present study domain, the Brisbane River, is located in sub-tropical southeast Queensland, Australia (Fig. 1). It has a catchment area of approximately 13,506 km² (Eyre et al., 1998). The river flows through the city of Brisbane and enters into Moreton Bay. The BRE is distinctly brown in colour, particularly after heavy rainfall in the catchment (Dennison and Abal, 1999). In addition to the main channel of the BRE, the Bremer River and Oxley Creek join the Brisbane River at 72 and 34 km respectively, upstream from the river mouth, as shown in Fig. 1. The Brisbane River estuary is micro-tidal, with a mean neap tidal range of 1 m and a mean spring tidal range of 1.8 m (Wolanski, 2014). The length of the tidal section within the BRE is approximately 80 km up to the junction of the Bremer River, and the depth along the estuary ranges from 15 m at the river mouth to about 4 m at the Bremer River junction (Hossain et al., 2004; Ecosystem Health Monitoring Program, 2007).

Fig. 2 shows the typical river discharge in the Brisbane River over a period of 10 years from 2002 to 2011. During the dry season (June to November), the average flow in the BRE was 3.2 m³/s. In contrast, during the wet season (December to May), the average flow increased to 7.7 m³/s without considering the occurrence of flood events. In recent decades, a number of significant flood events have occurred in the Brisbane Catchment. For instance, the peak runoff of the flood event in May 2009 was 874 m³/s, and the peak runoff of the severe flood event from December 2010 to January 2011 was up to 17933 m³/s (Yu et al., 2011; Yu et al., 2013a).

3. Study methods

3.1 Water samples collection and hydrodynamic data

The Ecosystem Health Monitoring Program (EHMP) is one of the most comprehensive freshwater, estuarine and marine monitoring programs in Australia (Ecosystem Health Monitoring Program, 2007). The EHMP has been conducted with continuous water sampling and monitoring at monthly intervals over the last decade. The water samples have generally been collected at the ebb tides at 16 monitoring sites along the BRE from the river mouth up to the tidal limit, as marked in Fig. 1. The profile of temperature, at depth intervals of 2 m, is measured with a YSI 6920 temperature sensor (Ecosystem Health Monitoring Program,

2007). The profile of salinity is derived from water conductivity which is measured using a YSI 6920 conductivity sensor (Ecosystem Health Monitoring Program, 2007). The turbidity at 90° from the light source is directly recorded using a YSI 6920 turbidity sensor consisting of a near-infrared LED with the wavelengths between 830 and 890 nm (Ecosystem Health Monitoring Program, 2007).

The Department of Environment and Heritage Protection (formerly, the Department of Environment and Resource Management), Queensland, Australia, regularly measures the river discharge at their stream monitoring sites. One site (ID: 143001C, which is located at 152.57° E and 27.44° S) has the closest proximity to the tidal limit of the BRE, as marked in Fig. 1. The river inflow recorded at this site is therefore applied in this study to represent the freshwater runoff entering the BRE. Additionally, tidal height data at the Brisbane bar (in the vicinity of the river mouth, as marked in Fig. 1) have been provided by Maritime Safety Queensland.

3.2 Numerical model

3.2.1 Model description and set-up

To conduct investigation into the variations in salinity and turbidity distribution during the tidal cycle, MIKE 11 DHI, a one-dimensional hydrodynamic model coupled with advection-dispersion modules has been applied in this study. The model, based on the dynamic wave description, solves the vertically integrated Equations of conservation of continuity and momentum, as defined in Equations (1) and (2)

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial h}{\partial x} + gAI_f = \frac{f}{\rho_w} \quad (2)$$

where Q is the river discharge rate, A is the cross-sectional area, q is lateral inflow, h denotes water level, I_f represents the flow resistance term, f is the momentum forcing, ρ_w is the density of homogeneous water and α is the momentum distribution coefficient (DHI Water and Environment, 2012). The advection-dispersion module applies the vertically and laterally integrated equation of mass conservation of a dissolved or suspended material, such as salinity and settling/suspended material concentration. The equation is defined as follows

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x} \left(AD \frac{\partial C}{\partial x} \right) = -AKC + C_2q \quad (3)$$

in which C is the salinity/suspended material concentration, D is the dispersion coefficient, K is the linear decay coefficient, C_2 represents source/sink concentration of the substance. Equation (3) assumes that the considered substance is completely mixed over the cross-sections and reflects two transport mechanisms: 1) advective transport is with the mean flow; and 2) dispersive transport is due to concentration gradients (DHI Water and Environment, 2012). The sediment in the BRE is river-borne silt, with a grain size of typically 0.004 mm (Wolanski, 2014). Based on Stokes law, the settling velocity of sediment particle is roughly estimated to be 1.4×10^{-6} m/s which is so slow that the settling can be ignored.

The main channel of the BRE from its tidal limit (Chainage 0 km, which is located at 152.99° E and 27.52° S) to the river mouth (Chainage 80 km, which is located at 153.13° E and 27.43° S), is shown in Fig. 3a by a blue-dotted solid line. Along the channel in this figure, a number of cross-sections were added, at an interval of 1 km, representing the transverse section of the flow area. The orientations of these cross-sections were individually adjusted to be perpendicular to the flow direction. Some typical cross-sections within the BRE are displayed in Fig. 3b to d. Within the upstream estuary, the cross-sections are usually shallow and narrow, for example the cross-section at Chainage 0 km (Fig. 3b). The cross-sections in the mid-estuary, such as the estuary at Chainage 40 km (Fig. 3c), remain narrow but become deep. Compared to the natural channel within the upper and mid estuary, the lower estuary is generally dominated by a deep 9 m dredged channel, associated with a 13 m-deep dredged channel at the river mouth (Eyre et al., 1998; Hossain et al., 2004). The cross-sections of dredged channel within the lower estuary are much wider and flatter than the natural channel in the upper estuary, for instance the cross-section at Chainage 80 km, as shown in Fig. 3d.

The hourly-measured river discharges and monthly-measured sediment concentration were used as the upstream open boundary conditions at the entrances of the BRE (Chainage 0 km), the Bremer River, and Oxley Creek, respectively, as shown in Fig. 1. The measured water levels at the river mouth (Chainage 80 km) and monthly-measured sediment concentration were applied as the downstream open boundary condition. The wind effects were not taken into consideration in this study, due to the lack of wind data along the estuary. The available observed turbidity data were recorded in NTU; however, the MIKE 11 DHI model only works with the concentration of suspended sediment (C_s) (DHI Water and Environment,

2012). In this case, the simple correlation proposed by Hossain et al. (2004), which described the relationship between the turbidity and SSC within the entire BRE and was defined in Equation (4), was applied here. The salinity and temperature records at 16 EHMP sites along the estuary, and the estimated SSC based on the measured turbidity were added to the model as the initial simulation conditions. Additionally, a number of characteristic parameters including the critical shear stresses for erosion and deposition and sediment settling velocity, were set as 0.05 N/m², 0.03 N/m², and 6.5×10⁻⁴ m/s, respectively (Margvelashvili et al., 2003; Bell, 2010). These values were tested in previous studies (Margvelashvili et al., 2003; Bell, 2010), which proved that they were able to produce appropriate simulated turbidity results in the BRE.

$$C_T = 1.25C_s + 9.85 \quad (4)$$

where C_s is the concentration of suspended sediment in (mg/L) and C_T is the turbidity in NTU.

To guarantee the stability of the numerical simulation that is described in Equation (5), the spatial space and time step were determined to be 500 m and 15 seconds, respectively. The simulation period in this study was from 1 January, 2006 to 2008. The model first ran for a 1-year spin-up period to allow the model to reach a steady dynamic state and to ensure that this spin-up would not impact upon final model outputs.

$$\frac{V\Delta t}{\Delta x} \leq 1 \text{ to } 2 \quad (5)$$

where V is flow velocity (m/s) and Δt is the time step in seconds.

3.2.2 Model calibrations and verifications

In the hydrodynamic model, bed resistance is a vital parameter which largely determines the behaviour of the river flow and the development of other suspended materials (Lemckert et al., 2011). In this study, *Manning's n* was used to represent the bed resistance. The *Manning's n* was uniformly adopted, with the assumption of constant roughness along the river in the model. The values of *Manning's n* ranging from 0.02 to 0.05 were found to be appropriate for open channels and all floodplains in the Brisbane Catchment, respectively (Brisbane City Council, 2003). Hence, the value of *Manning's n* from 0.01 to 0.06 with a step of 0.005 was individually tested in the simulation to evaluate the performance of the hydrodynamic model.

It was found that the model with the value of 0.03 for *Manning's n* produced the most comparable simulated results in this study, compared to other values for *Manning's n*. The value of 0.03 for *Manning's n* is close to the value of 0.025 which was used in Wolanski et al. (1997) to commonly represent sandy estuaries. Using the value of 0.03 for *Manning's n*, the simulated results were obtained. A comparison of simulated and measured daily-averaged water levels at Chainage 16 km is shown in Fig. 4. In a normal condition, the mean water depth generally stayed at a level of 6 m, but it increased to approximately 8 m following the significant flood event in November, 2008. The normalised root mean square error (NRMSE) and RMSE between the simulated and measured water levels are 2.37% and 0.06 m, respectively. The simulated water levels generally matched the observed water levels with an R^2 of 0.97.

Furthermore, within the advection-dispersion module, the dispersion coefficient (m^2/s) which largely influences the dispersive transport term due to concentration gradients, is defined as

$$D = aU^b \quad (6)$$

where U is the magnitude of mean flow velocity in m/s ; and a and b denote dispersion factor and exponent, respectively (DHI Water and Environment, 2012). In a previous study (Bell, 2010), the value of dispersion factor a , was estimated to range from 160 to 450 in the BRE, associated with the non-dimensional, constant dispersion exponent b , which was set as 1. Therefore, the dispersion factor a , is in meters. Based on Bell (2010)'s estimation, the value of dispersion factor a , ranging from 100 to 500 m with a step of 50 m, was tested.

The concentrations of salinity were used to calibrate and verify the dispersion coefficient in the BRE. For different values for dispersion factor (Run # 1 to 4), the calibrated results using the simulated salinity within the BRE from 2007 were listed in Table 1. It can be seen in Table 1 that the model with the constant dispersion factor, a , ranging from 350 to 500 was able to produce comparable simulated outputs, which drove RMSE values to around 2 psu. Furthermore, in order to represent the dispersion condition more accurately, the estuary was separated into 4 sections, namely Chainage 0 to 10 km, Chainage 10 to 20 km, Chainage 20 to 60 km, and Chainage 60 to 80 km, corresponding to the varying salinity reduction rates within different river reach sections (Refer to Section 4.2.1 for the details regarding the salinity variation rates). The dispersion factors (Run #5 in Table 1) reduced in magnitude from 500 at the river mouth to 350 at Chainage 10 km, and were set back to 400 in the vicinity of the tidal limit, resulting in the simulated results with an RMSE of approximately

1.78 psu. This set of values of the dispersion factor (Run # 5) was further verified using simulated salinity results from 2008, in terms of temperature and salinity. It can be seen in Fig. 5 that the NRMSE of the simulated temperature and salinity in the BRE are 6.02% and 4.88%, respectively, which indicates the high accuracy of the model.

Moreover, the estimated SSC based on the field-measured turbidity was compared with the simulated result in Fig. 6. With an R^2 of 0.9 and a NRMSE of 3.62%, the model produced a fairly comparable suspended sediment output, ranging from 0.9 to 650 mg/l. As shown in Fig. 6, a fraction of the simulated results were underestimated, particularly at the moderate SSC level. This underestimation might have arisen in three different ways. Firstly, the relationship between turbidity and SSC in nature is complex and varying. It is therefore difficult if only using the simple correlation to reflect the real turbidity and SSC conditions within the entire estuary under different flow conditions. Secondly, as wind is one of main factors causing fine sediment resuspension (Hughes et al., 1998), the exclusion of wind effects in the simulation would weaken the resuspension of fine sediment. The difficulty in determining the values of characteristic parameters, including the critical shear stress for bed erosion and deposition and sediment settling velocity, is likely the third factor.

Overall, the model performance has been verified in terms of water levels, temperature, salinity and suspended sediment concentration. As evident in Fig. 4 to Fig. 6, the model is able to accurately reflect flow characteristics and sediment development in the Brisbane River estuary.

3.3 Satellite remote sensing surface reflection

In addition to the usage of field observation data and model outputs, this study also used the MODIS Terra Surface Reflectance Daily L2G Global data to estimate the turbidity level within the estuary. These geometrically corrected data, with a spatial resolution of 250m at Bands 1-7, were downloaded from the EOSDIS, NASA. To exclude cloudy days, MODIS images were checked before surface water reflectance data were downloaded. Moreover, it was found that the water reflectance at Band 2 is significantly lower than the land radiance in the BRE, in the sense that the wavelengths at Band 2 clearly separate water bodies from land. For instance, Fig. 7 shows on 16 November, 2006, the surface reflection conditions at Band 1 (with wavelengths from 620 to 670 nm), and Band 2 (with wavelengths between 841 and 876 nm). The Brisbane River estuary cannot be seen in Fig. 7a; however, it is clearly distinguished from the land in Fig. 7b. The surface reflectance at Band 2 at the sites which

were marked in Fig. 7b was therefore selected to estimate the turbidity distribution in the BRE. As can be seen in Fig. 7c to e, the water reflectance at marked sites (at the narrowest channel within the river, approximately 150 m wide) were significantly different from the land reflectance, implying the data at selected sites are not impacted from the land.

4. Results and discussion

4.1 Salinity and turbidity variations under tidal effects

The semidiurnal tide heights at the Brisbane River mouth range from about 0.5 to 2.1 m for neap tides and about 0.2 to 2.7 m for spring tides. Using a verified one dimensional numerical model, MIKE 11, the investigation into the tidal effects on the variations of salinity and turbidity (ST) within the BRE was conducted.

4.1.1 Longitudinal ST profiles during the tidal cycle

The depth-averaged longitudinal salinity and turbidity along the BRE were simulated. Fig. 8c shows the depth-averaged longitudinal salinity profiles of the BRE during a spring tidal cycle, along with the velocity variation at the river mouth in Fig. 8a, and comparison of the simulated and field measured salinity data in Fig. 8b. with an R^2 of 0.99 and an RMSE of 0.67 psu. Note that the velocity is the result of the combined effects of the seaward river inflow and the tidal current; positive and negative velocities denote the flood tide and ebb tide directions, respectively. During the ebb tide period, the salinity in the mid and lower estuary decreased by 1.67 psu on average, while the magnitude of the velocity decreased between 10 a.m. and 1 p.m., as shown in Fig. 8a and c. As a result, the salinity longitudinal profile at 1 p.m. was lower than it was at 10 a.m., as indicated in Fig. 8c. During the flood tide period, the salinity level within the BRE progressively increased, with an average rate of 0.63 psu per hour from 1 p.m. to 3 p.m., and 0.69 psu per hour from 3 p.m. to 6 p.m. That is, the salt water intruded into the estuary at a higher rate after the magnitude of velocity reached its maximum. At the end of the flood tide, the freshwater-saltwater intersection (FSI) was pushed further upstream from approximately Chainage 39 km (at 1 p.m.) to Chainage 34 km (at 6 p.m.), indicating the position of FSI might be 5 km further upstream during the flood tide than during the ebb tide. Compared to the periodic variations in salinity which occurred in the mid and lower estuary, the longitudinal salinity distribution in the upper estuary was relatively steady during the tidal cycle.

As with the salinity profiles, the depth-averaged longitudinal turbidity profiles during the same period are shown in Fig. 9c, which are associated with comparison of the field measured and simulated turbidity in Fig. 9b with an R^2 of 0.98 and an RMSE of 1.58 NTU. Fig. 9c indicates that the turbidity was at lower levels generally, without existence of the ETM. During the ebb-flood tide, there were no significant variations in the turbidity levels, which demonstrated that the amounts of sediment in the estuary were similar. The main visible difference is the longitudinal shift of turbidity profiles during the ebb-flood tide. It can be seen in Fig. 9c that the turbidity profile at 1 p.m. had a similar shape to the profile at 10 a.m.; however, it shifted further downstream by approximately 5.6 km compared to the profile at 10 a.m. The turbidity profiles, such as the profiles at 3 p.m. and 6 p.m., then changed to shift back (upstream) while the estuary water flowed landwards. Although the tide has effects on fine cohesive sediment resuspension in an estuary (Rijn, 1993; Zhang et al., 2009), such impacts have not been discussed in this study due to the limitation of the one-dimensional model and available field measurement data.

Generally, the longitudinal variation in ST during the neap tidal cycle was similar to its variance during the spring tide within the BRE, such as in the position of FSI which was 5 km further upstream during the neap flood tide than during the neap ebb tide. However, the simulated results indicated that the salinity varied by approximately 0.45 psu per hour during neap ebb-flood tide, compared to the variation rate of 0.61 psu per hour during spring ebb-flood tide. In addition to the salinity, the slight difference of turbidity variation during spring and neap tides was observed. Compared to the shift distance of 5.6 km during the spring tide cycle, the longitudinal turbidity profile moved by almost 3.4 km during the neap tide.

4.1.2 Salinity-velocity and turbidity-velocity patterns

The model output velocities, associated with the salinity and turbidity in the upper (e.g. Chainage 20 km), mid (e.g. Chainage 30 and 40 km), and lower (e.g. Chainage 70 km) reaches of the BRE were selected during tidal cycles to examine the variations in salinity and turbidity in response to the fluctuation of flow velocity.

It can be seen in Fig. 10a. to d. that the salinity level was significantly sensitive to the flow velocity conditions, and had similar change patterns in the entire estuary. That is, the salinity reached its local highest value at slack water, which occurred before the direction of the river flow reversed (from positive to negative). The salinity then decreased during the ebb tide and reached its local lowest value at slack water before the river flow changed from negative to

positive. Although the same variation patterns in salinity were observed at all four sites, their fluctuation ranges were different. The largest variation range occurred at Chainage 40 and 70 km with ± 2.5 and ± 2.3 psu, respectively; the moderate range was observed at Chainage 30 km with ± 1.5 psu; and the smallest range was found at Chainage 20 km with ± 0.5 psu. Overall, the salinity fluctuated at the same pace as the tidal current variation; however, the ranges of resultant salinity fluctuation which occurred in the mid and lower reaches of the estuary were relatively larger than in the upper estuary.

Compared to the similar variations in the salinity in the entire BRE, the turbidity-velocity patterns varied at different sites. Fig. 10e shows the turbidity and velocity variations at Chainage 20 km. The turbidity at this site maintained a high level with an average value of 35 NTU most of the time, instead of fluctuating during the tidal cycle. The most likely reason might be that the site was close to the tidal limit; that is to say, the tidal impacts upon the turbidity variation were relatively weaker. In contrast, the turbidity at Chainage 30 km relied more upon the velocity conditions, as shown in Fig. 10f. It was observed that the turbidity continuously decreased during the flood tide, and reached its lowest local value at slack water. Conversely, during the ebb tide, the turbidity level rose progressively until it reached its highest local value. At Chainage 30 km, the striking feature was that the highest turbidity was sustained for nearly 2 hours at slack water, which occurred before the direction of the river flow reversed from negative to positive, and the turbidity then changed to decrease through the remainder of the flood tide. The turbidity variation pattern at Chainage 40 km was the same as at Chainage 30 km, but it fluctuated within a wider range. The turbidity at Chainage 70 km experienced a similar fluctuation; however, it retained a much lower turbidity level. The significant low level in the lower estuary might be explained by three reasons under non-flood circumstances: i) the salt water intruding into the estuary at flood tide was relatively cleaner than the river water in the estuary (Eyre et al., 1998); ii) the particles carried by the freshwater might have already settled in the upper and mid estuary before arriving at the lower estuary; and iii) the tidal straining effect. Overall, the turbidity generally increased at ebb tide, or decreased at flood tide in the mid and lower estuary. The water column, therefore, tended to clear up while the tide was changing from flood to ebb. This finding is in accordance with the conclusions of Schacht and Lemckert (2003). In the upper estuary, the turbidity remained at a higher level with less impact from the tide. Conversely, the turbidity in the lower estuary was maintained at a lower level and was sensitive to the tidal conditions.

4.2 Seasonal variations of salinity and turbidity

To focus only on the seasonal variations in the BRE conditions, the rainfall-driven flood events (with an average flow rate higher than 100 m³/s) which occurred over the last decade are excluded here.

4.2.1 Longitudinal and vertical distributions of salinity

Yu et al. (2013b) revealed that the salinity intrusion condition is a function of the upstream distance from the river mouth. In general, the surface salinity decreased continuously upstream from the river mouth in the BRE, as shown in Fig. 11. The salinity was approximately 32 and 33 psu at the river mouth during the wet and dry seasons, respectively; the salinity reduced to around 0 psu at the tidal limit which was 86 km upstream from the river mouth during both seasons.

To examine the dilution of salinity intrusion within the BRE, the salinity dilution rate $S_p(x)$ (in percentage) along the estuary was calculated from the field observation data. In Equation (7), the $S(x)$ (in psu) represents the value of salinity at the site x which is the chainage (in km) ranging from 0 to 80 km; hence, $S(80)$ denotes the value of salinity at the river mouth.

$$S_p(x) = \frac{|S(x) - S(0)|}{S(0)} \quad (7)$$

$$S_p(x) = \sum_{i=0}^4 p_i x^i \quad (8)$$

Fig. 12a and b show the changes in the dilution of salinity intrusion with upstream distance during the wet and dry seasons, and are associated with polynomial least square curves which fit the field measurement data. The function $S_p(x)$ is represented by the terms in Equation (8), where the coefficients of p_i ($i = 0, 1, 2, 3, 4$) are specified as 97.3, -0.4, 0.03, -1.3×10^{-3} and 9.1×10^{-6} for the wet season, and 96.5, -0.3, 0.02, -8.7×10^{-4} and 6.8×10^{-6} for the dry season with an R^2 of 0.99, an RMSE of 3 psu, and a NRMSE of 10%. In Fig. 12c, a comparison of salinity dilution rates from the river mouth (Chainage 80 km) up to the tidal limit (Chainage 0 km) is made between wet and dry seasons. During both seasons, there was a very slight reduction in salinity in Zone 1 as well as in Zone 4, as indicated in Fig. 12c. However, in Zone 2, the salinity reduction rate rapidly increased by 20 %. The saltwater was continuously diluted in Zone 3 and it was almost 90 % diluted before it entered into Zone 4. The significant difference of salinity change rates during the two seasons, which was up to 5 %, occurred in the section of site 20 to 60 km. It can be seen in Fig. 12c that the salinity decreased at a faster rate during the wet season than it did during the dry season. The rapid

dilution rate was primarily attributed to higher river inflow during the wet season; however, this had little effect on salinity distribution within the lower estuary. The variation in salinity distribution within the lower estuary, particularly in Zone 1 as shown in Fig. 12c, was therefore similar during the two seasons.

The BRE is typically a partially mixed, but tends to be partially stratified during periods of the ebb tides and can be stratified after large rainfall events (Wolanski, 2014). Based on this investigation of the salinity data, which all collected during the late stages of ebb tide, it was found that the lower BRE was stratified, particularly during the wet season – see the example of the salinity vertical distribution at Chainage 73 km as indicated in Fig. 13a. In contrast, the distribution at Chainage 60 km in Fig. 13b shows the mid and upper estuaries were vertically well-mixed during both seasons. Additionally, the salinity vertical distribution within the entire estuary during the dry and wet seasons was depicted in Fig. 13c to f. It can be seen that the front of the salinity intrusion, which is defined as the 30 psu isohaline, generally settled around 13 to 20 km upstream from the river mouth for both seasons. In contrast, the location of FSI in the estuary, in which the salinity isohaline is 5 psu, was considerably different in wet and dry seasons. Fig. 13 indicates that the FSI was located near the 40 km site upstream from the river mouth during the wet season. Compared to the FSI in the wet season, the FSI was located around the 50 km site which was much closer to the tidal limit. The distinct difference of the FSI position clearly illustrates the influence of the volume of river inflow on the salinity structure in the estuary, particularly in the upper estuary.

4.2.2 Longitudinal and vertical distributions of turbidity

Fig. 14 shows the monthly-averaged turbidity distribution within the BRE over the last decade. Although the turbidity distribution along the BRE varied frequently and was more irregular than salinity variance, there were two striking characteristics as shown in Fig. 14. The first feature was that the peak value of turbidity during the wet season was generally higher than during the dry season. The occurrence of higher peak turbidity during the wet season was mainly caused by three factors: i) the higher river inflow might have brought a large amount of sediment from further upstream into the estuary; ii) the higher river inflow possibly eroded the solid river bank, generating fresh sediment that deposited and settled in the estuary; iii) the higher river inflow, combined with winds and tides, would have intensified the suspension of fine sediments. The second feature was the ETM always occurred in the upper and mid BRE (between 40 and 60 km upstream) during both seasons.

The location of the ETM depended mainly on the influences of freshwater inflow and tidal straining (Uncles et al., 2006; Wang and Wang, 2010).

To adequately appreciate the turbidity distribution in the BRE under non-significant flood conditions, the frequency, site, and value of the peak turbidity for each month during a period of 10 years, were summarised in Fig. 15. During the wet season, Fig. 15a. illustrates that the peak turbidity usually occurred around 60 km upstream from the river mouth with occasional movements of about 10 km up or down-stream. In contrast, the peak turbidity often randomly occurred upstream between 25 km and 80 km and most often took place at around the 55 km site during the dry season, as shown in Fig. 15b. In addition to the site in which the peak turbidity occurred, the values of peak turbidity were recorded in Fig. 15c and d. The values which occurred most often for each month over the last decade, ranged from 50 to 120 NTU during the wet season, and were much larger than the often peak values ranging from 20 to 50 NTU during the dry season. Similar conditions were observed in the maximum peak values during the two seasons in Fig. 15d. Compared to the maximum peak turbidity which was around 110 NTU during the dry season, the maximum peak turbidity generally reached 200 NTU, with a largest value of 290 NTU, during the wet season.

Furthermore, the vertical distributions of turbidity are depicted in Fig. 16, taking the turbidity in January and February (the wet season), and July and August, 2008 (the dry season) as an example. Although the difference in magnitude of the turbidity was large during the two seasons, the vertical distribution patterns were much the same: the consistent turbidity distribution in the whole water column existed in the downstream estuary reach, at lower turbidity levels; the non-uniform distribution of the turbidity in the water column was observed from the mid reach up to the tidal limit of the estuary, at relatively higher turbidity levels due to high resuspension always occurring in this region. The occurrence of high resuspension was mainly attributed to tidal straining effect ($\frac{\partial u}{\partial z} \frac{\partial C}{\partial x}$) which was determined by the vertical gradients of current velocity and longitudinal gradients of suspended sediment concentration.

4.2.3 Seasonal variations of the FSI and ETM

The FSI and ETM are the characteristic features of saltwater intrusion and the turbidity distribution within a river estuary. The locations of the FSI and the ETM in an estuary and the length of the ETM might be different during the two seasons. The depth-averaged salinity

and turbidity longitudinal distributions for each month were calculated, and were further used to estimate the behaviours of the FSI and the ETM during the two seasons. In this study, the distance between the FSI (the salinity isohaline is 5 psu) and the tidal limit of the BRE is defined as x_s . Referring to the criteria applied in Bell (2010), the ETM zone in the BRE is defined as the area with turbidity values greater than 50 NTU. Hence, the distances between the tidal limit and character positions within the ETM including the head of the ETM (the landward boundary of the ETM), the site where the maximum turbidity occurred within the ETM, and the tail of the ETM (the seaward boundary of the ETM) are denoted as x_{t1} , x_{t2} , and x_{t3} , respectively. It implies that the $(x_{t3} - x_{t1})$ is equivalent to the length of the ETM, x_t .

Fig. 17 shows the seasonal variations in the FSI and ETM within the BRE from 2002 to 2011. The FSI generally occurred at 30 to 40 km away from the tidal limit during the wet season. In contrast, the FSI was located further upstream during the dry season, which was usually 20 to 30 km away from the tidal limit. For the head of the ETM in the first group (in Fig. 17a. and e.), x_{t1} the majority of data points were below the line in a slope of 1, implying that the heads of the ETM occurred further upstream than the corresponding FSI during both seasons. In the second group as shown in Fig. 17b, the peak turbidity sites were always located around 20 km away from the tidal limit, which was closer than the corresponding FSI during the wet season. During the dry season, the data points in Fig. 17f. mainly surrounded the line in a slope of 1. An R^2 of 0.52 between x_{t2} and x_s , indicates that the peak turbidity site within the ETM might be related to the corresponding FSI, particularly during the dry season. In Fig. 17f, 44 % of x_{t2} surrounded the FSI (for the x_{t2} which was 5 km further downstream or upstream than the x_s), 38% of x_{t2} which was positioned further downstream ($x_{t2} > x_s+5$), and only 18% of x_{t2} which was located further upstream ($x_{t2} < x_s-5$). As can be seen in the third group (Fig. 17c and g), the x_{t3} was significantly larger than the x_s , indicating the seaward boundary of the ETM was much closer to the estuary mouth than the FSI during the two seasons. Additionally, the lengths of the ETM, x_t , and the freshwater region, x_s , within the BRE were examined in the fourth group (Fig. 17d and h). Compared to the stable length of the freshwater region within the estuary, the length of ETM varied widely from 10 to 60 km, particularly during the wet season. Overall, the FSI were always located within the ETM region during both seasons. The site where the peak turbidity occurred in the ETM was very close to the corresponding FSI, particularly during the dry season. The results also demonstrate that a larger river inflow not only resulted in a longer ETM and caused the FSI to occur further downstream than those during the dry season. These findings are in

agreement with Uncles et al. (2006) which found the seasonally longitudinal displacements both of the FSI and ETM.

4.3 Turbidity condition under flood events

4.3.1 Estimation of turbidity from surface reflectance

To accurately and immediately estimate the surface turbidity level following flood events from surface reflectance, this study attempted to examine the natural connection between the surface reflectance collected by satellite at Band 2 and the field-observed surface turbidity level. The data from two different sources therefore should be collected on the same day at least. Due to the limitations of the available field-measured data and satellite remote sensing data, the data only on the certain days are applied, as indicated in Table 3.

The water reflectance at Band 2 is able to clearly separate the BRE from the land, compared to the reflectance at other bands, as shown in Fig. 7. Based on the field measurement turbidity and satellite remote observed water reflectance, a linear regression was derived from

$$\ln(T_{ur}) = a_1 + a_2 w_r \quad (9)$$

where T_{ur} represents the estuary's surface turbidity in NTU, a_i ($i = 1, 2$) denotes the coefficient, and w_r is the water reflectance at Band 2 in percentage. Given that turbidity values varied in a wide range within the BRE, the turbidity was therefore transformed by natural logarithm in the regression above.

Fig. 18a shows all data points ($n = 224$) under both non-flood and flood conditions, with an R^2 of 0.59. This R^2 reveals the satellite remote water reflectance is able to reflect the variations in surface turbidity level at both low and high flow rates; that is, the water reflectance increased as the turbidity level rose. A higher R^2 was obtained if different coefficients were applied in the regression, as shown in Fig. 18b and c. The values of R^2 were 0.75 and 0.76 under non-flood and flood conditions, respectively. These R^2 values were in accordance with the findings in Wang and Lu (2010) which had an R^2 of 0.78 between the water reflectance and suspended sediment concentration in the Lower Yangtze River, China, using 35 water samples. If the flood events were considered individually, for example two flood events which occurred in December 2008 and January 2011 as shown in Fig. 18d and e, there was more significant positive relationship with an R^2 reaching up to 0.9, implying the strong correlation between the turbidity and water reflectance. Although it is hard to determine the exact regression coefficients due to atmospheric impacts and other

environmental influences, the regression conducted in this study clearly indicated that the water reflectance observed by satellite can be successfully applied to estimate turbidity level in the estuary under not only non-flood, but also significant flood conditions. The regression coefficients a_1 and a_2 which ranged from 0.1 to 1.6, and from 1 to 3, respectively, might provide a reasonable approximation of turbidity.

4.3.2 Turbidity variations after flood

Intense rainfall (193 mm on average) in late November 2008 across South East Queensland, caused local flash flooding (455 m³/s in average) occurring in the Bremer River within the Brisbane River catchment (Winant, 1983). As a consequence, the level of turbidity rose up to 3000 mg/l in the BRE, which was about 70 times higher than the typical level under non-flood conditions.

In simulating this event, Fig. 19 shows the turbidity distribution on 10 December 2008. As can be seen in Fig. 19a. and b., the simulation results generally match the EHMP observation (a NRMSE of 9.61%) and satellite estimation (a NRMSE of 13.34%), not only implying reasonable accuracy of simulation results, but also showing the reliability of the estimation of turbidity from satellite data. Furthermore, Fig. 19d. demonstrates the depth-averaged longitudinal turbidity profiles during a spring tidal cycle. The level of turbidity was up to 650 NTU, which occurred in the mid estuary (around Chainage 45 km), while the ebb current reached its maximum at 9 a.m. as shown in Fig. 19c. As the ebb current decreased, the mean turbidity level decreased by 15.4% from 9 a.m. to 12 noon in the whole estuary, with the largest reduction occurring at around Chainage 45 km, revealing that the turbidity level in the ETM significantly dropped on the slack water periods during ebb-flood tides. This finding is in accordance with the Schacht and Lemckert (2003)'s observation in the BRE. After slack water periods, the turbidity level then gradually rose. In comparison with the slighter variation in the turbidity distribution during tidal cycles under non-flood conditions, the tides significantly impacted the turbidity levels after floods. This might be attributed to two reasons: i) the larger river runoff bringing a large amount of sediment into the estuary, which is expected to increase the concentration of suspended sediment before settlement; and ii) the stronger current and tidal straining effect causing the significantly high resuspension after floods.

5. Conclusions

A comprehensive investigation, both in the short- and long-term, into the salinity and turbidity distributions in the Brisbane River estuary in Australia, was conducted in this study. The numerical results show that the FSI was pushed approximately 5 km further upstream during the flood than the ebb tide. In the upper estuary, the turbidity stayed at a higher level with less impact from the tide, while the turbidity in the lower estuary was maintained at a lower level and was sensitive to the tidal conditions. A large reduction in turbidity was found in the mid estuary, revealing the turbidity level in the ETM significantly dropped on the slack water periods after floods. Furthermore, a fourth-order polynomial equation was proposed with an R^2 of 0.99, describing the longitudinal variation in salinity dilution changes as the upstream distance changes in the BRE during wet and dry seasons. Two striking characteristics of turbidity distribution were found in the BRE: i) the peak turbidity always occurred in the upper and mid estuary during the two seasons; and ii) the peak value of turbidity during the wet season was generally higher than during the dry season. The observed results also demonstrated that a larger river inflow not only resulted in a longer ETM, but also caused the FSI to occur further downstream. Significantly, an approach of using water reflectance observed by satellite to estimate the turbidity level in the BRE was firstly proposed in this study. A linear equation was validated with an R^2 of 0.75. Although there are a number of factors which influenced the accuracy of the calculation, the results in this study clearly indicate the feasibility of using water reflectance to estimate turbidity levels in the BRE, not only under non-flood conditions, but also under severe flood conditions. Therefore, this approach allows the ecosystem conditions to be immediately and effectively evaluated, which is particularly helpful for ecosystem health assessment after severe flood events.

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Fig. 1. The Brisbane River estuary (BRE), Queensland, Australia, and locations of observation sites along the estuary. The chainages (km), distance from the tidal limit to certain observation site, are marked for each site. Source: Geoscience Australia; and the Ecosystem Health Monitoring Program (EHMP) Organisation.

Fig. 2. Monthly-averaged river discharge rate during a period of the last decade (excluded the flood events which occurred from 2002 to 2011).

Fig. 3. (a) The cross-sections along the BRE indicated by orange lines. Three typical cross-sections at (b) Chainage 0 km, (c) Chainage 40 km, and (d) Chainage 80 km, are displayed respectively. The elevations are in reference to the 0 m Australia Height Datum (AHD).

Fig. 4. Comparison of the simulated and observed daily-averaged water levels in 2008.

Table 1. RMSE of salinity for varying dispersion factors in the BRE in 2007

RMSE (psu) Chainage (km)	Run (#)	#1	#2	#3	#4	#5	
		a=350 (m)	a=400 (m)	a=450 (m)	a=500 (m)	RMSE (psu)	a (m)
0~10		0.32	0.19	0.23	0.33	0.16	400
10~20		0.78	1.75	0.93	1.71	0.71	350
20~60		2.67	2.59	2.82	2.88	2.35	400
60~80		1.91	2.04	1.31	0.97	0.95	500
the entire river		2.01	2.37	1.93	2.12	1.62	-

Fig. 5. Comparison of the simulated and observed (a) temperature and (b) salinity within the entire BRE in 2008.

Fig. 6. Comparison of the simulated and observed SSC in 2008.

Fig. 7. The surface reflection at (a) Band 1 and (b) Band 2 within the Brisbane Catchment. The yellow circles represent the EHMP observation sites. Three sites at the narrowest BRE and one site at the river mouth are selected and displayed in (c) to (f), showing the reflectance at Band 2 within the BRE clearly separating water bodies from land.

Fig. 8. (a) The velocity variations at 10am, 1pm, 3 pm and 6pm on 11 September, 2008. (b) Comparison of the field-measured salinity which was collected at 10am on 11 September, 2008 and simulated salinity. (c) The depth-averaged salinity longitudinal profiles at the corresponding time.

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Fig. 9. (a) The velocity variations at 10am, 1pm, 3 pm and 6pm on 11 September, 2008. (b) Comparison of the field measured turbidity which was collected at 10am on 11 September, 2008 and simulated turbidity. (c) The depth-averaged turbidity longitudinal profiles at the

corresponding time.

Table 2 Longitudinal variation in ST during spring and neap tidal cycle

	Salinity		Turbidity
	FSI position (km)	Variation rate (psu/hour)	Longitudinal shift (km)
Spring tide	5	0.61	5.6
Neap tide		0.45	3.4

Fig. 10. Simulated time series of velocity against salinity (see Figures (a) to (d)) and turbidity (see Figures (e) to (f)) at different sites, as indicated above. Positive and negative velocities denote the flood tide and ebb tide directions, respectively. The 4350th time step represents 6 am, 30 June, 2008.

Fig. 11. Monthly-averaged surface salinity distribution in the BRE during (a) wet and (b) dry seasons over a period of 10 years from 2002 to 2011.

Fig. 12. Salinity decreasing percentage along the Brisbane River estuary during (a) wet and (b) dry seasons. (c) Comparison of the salinity decrease in percentage during two seasons. The entire Brisbane River estuary has been separated into 4 zones as indicated above.

Fig. 13. Vertical distributions of salinity in the BRE during the wet (e.g. January and February) and dry (e.g. July and August) seasons in 2008.

Fig. 14. Monthly-averaged surface turbidity distribution in the BRE during (a) wet and (b) dry seasons over a period of 10 years from 2002 to 2011.

Fig. 15. The occurrence of peak turbidity in the BRE for each month from 2002 to 2011 under non-significant flood conditions. (a) Wet season includes December, January, February, March, April, and May; (b) Dry season includes June, July, August, September, October, and November. (c) The peak values that occur most often and (d) the maximum peak values of the turbidity for each month from 2002 to 2011.

Fig. 16. Vertical distributions of turbidity in the BRE during the wet (e.g. January and February) and dry (e.g. July and August) seasons in 2008.

Fig. 17. The seasonal variations of x_s , x_{t1} , x_{t2} , x_{t3} , and x_t within the BRE during 2002 to 2011. The straight line is in a slope of 1.

Table 3 The available data from the following days are applied in the estimation

	2005	2006	2007	2008	2009	2010	2011
Non-flood ($< 100 \text{ m}^3/\text{s}$)	13 Dec	8 Feb	10 Mar	11 Apr; 10 May	7 Jul	8 Aug	16 Nov
Flood	-	10 Dec	-	-	9 Feb; 6 Jun;	-	24 Jan

Fig. 18. The field measured turbidity and satellite remote observed water reflectance at Band 2 in the BRE. (a) includes all data under both non-flood and flood conditions; (b) is plotted data only under non-flood conditions; and (c) shows the data only under flood conditions. (d) and (e) are the curve fitting for individual flood events.

Fig. 19. Turbidity distribution in the BRE during the flood in December 2008. The simulation results, which show the turbidity condition at 9a.m. on 10 December 2008, were compared with (a) the EHMP observation and (b) the satellite estimation of turbidity, respectively. (c) The velocities were at 9 a.m., 12 noon, 2 p.m., and 6 p.m. on 10 December, and (d) the depth-averaged turbidity longitudinal profiles varied at the corresponding time.