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Salinity and turbidity distributions in the Brisbane River estuary, Australia

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SUMMARY

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/h 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.

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

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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 770–860 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 841–876 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 km^2 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 subtropical southeast Queensland, Australia (Fig. 1). It has a catchment area of approximately 13,506 km^2 (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 m^3/s. In contrast, during the wet season (December to May), the average flow increased to 7.7 m^3/s without considering the occurrence of flood events. In recent decades, a number of significant flood