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ABSTRACT

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The Brisbane River estuary, Queensland, Australia, is a vital ecological region and of importance for people who live nearby. The estuarine health status has been influenced by both marine and riverine conditions. The estuary experiences high turbidity and salinity throughout most of the year, however, little is known about the actual turbidity and salinity structures within it. This study examined ten-years of field data to investigate the seasonal variations in salinity and turbidity. The results revealed that the salinity at the Brisbane River mouth was estimated to be 31.7 and 32.8 ppt during wet and dry seasons, respectively. The surface longitudinal salinity then decreased along the estuary, with the highest decreasing rates of 0.7 and 0.6 ppt/km occurring within the mid-estuary. The average salinity flux was 8.19×10^4 and 8.25×10^4 ppt m^3/s during the wet and dry seasons, respectively. The slight discrepancy of salinity fluxes between two seasons may be attributed to the lack of consideration of the other freshwater inflows to the estuary. The actual salinity flux through the estuary will therefore fall within the two estimated flux values. It was also found that the length of the turbidity maximum was approximately 35 km during wet season, which was three times as long as it is during the dry seasons. The values indicate the perceived, and actual, health of the estuary changes with season and location and thus care must be taken when interpreting ad-hoc measurements.

ADDITIONAL INDEX WORDS: *salinity intrusion, salinity flux, turbidity maximum.*

INTRODUCTION

An estuary forms an interaction region between coastal river and ocean environments. The health condition of an estuary is therefore subject to both marine impacts, namely tides and waves, and riverine influences, such as the influx of freshwater and sediment. Generally, an estuary brings marine conditions into a coastal river as far as the tidal limit, which raises a number of issues, such as the salinity intrusion and the existence of a possible turbidity maximum zone. The presence and movement of saltwater intrusion and the turbidity maximum not only affect the physical environment, but also lead to contamination of drinking water sources. Excess amounts of suspended particles can even contribute to environmental damage (Ecosystem Health Monitoring Program, 2007).

In recent years, a large number of studies have examined the characteristics of salinity intrusion and turbidity maximum variations in estuaries. Engedahl (1995) reported the salinity distribution in the Zuari estuary in India during one tidal cycle once every month from 1977 to 1978. Based upon analysis of the data, Rijn (1993) found that the Zuari estuary was partially stratified during wet seasons but vertically mixed during dry seasons. They also demonstrated two processes controlling the transport of salt: i) runoff induced advective transport out of the estuary and ii) tidally induced diffusive transport into the estuary during dry seasons. Hill *et al.* (1998) measured the turbidity at spring and neap tides during a one year period throughout the length of the upper Humber and Ouse Estuary, UK. Their data consistently exhibited a strong estuarine turbidity maximum (ETM) in the lower estuary during high-runoff winter but in the upper estuary during low-runoff summer. Studies (Kranck, 1980; Jimenez and Madsen, 2003) on suspended sediment dynamics within the Brisbane River estuary (BRE) indicated that the ETM extended from about 20 to 60 km upstream from the mouth, with the peak turbidity levels occurring at around 45 km. Additionally, Richardson and Zaki (1954) measured the salinity and turbidity at a single site in the BRE over a period of thirteen-months. A significant feature of their study was that the magnitude of turbidity measurements was strongly influenced by the sediment carried into the estuary from runoff. Although some previous studies confirmed the existence of the ETM within the BRE, no study regarding the seasonal variations of the salinity intrusion and ETM has been undertaken thus far.

The motivation for this study was therefore driven by the need to enhance the state of knowledge of the changes in salinity and turbidity distributions within the BRE, during wet and dry seasons, so that future river management strategies can be appropriately planned.

METHODS

Study Site

The Brisbane River is located in south-east Queensland, Australia and has a catchment of 13560 km^2 (Eyre *et al.*, 1998). It is distinctly brown in colour, especially after rain. It has low biological diversity, with a limited number of organisms that can survive the high turbidity, highly variable discharge and salinity

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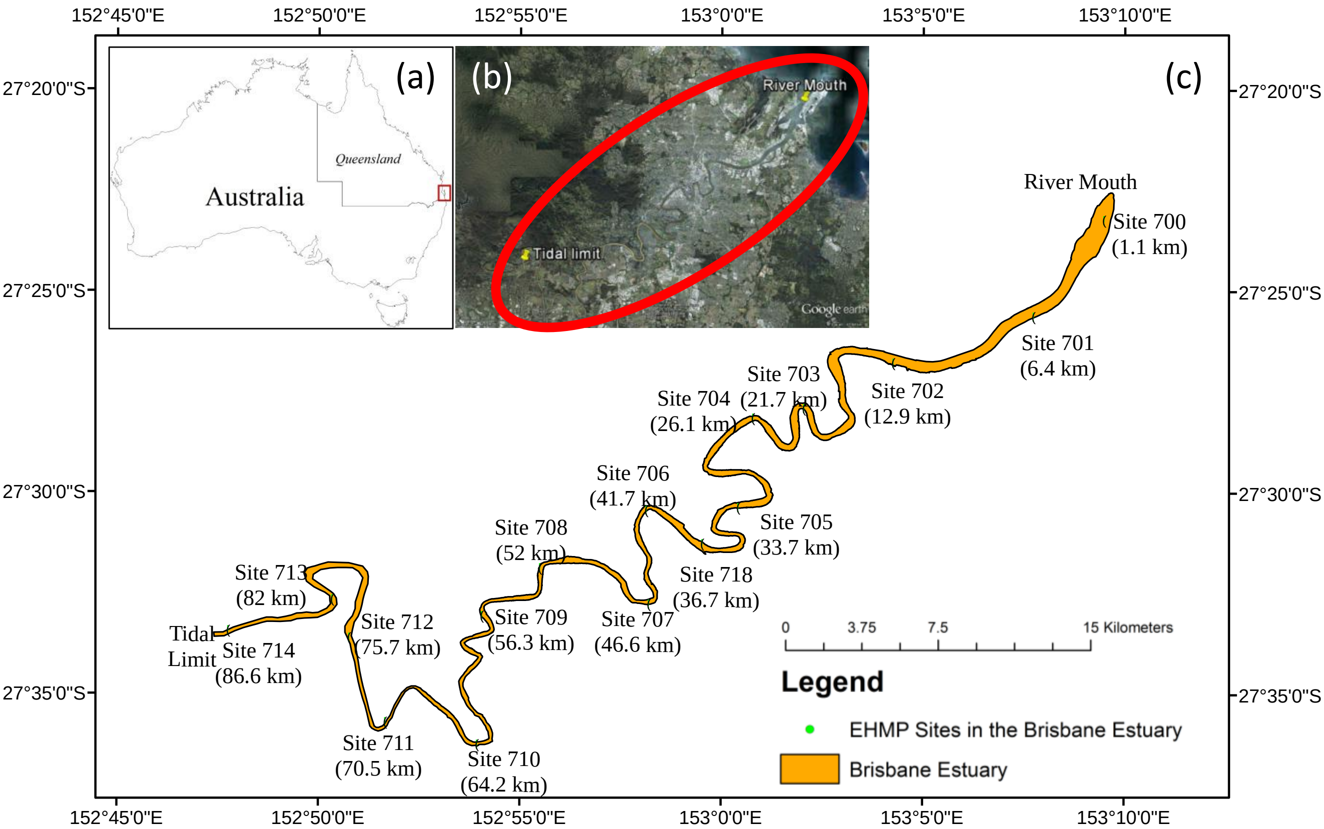

Figure 1. The Brisbane River estuary (BRE), Queensland, Australia. The green dots and their numbers indicate observation sites with their ID along the BRE. The AMTD (km) from the river mouth are marked for each site. (Data Source: (a) and (c) from Geoscience Australia; (b) from Google Map).

(Dennison and Abal, 1999). The Brisbane River estuary is a micro-tidal estuary, with a tidal section of approximate 80 km in length (Ecosystem Health Monitoring Program, 2007), and salt water intruding about 60 km upstream from the mouth for most of the year (Richardson and Zaki, 1954). The maximum depth along the estuary varies from approximate 15 m at the mouth to about 4m at the tidal limit (Eyre *et al.*, 1998). This micro-tidal estuary has a maximum spring tidal range of 2.6 m, with various dams along the estuary limiting estuary inflows to 1-2 m^3/sec during most of the year (Richardson and Zaki, 1954).

Salinity, Turbidity and Discharge Data

The Queensland Government Ecosystem Healthy Monitoring Program (EHMP) has implemented consistent water sampling and monitoring at monthly intervals along the BRE. There are currently 16 monitoring sites located along the axis of the estuary from the river mouth of the estuary to the tidal limit, as marked in Figure 1(c), with all measurements made on the ebbing tide. Profile measurements (at depth intervals of 2 m) of temperature, conductivity (from which salinity is derived) and turbidity (in NTU) were conducted at each site from 2002 to 2011 (Ecosystem Health Monitoring Program, 2007). Turbidity was observed with a YSI 6920 turbidity sensor consisting of an LED, near infrared light with the wavelengths ranging from 830 to 890nm. A YSI 6920 temperature sensor which comprises a thermistor of sintered metallic oxide was used to measure the water temperature. Salinity was measured indirectly with a YSI6920 conductivity sensor. The output from the sonde's conductivity and observed temperature were applied to calculate the salinity (American Public Health Association, 1998; Ecosystem Health Monitoring Program, 2007).

The Department of Environment and Heritage Protection, Queensland, Australia, regularly measures the volume of water at their stream monitoring sites. One site, named as the Brisbane River at Savages Crossing, has the closest proximity to the tidal limit of the BRE. The river inflow throughout the Savages Crossing site is used in this paper as an indicator of the seasonal variability of freshwater BRE inflow. To focus on the seasonal variation of the BRE condition, the rainfall-driven flood events (with the average flow greater than 100 m^3/s) are excluded here.

RESULTS

Longitudinal and Vertical Distribution of Salinity and Turbidity

The discharge was different from dry seasons (with an average flow of 5.8 m^3/s) during June-November to wet seasons (7.8 m^3/s) during December-May. Figure 2 presents the distribution of surface salinity along the BRE, together with the curves which are polynomial least square fits to the observation data. These curves describe salinity (S) in ppt as a continuous function of x, the

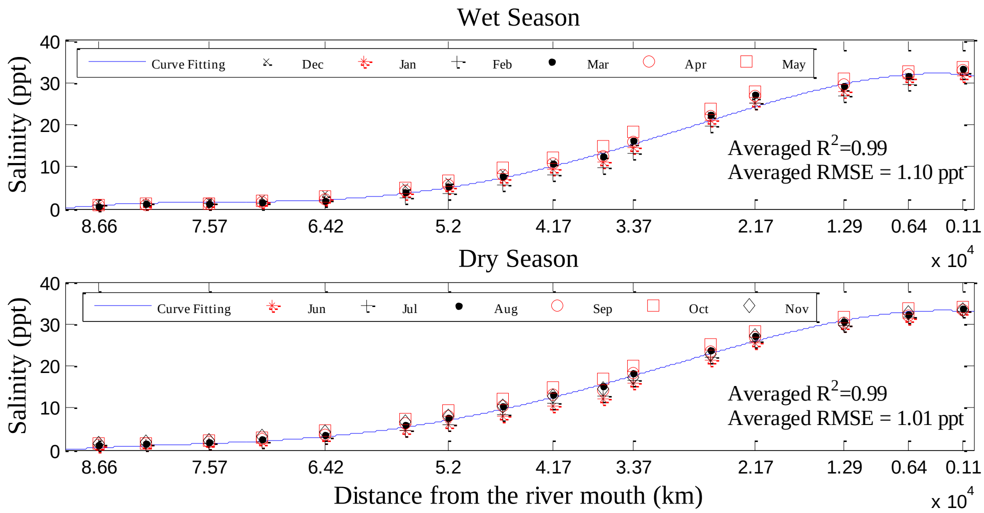

Figure 2. Monthly-averaged salinity distribution in the BRE. The horizontal axes indicate the distance from the river mouth. The observed values are denoted by a variety of markers. The solid lines represent polynomial fit $S(x)$ to the observed salinity along the estuary.

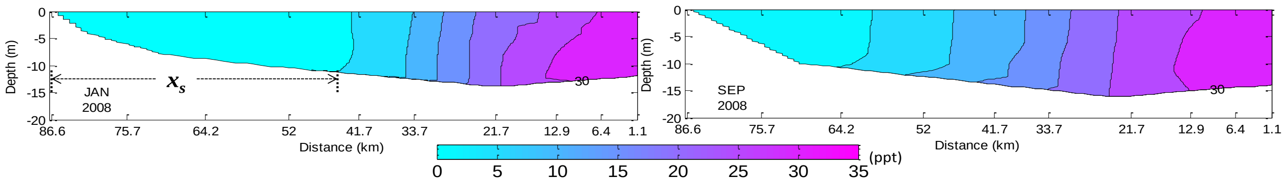

Figure 3. Vertical distributions of salinity in January (wet) and September (dry), 2008.

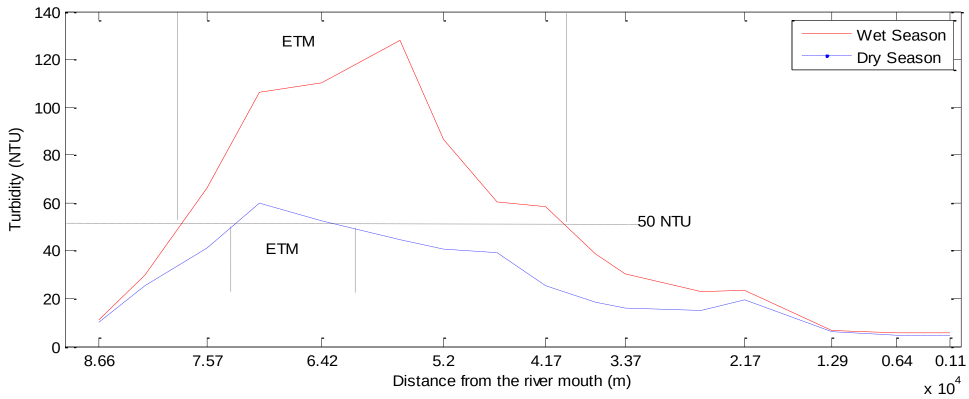

Figure 4. Monthly-averaged turbidity distribution in the BRE over the last 10 years, i.e. 2002-2011.

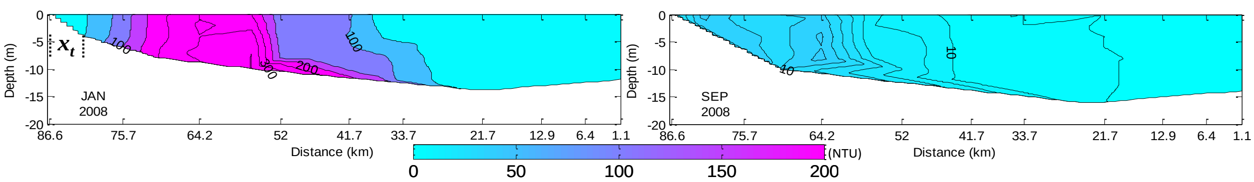

Figure 5. Vertical distributions of turbidity in January (wet) and September (dry), 2008.

upstream distance (in metres) from the Brisbane River mouth. Correspondingly, the function $S(x)$ is defined as:

$$S(x) = a_1x^4 + a_2x^3 + a_3x^2 + a_4x + a_5 \quad (1)$$

in which coefficients of a_i (i = 1, 2, 3, 4, 5) are specified as -2.48×10^{-18}, 5.39×10^{-13}, -3.48×10^{-8}, 2.02×10^{-4}and 32.8 for dry seasons and -3.37×10^{-18}, 6.95×10^{-13}, -4.22×10^{-8}, 2.77×10^{-4} and 31.7 for wet seasons, respectively.

It is estimated that the salinity was 32.8 and 31.7 ppt at the Brisbane river mouth during dry and wet seasons, respectively, which are in accordance with the findings in Yu *et al.* (2011). In addition, it was also found that the surface salinity decreases continuously upstream from the river mouth. The rates of salinity decrease were approximately 0.3 and 0.4 ppt/km up to 20 km upstream; 0.6 and 0.7 ppt/km along the mid-estuary; and 0.4 and 0.3 ppt/km from 60 km upstream to the tidal limit during dry and wet seasons, respectively. This indicates the salinity at the river mouth was lower and decreased faster along the estuary during the wet season compared to the dry season.

The observed data demonstrates the BRE is vertically mixed during ebb-tide for both seasons. As shown in Figure 3 the front of salinity intrusion (defined as the 30 ppt isohaline) extended around 12 km upstream from the river mouth during both seasons. However, the location of freshwater-saline interaction zone (FSI), where the salinity isohaline is 5 ppt, significantly differed between the two seasons. As seen in Figure 3, the FSI was located at 41 and 64 km from the river mouth during wet and dry seasons, respectively, demonstrating the effects of the large discharge during the wet season.

As shown in Figure 4 the turbidity along the BRE had a greater variation in character than the salinity pattern, with the location and magnitude of the turbidity maximum varying significantly between seasons. Figure 4 clearly shows that the ETM zone, which is defined as the region with values greater than 50 NTU (Bell, 2010), extended throughout the mid-estuary. The length of ETM was approximately 35 km during wet seasons, which was three times as long as it is during dry seasons. The peak turbidity levels occurred at 70 and 55 km upstream from the river mouth during dry and wet seasons, respectively. There might be two reasons to explain how the higher flow rates in wet seasons result in the larger turbidity: i) the larger discharge most likely eroded the soil from the river banks providing fresh sediment that deposited in the estuary; and ii) a greater level of resuspension of fine-grained sediments occurred, with wind, tides and higher discharge intensifying currents and subsequently resuspension (Zhang and Chan, 2003; Zhang *et al.*, 2004).

Figure 5 shows the vertical turbidity distribution in January and September, 2008. Although the difference in magnitude of the turbidity maximum was large, the vertical distribution patterns were similar during the two seasons. This indicates that the vertical structure of turbidity was stable and did not significantly change with the magnitude of discharge.

Seasonal Variations of the FSI and ETM

A spatially defined FSI is characteristic of the saltwater intrusion and the ETM is a feature of the suspended particulate matter distributions within the estuary. The distance between the FSI and the tidal limit is denoted as x_s, and the distance between the head of the ETM and the tidal limit is represented as x_t. Two quantities were determined from the longitudinal and vertical distributions of salinity and turbidity as functions of distance from the tidal limit, as shown in Figure 3 and Figure 5. These two variables are affected by the tidal conditions and thus vary frequently within a narrow range over the tidal cycle. Note that the evaluations of these variables in this study are based on the field data which were all measured on the ebbing tide. Therefore, their variations corresponding to tidal conditions are not considered here.

Figure 6 (a) shows the seasonal variations of estimated x_s and x_t within the BRE. The occurrence of the larger x_s (around 30 km) together with the smaller x_t (approximate 10 km) during wet seasons indicates the FSI was close to the river mouth but the head of the ETM was near to the tidal limit. During the dry season the FSI retreated but the ETM head moved toward the river mouth with the x_s and x_t being about 20 km and 23 km from the tidal limit, respectively. It was further found that the separation distance of the FSI and ETM head (x_s – x_t), is a function of the distance of the FSI from the tidal limit, x_s, during the wet season, as shown in Figure 6 (b). Positive values of the separation distance indicate the ETM front was on the left side of the FSI, implying that the head of the ETM occurred within the estuary where the salinity was less than 5 ppt. Therefore, all points in Figure 6 (b) indicate the ETM head was located in fresh or very low salinity

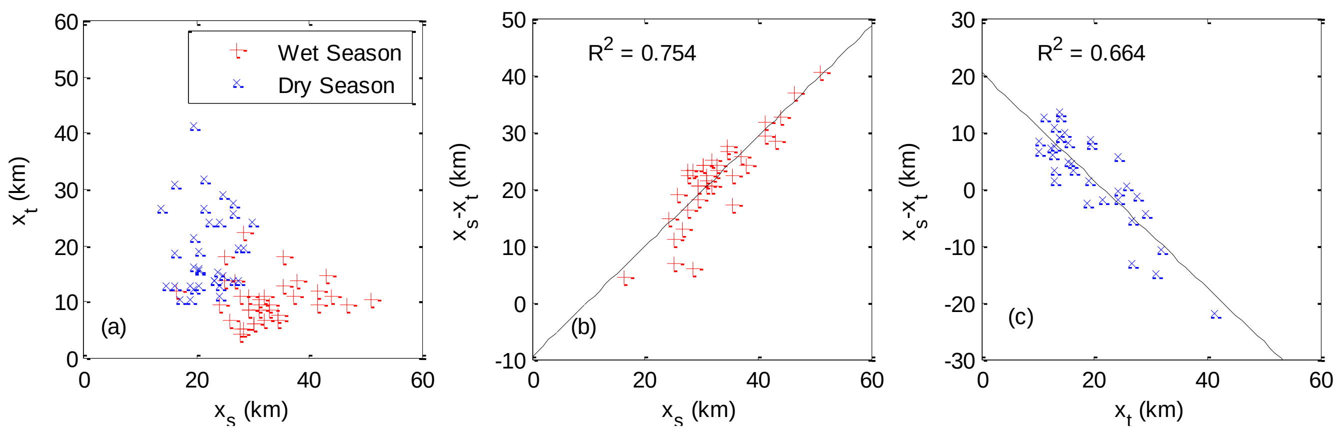

Figure 6. Seasonal variation of xs and xt within the BRE during 2002 to 2011. The (xs-xt) represents the separation distance of the ETM head and FSI.

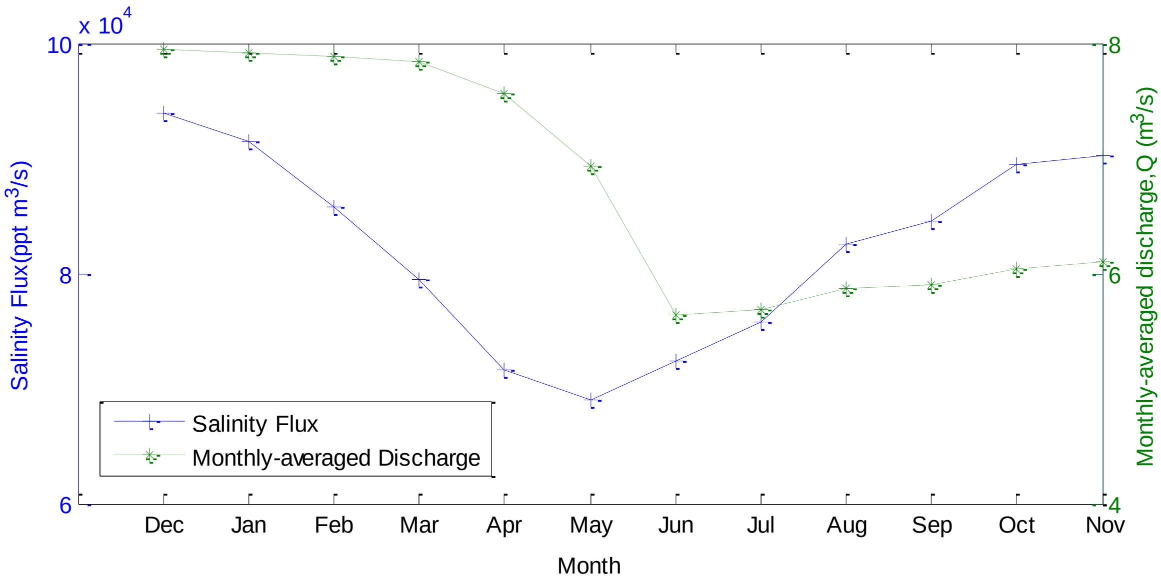

Figure 7 Monthly-averaged Salinity flux (ppt m^3/s) and monthly-mean river discharge (m^3/s) over a period of 2002-2011.

waters during wet seasons. With the onset of dry seasons, the ETM head might appear down-estuary of the FSI in some months, as shown by negative separation distances in Figure 6 (c). Additionally, due to the slight changes in xs, the separation distance mainly depends on the distance of the ETM head from the tidal limit, xt, during the dry season.

River Discharge Influences on the Salt Budget

Based upon the polynomial curve fitting functions in Figure 2, the total salt transported within the estuary over every month, F_s, is given by

$$F_s = \int_0^{86600} S(x)F_q(x)dx \quad (2)$$

where $F_q(x)$ represents the river discharge flux. The lower limit of the integral is the river mouth and the upper is the tidal limit.
As the vertical salinity is relatively uniform throughout the estuary as shown in Figure 3, the contribution of the gravitational circulation to the salinity transport is ignored here. Hence, the salinity flux of the estuary, F_s, is mainly determined by the discharge-induced salinity advection from the upper-stream boundary (the salt is running out of the estuary), and tidally-induced salinity diffusion from the lower-stream boundary (the salt is running into the estuary).

Figure 7 shows the monthly-averaged salinity flux and flow discharge over a period of 2002-2011. The salinity flux continually decreased during the wet season, implying that the decreasing amount of saltwater intruded into the estuary. Conversely, the salinity flux significantly increased during the dry season, indicating that the increasing amount of saltwater was intruded. The average salinity flux was 8.19×10^4 and 8.25×10^4 ppt m^3/s during the wet and dry seasons, respectively. The salt loss during the wet season were progressively recovered in the follwing months, due to the smaller flow discharge during the dry season compared to the wet season.

The slight discrepancy of salinity fluxes between two seasons may be attributed to the lack of consideration of the freshwater inflows from the Bremer River and Oxley Creek, which were the main two tributaries that joined into the BRE. Thus, the salinity flux during the wet season was underestimated; on the contrary, it was overestimated during the dry season. The actual salinity flux through the BRE would fall within the two estimated flux values; that is the actural salinity flux within the Brisbane River estuary was greater than 8.19×10^4 ppt but less than 8.25×10^4 ppt.

CONCLUSION

This study examined the seasonal variations of salinity and turbidity distribution within the Brisbane River estuary. The results revealed that the salinity at the Brisbane River mouth was estimated to be 31.7 and 32.8 ppt during wet and dry seasons, respectively. The rates of salinity decrease were approximately 0.3 and 0.4 ppt/km up to 20 km upstream; 0.6 and 0.7 ppt/km along the mid-estuary; and 0.4 and 0.3 ppt/km from 60 km upstream to the tidal limit during dry and wet seasons, respectively. This indicates the salinity at the river mouth was lower and decreased faster along the estuary during the wet season compared to the dry season.

During the wet season, the length of the turbidity maximum was approximately 35 km, which was three times as long as in the dry seasons. Although the distribution of surface salinity and turbidity varied significantly between wet and dry seasons, the vertical distribution patterns tended to be similar: salinity fairly well mixed but turbidity significantly stratified. It also found that the front of the ETM was located in fresh or very low salinity waters, particularly during the wet season.

The average salinity flux was 8.19×10^4 and 8.25×10^4 ppt m^3/s during the wet and dry seasons, respectively. The slight discrepancy of salinity fluxes between the two seasons may be attributed to the lack of consideration of the freshwater inflows from the Bremer River and Oxley Creek, which were the main two tributaries that joined into the BRE. Thus, the salinity flux during the wet season was underestimated; on the contrary, it was overestimated during the dry season. The actual salinity flux through the BRE will therefore fall within the two estimated flux values.

The values attained throughout the study can be used to evaluate changes and patterns when evaluating the health status of the Brisbane River estuary, as well as being utilised for numerical modelling purposes as a basis for further studies. However, due to a lack of field data over a tidal cycle, it is difficult to determine the variations in salinity and turbidity distributions corresponding with tidal changes. This therefore will be investigated in further studies.

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