

## Salinity observations in a subtropical estuarine system on the Gold Coast, Australia

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### ABSTRACT

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Saltwater Creek and Coombabah Creek are branches of the Coomera River estuary situated within the subtropical Gold Coast City region, Australia, where fresh water flushing occurs during the wet season. The two creek systems are physically adjacent to each other and join at a confluence before connecting to the lower Coomera River. Saltwater Creek is 17 km long and is joined again halfway up its tidal section, via an anabranch, to Coomera River. Coombabah Creek leads upstream to Coombabah Lake, a large shallow lake ringed by mangrove swamps. In order to develop an understanding of how these systems interact with each other, in particular their salinity dynamics, at time scales ranging from tidal to annual, three field studies were undertaken.

Field measurements confirmed that the salinity dynamics of these systems were dominated by rainfall and tidal events, typical of estuaries during the 'wet season' in subtropical environments. In contrast, the studies found that hypersaline conditions (salinity as high as 42 psu) developed upstream during the 'dry season' within Coombabah Lake due to the evaporative effects of its large shallow area and adjoining mangrove swamps. Further, the data also revealed that during the dry season, Saltwater Creek's high frequency salinity fluctuations were in-phase with tidal oscillations while Coombabah Creeks' were out-of-phase despite their close proximity. The mechanism for this was attributed to ebb tidal currents in Coombabah Creek which flushed hypersaline water out of the lake past the confluence, and the following flood tidal currents bringing that water into Saltwater Creek. The studies also identified a low frequency oscillation in Coombabah Creeks' salinity which was caused by the diurnal inequality in the tides.

**ADDITIONAL INDEX WORDS:** *hypersalinisation, hypersaline, diurnal inequality, longitudinal salinity gradient, residence time*

### INTRODUCTION

Saltwater Creek is a small micro-tidal estuary in the Gold Coast region of Australia (Webster and Lemckert, 2002). The creek system is approximately 17 km long, flowing from its head headwaters in the Nerang State Forest to the Coombabah Creek estuary confluence which connects to the Coomera River (see Figure 1). Its tidal limit is 10.5 km. It is also connected to Coomera River via an anabranch 6.5 km upstream from the confluence. The average width of Saltwater Creek is 30 m with the depth for the first 3 km typically 3 m (below MSL) with the remainder of the creek typically 1 m. The two canal estates adjacent to Sites 8 and 11 (see Figure 2) are connected to Saltwater Creek by navigation locks, which restrict tidal exchange between themselves and Saltwater Creek.

Coombabah Creek leads upstream to Coombabah Lake which is a very shallow body of water 2 km<sup>2</sup> in area, with an average depth < 1 m and is ringed by mangrove swamp (Lee et al., 2006). Coombabah Creek's northern bank is lined with mangroves, whilst most of its southern bank is lined with concrete and rock walls belonging to residential developments. The lower section of the creek has an average width of approximately 100 m and an

average depth of 4 m with relatively steep banks on its southern side and only a few exposed sand banks at low tide. The upper section, however, is approximately 200 m wide with an average depth of 1 m with many exposed sand banks at low tide.

This paper examines field measurements collected both in Saltwater Creek and Coombabah Creek and comments on short-term and long-term salinity distribution behaviour. Data was collected during three field studies: first, a short-term field study deploying 2 conductivity, temperature and depth meters (CTDs), one in Saltwater Creek and another in Coombabah Creek, to record high frequency changes in surface elevation and salinity; second, a one year field study collecting vertical profiles of salinity at 12 locations in Saltwater Creek; and third, a long-term study of 5 years of monthly salinity measurements at a single point in Saltwater Creek.

The short-term field study was designed to record changes in salinity in Saltwater Creek and Coombabah Creek over a spring-neap tidal cycle and for comparison with collected rainfall and tidal data. The purpose of the one year field study was to observe the longitudinal salinity profile of Saltwater Creek during different tidal and rainfall conditions. Finally, the long-term study was

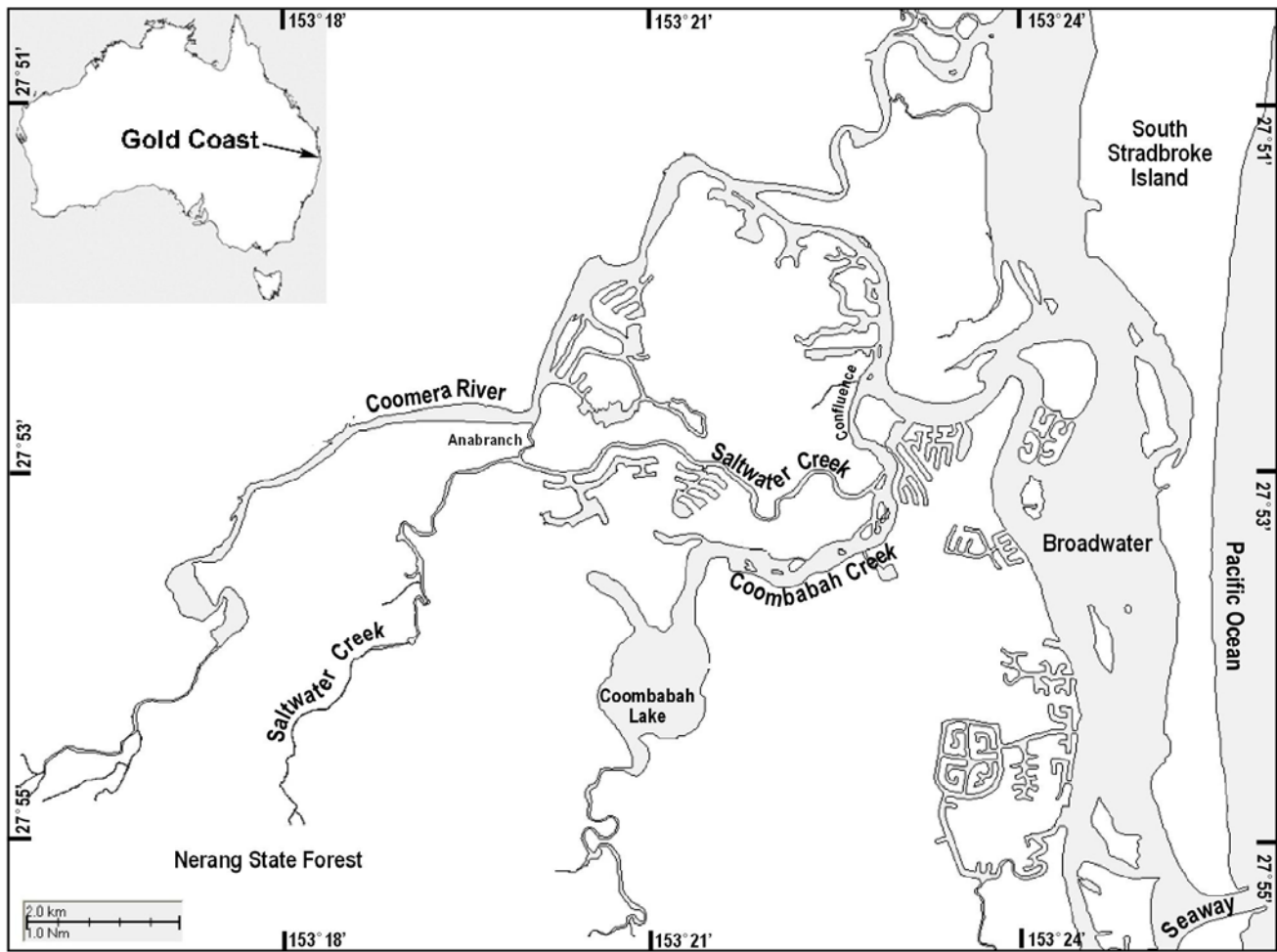


Figure 1. Map of the Coomera River estuary on the Gold Coast and its two adjacent estuaries, Saltwater Creek and Coombabah Creek.

designed to identify seasonal variability in salinity and temperature within Saltwater Creek.

## METHODS

The short-term field study consisted of 2 Greenspan 350 CTDs that were bottom deployed in the system for up to 2 months at Sites 9 and 13 (see Figure 2). Battery life and memory size restricted the sampling rate of the CTDs to 4 per hour and this was enough to capture most high frequency fluctuations in salinity and surface elevation. Rainfall data was sourced from the Australian Bureau of Meteorology from a weather station adjacent to Coombabah Lake. These datasets were compiled into time-series graphs for analysis (shown in Figures 3 and 4).

The one year field study involved casting a SBE19 CTD through the water column, at 12 locations (Sites 1 – 12 in Figure 2), once a month, for one year along Saltwater Creek. The CTD sampled every 0.5 seconds, as it was lowered, to capture a vertical profile at the site. The vertical profiles were then processed in contouring software (Surfer 8™) which created longitudinal salinity profiles of Saltwater Creek for each month, shown in Figure 5.

Data for the long-term study was sourced from a previous water quality monitoring report (WBM 2004) and consisted of monthly depth-averaged salinity measurements at a single point in Saltwater Creek (Site 6 in Figure 2) for the period of January 2000 to December 2004 (as shown in Figure 6). Again rainfall was

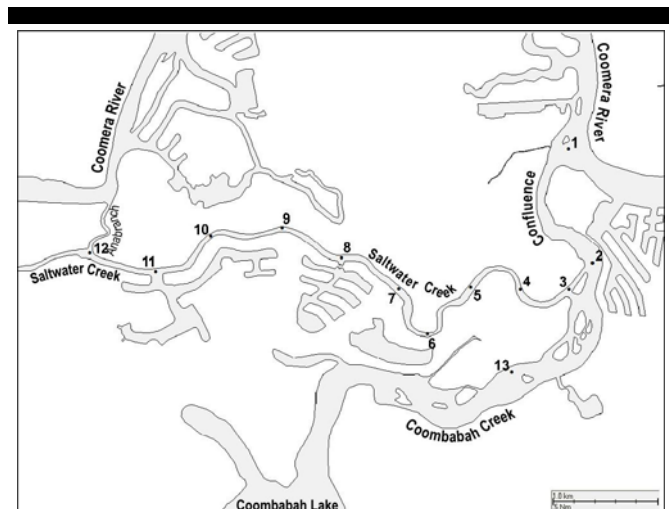


Figure 2. Map of the instrument deployment sites in Saltwater Creek and Coombabah Creek. Sites 1 – 12 were the vertical salinity profile sites for the one year field study; Sites 9 and 13 were the bottom mounted CTD sites for the short-term field study; and Site 6 was the single point, depth-averaged salinity site for the long-term study.

sourced from the Australian Bureau of Meteorology for this period.

**RESULTS**

**Short-Term Field Study**

Salinity measurements from the two deployment sites (Sites 9 and 13 in Figure 2) were compared with daily rainfall and tidal fluctuations at these sites (see Figures 3 and 4). Results indicated that there were three main factors influenced salinity dynamics in Saltwater Creek and Coombabah Creek; rainfall/runoff, evaporation and tidal energy.

The top graph of Figure 3 shows a time-series of salinity at Site 9 compared with daily rainfall, for a period corresponding to the end of the dry season. Note that historical averaged oceanic salinities in this region are approximately 35.5 psu at this time of year (AODC 2000). Figure 3 (top) shows that after an extended period of little or no rainfall, daily averaged salinity, at this site, reached 38.5 psu shown with a maximum of 40.1 psu. Given that these salinity measurements exceeded oceanic levels suggested that large scale evaporation was occurring in the system.

Note also in Figure 3 (top) that there was one rainfall event that produced 93 mm of rain during this measurement period. The reaction of the creek was a sudden plummet in salinity to 19 psu one day after the rainfall event began. The large range in salinity experienced at Site 9 following the rainfall event (19 – 35 psu) suggested that there was a steep longitudinal salinity gradient set up in the creek that oscillated in and out with the flood and ebb tide. The daily salinity range decreased over the following several days as the longitudinal salinity gradient broke down. After that time daily salinity fluctuations settled into a range of 4 psu per day as observed prior to the rainfall event, albeit with a lower mean value.

The bottom graph of Figure 3 shows a time-series of salinity at Site 13, compared with surface elevation measurements for the same period as the top graph in Figure 3. Site 13 measurements in Figure 3 (bottom) showed that after an extended period of little or no rainfall, daily averaged salinity, at this site, reached 39.6 psu

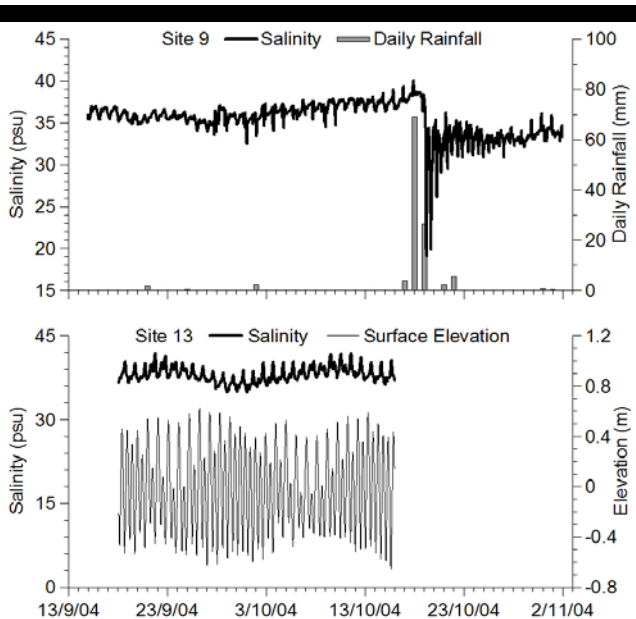


Figure 3. Salinity measurements at sites 9 compared with daily rainfall (top) and at site 13 compared with surface elevation measurements (bottom).

with a maximum of 42 psu. Thus, Coombabah Creek also experienced hypersaline conditions at a level greater than Saltwater Creek.

The top graph of Figure 4 shows a time-series of salinity at Site 9 compared with surface elevation measurements for a 7 day period starting 2 days after the rainfall event, shown in Figure 3 (top). Salinity fluctuations were in-phase with the surface elevation oscillations, as would be expected during a recovery period after a major rainfall event, as saltwater reenters the system during incoming tides. However, prior to the rainfall event, during hypersaline conditions, the in-phase fluctuation of salinity was also observed, with a range of 4 psu per day (not shown). This suggested the source of the hypersaline water was not upstream in Saltwater Creek but rather, entered at its mouth.

The bottom graph in Figure 4 shows a time-series of salinity at Site 13 compared with surface elevation for a 7 day period prior to the rainfall event. The salinity fluctuations at this point were out-

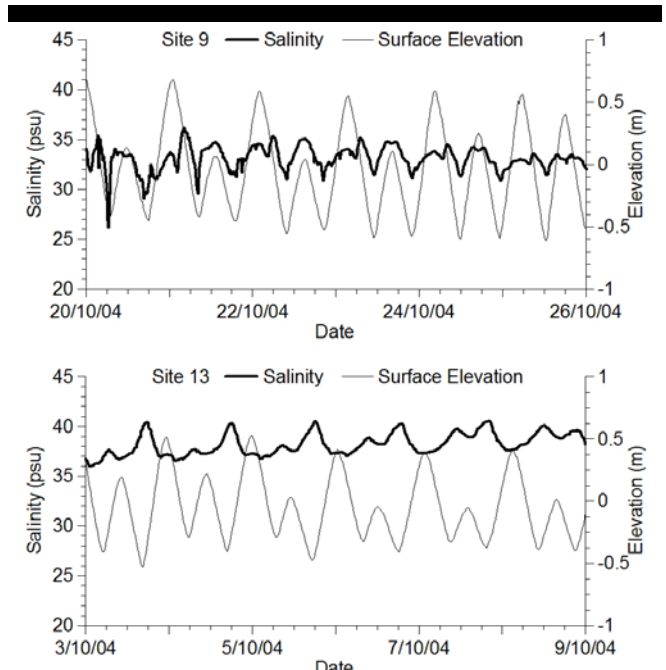


Figure 4. A sample of salinity measurements compared with surface elevation oscillations for Site 9 (top) and Site 13 (bottom).

of-phase with surface elevation oscillations, i.e. highest salinity occurs at low tide, which indicated the source of hypersaline water was upstream of this point, i.e. Coombabah Lake.

Coombabah Lake is a very shallow lake with an average depth < 1 m, an area of 2 km<sup>2</sup> and is surrounded by mangrove swamps. Consequently, the loss of fresh water due to evapotranspiration by the mangroves and evaporation from the large shallow basin area must exceed the supply of fresh water via precipitation and runoff during the dry season. This mechanism would explain the hypersalinisation and phasing of salinity fluctuations in Coombabah Creek. Given the close proximity of Saltwater Creek, hypersaline measurements and dynamics was due to the ebb tidal currents in Coombabah Creek moved hypersaline water out of the lake and past the confluence with Saltwater Creek, and subsequent flood tidal currents then transported this water into Saltwater Creek.

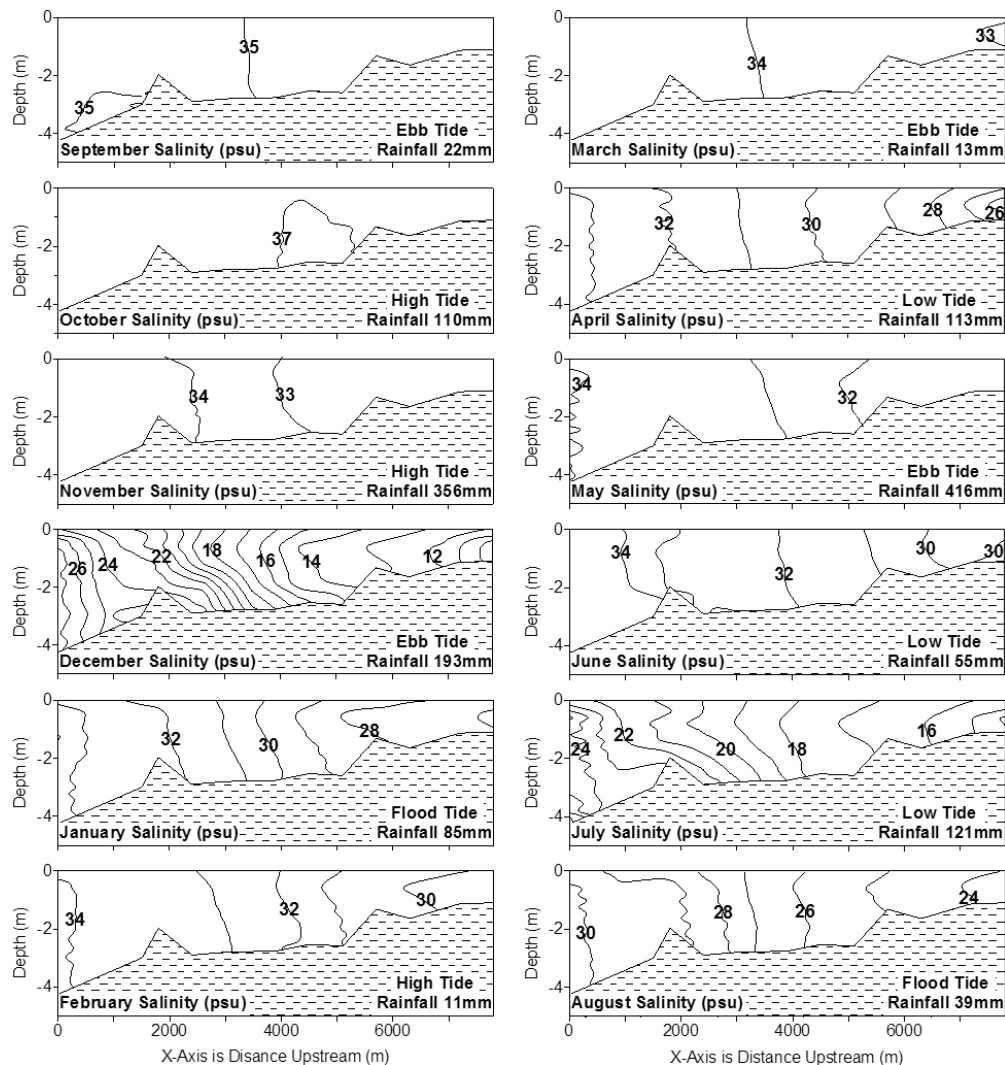


Figure 5. Longitudinal salinity contour graphs up Saltwater Creek starting September 2004 and finishing August 2005 and also showing the phase of the tide when measurements were taken and accumulated rainfall for the month.

It can also be seen in the bottom graph of Figure 3 that there was a low frequency oscillation in the salinity with a period of approximately 17 days. This oscillation was attributed to the spring neap cycle of the tides. Specifically, during neap tides, when the diurnal inequality of the tides was more pronounced daily averaged salinity increased. This was due to a reduction in the advection of water in and out of Coombabah Lake at this time. Less advection of water caused a reduction in mixing in two ways: firstly, less oceanic water was introduced to the system by the flood tide and less hypersaline water was removed during the ebb tide; and secondly, there was less tidal energy to drive tidal stirring in the system.

### One Year Field Study

The one year field survey of salinity profiles along Saltwater Creek were plotted for each month and shown in Figure 5. These plots show the longitudinal salinity profiles that were set up in Saltwater Creek under various conditions starting at Site 1 (0 km upstream), where the confluence joins the Coomera River, to Site 12 (7.8 km upstream), where Saltwater Creek joins the Coomera River via the anabranch. Indicated in Figure 5 also is the

accumulated rainfall for each month and the phase of the tide when the casts were done. Analysis was carried out to determine the number of days since the last significant rainfall event and what stage of the spring-neap cycle the tides were in (not shown). The majority of casts were carried out during spring phase tidal cycles with November, January, February and April the only exceptions.

When the first casts were carried out in September 2004 oceanic salinity levels were evident throughout Saltwater Creek. Note that the last significant rainfall event was 150 days prior to this measurement. By the following month (October) hypersaline conditions were measured from the mouth to the anabranch in Saltwater Creek. Further, the October profile (in Figure 5) also shows an isolated patch of water with salinity > 37 psu at high tide. This has come about due to hypersaline water moving from Coombabah Lake into Saltwater Creek, as described in the previous section, and then oceanic waters moved from Coomera River up the confluence and into Saltwater Creek after the hypersaline water, which caused it to be trapped. This process is similar to that of tidal "trapping" as described in Fischer et al. (1979) which is due to phase lags between adjacent estuaries.

Additional patchiness in the longitudinal salinity gradient in Saltwater Creek was also observed at low tide near the upstream connection to the Coomera River via the anabranch, as seen in the June profile (Figure 5). At this location water from the anabranch has created a patch of fresher water surrounded by salinities that exceeded 30 psu. A possible mechanism to explain this observation would be flood tidal currents transported water with salinity > 30 psu past the anabranch and during the following ebb flow fresher water entered from Coomera River via the anabranch and mixed with the water in Saltwater Creek and created the patch of less saline water. Webster and Lemkert (2002) confirm the flow of water from Coomera River to Saltwater Creek via the anabranch during the ebb tide due to phase lags between the two estuaries.

From Figure 5 it is also important to note that Saltwater Creek is a well mixed estuary for part of the year and a stratified estuary for the remainder. After major rainfall events, salinity contours such as the one shown in the December profile (Figure 5), where a difference of 4 psu through a 3 m water column can be observed, are not uncommon. However, calculations using the bulk densimetric Froude number and the Estuarine Richardson number (Fischer et al. 1979) and the stratification-circulation diagram by Hansen and Rattray (1966) indicated that even in this state, Saltwater Creek can still be classified a well mixed estuary.

The December plot in Figure 5 also shows the longitudinal salinity gradient that was set up after a significant rainfall event at the beginning of the wet season. The longitudinal salinity gradient at this time ranged from 10 psu to 27 psu over a distance of 8 km. This illustrated an extreme condition in the system and it was not observed in the following month.

Collectively the monthly salinity profiles along Saltwater Creek in Figure 5 demonstrate both temporal and spatial complexities in the salinity structure and dynamics in the system.

### Long-Term Study

Monthly depth-averaged salinity and water temperature measurements collected at Site 6, between January 2000 to December 2004, was plotted with monthly rainfall data, as shown in Figure 6. Given that short-term salinity dynamics have been explained in previous sections the long-term data was only used to observe inter-annual seasonality in these parameters.

In most years, February and March (summer) had the most rainfall with a combined average and maximum of 410 mm and 770 mm, respectively; thus defining the peak of the "wet" season. In contrast, July to September (winter) experienced the lowest recorded rainfalls with a combined average of only 95 mm, thus defining the peak of the "dry" season. The salinity in Saltwater Creek followed this simple wet season – dry season cycle, with lower salinity and higher water temperatures during the wet,

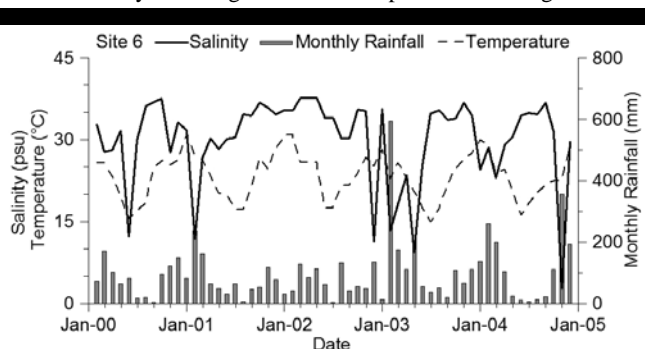


Figure 6. Monthly salinity, water temperature and cumulative rainfall data collected at Site 6, from January 2000 to December 2004.

warmer, summer months and higher salinity and lower water temperature during the dry, cooler, winter months. This behaviour is also present in other systems in the Gold Coast region, for example, the Burleigh Lakes system described in Zigic et al. (2002).

Saltwater Creek experienced hypersaline conditions typically for 3 month periods for each year, as shown in Figure 6. Note that on February and March 2002, at a time of less than average rainfall (~170 mm), the low salinity event in Saltwater Creek missed a "beat" in its cycle and salinity remained high for a 12 month period. This event, coupled with the salinity and water temperature fluctuations that were out-of-phase (see Figure 6) indicated that the system depended primarily on rainfall rather than temperature to influence the salinity dynamics.

### DISCUSSION

Seasonal hypersalinisation is a natural state for some systems (Largier et al. 1997) and while it is not an indication of health in itself, it does indicate the potential for water quality issues. Longer than average residence times that are associated with hypersalinisation can result in higher pollutant loading and, as discussed by Lee et al. (2006), this can be detrimental to the system if the catchment area is not managed appropriately.

Residence times are frequently used as an independent variable when processes and biogeochemical properties from estuaries are discussed (Rasmussen & Josefson 2002). These properties include evaluation of nutrient export and import (Nixon et al. 1986, 1996), the quantification of possible effects of changes in nutrient load on nutrient concentration levels (Balls 1994; Kelly 1997), chlorophyll concentrations (Monbet 1992), primary production (Jorgensen & Richardson 1996), and benthic fauna secondary production (Josefson & Rasmussen 2000). These studies demonstrate the importance of understanding the residence times of estuarine systems and management of these areas to ensure no deterioration of water quality within them.

Estimates of the e-fold residence times in Saltwater Creek, determine from data collected in the short-term study at Site 9 as well as long-term data from Site 6, using "flushing time" calculations described in Wolanski et al. (1990), were between 30 - 50 days. Note these calculations were based on changes in measured salinity concentration following a rainfall event without taking into account the hypersalinisation dynamics of Coombabah Lake; hence it is believed that the actual e-fold residence time likely to be as high as 50 days.

Largier (1997) expressed a simple one-dimensional salt balance, of any estuary, as a function of evaporation, rainfall/runoff, horizontal diffusivity and the size of the estuary. This relationship was illustrated precisely in the data from the short-term field study. While the size of the estuary was constant throughout the field study the other three factors varied and the associated effects were seen in the salinity dynamics. During a period of little or no rainfall, evaporation was the dominant factor and a net landward flux of salt was observed. The horizontal diffusivity, which in this case varies between the spring and neap cycle of the tide, limited the effects of evaporation on the salinity dynamics by periodically increasing mixing in the system. Further, after a rainfall event rainfall/runoff was observed to be the dominant factor causing the salinity to decrease at these times.

### CONCLUSION

The three field studies were undertaken to observe salinity in Saltwater Creek and Coombabah Creek, at time scales varying from tidal to inter-annual, to determine the salinity dynamics and the driving forces behind the periodic hypersalinisation of the

system. It was found that the hypersalinisation of the system follows the seasonal variability of the rain over the long term rather than following the temperature cycle.

High frequency salinity fluctuations, compared with daily rainfall data and tidal oscillation in both creeks, revealed Coombabah Lake as the source of hypersaline water in the system. Coombabah Lakes' large shallow basin promotes rapid evaporation and the mangrove swamp surrounding it also removes fresh water from the system. The short-term data also identified evaporation, horizontal diffusivity and rainfall/runoff as the controlling factors of the salinity budget.

Results from the one year field study supported data from the short-term field study that showed a longitudinal gradient set up in Saltwater Creek oscillating in and out with the tides. Horizontal diffusivity degraded the salinity gradient over time as new water was introduced into Saltwater Creek at the confluence and also at the anabranch.

Results suggest that phase lags between Coombabah Creek, Saltwater Creek and Coomera River create a very complex hydrodynamic environment resulting in unique salinity dynamics, both temporally and spatially. Numerical modeling of this system would lead to further understanding of these processes.

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