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Observation and Analysis of Hydrodynamic Parameters in Tidal Inlets in a Predominantly Semidiurnal Regime

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ABSTRACT

MIRFENDERESK, H. and TOMLINSON, R., 2008. Living with sea-level rise and climate change: observation and analysis of hydrodynamic parameters in tidal inlets in a predominantly semidiurnal regime. *Journal of Coastal Research,* 24(5), 1229–1239. West Palm Beach (Florida), ISSN 0749-0208.

Gold Coast Seaway and Jumpinpin Bar are two tidal inlets that connect the Pacific Ocean to the extensive Gold Coast estuarine system. While the Gold Coast Seaway has been stabilized in the mid-1980s by two rock walls, Jumpinpin Bar has remained a highly dynamic tidal inlet. A detailed study of these two tidal inlets is overdue and has been hindered for a long time by the lack of comprehensive field data. This study provides an extensive hydrodynamic data set, which on one side provides an insight into the hydrodynamic behavior of these two tidal inlets and on another side provides a base for their further study. The measured data show relatively high flow velocities at both locations exceeding 2 m/s. It also shows a strong spatial asymmetry in flow velocity distribution across the Gold Coast Seaway during the ebb tide, which accounts for some of the morphological changes at the study area. A five-month water-level measurement indicates a mixed, predominantly semidiurnal tidal regime at these tidal inlets. Examination of tidal variation shows minor temporal tidal asymmetry at both inlets with potential impact on the sediment transport regime at the inlets. In terms of stability, investigation into the tidal prism and cross-sectional area relationship for both inlets can be described using existing relationships obtained from regression analysis of tidal inlets on Pacific and Atlantic coasts. In regards to stability analysis based on tidal prism–littoral drift relationship, the Gold Coast Seaway seems to be approaching stability while Jumpinpin Bar seems to be more of a dynamic inlet.

ADDITIONAL INDEX WORDS: *Tidal inlet, hydrodynamics, semidiurnal.*

INTRODUCTION

Gold Coast City is located in the southeast corner of Queensland in Australia, extending from the New South Wales border north to the Logan River. This city has over 230 km of natural and man-made tidal waterways. The Broadwater, located at 153.41E, 27.88S, is an important component of this system. It is a shallow inshore area that is separated from the Pacific Ocean by two barrier islands, South and North Stradbroke Islands (Figure 1). The connection between Broadwater and the Pacific Ocean is through a man-made navigation channel (Gold Coast Seaway) and an opening further north (Jumpinpin Bar), which separates the two above-mentioned islands. Four major river systems of the region (Nerang, Coomera, Logan-Albert, and Pimpama) and several smaller creeks (Loders and Biggera) flow into the Pacific Ocean through the Broadwater. All these rivers and creeks are navigable, and some of them include very long navigable man-made canal states. On the northern side, Broadwater joins the Pacific Ocean through Moreton Bay. Gold Coast Seaway and Jumpinpin Bar play an important role in the health of the estuarine waterway system in the Gold Coast because they control the exchange of fresh and saline water, sand, nutrients, planktonic organisms, and pollutants between the Gold Coast estuaries and open ocean. The Broadwater in its current form acts as a buffer zone, which has to absorb and then convey all the pollutants from sewage outflow, storm water, agricultural runoffs, *etc.,* of more than 90% of the Gold Coast City through mixing and exchange with the open ocean. The tide is the main driving force, moving water in and out of the Broadwater through these two inlets. Large eddies, which move as a coherent structure, are formed on the ebb tide (TOMLINSON, 1990) and carry the bulk of pollutant load to the Pacific Ocean. If as a result of tidal asymmetry the ebb discharge does not get far enough from the inlet, the discharge would return to the estuary during the following flood tide. Potentially, some of the load may go through several cycles before permanently leaving the Broadwater. In the same way, some of the organisms, which rely on spending some of their life cycle within the estuarine waters, use the same mechanism to enter the Broadwater. Therefore, any activity that changes the performance of these tidal inlets can have an impact both on estuarine and adjacent ocean environment.

These two tidal inlets similarly play an important role in coastal processes in the region as they interrupt the long shore continuity of shoreline processes and sediment trans-

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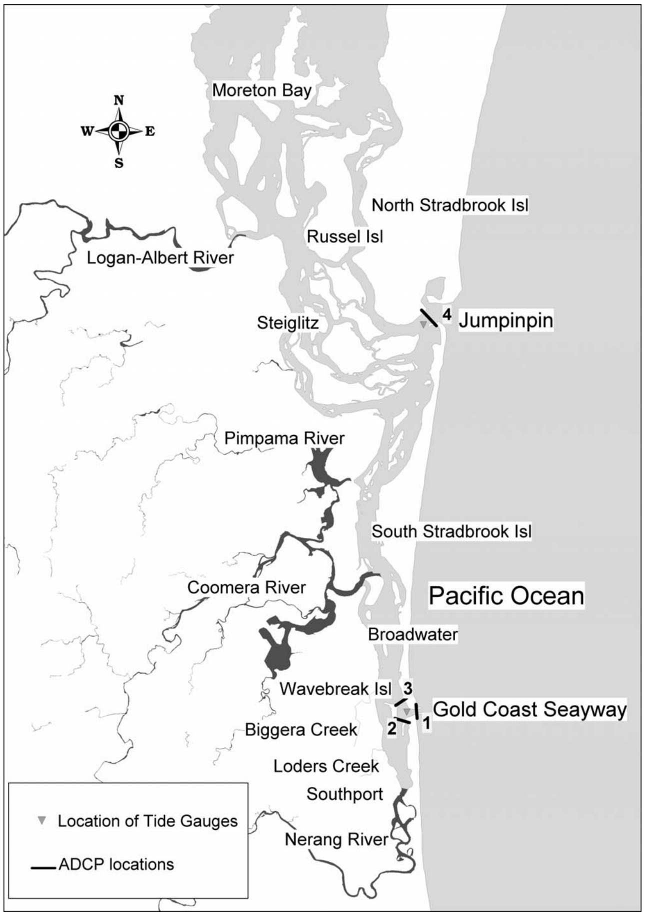

Figure 1. Layout of the study area.

Figure 2. Gold Coast Seaway. **For a color version of this figure, see page 1219.**

port. Having a tidal range between 1 and 2 m classifies the Broadwater as a top range microtidal estuary. From a morphological point of view, features of a wave-dominated estuary are visible at the Broadwater. This includes a barrier system, ebb tide shoals and flood tide shoals in the outer zone of the estuary and mudflats, and mangroves and salt marsh in the central zone of the estuary.

A brief review of the existing situation at the Gold Coast Seaway and Jumpinpin Bar shows that due to the dynamic characteristics of these two tidal inlets, there are many questions that need to be answered. This paper aims at the collection and analysis of hydrodynamic parameters associated with these inlets. This base data supported by a previously verified hydrodynamic model of the Gold Coast estuarine waterways (MIRFENDERESK, 2006) provides insight into the hydrodynamic characteristics of these two inlets, resulting in a better understanding of the processes that have produced the current morphology of the tidal inlets. The collected data will also create a reliable database for future studies of these inlets.

STUDY AREA

Gold Coast Seaway

The Broadwater has originally been a bar-built estuary that was separated from the ocean by barrier islands and was connected to the Pacific Ocean through a shallow channel created either due to floodwater cutting through sand dunes or storm-induced breaching. The location of this channel was approximately 500 m north of the current position of the Gold Coast Seaway at the time of the construction. Historical evidence suggests that this interconnecting channel has been further south of the Southport and has migrated toward the north as a result of bar building by littoral drift, which have a net northerly direction at the Gold Coast.

In the mid-1980s, this channel was stabilized by two rock walls, and since then it has been known as the Gold Coast Seaway. The Seaway is the main navigable connection to the Pacific Ocean from the Broadwater. Unlike the previous interconnecting channel, the Seaway is a wide, deep waterway (250 m wide with an approximate average depth of more than 11 m) and therefore has a much higher conveyance compared with the old natural opening. As a result, its construction has had a significant impact on the hydrodynamic and sediment transport regime of the Nerang River Estuary.

Figure 2 shows the general layout of the Gold Coast Seaway and also the current bathymetry of this inlet (surveyed in 2005). Wave energy, which approaches the Gold Coast Seaway inlet, is dissipated by the northern and southern rock walls, which extend 200 and 400 m, respectively, into the ocean. The mean tidal range at the Gold Coast is over 1 m. Typical significant wave height in the region (50% exceedance) is approximately 1 m, which from an energy-level point of view compares well with tidal variations in the region. The comparable energy level of the wave and tide in the region has manifested itself in features associated with a mixed energy inlet at the Gold Coast Seaway (Figure 2). This includes an ebb shoal extending into the Pacific Ocean and a flood tidal delta in front of Wave Break Island, where the velocity of the tides decreases rapidly.

The flood delta shown as area A is formed by the sand carried into the Broadwater by the flood tide and deposited in front of Wave Break Island; the shape of the shoal is triangular with its head at the inlet, having been grown laterally inside the Broadwater. More flood shoals can be seen on the northern and southern sides of Wave Break Island. In addition to flood shoals, many other typical features of a microtidal inlet can be seen in Figure 2. This includes a deep tidal channel (area B), extending into the ocean, and various types of ebb shoals. Area C shows the crescent shape ebb shoal.

An up-drift attachment bar, up-drift bypassing bar, down-drift bypassing bar, and down-drift attachment bars are shown by D, E, F, and G, respectively. Figure 2 shows that the main channel has been deflected down drift due to the buildup of sand on the up-drift side of the channel and due to wave action.

It can be seen that the ebb tide delta is skewed due to dominant northward alongshore transport and also due to waves dominantly from the southeast. Figure 2 also shows that the crescentlike terminal lobe of the ebb delta has connections to both upstream and downstream sides of the tidal inlet. This indicates that in addition to a mechanical sand bypassing system, which carries the bulk of the alongshore sediment load across the inlet, some sands naturally bypass the inlet by moving along the seaward portion of the ebb tide delta onto the down-drift shore. The sand accumulated in area H and G, alongside the crescent-like terminal lobe of the ebb shoal, indicates the likelihood of the existence of an eddy with a scale close to a kilometer being active right outside the inlet.

Jumpinpin Bar

The openning of Jumpinpin, approximately 100 years ago, resulted in division of the Stradbroke Island into northern and southern sections. The exact reason behind the opening of Jumpinpin Bar is yet to be determined. Historical evidence suggests that a series of natural events and also human interference contributed to the creation of this opening. Jumpinpin is not regarded as navigable due to the dynamic nature of the channel. The opening of Jumpinpin Bar has had a substantial impact on the tidal behavior at the northern part of the Gold Coast estuarine system because it created direct ocean access to the Broadwater midway between Southport and Moreton Bay. It is believed that the tidal amplitude at the vicinity of Jumpinpin Bar (at Jacobs Well) increased substantially once this opening was created. The Jumpinpin opening has also resulted in morphological changes across the study area in the form of large areas of sand banks and islands interspersed by narrow waterways in the area between Jumpinpin Bar and Moreton Bay. Old maps, dating from before the opening of Jumpinpin Bar, do not show many of these sandbanks and islands. These sandbars and islands maybe an indication of a net sediment transport rate from the ocean into the Broadwater through the Jumpinpin opening in the past.

Figure 3. Jumpinpin Bar in 2005. **For a color version of this figure, see page 1219.**

Figures 3–6 show Jumpinpin in 2005, 1998, 1989, and 1982 (before construction of the Seaway). In its current form, Jumpinpin shows typical features of a mixed energy-level inlet, indicating that both wave and tidal energy are actively contributing to morphological processes inside the inlet. This includes a relatively deep channel going through the ebb tide delta, flanked by long channel-margin bars, an ebb-tide delta that extends into the ocean, and bar-building activities on the up-drift side of the inlet. Figures 3–6 show dramatic changes in morphology of the inlet between 1982 (prior to the construction of the Seaway) to 1989. As can be seen, at some time prior to 1982, water flow cut a channel through the spit platform to find a shorter and hydraulically more efficient way to the ocean. By 1989, the shortcut channel was almost refilled with sand. There are three features of Jumpinpin Bar that need more attention.

The first feature is the direction of the tidal ebb channel. Both in 1982 and 1989 as well as in 1998, it can be seen that the direction of main tidal channel—and as a result the ebb jet flow—is toward the northeast. This fits well with the net transport drift along the Gold Coast from south to north and

Figure 4. Jumpinpin Bar in 1998. **For a color version of this figure, see page 1220.**

also with the dominant wave direction, which is from southeast to northeast. There is no evidence to suggest that the net long shore sediment transport rate or general wave propagation direction has undergone significant changes during the last 25 years. However, the 2005 image shows that the direction of the main tidal channel has changed significantly and is currently toward the southeast. Wave diffraction around the ebb shoal, local eddies created due to the offset of the shoreline (between northern and southern banks of the inlet), and to a lesser extent northerly wind-induced currents can be regarded as potential reasons for the possible local reversal of the long shore drift, resulting in a southward-oriented ebb shoal at Jumpinpin Bar. A closer look at these photos shows substantial erosion and deposition in both the up-drift and down-drift sides of the inlet. Figure 5 shows that the ebb flow in the northeasterly direction coincides with erosion of the down-drift shoreline and growth of a sandbar in the up-drift side of the inlet. At one stage, it seems that the ebb channel breached through the ebb shoal on the up-drift side and steered to a southeast direction in the last couple of years. As a result, the sediment, which was accumulated on

Figure 5. Jumpinpin Bar in 1989. **For a color version of this figure, see page 1220.**

Figure 6. Jumpinpin Bar in 1982. **For a color version of this figure, see page 1220.**

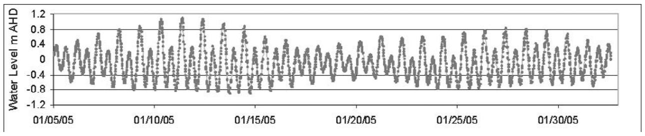

Figure 7. Water-level variation at Seaway.

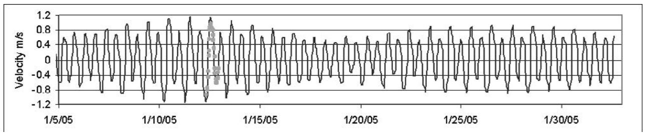

Figure 9. Cross-sectional averaged current speed time history at Seaway.

the up-drift side, has been bypassed to the down-drift side and eventually welded (Figure 3) to the down-drift shoreline. This seems to be the beginning of a new progradational cycle (SEXTON and HAYES, 1982).

Another feature shown in Figures 3–6 is the accretion of sand on the northern side of Jumpinpin Bar. It seems that between 1998 and 2005 more sand has been transported across the tidal channel. This fits well with the change of direction of the ebb tide channel. The accretion of sand has extended the northern bank of the inlet into the ocean and accentuated the offset of the shoreline.

What happens next in Jumpinpin may depend on rainfall and storm patterns during the next couple of years. Under the current regime (drought condition), the ebb flow continues eroding the southern bank of the North Stradbroke Island at Swan Bay, and there will be more northward sand accretion on the up-drift side of the inlet and more accretion on the shoreline of the North Stradbroke Island on the northern bank of the inlet. As a result, the curvature of tidal flow path at the inlet continues to increase. This will result in having a less and less hydraulically efficient flow path as time passes. The timing of tidal flow cutting a shortcut across the spit platform or across the ebb-tidal delta similar to what can be seen in Figure 6 probably depends on the strength of storms and the time needed until hydraulic efficiency of the existing flow path reaches failure threshold. It seems that the creation of a shortcut path is an event waiting to happen, most likely needing a storm event as a trigger.

DATA ACQUISITION

Water Elevation

Two tide gauges were used to measure changes in water level at the Gold Coast Seaway and Jumpinpin Bar. The recording time interval for the gauges was set to 15 min with an averaging interval of 10 s (to minimize the impact of ripples, wind-generated waves, localized boat wash, *etc.*) The sensor sampled the water level at a rate of 1 sample/2 s. The tidal gauges were installed on two marine beacons fixed at the location of the inlets (see Figure 1). The data record span for the Gold Coast Seaway was 90 days, and for Jumpinpin Bar, it was 150 days, providing an adequate time period for resolving the primary tidal constituents at each site. Because these gauges measure absolute pressure, the water pressure readings were corrected for variations in atmospheric pressure once the data was downloaded from each gauge.

Data obtained from the Bureau of Meteorological (BOM) station at the Seaway was used to make atmospheric pressure corrections. Conductivity and temperature data was collected simultaneously with water-level measurements. This data was used to correct the impacts of salinity and temperature on the measured pressure. To this end, first conductivity data was converted to salinity using the UNESCO Practical Salinity Scale, and then the density of the water was calculated based on the calculated salinity and the measured temperature. Measurements show that density variations within the water column were minor at both measurement sites. This can be attributed to the strong mixing processes at the measurement sites. On this basis, density variation inside the water column was not applied to the readings. Field data shows that the salinity at both inlets during normal conditions is almost equal to ocean salinity at the study area, that is, between 30 and 34 ppm. This is mainly due to the insubstantial base freshwater inflow from the river system. To adjust the measured water level to a known vertical datum, the tidal gauges were surveyed relative to benchmarks. The result for each gauge is a time series representing the variations in water surface elevation relative to the Australian Height Datum. Australian Height Datum is a standard vertical reference representing mean sea level in the region.

Figures 7 and 8 depict the time series of water-level variations at the Seaway and Jumpinpin Bar, respectively, for an arbitrary 28-day time interval, covering both spring and neap tide periods. Field data have been shown by dot points on the model results for comparison.

Figures 9 and 10 show the cross-sectional averaged current speed time history at the Gold Coast Seaway and Jumpinpin Bar for the same period. This data is simulated by a cali-

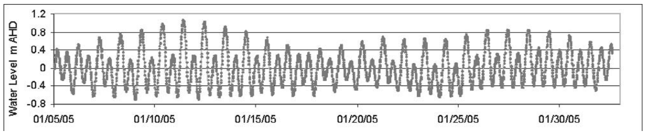

Figure 8. Water-level variations at Jumpinpin Bar.

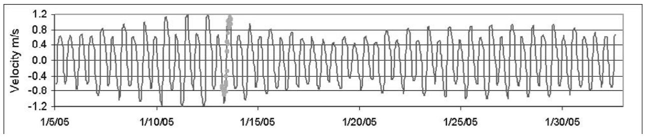

Figure 10. Cross-sectional averaged current speed time history at Jumpinpin Bar.

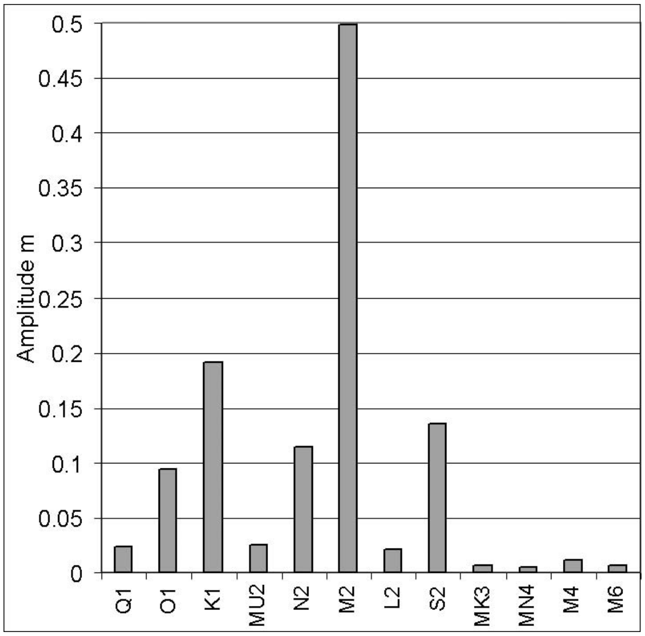

Figure 11. Tidal-level constituents (Seaway).

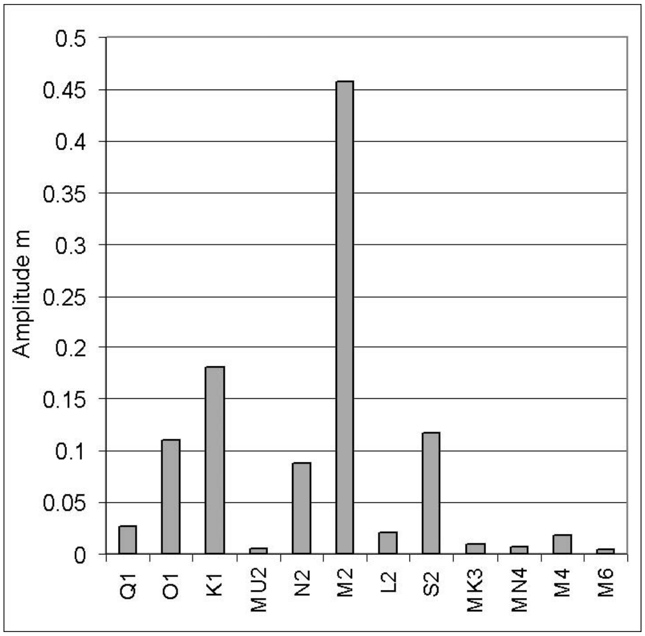

Figure 12. Tidal-level constituents (Jumpinpin Bar).

brated tidal model of the Gold Coast estuarine waterways. Measured velocity data for a tidal cycle, which has been shown on these figures as dot points, demonstrate a good match between model results and field data. These figures show that the average current speed at the Seaway varies between −0.85 to 1.2 m during spring tide and between −0.75 and 0.8 m/s during neap tide. Average current speed at Jumpinpin varies between −1.2 to 1.2 m/s during spring tide and between −0.9 to 0.9 m/s during neap tide.

To quantify the tidal characteristics in the study area, a frequency domain analysis was carried out for the measured tidal time series. The purpose of the tidal analysis is to determine the amplitude and phase (tidal harmonic constants) of the individual cosine waves, each of which represents a tidal constituent. Tidal harmonic analysis of water level and current speed were carried out using the Institute of Ocean Sciences tidal package methodology. Figures 11 and 12 depict amplitude for the main diurnal and semidiurnal constituents for the Seaway and Jumpinpin stations. These constituents were derived from a 90-day time series of water-level variations at the Seaway and 150-day time series of water-level variations at Jumpinpin. The results show the dominance of M_2 and K_1 constituents. Figures 13 and 14 show current speed amplitude for the main diurnal and semidiurnal constituents at the Seaway and Jumpinpin Bar, respectively. Just as was seen for current velocity, M_2 and $K1$ are the dominant lunar and solar components.

Current Measurements

The purpose of this exercise was to collect observations of the spatial and temporal variations in tidal current at these two inlets. A broadband 1200-kHz Acoustic Doppler Current Profiler (ADCP) was used for collecting current velocity data within the study area. The ADCP was interfaced with a differential GPS receiver. Clock synchronization between the GPS and the computer, which controlled the ADCP, allowed an accurate positioning of the ADCP output data. The ADCP was oriented to look downward into the water column. The

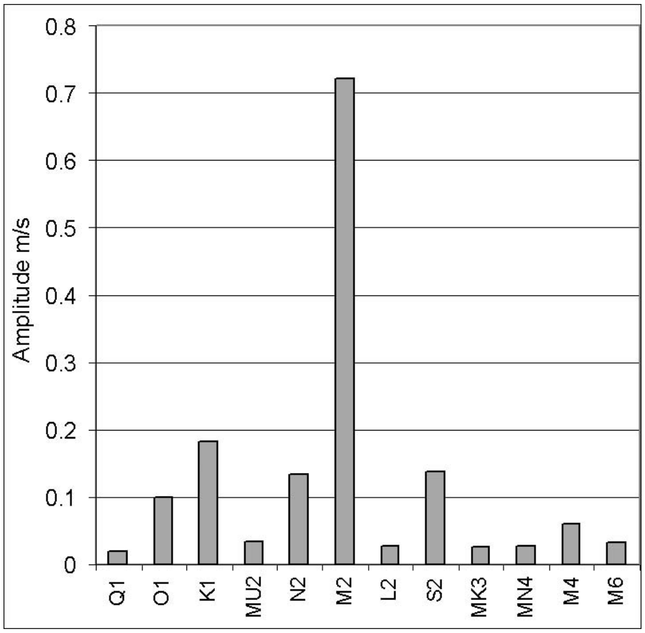

Figure 13. Tidal current speed constituents (Seaway).

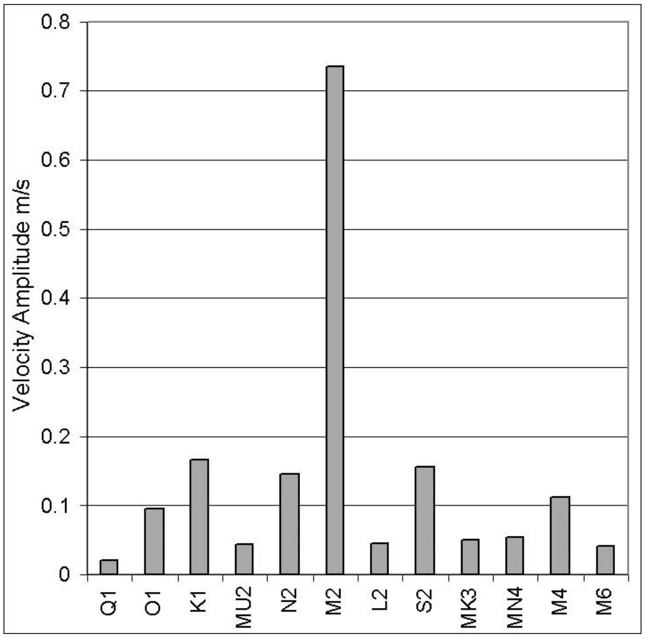

Figure 14. Tidal current speed constituents (Jumpinpin Bar).

instrument was mounted to a mast, which was rigidly attached to a small survey vessel.

Measurement Plan

Three transect lines at the Gold Coast Seaway and one transect line at Jumpinpin Bar were chosen for current measurements as shown in Figure 1. The boat repeatedly navigated these transect lines over a full tidal cycle with the ADCP continuously collecting current data. To ensure that a full tidal cycle had been recorded, the measurements were extended 1 h either side of low and high slack water. On this basis, every data collection session took between 14 and 16 h. Lines 1 and 4 (Figure 1) were designed to provide a quantitative measure of the volume flux, which is exchanged between the open ocean and the estuarine system during a tidal cycle via Seaway and Jumpinpin, respectively. Two regularly maintained navigation channels connect the Seaway to the Nerang and Coomera systems on the south and north of the Seaway, respectively. Line 2 runs between Wave Break Island and the Spit in an east-west direction and was used estimate the volume of water that goes through the southern access channel. Line 3 runs between Wave Break Island and South-Stradbroke Island in an east-west direction and was used to estimate the volume of water that goes through the northern access channel.

Current Measurement Results and Discussion

Figures 15–18 show the horizontal distributions of the velocity across each transect. We endeavoured to measure current velocities during spring tide, when the tidal range is maximum. At the Seaway, tidal variation during ADCP measurement was recorded at approximately 1.8 m, which was about 10% lower than maximum tidal variations at this location during a typical spring tide period.

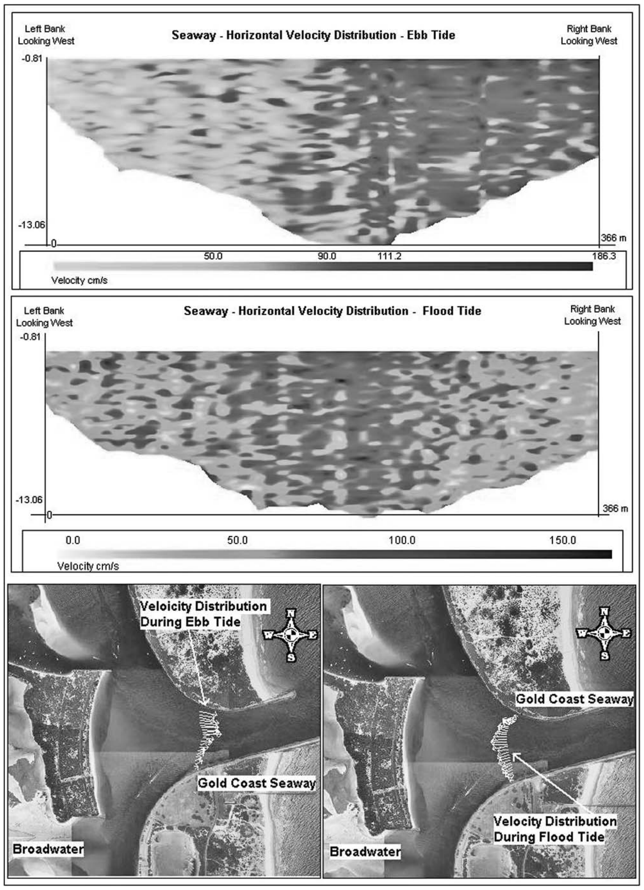

Figure 15. Flood and ebb tide at the Seaway—main channel. **For a color version of this figure, see page 1221.**

Similarly, ADCP measurement at Jumpinpin was conducted during a spring tide period. Due to bad weather, the boat missed the maximum tidal range. Tidal range during the ADCP measurement was recorded at 1.5 m, which was about 20% lower than the maximum tidal variation at this location during a typical spring tide period.

On this basis, the results shown in Figures 15–18 are not the maximum current velocities at Seaway and Jumpinpin. As a rough estimate, the maximum current velocity at Seaway can be estimated to be approximately 10% greater than the measured value. In the case of Jumpinpin, the maximum velocity can be estimated to be 20% greater than the measured value.

Figure 15 (transect 4 in Figure 1) shows the velocity distribution across Gold Coast Seaway during flood and ebb tide. The horizontal velocity distribution shows a symmetrical flow across the waterway with a maximum velocity of 1.7 m/s in the middle of the channel during flood tide. Figure 15 also shows a strongly asymmetric horizontal velocity distribution across the seaway during ebb flood. The horizontal velocity from the middle of the canal to the southern wall varies be-

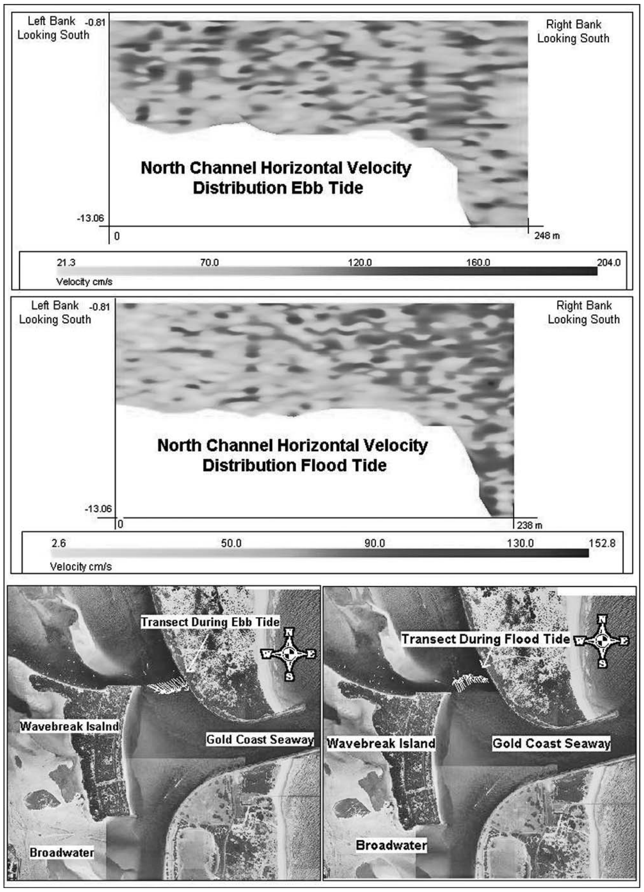

Figure 16. Flood and ebb tide at the Seaway—northern access channel. **For a color version of this figure, see page 1221.**

tween 0.5 and 0 m/s, whereas on the northern half, the velocity is well above 1 m/s in most parts; and reaches a maximum close to 2 m/s. As it will be seen in the next few figures, the main reason for this strong asymmetry in velocity distribution is the fact that approximately 80% of the Seaway's tidal prism water is discharged through the northern access channel to the Seaway.

Figure 16 shows an asymmetric horizontal velocity distribution during flood tide and a relatively homogeneous horizontal velocity distribution during ebb tide at the northern access channel. During flood tide, the velocity at the shallow berm of the South Stradbroke Island varies between 0 to 0.5 m/s and reaches more than 1.5 m/s at the deeper part of the channel close to Wave Break Island. This asymmetry could be attributed to the momentum of flow as it turns toward the north, leaving a region of low velocity at the inner part of the curve and a region of higher velocity at the outer part of the curve. The velocity can reach more than 2 m/s during ebb tide.

Figure 16 also shows that the horizontal velocity distribution at the northern access channel during ebb tide is relatively homogenous and can reach more than 2.0 m/s. The vertical velocity profile shows a striplike pattern, which indicates that vertical eddies with length scales equal to their water depth are active at the cross section. The vertical velocity can reach up to 0.35 m/s during ebb tide in this cross section.

Figure 17 shows that there is slight spatial asymmetry in the horizontal velocity distribution at the southern access channel to the Seaway during flood and ebb tide. The left portion of the cross section (close to Wave Break Island) experiences higher velocity (close to 1.3 m/s) compared to the right portion. Figure 17 also shows velocity asymmetry during ebb tide at the southern access channel. During ebb tide, unlike flood tide, the right portion of the cross section (close to the spit) has higher velocity (close to 1.45 m/s) compared to the left section (close to 0 m/s).

Figure 18 depicts the horizontal velocity distribution at Jumpinpin Bar during flood and ebb tide. It can be seen that this cross section includes a deep channel in the middle and two sandy arms reaching to the North and South Stradbroke Islands. The velocity at the left portion of the channel (closer to South Stradbroke Island) is higher (close to 1.3 m/s) than that at the right portion. Figure 18 also shows slight asymmetry in horizontal velocity distribution in the main channel of Jumpinpin Bar during flood tide. A more homogenous pattern of horizontal velocity distribution can be observed during ebb tide. The maximum velocity (1.65 m/s) during ebb tide is higher than that during flood tide.

DISCUSSION

Tidal Condition

At the Gold Coast Seaway and Jumpinin Bar, tidal movement is the main driving force for the horizontal water flow at the Broadwater (except for storm water condition that may occur during the rainy season). The semidiurnal M2 constituent is the dominant component of tidal regime at these two inlets. The tide has an average range of over 1 m at these two inlets. The tidal range increases typically up to 2 m during spring tide, while during neap tide, it reduces to approximately 0.8 m.

Tidal characteristics at the Gold Coast Seaway and Jumpinpin Bar has been identified as mixed predominantly semidiurnal using the form number as defined by (Pugh, 1987):

$$N = \frac{O_1 + K_1}{M_2 + S_2}. \tag{1}$$

The form number for both the Seaway and Jumpinpin Bar is approximately 0.5. A form number between 0.25 and 1.5 is regarded as that of a mixed, predominantly semidiurnal, regime.

Tidal Asymmetry

Asymmetry of the tidal current is a common phenomenon in tidal inlets and plays an important role in sediment transport processes and transport of pollutions within an inlet. Tidal asymmetry can be spatial and/or temporal, and it can be flood or ebb dominant. Flood dominant asymmetry occurs when the flood current is stronger than the ebb current, and ebb dominant asymmetry occurs when ebb current is stronger than the flood current.

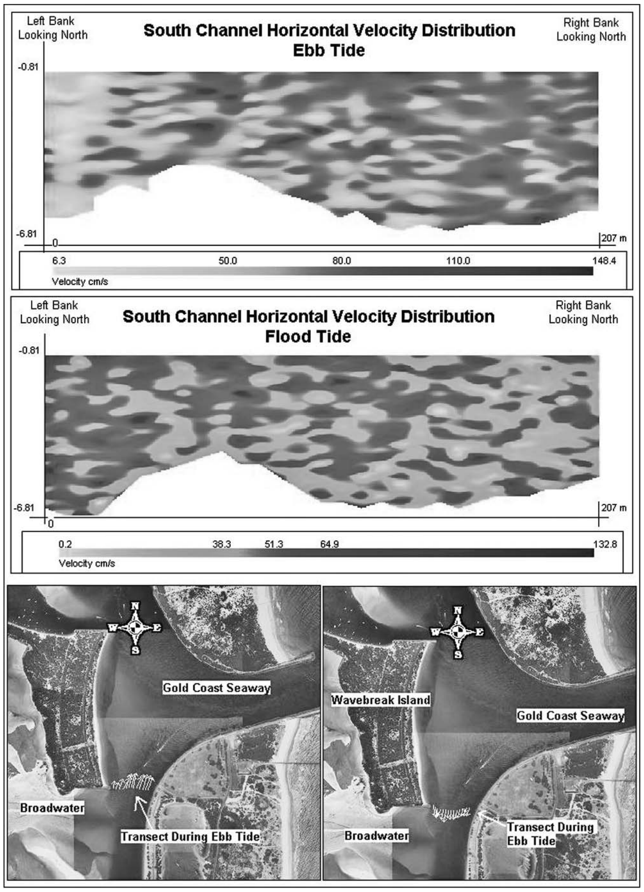

Figure 17. Flood and ebb tide at the Seaway—southern access channel.

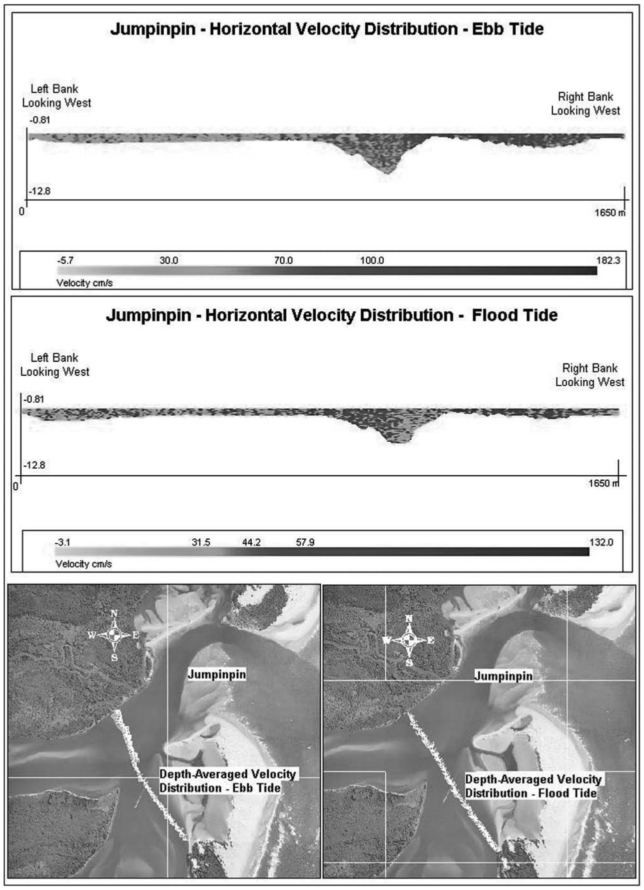

Figure 18. Flood and ebb tide at Jumpinpin Bar.

AUBREY and SPEER (1985) showed that the phase difference, $2\theta_{M_2} - \theta_{M_4}$, where θ is the phase of the tidal height, determines whether an estuary is flood dominant or ebb dominant. A 90° phase difference of tidal height means shorter flood duration (compared with ebb duration). This results in a higher flood current velocity and consequently a flood dominant situation. A 270° phase difference of tidal height means longer flood duration, which can result in a higher ebb current velocity than flood current velocity. AUBREY and SPEER (1985) and FRIEDRICHS and AUBREY (1988) conducted theoretical studies and fieldwork on tidal asymmetry for estuaries with semidiurnal tidal regime. Based on their studies, under a semidiurnal regime, an estuary has flood-dominant current when

$$0^\circ < 2\theta_{M_2} - \theta_{M_4} < 180^\circ \qquad (2)$$

and ebb-dominant current when

$$180^\circ < 2\theta_{M_2} - \theta_{M_4} < 360^\circ \qquad (3)$$

Expressions 2 or 3 refer to the phase difference of M_2 and M_4 components of tidal height. Harmonic analysis of tidal height at the Seaway and Jumpinpin show that the values for the expression $2\theta_{M_2} - \theta_{M_4}$ are 291° and 210°, respectively. This indicates ebb-dominant conditions at both inlets.

RANASINGHE and PATTIARATCHI (2000) examined the variability in the occurrence of flood and ebb dominance by measuring the long-term duration of the falling and rising tide for each tidal cycle. On this basis, if the falling duration is longer than the rising duration, the cycle will be flood dominant, and if the falling duration is shorter than the rising duration, the cycle will be ebb dominant. Comparison between the time of rising and falling tide, based on tidal measurements over a period of 90 days at the Seaway and 150 days at Jumpinpin Bar, is inconclusive because, first, the time of rise and fall of the tide at each cycle are very close to each other and, second, the number of ebb dominant and flood dominant cycles are very close to each other. In addition, the duration of the measured time series does not seem to be long enough to provide a conclusive result. Based on the two above-mentioned methods, it seems that if there were temporal asymmetries at the Seaway and Jumpinpin, they would be minor and ebb dominant.

It is important to note that tidal asymmetry does not necessarily result in a nonzero net discharge across the inlet, which is the case in these two tidal inlets. Both a simulation and measurements indicate that net discharge at the Seaway is zero despite minor tidal asymmetry. This phenomenon can be attributed to the shape of the velocity curve and also to

Table 1. *Tidal prism minimum channel cross-sectional area relationship (Jarrett, 1976).*

Location	Relationship
Atlantic coast	$A = \Omega^{1.05} \times 7.75 \times 10^{-5}$
Pacific coast	$A = \Omega^{0.84} \times 9.311 \times 10^{-4}$
Gulf coast	$A = \Omega^{0.91} \times 2.833 \times 10^{-4}$

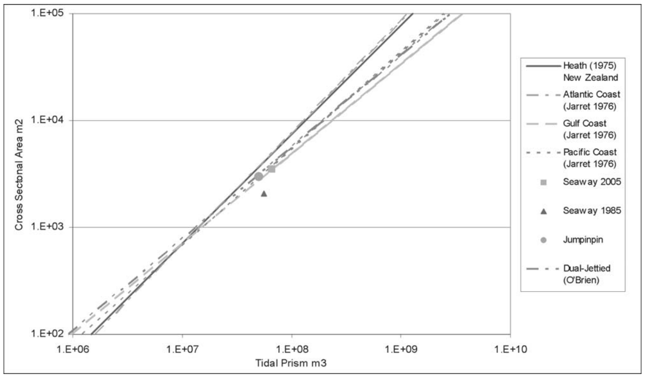

Figure 19. Tidal prism relationship to cross-sectional area. **For a color version of this figure, see page 1220.**

the phase lag between the water level and current. The mean zero velocity through the Seaway and Jumpinpin Bar indicates that the longer flood duration is balanced by a higher peak velocity during the ebb tide cycle. Both Gold Coast Seaway and Jumpinpin Bar exhibits spatial asymmetry, as shown in Figures 15 and 18. Spatial flow asymmetry at the Seaway occurs during the ebb tide, whereas at Jumpinpin Bar, it happens during the flood tide.

Tidal Prism and Inlet Stability

Tidal prism plays an important role in developing the morphology of tidal inlets and their associated barrier islands. A large tidal prism, in the absence of high wind-generated wave energy, can result in the development of large ebb tidal deltas. Well-developed ebb tidal deltas are visible both at the Seaway and Jumpinpin Bar. Calculation of the total volume of water moving past the throat of the Seaway during flood tide (referred to as tidal prism) show that tidal prism at the Gold Coast Seaway for a typical flood tide is approximately 66,000,000 m^3, for an approximate cross section area of 3500 m^2. The same type of calculation for Jumpinpin Bar shows that tidal prism associated with Jumpinpin is approximately 50,000,000 m^3, for an approximate cross section of 3000 m^2.

HEATH (1975) fitted the following curve to 16 New Zealand inlets:

$$\Omega = A^{0.98} \times 10^{4.21} \tag{4}$$

where Ω is the tidal prism and A is the cross-sectional area. According to HUME and HERDENDORF (1985), this relationship has been used by numerous researchers and engineers to assess the degree of inlet stability. Inlets having a smaller cross section or larger tidal prism are classified as erosional inlets, and those having a larger cross section or smaller tidal prism are classified as depositional inlets (Figure 19).

JARRETT (1976) studied tidal inlets in various regions with different tidal characteristics. Through regression analysis between tidal prism and cross-sectional area at the inlets, he developed relationships between the two for the Atlantic, Pacific, and Gulf areas in the U.S.A., shown in Table 1. Figure 19 shows that the Jarrett relationship for the Atlantic coast fits very well with the Heath relationship, whereas the inlets on the Pacific and Gulf coasts show a different behavior. The triangular symbol in Figure 19 is associated with the Gold Coast Seaway once the rock wall was constructed in the year 1987, indicating a tidal prism of 50,000,000 m^3. It can be seen that it is far from the best-fit lines and is closer to the erosion-in-inlet region. Historical evidence shows the same thing: the Gold Coast Seaway has been eroding during the last 20 years, and as a result, its cross section has increased. The square symbol shows the inlet status in the year 2005, which is closer to the best-fit lines. This indicates that the inlet has approached a more stable condition during the last 20 years. The facts on the ground also show the same thing: the inlet has been in a relatively more stable condition in recent years, and bed erosion of the inlet has been limited. Similarly, the circular symbol is associated with Jumpinpin Bar. It seems that Jumpinpin Bar is in dynamic equilibrium.

BRUUN (1978) introduced a different approach for investigating tidal inlet stability based on the relationship between tidal prism Ω (in m^3) and total littoral drift M_{total} (in m^3/year). Table 2 shows how inlets can be graded in terms of these two parameters.

The approximate pumping rate of the Seaway by-passing system is on average 450,000 m^3/year. The average northerly littoral transport rate at the Gold Coast embayment is approximated at being 760,000 m^3/year, whereas average southerly littoral transport rate is approximated at being 260,000 m^3/year. This results in an average net northerly littoral transport rate of. 500,000 m^3/year (TURNER, TOMLINSON, and WATSON (1998)). Using these numbers, the average total littoral drift toward the Seaway can be approximated at 570,000 m^3/year and that toward Jumpinpin Bar at 1,020,000 m^3/year. On this basis, in terms of stability, Gold Coast Sea-

Table 2. *Inlet stability ratings (Bruun, 1978).*

Grade	Relationship	Description
1	$150 < \Omega/M_{\text{total}}$	Conditions are relatively good, little bar formation, and good flushing.
2	$100 < \Omega/M_{\text{total}} < 150$	Conditions become less satisfactory, and offshore bar formation takes place.
3	$50 < \Omega/M_{\text{total}} < 100$	Entrance bar or shoals may be rather large, and they may be penetrated by a channel through the bar.
4	$20 < \Omega/M_{\text{total}} < 50$	All inlets are typical bar-bypassers.
5	$\Omega/M_{\text{total}} < 20$	Descriptive of cases where entrances may become unstable "overflow channels," impossible for navigation.

way and Jumpinpin Bar can be rated as grades 2 and 3, respectively.

SUMMARY AND CONCLUSION

In this study, a hydrodynamic data set for two tidal inlets of the Broadwater estuary have been presented. The collected data and the results of a previously verified model show that the tidal regime in the study area is predominantly semidiurnal; both inlets exhibit slight temporal asymmetry, and tidal flow at both inlets seems to be ebb dominant. The temporal asymmetry can be attributed to the generation of higher frequency tidal components such as M_4 that distorts the M_2 component. Examination of the velocity distribution across the cross section shows spatial flow asymmetry at both inlets. This type of asymmetry is very strong at the Seaway and occurs during ebb tide. The reason for this asymmetry is that the majority of the water, which is stored in the estuary as tidal prism during flood tide, approaches the Gold Coast Seaway (during ebb tide) from the north and only a small part from the south. Spatial asymmetry at Jumpinpin Bar is less than that at the Seaway, and it occurs during flood tide.

Examination of field data shows the existence of strong vertical mixing processes at both inlets, and therefore there is little chance of stratification at the inlets in normal conditions. It seems that large-scale local eddies just outside the inlets can play important roles within the study area. These local eddies can have an impact on the discharge of tidal water (and anything carried by the water) from the Broadwater into the ocean through the Seaway and Jumpinpin Bar. The behavior of these eddies and their impact on these inlets requires more study and will be covered in future research of this area. In addition, a brief description of the inlets based on historical evidence and air photos shows that significant modification of the Gold Coast Seaway in the mid 1980s could have had an impact on hydrodynamic characteristics of the second inlet at Jumpinpin Bar. This issue also needs further investigation.

In terms of stability, the investigation into the tidal prism and cross-sectional area relationship for both inlets can be described by existing relationships obtained from regression analysis of tidal inlets on Pacific and Atlantic coasts. Using conclusions based on analysis of the tidal prism and littoral drift relationship, the Gold Coast Seaway seems to be becoming a stable inlet while Jumpinpin Bar seems to be more of a dynamic inlet. It is important to note that annual variability of littoral drift at the Gold Coast is very high, and depending on the climate conditions, these inlets can change one or two grades in terms of stability rating in different years.

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