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Dynamics of a wave-dominated tidal inlet and influence on adjacent beaches, Currumbin Creek, Gold Coast, Australia

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Abstract

Currumbin Creek on the Australian Gold Coast is a wave-dominated tidal inlet which exhibits a particularly active morphology. The recent history of Currumbin Creek entrance has seen rapid growth of the entrance for access to the ocean by fishermen, as a world class surfing site, and as a recreational area. Before the construction of two groynes in the 70's, Currumbin Creek entrance was highly variable in terms of inlet location and sand bar characteristics due to a cyclical behaviour of spit migration. Nowadays, the entrance is stabilised. However, natural processes continue with the entrance infilling causing flood and navigation issues, resulting in a regular dredging program to maintain an open entrance and for regular beach nourishment plans.

This paper investigates the behaviour of the entrance and adjacent beaches from aerial photographs and numerical modelling. Before groyne construction, sand by-passing was intense resulting in channel migration and sometimes the closure of the mouth. After training works, the longshore drift is diverted further north from the mouth leading to new circulation patterns behind the headland. During fair weather conditions, the sand transported by the longshore current is trapped by Currumbin rock groyne resulting in a negative sediment budget in Palm Beach. For high energy conditions, the diverted longshore current splits in the southern Palm Beach, resulting in a circulation cell. The sediment of the southern beaches is stirred up and transported both northward and toward the inlet.

Keywords: Tidal inlet; Longshore drift; Mouth infilling; Modelling; Dredging activity; Adjacent beach erosion

1. Introduction

Coastal zones can be considered as open systems, continuously remodelled by wave and tidal action. In particular, tidal inlets are prone to rapid evolution: channel migration, loss of sand and erosion or accretion of adjacent beaches.

According to Hayes (1979), tidal inlets occur usually in meso-tidal environments, with moderate wave energy (about 0.6 to 1.5 m). Tidal inlets are considered as a channel developed across a barrier, where tidal currents are accelerated. Sediment transport, sediment budgets and resulting morphological evolution of tidal inlets have already been widely studied by coastal engineers and sedimentologists (Oertel, 1972, 1975; Dean and Walton, 1975; Hayes, 1980; Fitzgerald, 1996; Komar, 1996; Balouin et al., 2001; Bertin et al., 2005). Sedimentary processes and tidal inlet morphology are related to the combined action of tidal currents and the wave-induced currents. Their relative influence results in complex channel and bank migration (Fitzgerald et al., 1984; Hicks and Hume, 1996; Jaffe et al., 1997). Variations of hydrodynamics (flood event, changes in offshore wave conditions, etc.) can generate changes in sediment transport, which will act on the sand volume transferred to the coast downstream, influencing accretion or erosion of adjacent beaches.

The channel migration and the sediment by-pass play a key role in adjacent beach morphology. The mechanisms controlling

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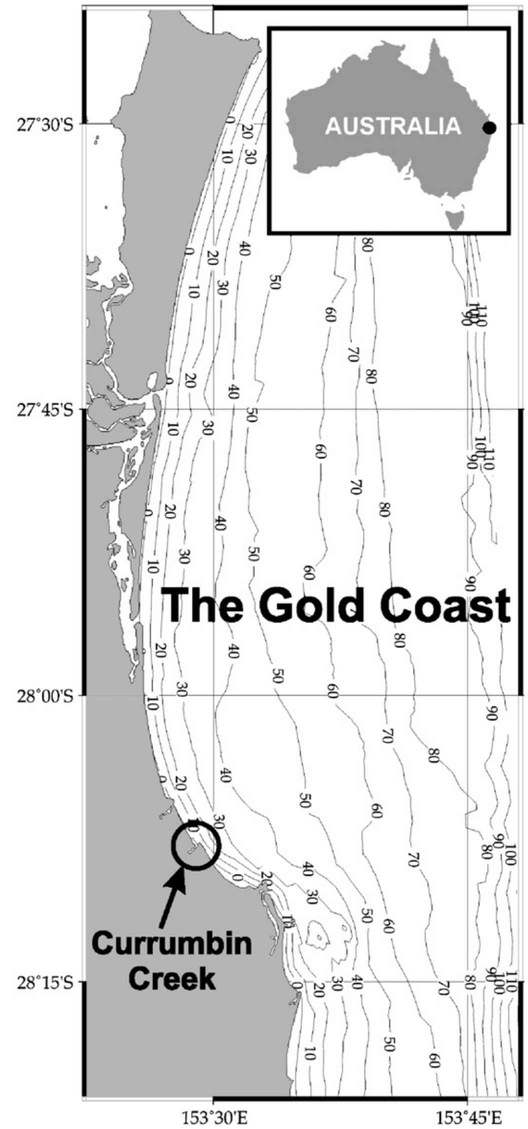

Fig. 1. Location of Currumbin Creek on the Gold Coast, Queensland, Australia.

the by-pass of sediments have already been studied in the past (Brunn and Gerritsen, 1959; Tomlinson and Foster, 1987; Fitzgerald et al., 2001) and some conceptual models of estuarine entrance evolution and by-passing have been proposed (Fitzgerald, 1996). Tidal inlets interrupt the longshore drift affecting the adjacent beach morphology and the formation of shoals on both sides of the inlet. Several authors used empirical formulas to quantify the inlet interference with the littoral drift (Brunn and Gerritsen, 1959; Fitzgerald et al., 1978; Brunn, 1986). The formulation commonly used is:

$$r = \Omega / M_{\mathrm{tot}} \tag{1}$$

where Ω is the tidal prism (m^3) and M_{tot} the total amount of littoral drift (m^3/year). Five types of inlet were defined depending on the value of r, from tidal dominated inlet ($r>150$) to wave dominated and unstable inlets likely to close easily ($r<20$). Later, Oertel (1988) used r and the comparison between the Seaward Limit of a natural inlet Jet SL_{jf} and the adjacent Littoral Zone (SL_{lz}) to describe 4 types of inlets. These different empirical formulations were widely used to classify inlets (Gao and Collins, 1994; Michel, 1997). Numerical models were also used to investigate waves, flows, sediment transport and morphological evolution of tidal inlets (Wang et al., 1995; Cayocca, 2001; Van Leeuwen et al., 2003). Such models were used successfully to simulate water motion and morphology of tidal inlets on timescales of several weeks to several years.

Currumbin Creek is a major waterway estuary within the City of the Gold Coast. Even though it is a small scale creek, its recent history has seen rapid growth in the use of the entrance for the access to the ocean by fishermen, as a world class surfing site, and as a recreational area accommodating still and open water activities. The entrance is also an integral part of active littoral sand movement along the southern Gold Coast beaches. Prior to the 1970's, the entrance was highly variable, in terms of position and morphology, and the creek was trained with a rock wall (1973) and then with a groyne (1980) to stabilize the inlet. Nowadays, the entrance infilling has become a major issue and dredging works are undertaken to keep the entrance open.

The purpose of this work is to investigate the tidal entrance behaviour in relation to wall constructions and coastal processes, and to propose a schematic model of entrance evolution, from aerial pictures and numerical modelling.

2. Study area

2.1. Characteristics of Currumbin Creek entrance

Currumbin Creek is located at the south extremity of Palm Beach on the Gold Coast, Queensland (see Fig. 1). Fig. 2 is a map of Currumbin Creek and Palm Beach showing the entrance

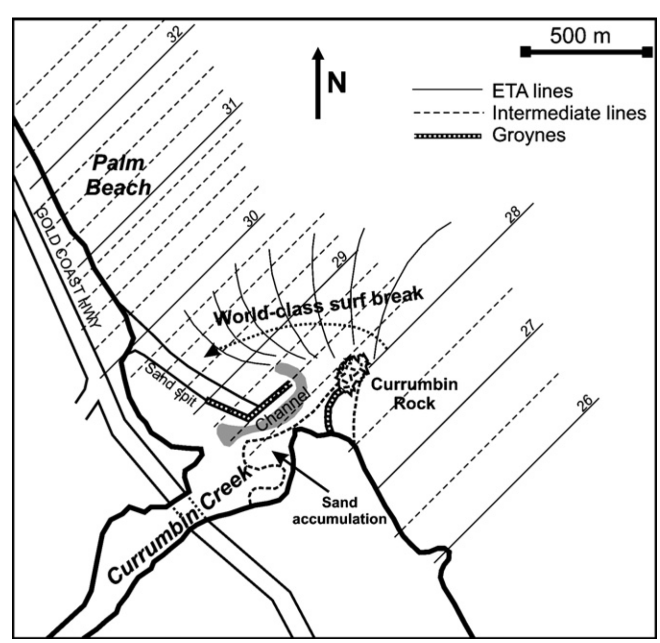

Fig. 2. Currumbin Creek and the southern part of Palm Beach in current configuration. Location of the groynes, the sand spit, the channel, the surfing break and the ETA lines.

configuration with the location of the groynes, the channels, and sand accumulations. This figure also displays the established lines (called ETA lines) along which beach profiles are surveyed. The alongshore spacing between each ETA line is 400 m, with further subdivisions for some beach compartments. The estuary enters the ocean downdrift from a headland (Currumbin Rock).

The freshwater discharges are very low, about 6–70 Mm^3/year. Due to the weak river discharges, the creek is characterized as a tidal inlet rather than an estuary with a persistent freshwater flow. The Currumbin tidal cycle is as for all Gold Coast beaches, with a semi-diurnal cycle, varying from 0.2 to 2 m, with a mean of 1 m.

The area is exposed to energetic swells. Three swell regimes can be considered dominant on the coastal dynamics. The first one is South to Southeast swells in winter and spring, generated by intense low pressure systems off the NSW coast. These contribute to the main component of the northerly littoral drift. The second swell regime is generated by tropical cyclones during the November to April period. During this period, tropical cyclones develop in the Coral Sea and can move southward into the south Queensland coastal region. Most systems weaken considerably as they move southwards into the region and many pass well out to sea. Even if tropical cyclones are not responsible for the majority of the high wave events on the Gold Coast (Allen and Callaghan, 1999), they can generate a northeast to east swell, sometimes with a destructive power (Hobbs and Lawson, 1982), with significant wave height up to 8 m. The third swell regime is generated by East Coast Lows which is a common storm type on the Gold Coast region. They occur more frequently between March and July and can produce severe gale conditions over periods of up to several days (Callaghan, 1986), associated with Northeast to Southeast swells, often resulting in loss of life and property from flooding and maritime incidents (Allen and Callaghan, 1999).

The sediment consists of fine sand (d_{50}=200 μm). The creek has a relatively small average sediment load estimated to be 994 m^3/year, and does not contribute significantly to sediment budget. The Gold Coast longshore drift is 500,000 m^3/year on average, towards the north. This net transport is estimated to comprise approximately 650,000 m^3/year toward the north, and 150,000 m^3/year toward the south (Turner, 2006).

2.2. History of Currumbin Creek and impact on Palm Beach

Prior to the 1970’s, the entrance was highly variable, in terms of position and morphology (see Fig. 3A). A permanent meandering of the Currumbin creek mouth to the North was forced by a net northerly longshore drift. The sand was transported by the longshore current through the gap between Currumbin Rock and the shoreline. The Currumbin entrance acted both as a sediment source and a sediment sink, as the sand drift that filled the entrance during high littoral transport was released into the beach system during flood events. The meandering of Currumbin Creek mouth also caused periodic erosion of South Palm Beach. As part of recommendations for beach management (DHL, 1970), it was proposed to train the entrance to prevent entrance migration and the blocking of the mouth during flood conditions. The need to stabilise the entrance was addressed with the construction of the Currumbin Seawall in 1973 (see Fig. 3B). Since this construction, Currumbin Rock acts as a headland allowing natural sand bypassing under sufficient wave conditions.

Palm Beach erosion and entrance instabilities continued after the seawall construction. In February 1974, two cyclone events completely destroyed the sand spit, allowing wave to penetrate through the mouth. It caused the majority of the littoral drift to be interrupted with rapid infilling of the entrance. The spit was rebuilt to avoid massive erosion of downdrift beaches due to a lack of littoral drift to Palm Beach. Later, a semi-cyclonic event caused another breach in the spit, triggering a decision to

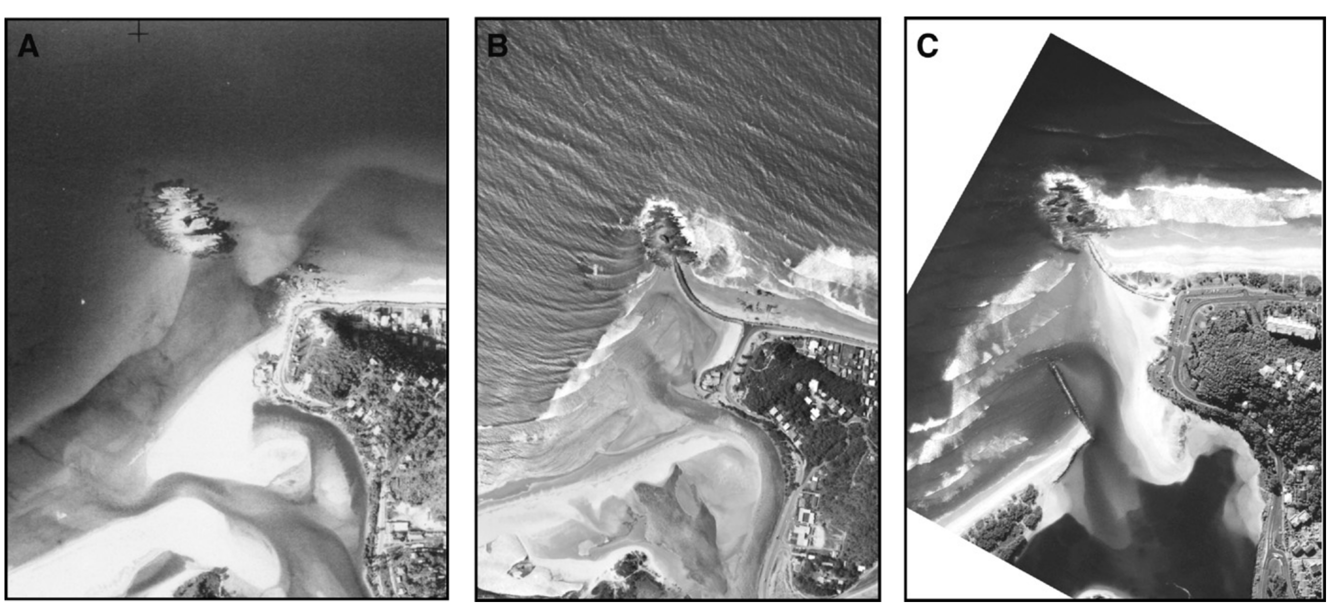

Fig. 3. Aerial photograph of Currumbin Creek. A: Before 1973 in its natural configuration; B: after construction of the first groyne; C: actual configuration.

armour the end of the spit. Due to a lack of finance a single groyne was added only in 1980 (see Fig. 3C).

Nowadays, construction of the entrance training works keeps the estuary clean for recreational activities, reduces the closure problem, and permits the estuarine sand reserve to be used for beach nourishment on Palm Beach. However, Currumbin entrance infilling and Palm Beach erosion are still highly problematic (D'Agata and Tomlinson, 2001). A series of dredging programs was done in the internal delta of the mouth, in the 1980's and 1990's to continue to provide small boat access to the ocean, and to nourish Palm Beach. These dredging programs raised some important issues and generated criticism from various sectors. Alternative innovative and cost-effective approaches to channel maintenance and downdrift beach nourishment are now being sought.

2.3. Constraints

Developing a sustainable long-term channel maintenance strategy for Currumbin entrance will require addressing various constraints on the natural characteristics of the estuary and adjacent beaches, on recreational users and costs. Six major issues can be put forward.

[1] The cost of dredging is high. A robust scientific approach to the investigation of workable options for low-cost dredging options is required. Table 1 shows the previous dredged quantities from Currumbin Creek. After all those dredging works, it has been observed that the hole created by the dredging refills at an amazing speed. After only a few months, the initial delta shape reformed as quickly as the maximum rate of sand transport (D'Agata and Mc Grath, 2002). Fig. 4 displays a sequence of Currumbin Creek entrance area before, during and 6 months after the 30,000 m^3 dredging exercise in 2001. This sequence highlights that the Currumbin inlet dredged area tends to infill very quickly after the dredging work.

[2] Flood risk assessment is a major issue. The channel must be deep enough during high rain fall events to prevent the flooding of adjacent areas. Development upstream near

Table 1
Dredge quantities from Currumbin Creek, after D'Agata and Mc Grath (2002)

Year	Volume (m^3)
1974/1975	148,450
1976/1977	111,325
1978/1979	124,000
1979/1980	153,470
1980/1981	57,000
1981/1982	300,000
1983/1984	48,850
1984/1985	0
1985/1986	90,000
1986/1990	0
1990/1991	40,000
1991/1992	70,000
1992/1993	65,000
2001	30,000

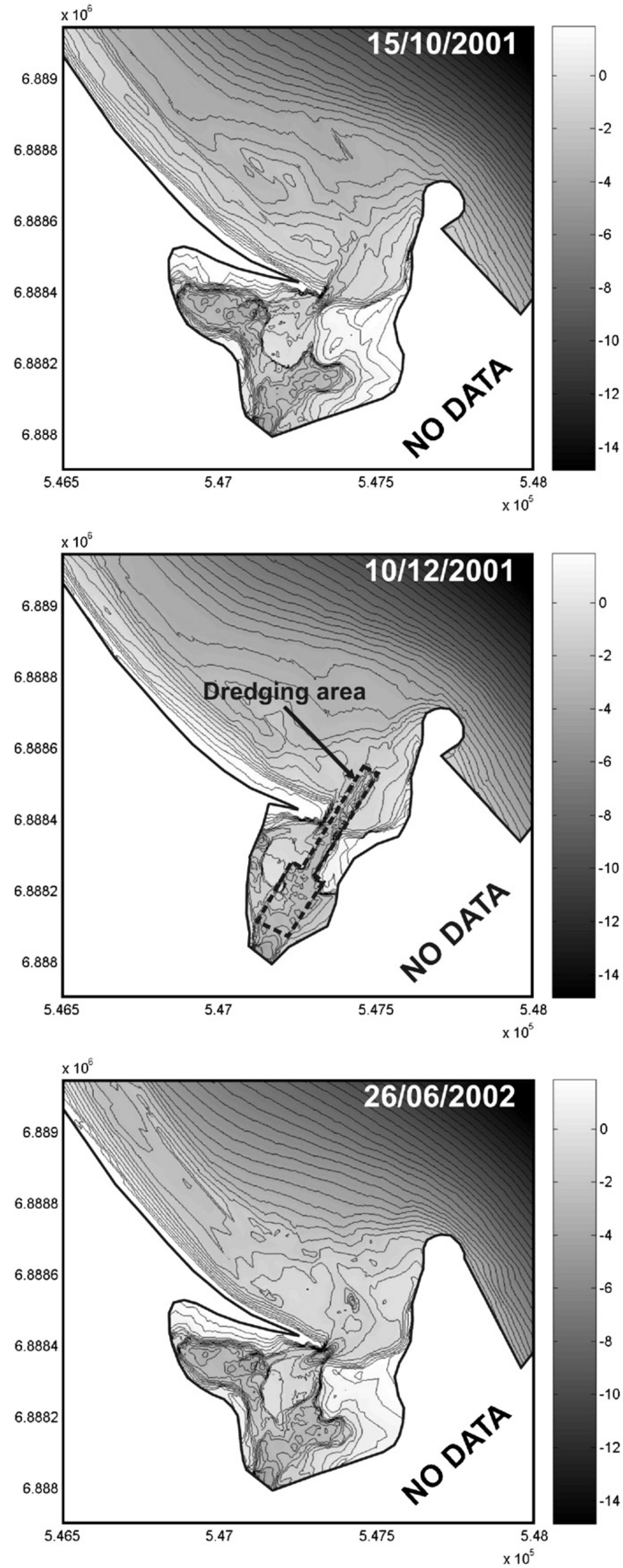

Fig. 4. Sequence of Currumbin Creek entrance area before (15/10/2001), during (10/12/2001) and 6 months after (26/06/2002) a 30,000 m^3 dredging work.

Table 2
Previous beach nourishment of South Palm Beach, after D'Agata and Mc Grath (2002)

Year	Volume (m^3)	Nourishment length (m)	Volume per unit length (m^3/m)	Nourishment location	Effectiveness
1973/1974	400,000	500	800	Spit 28.25–29A	High
1975	15,000	100	150	Spit 28.25–28A	High
1976	100,000	400	250	30–31	Nil
1978–1979	200,000	500	400	Spit 28.25–29A	Nil
1980–1981	100,000	400	500	29A–30A	Nil
1985	100,000	600	166	31–32A	High
1987	90,000	600	150	29–30A	Nil
2001	30,000	200	150	28–28A	Nil

Currumbin Creek means there are increasing concerns over water quality and flooding. Recently, the flooding event of the 30th of June 2005 strongly highlighted the need of a careful flood risk assessment for further dredging works.

[3] The impact on recreational users must be taken into account. This entrance is one of the busiest in Queensland for all type of crafts (swimmers, boats, canoe, jet-ski, surf, longboard, etc.) and the community engagement is high on the Gold Coast. Community attitude assessment and community involvement in coastal engineering are now part of each coastal engineering project on the Gold Coast. Indeed, the recent Palm Beach Protection Strategy generated considerable objections from the local community, and strongly demonstrated the need for in-depth community involvement.

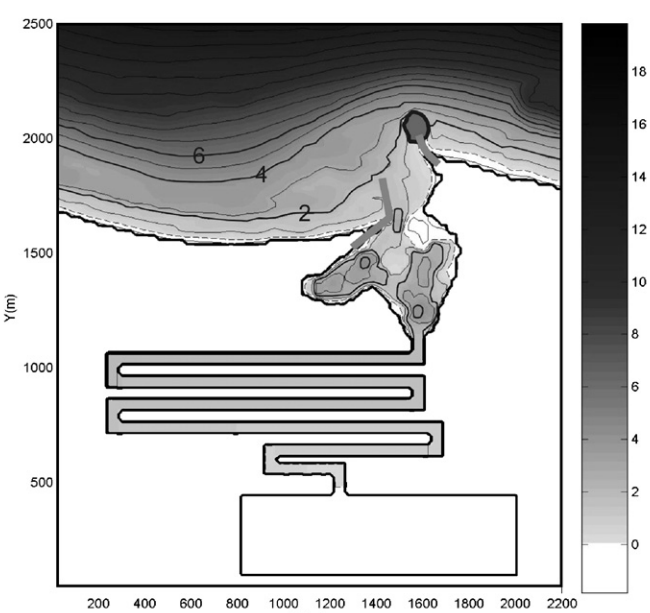

Fig. 5. Numerical bathymetry of Currumbin Creek used for simulations (actual configuration), $\Delta x = \Delta y = 20$ m. An artificial extension of Currumbin is done to allow the tidal wave to go through the river and generate tidal currents.

[4] Adjacent beach erosion is one of the major problems. Huge erosion can be observed in the southern part of Palm Beach, situated just downstream of Currumbin entrance (Fig. 2). This erosion process is often observed for high energy conditions, but also during a very long period of calm conditions. For example during the period 1976–1985, no major storm occurred, allowing only weak Gold Coast headlands by-passing of the littoral drift. It resulted in local erosion shadows downdrift of all the Gold Coast headlands, and particularly on Palm Beach (Smith and Jackson, 1993). Table 2 describes the previous beach nourishments of South Palm Beach and their effectiveness.

[5] Dredging of Currumbin entrance can have an impact on the natural reef located seaward to the northern part of Palm Beach. The dumped sand can influence water turbidity and sea life around the natural reef. Dumping areas have to be chosen carefully, i.e. far enough from the natural reef and within the southern part of Palm Beach.

[6] Training works around Currumbin Creek could have disastrous effects on this world class surfing site (see Fig. 2) with a wave which breaks over the offshore bar all

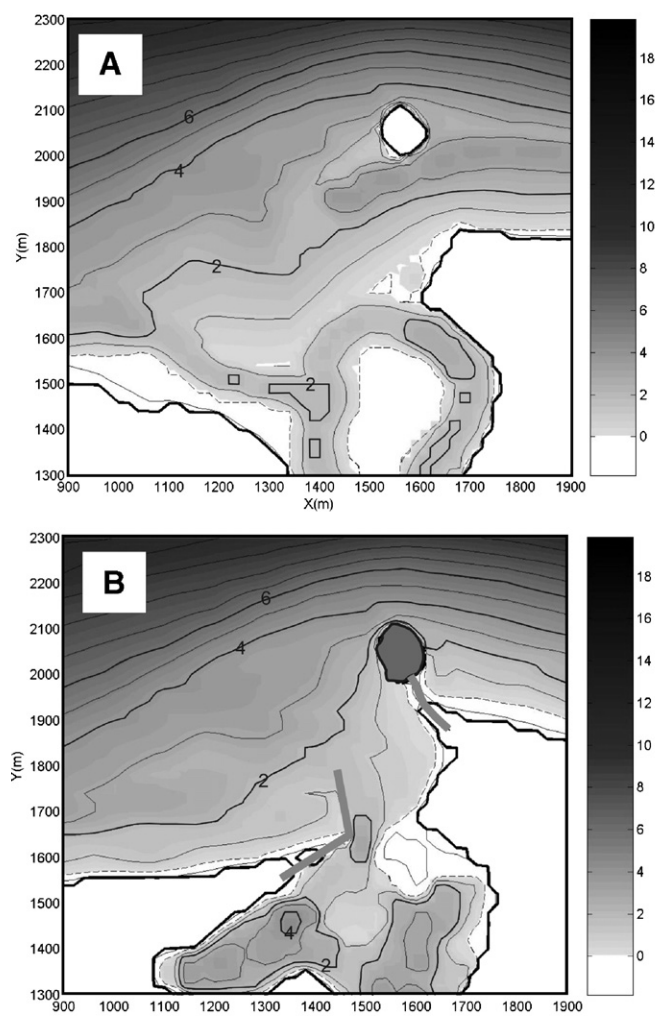

Fig. 6. Zoom around Currumbin Creek mouth: numerical bathymetry and water depth at low tide. A: Natural configuration; B: actual configuration.

the way through from Currumbin Rock to the spit. During a week-end of good waves, hundreds of surfers can be observed in the breaking zone. For this reason and the community criticism and involvement, dredging is not undertaken on the offshore bar (where the waves break) and restricted to the internal shoals.

3. Model

3.1. Delft 3D

The modelling system Delft 3D is developed by Delft Hydraulics (Roelvink and Banning, 1994; Lesser et al., 2004). Delft 3D is a software package which consists of several modules coupled together to provide a complete picture of three-dimensional flow, surface waves, water quality, ecology, sediment transport and bottom morphology in complex coastal areas. The modules to be used in the present study are WAVE and FLOW. Delft 3D has been used extensively world-wide for coastal process studies and is well suited for beach and tidal inlet morphodynamics and hydrodynamics.

The wave model used in the present study is SWAN (Booij et al., 1999) which requires no restriction on wave approach angle or directional width. SWAN solves the spectral action balance equation (Hasselmann et al., 1973) and is able to simulate accurately the wave field in coastal areas where reflection and diffraction are not significant (Ris et al., 1998; Castelle et al., 2006). According to field observations and aerial photographs, wave refraction and depth-induced breaking are the predominant processes which control the wave field around Currumbin Creek. The model considers a set of steady state situations that requires the time of propagation of the waves through the domain to be short compared to the variation of water level and current. Triad interaction is taken into account in the computations. As wave refraction by the tidal currents can lead to an increase of the wave height by 50% in some estuaries (Bondzie and Panchang, 1993), wave-current interaction is therefore taken into account. The breaking wave model chosen herein is the bore-based model of Battjes and Janssen (1978), with a constant breaker parameter $\gamma=0.73$ following Battjes and Stive (1985). The driving terms of the hydrodynamic model are given by the radiation stress components (Longuet-Higgins and Stewart, 1964).

The flow module used herein is 2-D mode (depth averaged). The governing equations of the flow module are the depth-averaged continuity equation and the depth-averaged momentum

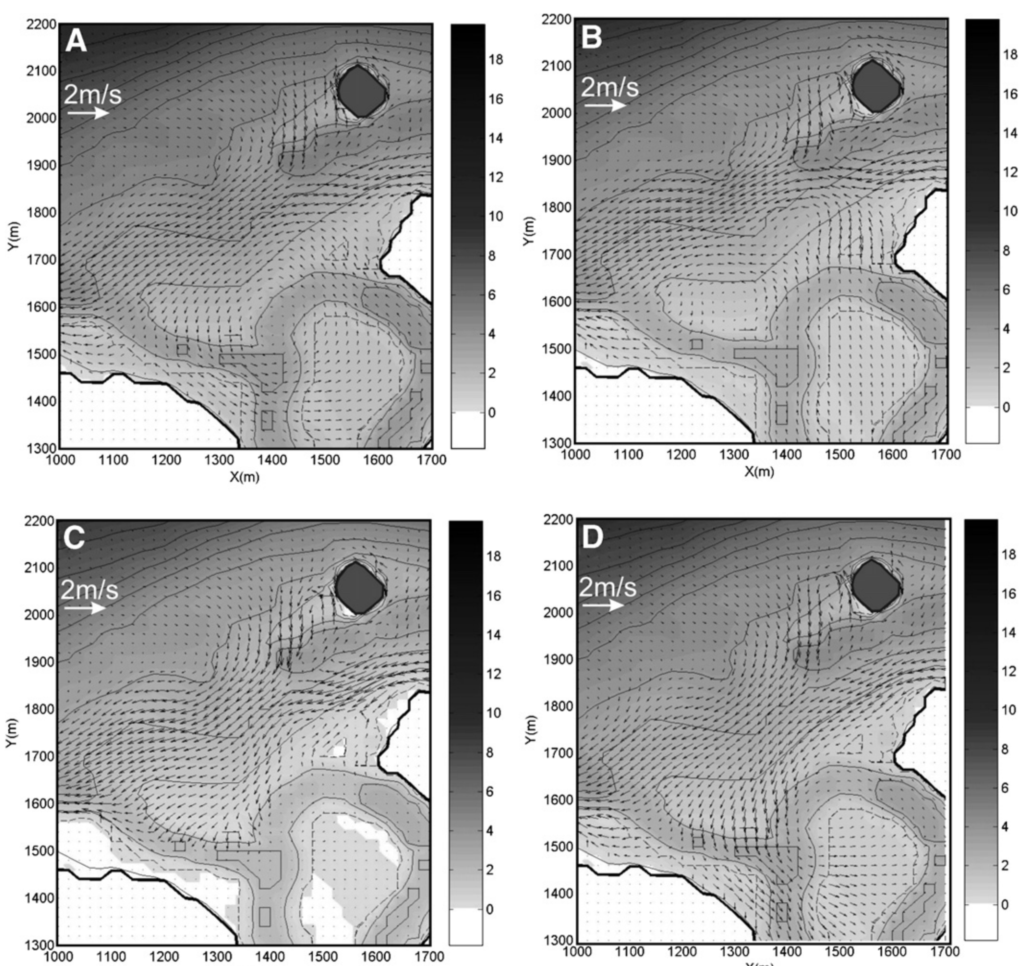

Fig. 7. Simulation of flows at Currumbin Creek area during a tidal cycle (tidal range of 1.5 m) in its natural configuration, zoom on the mouth. Offshore wave conditions: $H_s=1.2$ m, $T=10$ s, $\theta=45°$. A: high tide; B: mid-falling tide; C: low tide; D: mid-rising tide.

equations in horizontal direction. The shear-stress at the bed is given by a quadratic friction law and a spatially constant Chezy coefficient. The Reynold's stresses are determined using the eddy viscosity concept (Rodi, 1984). For the present study, the horizontal eddy viscosity is chosen to be 1 m^2/s. The wave induced force is given by the spatial gradient of the radiation stress tensor (Longuet-Higgins and Stewart, 1964), and tide forcing is implemented at the offshore boundary. Van Leeuwen and De Swart (2002) showed that, for large scale tidal inlets, the progressive Kelvin wave could have a significant impact on flow patterns and resulting sediment transport. A very small scale tidal inlet is investigated in this study, that is why tidal phase difference was not taken into account at the offshore boundary conditions.

3.2. Model settings

To develop such a predictive capability for changes within Currumbin Creek and Palm Beach for period over periods days to months, accurate bathymetric data is required. Bathymetric surveys provided by the council (ETA lines, and survey area around the mouth during 2001), Geosciences Australia data for the continental shelf, and shoreline surveys are used to create a refined numerical bathymetry of the area.

The computational grid is rectangular, with square meshes of 20 * 20 m. It includes Palm Beach and Currumbin Creek. Wave boundary conditions are provided by a wave model which covers the Gold Coast as far as 50 m depth and extends northward and southward about 5 km alongshore. Fig. 5 shows the numerical bathymetry of Currumbin Creek in its actual configuration used for simulation. Due to the lack of survey data upstream of Currumbin estuary, an artificial tidal basin was implemented in order to allow the tidal wave to generate tidal currents in the inlet. The size of the tidal basin was deduced from the estimation of the tidal prism and data on the magnitude of the tidal current in the estuary mouth.

From aerial photographs and engineering reports on Currumbin Creek, a numerical bathymetry in its natural state (i.e. with no groyne, before 1973) was created. Fig. 6 shows a zoom on the Currumbin Creek inlet numerical bathymetry. Before groyne constructions, the estuary mouth was wide with one channel (Fig. 6A). A single channel follows the northern coast (called North channel), while a second channel (called South channel) tends to open up on the southern side of the

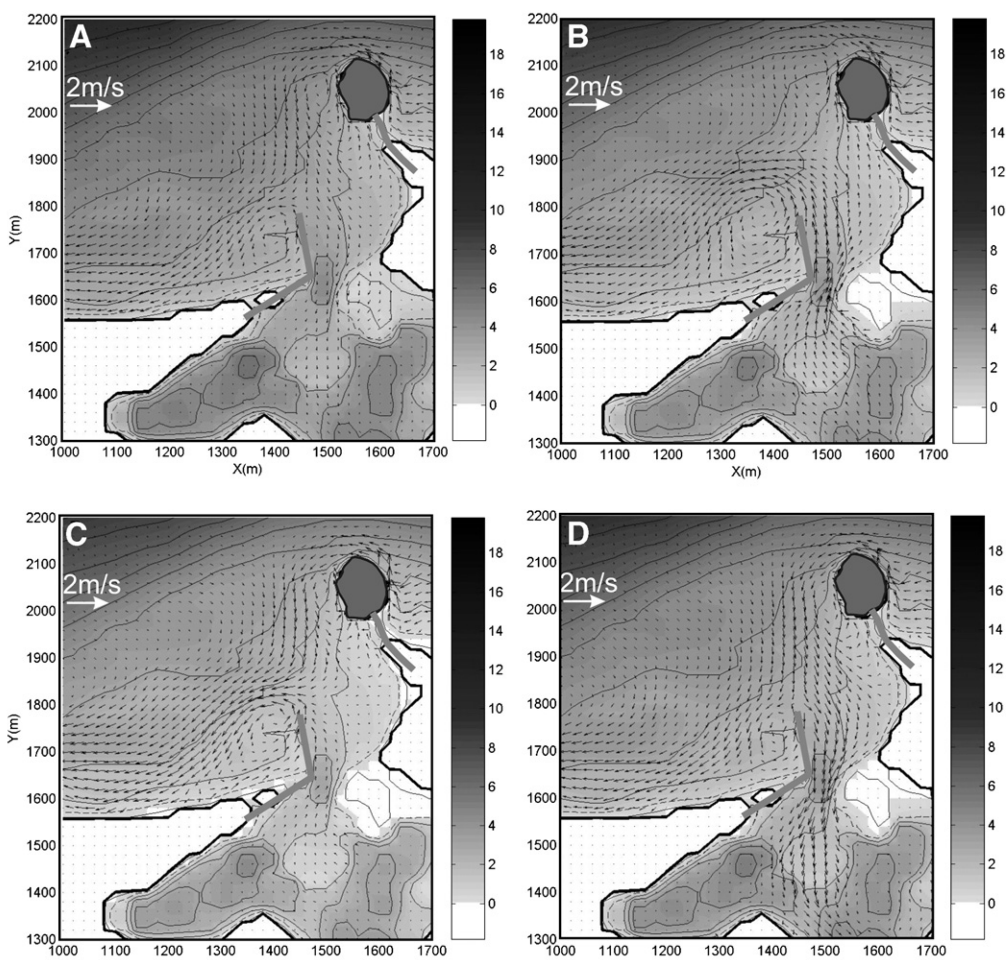

Fig. 8. Simulation of flows at Currumbin Creek area during a tidal cycle (tidal range of 1.5m) in its actual configuration, zoom on the mouth. Offshore wave conditions: H_s=1.2 m, T=10 s, θ=45°. A: high tide; B: mid-falling tide; C: low tide; D: mid-rising tide.

mouth. This kind of morphological configuration was often observed on aerial photographs and often preceded the infilling of the North channel and the opening of the South channel. This is why this particular configuration was chosen to be representative of Currumbin Creek estuary in its natural state. After groyne constructions, the numerical bathymetry deduced from accurate bathymetry surveys shows a narrow inlet between the sand spit and Currumbin Rock (Fig. 6B).

After an initial calculation of the waves, the flow is calculated. The flow time step is chosen to be 6 s. After 300 time steps (i.e. 30 min.), the waves are recomputed with the new tide level to provide a new wave forcing. Computations are done for two tide cycles. During the beginning of the first tide cycle, a transition state is observed. In the following, results are dealing with the second tide cycle flows which are not disturbed by the initial conditions.

4. Results

4.1. Quantification of Currumbin inlet interference with littoral drift

Human related changes affecting inlet morphology such as dredging or groynes in order to increase the tidal prism and to maintain the efficiency of the channel are poorly documented (Cleary and Fitzgerald, 2003; Bertin et al., 2005). Because the bathymetry survey of 2001 (from which the numerical bathymetry on Fig. 6B is deduced) constitutes the most accurate data on Currumbin inlet, it is used to estimate the interference of the inlet with the littoral drift. To get an estimation of the tidal prism Ω, the empirical relation of O'Brien (1931) between the inlet throat and the tidal prism is used:

$$\Omega = (A/C)^{1/n} \tag{2}$$

where A is the inlet throat cross sectional area (m^2), and C and n are constants determined from regression analysis (O'Brien, 1931; Metha, 1976; Goodwin, 1996; Michel, 1997). After a literature review of several inlets by Michel (1997), the values of $C=10.10^{-4}$ and $n=0.9047$ were chosen. According to the 2001 survey, the throat A of the tidal inlet is 165 m^2. The tidal prism with the actual characteristics of the inlet is then about 1.610 m^3. With a longshore drift of approximately 500,000 m^3/year, the ratio r (Eq. (1)) obtained is 3.2. This indicates that by-passing is much more important than tidal effects and therefore corresponds to inlets which are not stable and easily closed. However, these empirical formula do not take into account the presence of the headland (due to the groyne between Currumbin rock and the shoreline), and the groyne at the spit extremity which stabilised the channel.

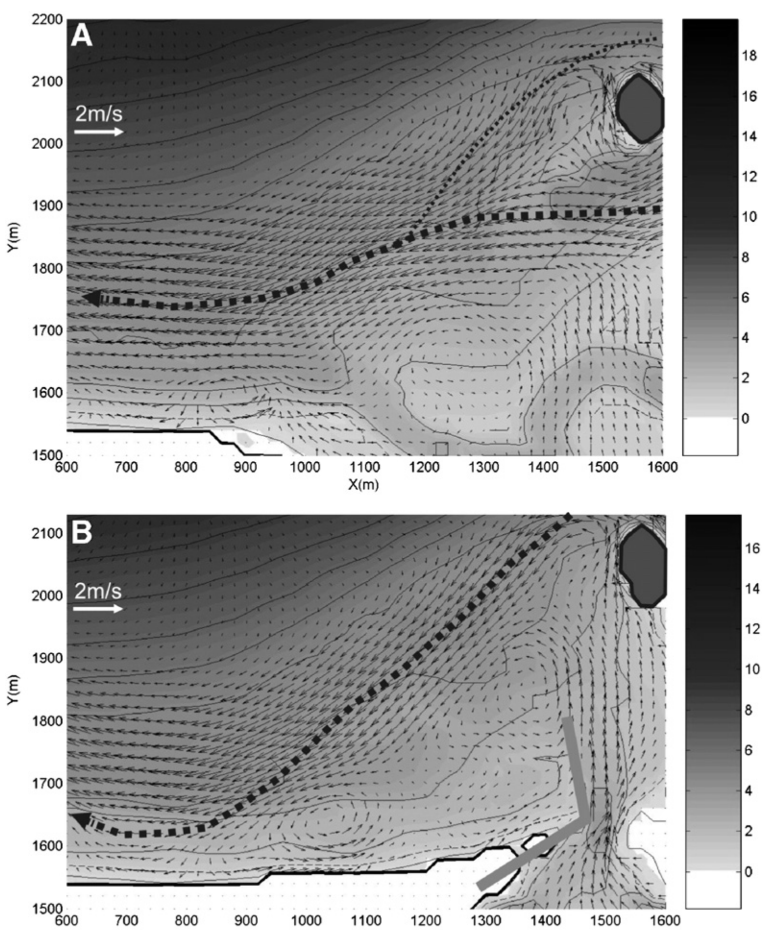

Fig. 9. Simulation of flows at Currumbin Creek area during at mid-falling tide zoom on the mouth. Offshore wave conditions: $H_s=2$ m, $T=10$ s, $\theta=45°$ allowing sand by-pass. A: natural configuration; B: actual configuration.

4.2. Model results

Simulations were performed for different offshore wave conditions for both Currumbin Creek configurations (Fig. 6A and B). The offshore wave conditions were chosen to be the most representative of Currumbin wave conditions for their influence on littoral drift. Given the wave climate and the littoral drift described in Section 2.1, 3 low energy to moderate energy SE swells and a high energy E–NE swell were chosen for the following simulations.

Fig. 7 shows the instantaneous flow field during a spring tide cycle (tidal range of 1.5 m), for offshore significant wave height $H_s = 1.2$ m, wave period $T = 10$ s and offshore wave angle to the East direction of $\theta = 45°$ (SE swell). These offshore wave conditions are typical of winter conditions on the Gold Coast, and responsible for the main component of the annual littoral drift. At high tide (Fig. 7A), wave-induced currents are predominant with a longshore current present across the whole inlet. In the estuary, upstream of the longshore current, an anti-clockwise circulation eddy is observed which would tend to infill the North channel and open the South channel. This tendency is reinforced for the ebb (Fig. 7B) when the circulation almost disappears. It is replaced by flows oriented seaward located at the southern part of the mouth. At low tide (Fig. 7C), the estuary is almost connected to the ocean only at the North channel. It results in a predominant longshore current in front of the mouth, without the strong influence of tidal currents. During the flood (Fig. 7D), tidal currents are intense with a anti-clockwise circulation eddy which is nourished by both the longshore current and the flood current. From these simulations, it seems that the waves affect the currents inside the tidal inlet, particularly during flood when a large part of the littoral drift can enter the entrance. As sand is transported by the longshore current through the gap between the Currumbin rock and the shoreline, by-passing is intense. The wave forcing used for this simulation (Fig. 7) would quickly lead to a closure of the North channel and an opening the South channel.

Fig. 8 shows the instantaneous flow field during the same conditions as Fig. 7, for the actual configuration of Currumbin Creek. At high tide (Fig. 8A), tidal currents are not significant and the longshore current is predominant. However, this longshore current is weaker than for the natural configuration (of the order of 0.4 m/s instead of 0.7 m/s). Due to the seawall between Currumbin rock and the shoreline, the longshore current is

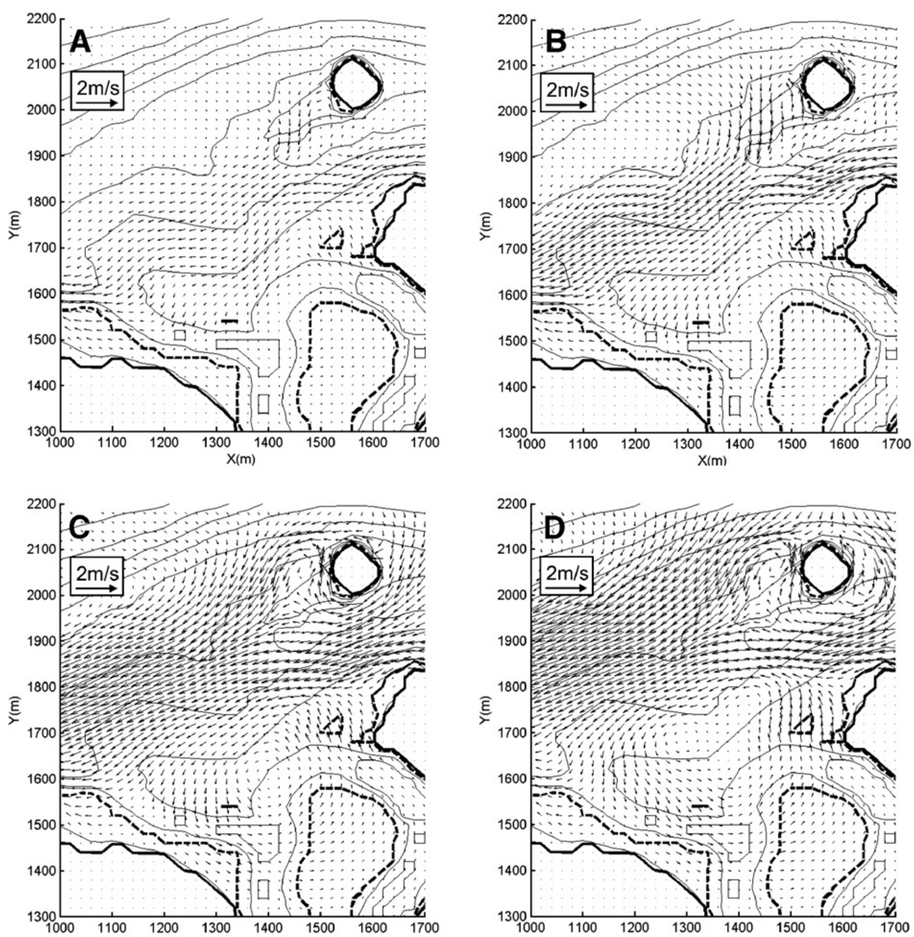

Fig. 10. Residual flow velocity field over a tide cycle at Currumbin Creek area in its natural configuration; thick line: spring high tide level; dot line: spring low tide level. A: $H_s = 0.7$ m, $T = 8$ s, $\theta = 45°$ (SE swell); B: $H_s = 1.2$ m, $T = 10$ s, $\theta = 45°$ (SE swell); C: $H_s = 2$ m, $T = 10$ s, $\theta = 45°$ (SE swell); D: $H_s = 3$ m, $T = 10$ s, $\theta = -10°$ (E–NE swell).

diverted further out of the mouth. The change of shoreline orientation induced by sand accumulation updrift the headland also leads to reduction of the wave angle to the shore at the breaking point, which results in weaker longshore radiation stress gradients. The waves refracting around Currumbin rock approach almost shore-normally behind the headland. This results in an almost shoreward oriented longshore current behind the headland. This flow escapes feeding the longshore current in Palm Beach and developing a circulation cell near the spit groyne. This circulation cell is bigger and more intense during ebb (Fig. 8B). The tidal current in the inlet nourishes the circulation cell where maximum flow velocity reaches 0.5 m/s. At low tide (Fig. 8C), the circulation cell is weaker and smaller. The longshore current is still observed on Palm Beach with maximum flow velocity of about 0.5 m/s. During flood (Fig. 8D), this circulation almost disappears. Wave refraction around Currumbin rock and tide induced currents result in an onshore flow from the headland toward the inlet. A longshore current is still observed on Palm Beach, but starts about 400 m northward of the groyne.

For high energy conditions, the flow patterns are quite different. During winter, periods of high northerly littoral drift are related to the occurrence of high energy southerly swells. Fig. 9 displays the flow simulation for offshore southerly energetic wave conditions (H_s=2 m, T=10 s, θ=45°) during ebb. For the natural configuration (Fig. 9A), a strong longshore current is observed with maximum flow velocity reaching 1.2 m/s. The longshore current is not disturbed by tidal flow and sand by-passing is intense. For the actual configuration of Currumbin Creek (Fig. 9B), the longshore current is intense too, with maximum flow velocity reaching 1.2 m/s out of the mouth. Sand by-pass is intense for these wave conditions; however the shape of the longshore current is strongly different than the longshore current simulated for the natural configuration. On Fig. 9B, the longshore current is strongly shoreward oriented and is diverted on southern Palm Beach. It then becomes longshore oriented. Thus, during these particular conditions, this rotation of the longshore current is likely to stir up large amount of sediment of the sediment of southern Palm Beach. This sediment can be transported northward or can be deposited near the groyne where flows are weak.

Sensitivity of the flow field to offshore wave conditions can be addressed looking at the residual flow field over a tidal cycle. Fig. 10 shows residual flow field over a tidal cycle, for Currumbin Creek in its natural configuration, for 4 different offshore wave conditions. For SE offshore wave conditions

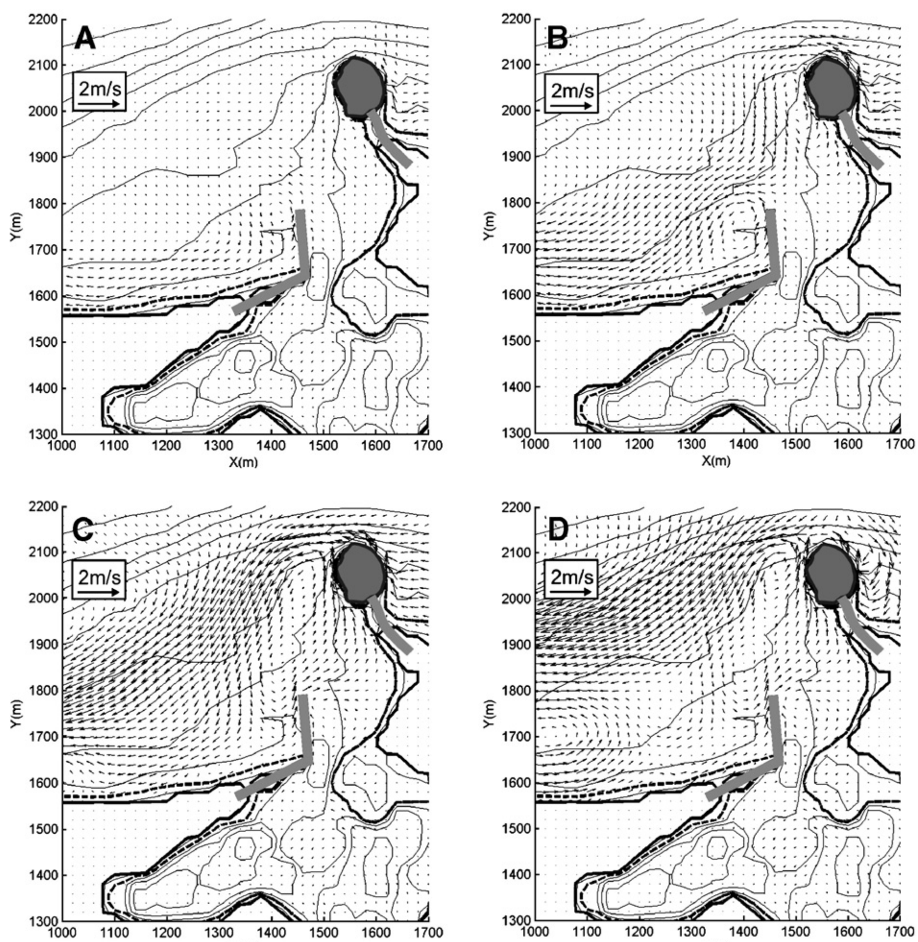

Fig. 11. Residual flow velocity field over a tide cycle at Currumbin Creek area in its actual configuration; thick line: spring high tide level; dot line: spring low tide level. A: H_s=0.7 m, T=8 s, θ=45° (SE swell); B: H_s=1.2 m, T=10 s, θ=45° (SE swell); C: H_s=2 m, T=10 s, θ=45° (SE swell); D: H_s=3 m, T=10 s, θ=−10° (E–NE swell).

(Fig. 10A, B and C), the longshore current is always predominant, allowing the entire longshore drift to be transported through the gap between Currumbin rock and the shoreline. During low to average energy conditions (Fig. 10A and B), almost the entire longshore drift is transported to Palm Beach. Simulations show that for energetic SE swells (Fig. 10C), a significant amount of the littoral drift can enter the estuary via the North channel, resulting in a possible infilling of the mouth. For energetic cyclone generated E–NE swells (Fig. 10D), waves roll directly up the estuary with almost no refraction. A predominant longshore currents still exists in front of the mouth, and flow patterns are similar to the one shown on Fig. 10D for energetic SE swell. The residual flow fields over a tide cycle of Currumbin Creek in its actual configuration for the same offshore wave conditions are shown on Fig. 11. For low energy SE swells, the longshore current is completely stopped by the Currumbin rock groyne (Fig. 11A) and a weak longshore current (on the order of 0.4 m/s) restarts on the southern part of Palm Beach. From average to energetic SE swell (Fig. 11A and B), the longshore current is diverted further out from the mouth by the Currumbin rock groyne, and a significant amount of sand is likely to be trapped by the Currumbin rock groyne.

5. Discussion

Quantification of the inlet interference to the littoral drift and simulation both showed that, prior to the groyne construction, Currumbin inlet was strongly wave-dominated. Intense bypassing was observed in the inlet, with most of the sand passing through the gap between Currumbin rock and the shoreline. Even if there is no data available on the inlet morphology allowing an estimation of the past inlet throat cross-sectional area, aerial photographs show that Currumbin inlet had a small scale channel before groyne construction. Archives often show a very shallow meandering channel. Jackson (1995) and Andrews (1999) did historic studies of Currumbin Creek. They showed that the entrance prior to training was generally very shallow with a reduced tidal range in the lower estuary. Currumbin Creek was often closed to the ocean and this sometimes resulted in increased flooding to upstream properties. Also, the mouth was periodically driven northward by the longshore drift causing erosion at southern Palm Beach. A rapid growth of the sand spit northward from the southern side of the entrance was also a common feature before training. The average cycle time for spit growth and migration to breakthrough was approximately 7 years (Jackson, 1995). This sand spit cycle was directly related to the inlet migration cycle. After archives, engineering reports and the simulations presented in this paper, Fig. 12 shows the schematic evolution of Currumbin Creek prior to training works. Three phases are displayed. Starting from a configuration with a single channel following the southern coast of Currumbin Creek, the channel progressively drifts north. This channel continues to migrate northward, eventually reaching south Palm Beach, associated with a second channel starting to open up following the southern coast of Currumbin Creek. Eventually, the infilling of the northern channel and the opening of a new southern channel are observed. The cycle was approximately of 7 years on average but strongly depended on extreme wave events and flooding events.

Stabilisation of the entrance was initially by construction of Currumbin rock groyne. The desired effect was to divert the longshore drift out from the mouth to avoid infilling of the entrance. After the training work, the groyne trapped the sand updrift of the rock as predicted, but also created a large sand sink to the north of the rock. This offshore sink proved to be a long-term problem contributing to erosion of Palm Beach. During fair weather condition, the longshore drift was stopped by the groyne resulting in a negative Palm Beach sediment budget. During sufficiently energetic conditions, sand by-passing was efficient, but a large amount of this sand contributed to the entrance infilling. Indeed, the rotation of the longshore current behind the headland leaded to the formation of an escape current contra to the littoral drift. This escape current extended to the inlet. Fig. 13 shows a schematic representation of the estuary hydrodynamic regime during this period. These circulation patterns behind the headlands raised some important issues. The escape current tended to stabilise the location of the inlet, but also tended to infill it. The splitting of the longshore current in front of the spit stirred up the sediment from the beach leading to an erosion of the spit. The spit was then breached easily during cyclone or flood events. As a large amount of dredged sand from the creek was used to restore the spit during this kind of event, there was only a small sand source left to available to nourish Palm Beach. The priority for engineers was then to stabilize the spit. This was done in 1980 with the spit groyne construction.

After the construction of the second groyne at the spit extremity, circulation patterns strongly changed in comparison with the natural configuration (Figs. 7 and 8). The main difference with the previous configuration (Fig. 13) is that the escape current is now diverted by the second groyne, leading to the formation of a circulation cell while, during fair weather condition, the flow patterns are very close due to the longshore current being still stopped by the first groyne. Simulations show that this circulation cell is present during sufficiently energetic southerly swells. Fig. 14 shows the resulting schematic representation of Currumbin Creek in its current configuration with flow pattern during a southerly swell. The splitting of flows in southern Palm Beach still results in the stirring up of sediment and local erosion. This sand is now transported by the circulation eddy to the extremity of the groyne, where the outlet of the channel is. The spit is now armoured and cannot be breached, so all the sediment dredged in the estuary is now available for beach nourishment at Palm Beach.

For almost all the offshore wave conditions used in this study, the model shows flow patterns likely to erode southern Palm Beach. This is due to the presence of the groyne between Currumbin rock and the shoreline which creates a deficit in the sediment budget. This is confirmed in the field by frequent beach nourishment work undertaken on Palm Beach (Tables 1 and 2). Moreover, abnormally intense erosion of Palm Beach has been observed each time a dredging work was undertaken on the internal delta of Currumbin estuary. It appeared that the hole created by the dredging refills very rapidly (Fig. 4). This

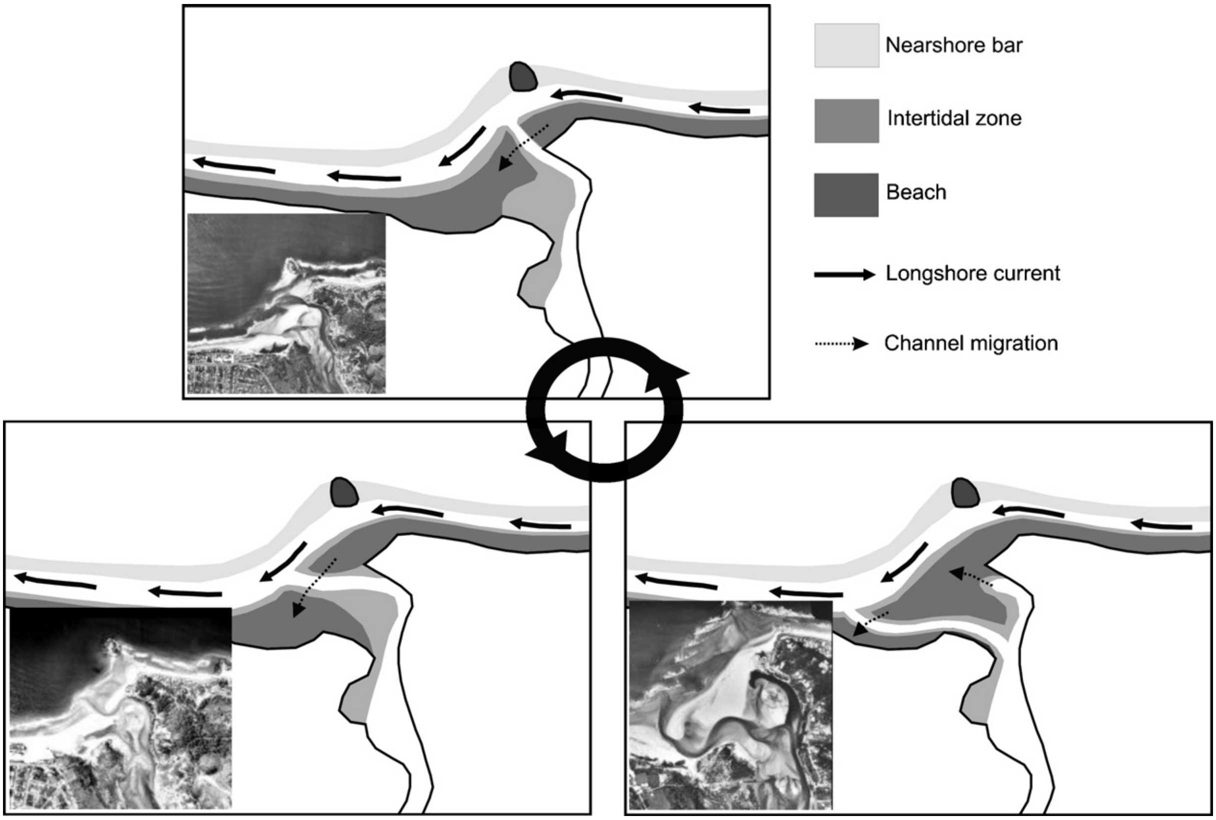

Fig. 12. Schematic evolution of Currumbin Creek prior training works (natural configuration): flows and sand bar migration.

response seems to correspond to a natural storage of sand to recover the unnatural removal of sand from the estuary (D'Agata and Tomlinson, 2001). Southern Palm Beach provides the quickest response to recover sand losses of the internal delta of Currumbin entrance, leading to sand being transported from south Palm Beach into the sink created by the dredging. This sand appears to be transported via the circulation cell induced behind the groyne at the spit extremity (Fig. 14) and tidal currents. Due to the lack of data, this assumption needs further field experiments combined with numerical modelling to be confirmed.

The Currumbin history shows that it is very difficult to find a balance between dredging, inlet stability and nourishment. Periods of intense erosion of Palm Beach were related with high volume of sand dredged from the internal shoals. Involving a relatively small amount of sand, the 2001 dredging experiment showed that the channel was refilled after just 6 months and that it did not have any significant impact on Southern Palm Beach erosion. It suggests that small amounts of sand have to be dredged from the creek in order the natural system to recover its equilibrium without involving external sand from the adjacent beaches. Permanent artificial sand by-passing systems are

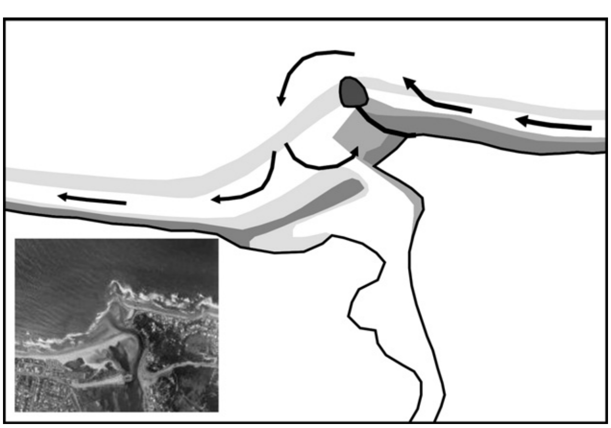

Fig. 13. Schematic representation of flows around Currumbin Creek after construction of the seawall between Currumbin rock and the shoreline.

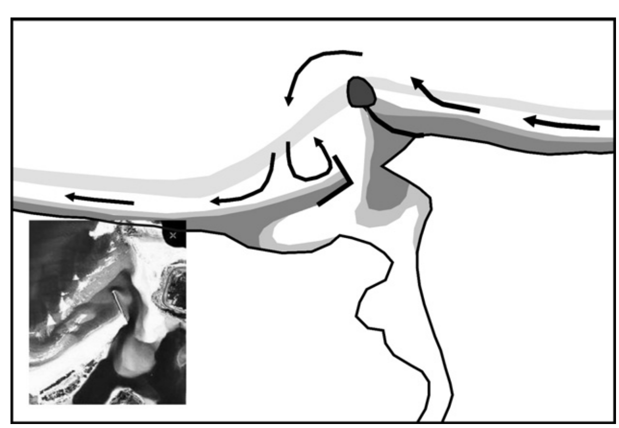

Fig. 14. Schematic representation of flows around Currumbin Creek after training works (actual configuration).

implemented on the Gold Coast at both the Gold Coast Seaway at the northern extremity, and the Tweed River inlet at the southern extremity. This kind of system could also be implemented at Currumbin Creek. However, the cost would be high and the surfing break would be significantly affected. Non-permanent pumped sand from the updrift beach to the downdrift beach associated with small dredged volumes from the internal shoals could also be worthy of evaluation. Further simulations involving sediment transport and morphological evolution are needed to investigate those scenarios.

6. Conclusion

Aerial photographs and numerical modelling were used to investigate the Currumbin Creek estuary behaviour, in response to training works. The model reproduces several characteristics of flows around the entrance which explain the unstable behaviour of the discharge point prior to training works. Cyclic channel migration and related erosion problems at Palm Beach were addressed with the construction of two groynes. The first groyne trapped the sand during fair weather conditions and diverted the longshore drift in front of the mouth during sufficiently high energy wave conditions. It resulted in a stabilisation of the mouth and the sand spit. However, breaching of the spit and continuing problems of erosion at Palm Beach due to a sediment budget deficit forced the construction of a second groyne to armour the spit. Nowadays, training works stabilise the estuary for recreational activity, closure problems are reduced and large amounts of estuarine sand reserve can be used for beach nourishment on Palm Beach. However, entrance infilling remains an open problem. On the one hand boats cannot cross the bar at times due to the lack of water depth and/or hazardous wave conditions. On the other hand, various sector criticisms concerning the offshore bar restricts the dredging program to the internal shoals which cannot completely solve the navigation problem.

This work clearly identified the dynamics of flow and induced sediment patterns and its influence on channel dynamics, infilling problems and adjacent beach erosion. It also presents an obvious example of a man-made construction influencing the coastal environment and its interference with the local community wishes. At the moment, there is no clear method of achieving a low-cost sustainable long-term channel maintenance strategy for Currumbin Creek. The numerical model presented herein will be used to simulate morphological evolution of the creek in order to test different scenarios including groyne extension or reduction and changes in dredge and dump areas.

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