Inlet Migration and Flood-Tidal Delta Morphodynamic Evolution: Case Study of Noosa - QLD, Australia

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Abstract

This paper investigates the natural patterns of variability of the Noosa inlet established after decades of adaptation to the new configuration of the river system resulted from man-made structures installed in the 1970-80’s. Features such as the Northern Spit, Southern Spit, flood-tidal deltas, river channel and surrounding shorelines were mapped, measured and compared based on aerial images from recent years (2010-2018) in a Geographic Information System (GIS). The analysis revealed that Noosa River has currently fluctuated between two dominant patterns of inlet migration integrated with the Northern and Southern Spits development and meandering variability. With a fully-developed flood-tidal delta, Noosa River presents ~ 400,000 m² of stable sand deposits, including some vegetated areas, towards the northern river bank. These formations and the Northern Spit have constrained the Northern Channel that became essentially inactive. In this configuration, Middle and Southern Channel have dominated the river’s morphodynamics. Under a Middle Channel Dominance a quasi shore-parallel migration of the Northern Spit occurs, with the inlet throat migrating towards the training wall. This pattern presents relations to positive rainfall anomalies, mostly during strong La Niña years. The Southern Channel Dominance occurs when wave-dominated conditions favour the longshore sediment transport that builds up the Southern Spit and, consequently, pushes the inlet towards a northward orientation. As a response, the river meandering intensifies the currents that erode Noosa Woods beach. This scenario was observed after a sequence of strong El Niño years. A broad understanding of the flood-tidal delta morphodynamics facing anthropogenic interventions and climate drivers was proven to be a fundamental tool for the management of the Noosa River and adjacent area.

Keywords: Inlet dynamics, sediment bypassing, spit development, beach erosion.

1. Introduction

Navigation, harbor facilities, fishing, tourism and leisure activities and natural breeding environments, among other functions, comprise the list of valuable ecosystem services that tidal inlets and associated water bodies provide to coastal communities. In an attempt to control an inlet’s natural variability and expand the environment uses, coastal engineering approaches have been employed, such as the construction of training walls and other hard structures to maintain entrance stability, the dredging of the channel to increase its capacity for water movement and navigability, and the creation of artificial islands and beaches in the middle lagoon region to enhance residential and recreational areas. However, each of these implemented man-made elements might result in different responses from the river system.

Noosa River (Figure 1) on the Sunshine Coast (Queensland, Australia) is an example of a highly important region encountering some adversities due to the adaptation between river system dynamics and progressive urban development. Prior to the late 1960’s, records indicate that the river system presented a natural variability and response to weather conditions [4], [13], [14]. In a high rainfall event, estuary flooding would form a straight more easterly-oriented channel and migrate the inlet entrance towards southeast, resulting in some erosion of the Southern Spit [4], [13], [14]. In the early 1970’s, a sequence of storms and some channel dredging established the entrance at the Southern Channel, while the Northern Channel was completely closed. This different configuration caused erosion problems at Hayes Island, currently called Noosa Sound (Figure 1) [4], [13], [14]. In 1977, a drier climate allowed the Northern Channel to re-establish as the main flow pathway. In the next year, an extension of the Southern Spit and the training wall at the entrance were completed, moving Noosa River inlet towards the northwest, in order to prevent the erosion of Noosa Sound [4], [13], [14]. Attached to the Southern Spit, an internal spit was developed, infilling the region which was previously the Southern Channel and turned it into the area now known as Noosa Woods (Figure 1).

Although the training wall prevents the entrance moving towards the Southern Spit, the construction of a single wall is not able to completely stabilize a tidal inlet [10]. Tidal inlets are active systems that may vary several meters in position per year due to longshore sediment transport and tidal current action [3], [11], [12]. Their migration and orientation shifts are products of the volume of sand depositing at the entrance or bypassing it [8], [9], [12]. These
movements have an effect on the immediately internal river basin [15]. Every modification at the inlet mouth reflects a natural reworking of the river meandering and floodplain, and vice-versa [5], as part of a see-saw pattern that drives a river’s adaptation.

Completing this complex behaviour, there are the climate-induced river drivers such as rainfall levels and wave climate variability. Waves influence the longshore sediment transport, moving sand around the inlet entrance and frequently allowing a fraction of it to be transported into the river system by the flood tidal currents [8], [9], [12]. Positive rainfall anomalies, on the other hand, increase the ebb tidal currents, scouring the river bed and releasing sediment into the down-drift currents [8], [9], [12]. Both of these drivers are directly guided by climate variability, adding complexity to the overall understanding of the river basin variability.

In this paper, we investigate the natural process of adaptation of the Noosa River in response to man-made structures installed in the 1970-80’s. Aerial images from recent years (2010-2018) are analysed to describe the newly established river behaviour that has resulted in bank erosion of the Noosa Woods Spit and lead to consideration of renewed management action. This paper highlights the needs for coastal planners to have a broad understanding of the environmental responses to climate drivers in order to mitigate the ramifications of any future anthropogenic intervention.

2. Methods

The methodology consisted of a geospatial analysis of a set of 30 high resolution aerial images (Nearmap®) from July 2010 to November 2018, with a quasi-regular monthly time-scale. The imagery was acquired with a vertical view and an approximately 1:10,000 absolute scale.

Image rectification was performed in a GIS environment (ESRI® ArcGIS 10.3). All the images were referenced to the World Imagery base map (ESRI® ArcMap™ 10.3), that provides one meter or better resolution imagery from multiple sources (Figure 1). For the rectification process at least 20 control points were distributed evenly throughout the image, linking the coordinates of the ESRI Base map to the aerial images. In view of the number of control points, the image transformation was done using “Adjust”. The images were projected in the geographic coordinate system referenced to the WGS 1984 Datum. The 95% confidence interval error was calculated for each image based on the root mean-square (RMS) errors, following [6] and [1]. Maximum RMS value was 0.80 m (or 1.38 m with 95% confidence interval) from the July 2010 image. Considering that the changes in the coastal features are on the order of ten’s to hundreds of meters, an error of ±1 to 2m is considered negligible for the analysis.

Using all of the rectified aerial images, the morphological features that comprise the Noosa River system were mapped. Wet-dry shoreline indicator [2] was delimited at the Northern Spit, Southern Spit, Noosa Woods beach, Noosa Sound and Munna Point (Figure 1). The river channel system, consisting of three main channels - Northern, Middle and Southern (Figure 1), was mapped to observe the inlet migration and width as well as the main ebb channel alternation. Finally, the flood- and ebb-tidal delta deposits were analysed as a function of their area, position and stability (Figure 2).

Figure 1: Study area location: Noosa River, Sunshine Coast, QLD - Australia. (Source: ESRI® ArcGIS)

3. Results

Noosa River is a wave-dominated barrier estuary, with a well-developed multilobe flood-tidal delta in the central basin and wave-built bars formed around the entrance. The major estuarine dynamic processes are found in the first ~1 km from the entrance to upstream (Figure 2). Landward of this region, a persistent flood-tidal delta formation is observed with a sand deposit covering ~ 200,000 m² (Figure 2). Between this sand deposit and Noosa...
Woods, an intermittent sand shoal emerges and reaches an area of up to ~78,000 m² (Figure 2), obstructing the connection between the entrance region and the upstream river. Closer to the river entrance, a ~186,000 m² sand deposit is observed as a steady feature with some vegetated islands (Figure 2). It creates an attachment surface for the Northern Spit to anchor in the interior of the estuary (Figure 2). The Northern Spit has been responsible for maintaining the Northern Channel closure for several years (2010 to 2018) and for inducing the other channel’s migration. The variation of the main ebb channel is a result of the direction of growth of the Northern Spit towards the training wall (Figure 2). In this situation, the inlet is forced to move east-southeast, positioning its throat adjacent to the training wall, where the ebb currents remove any sand deposits (Figure 3). This configuration sustains the Middle Channel as the main water path by preventing sediment deposition around the Southern Spit. A small river passage formed by the Northern Channel breaking through the Northern Spit is observed, but there is no signal of this influencing on the process of variability of the main ebb channel. Meanwhile, the Northern Spit expands reaching an area > 300,000 m², nourished by large sand bar formations at the northern side of the inlet (Figure 3), that provide sediment to the northern Noosa shoreline progradation and spit development (Figure 3). This scenario persisted between 2011 and 2013 (Figure 3).

Middle Channel Dominance

The Middle Channel Dominance occurs in response to a strong river flow and the growth of the Northern Spit towards the training wall (Figure 3). In this situation, the inlet is forced to move east-southeast, positioning its throat adjacent to the training wall, where the ebb currents remove any sand deposits (Figure 3). This configuration sustains the Middle Channel as the main water path by preventing sediment deposition around the Southern Spit. A small river passage formed by the Northern Channel breaking through the Northern Spit is observed, but there is no signal of this influencing on the process of variability of the main ebb channel. Meanwhile, the Northern Spit expands reaching an area > 300,000 m², nourished by large sand bar formations at the northern side of the inlet (Figure 3), that provide sediment to the northern Noosa shoreline progradation and spit development (Figure 3). This scenario persisted between 2011 and 2013 (Figure 3).
Southern Channel Dominance

In a second scenario, the Northern Spit develops in a 30° orientation from the river entrance, migrating more toward the south-southeast. In this process, the Northern Spit attaches to a flood-tidal delta deposit placed in front of Noosa Woods spit. This formation creates one single feature that obstructs the Middle Channel and forces water movement through the Southern Channel (Figure 4). The Southern Channel dominance occurs as an “S” shape meander influenced by the sand deposition around the Southern Spit and training wall (Figure 4). In this configuration, the net northward littoral drift plays a major role transporting the sediment that deposits in the southern side of the entrance and forces the inlet to migrate towards north-northeast (Figure 4). The migration of the inlet causes erosion on the Northern Spit (Figure 4).

During the Southern Channel dominance, the river flow currents intensify near Noosa Woods. As a result, Noosa Woods beach suffers severe erosion. Between 2012 and 2013, Noosa Woods beach was nourished with more than 100,000 m³ of sand. Additionally, a geotextile sand container wall was constructed at the western end (Noosa Council), establishing a healthy shoreline until 2016, when the Southern Channel started to predominate. Between 2016 and 2017, around 9,000 m² of sand from Noosa Woods beach was eroded, removing the all-tide accessibility of this beach (Figure 4).

Transitiing Periods

The transitioning periods between the two previously presented scenarios correspond to an alternation in the principal driver that dominates the morphodynamical processes of Noosa River. The shift from the Southern Channel to the Middle Channel stage requires the dominance of the river flow over the wave action, while the contrary process relies primarily on the influence of the longshore sediment transport due to waves. These changes result in modifications of the flood-tidal delta deposits, and consequently the shift between the main ebb channels. In both cases, the Northern Spit has been shown to decrease in area by up to ~250,000 m², where around 75% of its area consists of the permanent sand deposit (Figures 5 and 6).

When the net northward sediment transport dominates over a less-intense river flow, sand deposits increase around the Southern Spit and force the inlet migration northward (Figure 5). At this point, the Northern Spit starts to erode due to the inlet shift (Figure 5). On the other side, the flood-tidal delta deposit in front of Noosa Woods expands (Figure 5) due to waves pushing sediment into the river system and the large sand barrier obstructing the river entrance. The flood-tidal delta deposit connects to the Northern Spit, providing sediment for its development (Figure 5). Seeking meandering stability, the Southern Channel becomes dominant, and combined with the growth of the Northern Spit towards Noosa Woods causes blocking of the Middle Channel (Figure 4).

In order to reverse this scenario, a strong and persistent river flow is necessary such that the Middle Channel would be able to break through the Northern Spit extension, pushing sediment out of the estuary (Figure 6). This process tends to enlarge the ebb-tidal delta and releases sediment into the littoral drift cell. This sand then nourishes the northern shoreline, which starts to push the river inlet towards southeast, in the direction of the training wall. The higher river outflow prevents sediment deposition around the Southern Spit and scours the riverbed along the Middle Channel, amplifying the water pathway.
This process occurred between 2010 and 2011, leading to the Middle Channel Dominance between 2011 and 2013 (Figure 3). A reverse transitioning period occurred from 2014 until mid-2016 (Figure 5), with a decreasing of the river outflow and increasing of the sand deposition at the Southern Spit leading to the Southern Channel Domi-nance between 2016-2017 (Figure 4). By the end of 2017 and beginning of 2018, a river flood broke through the Northern Spit creating an opening for the Middle Channel (Figure 6). However, in order to properly transition to a Middle Channel Dominance, ebb currents need to intensify, which means that it is necessary to have a period with positive rainfall anomalies increasing the river flow. Otherwise, the sand deposit blocking the Middle Channel may build up again and the erosive Southern Channel Dominance would persist.

4. Discussion

After the south margin of the inlet was permanently stabilized, the Noosa River has responded by adapting to a new meandering configuration. In recent years, the river system dynamics basically relied on two predominant patterns of variability: Middle Channel Domi-nance with inlet throat deeper and shifted towards the training wall or Southern Channel Domi-nance with a shallow inlet oriented northward. Previously, however, the Northern Channel presented the major influence as the main ebb channel [4], [14]. The Northern Channel dominance was related to the ability of the inlets to migrate southward, allowing a shore-parallel growth of the Northern Spit and fulfilling the river meandering necessity. This condition tended to cause erosion of the Southern Spit and coastal management issues, which were addressed by the extension of the Southern Spit and training the river entrance [4], [14]. Under this new configuration and with the construction of Noosa Woods, the Northern Spit was forced to develop towards the interior of the river system and the flood-tidal delta deposits on the middle lagoon area migrated towards the northern margin. The expansion of these deposits led to constraining of the Northern Channel, since 1985 [4]. Since the early 2000’s, the Northern Channel river flow has not been strong enough to become the main ebb channel [4].
In agreement with previously described models for tidal inlet migration [7], [12], the Southern Channel Dominance has been triggered by the northward migration of the inlet associated with sand deposition at the Southern Spit. This setting is responsible for severe erosion on Noosa Woods beach due to an elongation of the channel in its direction. In order to manage this erosion process, it is necessary to prevent sand accumulation at the southern side of the entrance. Backpassing sand from the river entrance is an approach that has been used in the region, on an irregular-basis, to prevent the erosion process on Noosa Main Beach. In 2013, >33,000 m³ was pumped, delaying sand accumulation around the training wall. In the short-term, this could be an effective measure to avoid sand building at the Southern Spit and triggering the Southern Channel Dominance. However, after some years of this volume of sand being backpassed, representing an artificial input into the sediment transport cell, the sand will arrive at the inlet entrance again. The large Southern Spit sand deposit in 2017 (Figure 4) is believed to be a response to that. Moreover, a variety of engineering techniques to address the erosion of Noosa Woods can be considered, but a certain result for any of them is that there will be side effects as a response to any man-made intervention. Therefore, this paper highlights the importance of understanding the natural variability of the system to embrace a “Building with Nature” approach.

In terms of natural influences upon the main ebb channel changes, increased rainfall contributes to river flooding that results in the opening of the Middle Channel. Average precipitation in Australia was among the highest on record between 2010 and 2011, according to the Bureau of Meteorology records (BOM – Australia). According to the rainfall observations from the Tewantin RSL Park Station (0.5 km from Noosa Heads) (BOM – Australia), the year of 2010 had the second highest precipitation level in last 20 years (2344 mm/year). As a response, the Noosa river system shifted to Middle Channel Dominance, which continued throughout 2012-2013 (Figure 3). During those years, the rainfall anomalies stayed above the average values maintaining the dominant pattern. Between 2014 and 2016, on the other hand, extremely dry weather with the lowest rainfall values in 20 years (1090 mm/year) resulted in a decreased river flow, favouring sediment deposition inside and at the entrance of the estuary. This process led to Southern Channel Dominance from 2016. Between October 2017 and February 2018, around 43% above average rainfall level (1240mm) for the period was reported in the study area, causing an increase in river flow and an opening of the Northern Spit (Figure 6), although not enough to move to a Middle Channel Dominance. Transitioning to a Middle Channel Dominance was shown to be a shorter process that requires a strong flooding event and some months to a year of intense wetter conditions. Alternatively, shifting towards the Southern Channel apparently requires a longer transitional period (2 years or more) of predominantly dry weather.

Rainfall anomalies in Australia have been related to climate indexes, such as El Niño Southern Oscillation (ENSO). According to the Oceanic Niño Index (ONI – NOAA), strong La Niña anomalies persisted between 2010-2011 (Figure 7), resulting in increased rainfall levels over eastern Australia. The following years were of weak-to-neutral ENSO until 2014 to mid-2016 followed by the occurrence of a very strong El Niño period (Figure 7). In this climate state, negative rainfall anomalies are predominant. In addition, El Niño has been associated with shifts in wave climate, reinforcing the southerly swells and the northward net sediment transport in embayed environments of the region [16], such as Noosa. Within these circumstances, sand accretion at the Southern Spit is more likely to occur, triggering the Southern Channel Dominance. In this context, coastal management solutions planned to control the Noosa Woods erosion need to take into consideration climate projections in order to predict the Noosa River system response.

![Graph showing El Niño and Southern Oscillation Indexes](image)

Figure 7: The Oceanic Niño Index (ONI) curve provided by the National Oceanic and Atmospheric Administration (NOAA – US). The index presents the running 3-month mean Sea Level Temperature (SST) anomaly for the Niño 3.4 region. Periods of anomalies above (below) 0.5° indicate warm (cold) events, meaning El Niño (La Niña) state.

5. Conclusions

After the implementation of the training wall in 1978, the Noosa River underwent two to three decades of adaptation until a fully-developed flood-tidal delta evolved with ~ 400,000 m² of stable sand deposits, including some vegetated areas. In addition, the Northern Channel was constrained by these sand formations and the Northern Spit migration, becoming an inactive channel. In this configuration,
only the (1) Middle and (2) Southern Channel are currently controlling the hydraulic and morphological processes occurring within Noosa River. These are: (1) An ebb-dominated condition where the Middle Channel is the main path for the ebb currents. In this condition a quasi shore-parallel migration of the Northern Spit occurs, pushing the inlet throat against the training wall. This pattern is associated with increased rainfall anomalies, usually as a product of strong La Niña years. (2) A wave-dominated condition where longshore sediment transport drives sand to the southern side of the inlet, shifting the inlet orientation northward. As a response, the river meandering causes the Southern Channel Dominance. In this scenario, intense currents erode the Noosa Woods beach. This pattern is associated with a drier climate, normally due to El Niño predominance, which also enhances the northward littoral drift.

This paper applied a geospatial analysis of aerial images to explain the erosion process taking place at Noosa Woods beach. The analysis technique proved to be efficient enough to develop a conceptual model of the river system variability in response to the anthropogenic modifications of the study area. Considering the time-scale of the changes, a long-term analysis using a year-resolution set of aerial images together with numerical modelling of dynamic drivers could bring more detailed information to the general concept presented here.

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7. References