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Predicting the dynamics of intermittently closed/open estuaries using attractors

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ABSTRACT

The mouths of many barrier estuaries open and close intermittently under the influence of a wide range of environmental parameters. While there have been systematic observations of this behaviour, particularly of the South African estuaries, there has been no overarching theory to explain or to guide the observation and management of these resources. Using a simple dynamic process model, the evolution of the estuary entrance has been simulated for hundreds of years for thousands of cases. The long term states ('attractors') have been identified as functions of the environmental conditions and the initial depth of the entrance. For a given estuary these attractors may be shown on a simple diagram, revealing the response under steady conditions and the vulnerability to catchment or coastal storms. The attractors predict and explain the occurrence of intermittent behaviour and the observation that intermittent estuaries fall into one of two classes: normally closed or normally open.

1. Introduction

The term Intermittently Closed/Open Lake or Lagoon (ICOLL) is used in SE Australia (DPI, 2014) to describe barrier estuaries in which the entrance channel is open to the ocean intermittently. Similar estuaries in South Africa are called Temporarily Open/Closed Estuaries (TOKE) (Whitfield, 1992). When there is sufficient water flowing into the lake or lagoon from the catchment area, water levels in the ICOLL rise and eventually the water in the ICOLL overtops the entrance sand barrier and drains to the ocean. Very small ICOLLs may be opened by wave overwash filling the lagoon (Nielsen, 2014). This flow quickly scours an entrance channel through the barrier and reopens the ICOLL to the ocean. When ICOLLs are open they become tidal with seawater moving into and out of the estuary with the daily tidal cycles. ICOLLs close when marine sand, carried in by tidal currents or by onshore wave transport obstructs the entrance channel.

Estuaries have long been sites for human settlement and establishment of towns. They offer access to the sea for fishing, trade and waste disposal, river water for drinking, agriculture and industry, access to the hinterland, and a coastal plain for settlement. An understanding of the hydro and sediment dynamics of estuaries is essential if these many competing uses are to be managed. ICOLLs add the additional complexity of unpredictable closure causing environmental changes and impacting all uses. This paper addresses the need for predictability by identifying the factors leading to an estuary becoming an ICOLL and predicting the long term regime towards which an estuary is evolving. From the hydrodynamics and sediment transport equations, we predict these regimes, or attractors in the jargon of non-linear dynamics, using numerical simulations of thousands of environmental conditions over very long durations.

The state of the entrance determines conditions within an ICOLL and its future trajectory towards a stable opening or closure. For this study, the state of the entrance will be characterised by its hydrodynamic resistance and the ratio of the entrance depth to the tidal amplitude. While other variables play a part, as will be discussed below, these two are dominant.

The entrance resistance determines the attenuation of the tide and hence the tidal range in the estuary, the volume inflow and outflow through the entrance and the phase difference between the water level and the velocity in the entrance. The last factor strongly influences the magnitude and direction of the net sediment transport.

The entrance depth strongly affects entrance resistance and is important in limiting the level of low tide in the estuary and the volume of inflow and outflow through the entrance. The depth also determines the strength of spring tidal pumping, which is the increase in mean waterlevel in a tidal lagoon or estuary due to spring tides (McLean and Hinwood, 2011). This in turn determines the limiting tidal elevations in the estuary and, particularly for large but constricted estuaries, provides an important flushing mechanism.

Other variables which affect tidal flows and asymmetry, but generally are not as significantly as resistance and depth, include the cross-

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sectional shape of the inlet channel and the elevation and plan form of any shoals or bars in the entrance; we have not considered these details here.

In the next section we review the studies of ICOLLs, in particular field studies. In Section 3 we outline the numerical model used to find the attractors, which we show and explain with the aid of the attractor map in Section 4. In Section 5 we compare these predictions with the field data of Section 2.

2. Previous studies of ICOLLs

2.1. Early studies of stability

Quantification of inlet channel behaviour could be considered to have started with the field studies of Stevenson (1886), the hydrodynamic analysis of Brown (1928), and data analysis of O'Brien (1931) who classified the entrances to tidal inlets of estuaries as stable or unstable. The stable entrances tended towards a consistent relationship between entrance area and tidal prism. The unstable entrances tended towards closure, although this limit was not considered by the early workers. The understanding of the role of sediment supply by longshore transport was made by Brown but the first attempt at a mathematical description of it was made by Bruun and Gerritsen (1960) and Bruun (1966). In a dimensional analysis of the entrance stability, Bruun and Gerritsen added river inflow to the tidal prism, but then omitted it in their quantitative developments. These and later studies are reviewed in Hinwood et al. (2012).

Contemporaneously with the empirical studies, Escoffier (1940) plotted the equations developed by Brown to show the relationship between inlet cross sectional area and maximum tidal velocity (equal on ebb and flood tides as the inlet area was taken as constant and there was no river inflow). This simple formulation of the hydrodynamics of inlet flow was then used to predict stability of the inlet. O'Brien and Dean (1972) then added a line for the empirical "equilibrium velocity" which provided real insight into the role of the physical processes and was extended by van de Kreeke (1967, 1992). Several others developed alternative hydrodynamic models of the inlet flow (including Keulegan, 1951). The importance of the freshwater inflow to inlet stability was recognised by modellers (Escoffier and Walton, 1979; Gao and Collins, 1994; Hinwood and McLean, 2001; van de Kreeke, 1967) who included freshwater inflow in their simplified hydrodynamic models. To parameterise the effect of the river inflow, van de Kreeke (1967) proposed a modified ebb velocity, Gao and Collins (1994) equivalently used a modified tidal prism, while Hinwood and McLean introduced the river flow into the tidal basin continuously over time. The last of these is the forerunner of the hydrodynamic module in the HydSed model used here.

None of these previous one or two cell models permitted the entrance depth to vary over the tide cycle. There is usually a large phase lag between the entrance velocity and the entrance water level so that the flood tide occurs on average with greater entrance depth than the ebb. This asymmetry biases the sediment transport. The asymmetry also leads to spring tidal pumping (Hinwood and Aoki, 2013; McLean and Hinwood, 2011), which has a significant effect in estuaries where the entrance resistance is high — as it is near entrance closure.

Limitations of the purely hydrodynamic models are firstly that the stability, that is the tendency to stay open or to close, is based on an empirical velocity for sediment transport at a chosen phase of the tide — usually the maximum tidal velocity. In practice, most entrances have sediment transport during both flood and ebb tides and a stable entrance is one where these two transports are equal. Although this was recognised by Escoffier (1940) and by van de Kreeke (1992) it could only be allowed for by an arbitrary selection of the tidal conditions used. The second limitation of these models is that the bed elevation or area of the entrance is fixed and thus the entrance does not evolve over time and its final state cannot be directly obtained.

2.2. Regional catalogues and classifications

Consideration of large numbers of estuaries provided insight into the features that distinguished ICOLLs from more stable estuaries. Catalogues of Australian estuaries have been prepared by several teams, mainly with the aim of assisting in regional management. Bucher and Saenger (1991), followed by Digby and Ferguson (1996) Digby et al. (1998) who compiled an exhaustive list of Australian estuaries, with principal dimensions, tidal and river inflow data. An updated and expanded national database is now available on-line (Oz Coasts, 2014). Haines et al. (2005) catalogued NSW estuaries, including smaller estuaries than in previous lists, identifying about 70 as ICOLLs. They tabulated additional morphometric data and rainfall statistics where river gaugings were unavailable. Both of these studies classified estuaries, identifying ICOLLs explicitly, although there were a few misidentifications in the former list. Haines et al. introduced an "entrance closure index", which is the fraction of time that the entrance of an ICOLL is closed, shown in Fig. 1. Based on the fraction of time that an ICOLL is open, their data shows that there were two groups of estuaries, one that is generally open but closes occasionally, usually for a short duration, and the other that is generally closed but opens briefly.

An earlier catalogue of NSW estuaries by Roy (1984) provided the basis for his geomorphic classification of estuary type and the stages of evolution of each type. This was entirely descriptive but remains the most useful physical classification of barrier estuaries, ICOLLs and their life cycles. A narrower but quantitative geomorphological classification of estuary entrance types, based on 82 New Zealand estuaries, was made by Hume and Herdendorf (1988), but did not include ICOLLs.

The most comprehensive regional studies were made over several decades in South Africa. As in Australia, many of these studies were intended to directly aid management but others were directed more at understanding their dynamics and this formed a part of all of the studies. An excellent example is the monograph of Begg (1978) who catalogued the 73 estuarine systems in Natal, concisely summarised the knowledge of their hydrology, geomorphology, biology and economic value and then summarised the common factors that influenced these characteristics. Whitfield (1992) in an extensive survey stated that the majority of southern African estuaries are intermittently

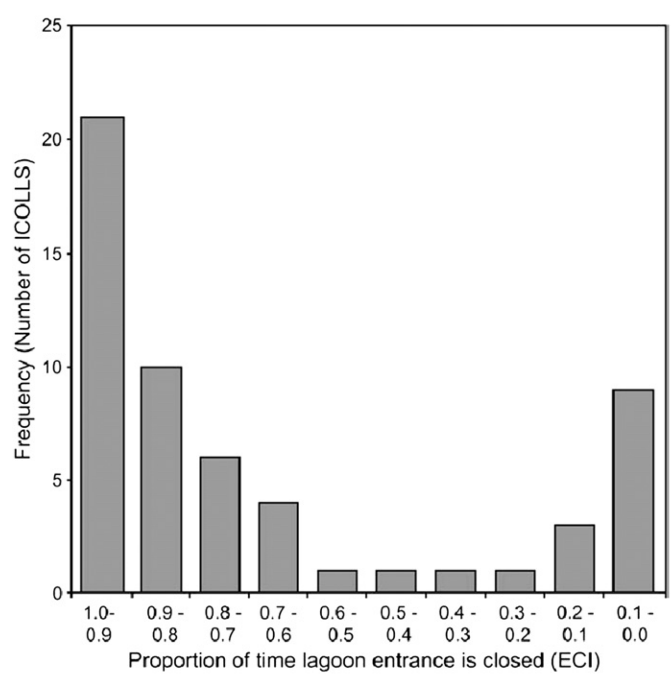

Fig. 1. Percentage of ICOLLs in NSW with a given fraction of time in the closed state, showing the existence of two groups of estuaries (Haines et al., 2005).