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# Investigating the Stability of Double-Inlet Tidal Systems Using a Process-Based Modelling Approach

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## ABSTRACT

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Tidal inlet systems provide a dynamic connection between the ocean and water mass behind their barriers and are subjected to human intervention and natural changes. An understanding of the dynamic processes in tidal inlet systems is important for decision makers managing these areas. Most previous studies are focused on a basin connected to the ocean via a single inlet. But multi-inlet systems have more complexity than the typical single-inlet system, especially considering the interaction among different inlets. In this study, following the realistic analogue approach, we have adopted a morphodynamic process-based model (Delft3D) as a numerical lab and set up a model for a schematized double-inlet tidal system to investigate the stability of such systems. We have carried out a series of simulations and systematically changed the width and initial depth of the inlets and also the amount of sediment coming to the inlet due to littoral drift along the coast. Based on the result of these simulations, first, we developed “Escoffier” type stability curves for each inlet in every simulation. In the second step, we have fixed the cross-sectional area of one inlet and allowed the second inlet to evolve. We used the results of this set of the simulations to develop a 3D stability “Escoffier” curve as a function of the cross-sectional areas of both inlets and equilibrium velocity and identified stable and unstable equilibrium conditions. In the third step, to test these equilibrium points, we altered the stable system in seven different ways to show that the system goes back to one of these equilibrium conditions.

**ADDITIONAL INDEX WORDS:** *Tidal inlets, Morphodynamic Equilibrium, Process-based model.*

## INTRODUCTION

Tidal inlet systems are commonly found in coastal areas. A tidal inlet system has four main elements: ocean, barrier islands, tidal inlet, and back barrier basin. These systems are morphologically very dynamic and are influenced by several natural forcings such as wind, waves, tides, sediment transport, as well as anthropological interventions. Understanding the morphological behavior of tidal inlet systems is necessary to help decision makers in efficiently managing this type of coastal environment.

Back barrier basins can interact with the ocean via one or a number of tidal inlets. These tidal inlets may have developed naturally or due to human activities (e.g. for navigation channels). Most previous studies are focused on a basin connected to the ocean via a single inlet and a few conceptual models and empirical relations have been developed for single-inlet systems.

However, multi-inlet system are more complex systems and have been the subject of very few studies. Thus, factors that drive the (in)stability of multi-inlet systems are poorly understood. (Van de Kreeke, 1985, 1990, Brouwer et al. 2012, 2013, Roos et al. 2013)

## Background and Goal

The most widely used method to determine the equilibrium and stability of a tidal inlet is that formulated by Escoffier (1940) who developed the concept of the closure curve. In this curve, Escoffier (1940) related flow velocity in the inlet to the cross-sectional area of the inlet based on the balance between sediment deposited in the inlet due to littoral drift and sediment eroded from the inlet due to tidal currents. He assumed that there is an equilibrium velocity amplitude,  $U_{eq}$ . Velocity amplitudes higher than the equilibrium velocity cause net erosion and therefore an increase in the cross-sectional area of the inlet. Otherwise, for velocity amplitudes lower than  $U_{eq}$ , there is net sedimentation and a decrease in the inlet cross-sectional area. When the line of  $U_{eq}$  has two intersection points with the curve one point indicates a stable equilibrium and one an unstable equilibrium. Comparisons between this empirical relation and results of complex process-based morphodynamic models have shown good agreement (e.g. Tran et al., 2012).

When a second inlet is connected to the basin, the first inlet can be affected as part of the tidal prism is captured by the new inlet. When assuming a uniform elevation of basin water level in calculating the inlet velocity, the extension of the stability concept of Escoffier for multiple inlets leads to the conclusion that no multiple stable equilibria exist and only one of the inlets will remain open (Van De Kreeke, 1990). However, observations show that stable systems with multiple inlets do exist, for example, the inlets in the Ria Formosa (Portugal) and the Wadden

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Sea have been in a stable equilibrium for centuries (Van De Kreeke *et al.*, 2008). Few model studies have shown methods to derive a stable two inlet system: including a topographic high in the basin between the inlets (Van De Kreeke *et al.*, 2008), including entrance/exit losses near the inlet (Brouwer *et al.*, 2012), accounting for spatial water level variations in the basin (Brouwer *et al.*, 2013) and including non-linearity by adding tidal distortion and residual circulation or hypsometry. The aim of this study is to understand the dynamics and behavior of a double inlet system and processes resulting in stable or unstable conditions using a process-based modelling approach.

### METHODOLOGY

In this study, following the realistic analogue approach (Roelvink & Reniers, 2011, Dastgheib *et al.* 2008, 2009), we have adopted a morphodynamic process-based model (Delft3D) as a numerical lab and have set up a model for a schematized double-inlet tidal system (Figure 1). In this schematized system only the bottom of the inlet is erodible and the back barrier islands are considered to be fixed. The forcing is simplified to a tide with amplitude of 0.5 m at the offshore boundary and propagating perpendicular to the coastline.

To investigate the stability of these inlets, we have carried out a series of 50 year long simulations (with morphodynamic updating) and systematically changed the width and initial depth of the inlets and also changed the amount of sediment coming to the inlet due to littoral drift. To model the sediment import to inlet due to littoral drift we have simplified the process to direct uniform sediment deposition in the inlets.

Simulations for the following scenarios were carried out:

Table 1. *Different simulations.*

Scenario	Inlet dimension			Erodible Bed Thickness (m)	Sediment import (m <sup>3</sup> /year)
	$l_i$ (km)	$b_i$ (km)	$h_i$ (m)		
1	6	3	4	15	0
2	6	6	4	15	
3	6	9	4	15	
4	6	6	2	17	
5	6	6	4	15	
6	6	6	12	7	
7	6	6	4	15	120,000
8	6	6	12	7	
9	6	6	18	1	
10	6	6	4	15	240,000
11	6	6	12	7	
12	6	6	18	1	

For each scenario changes of the cross-sectional area as well as the changes of the maximum velocity during the 50 year simulation was recorded. Based on these values we have generated an Escoffier curve for each scenario.

### RESULTS AND DISCUSSIONS

To check the stability of inlets with 6x6 km dimension under different conditions, a comparison of the similar model with 2 m, 4 m, and 12 m initial depth is conducted (scenario 4-6) and the result of above-mentioned analyses and corresponding Escoffier curve are shown in Figure 2. Despite the fact that the simulated tidal inlets reach a similar status after 50 years, the inlets never

reach an equilibrium point and the cross-sectional area continues to grow wltough with a very low rate. This observation is related to the fact that in these scenarios there is no sediment source in the inlet compensating for lack of wave driven littoral drift in the model.

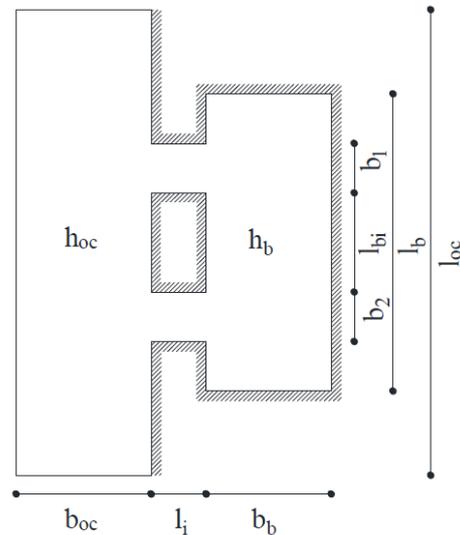


Figure 1. The schematized double-inlet system.

Figure 3 shows the results for scenarios 7-9, in which the impact of littoral drift on the stability of the inlet is taken into account as a uniform sediment deposition of 120,000 m<sup>3</sup>/year in the inlets.

Figure 3 (a) shows the relation of areas of both inlets ( $A_1$  and  $A_2$ ). Figure 3 (b) shows the Escoffier curve based on the result of simulations for all 3 cases and the direction of evolution of inlets along the curve. Regardless of initial depth, Each inlet in the system tends to reach an area of 6000-7000 m<sup>2</sup>. The simulation with initial depth of 4 m shows the erosion process, in the early stages of this simulaiothn, the sediment source simulating the littoral drift, cannot keep up with the erosion rate due to tidal current thus the cross-section increases till the balance between these two forces is reached. In the simulation with initial depth of 18 m (yellow square), the accretion process dominates, in which the inlet is getting smaller over time. The simulation with initial depth of 12 m happened to be very close to the equilibrium point.

From Figure 3 (c), it can be seen that inlet with an initial area of 2400 m<sup>2</sup> (or initial depth of 4 m) tends to be eroded quickly and the erosion rate decrease around the equilibrium point. Meanwhile, in the other two simulaiothns cross-sectionanl area of the inlets get samllr and smaller while the velocity of tidal current increases to the point that all the sediment deposited in the inets is eroded by tidal currents. Figure 3 (d) illustrates that all different simulations reach the same value of average flow velocity (equilibrium velocity) which is approximately 0.4 m/s.

To establish the combined stability diagram for both inlets, the basic principle of the Escoffier theory is used. We have carried out a set of simulations with one inlet set at sixteen different constant cross-section areas, while the other inlet has initial inlet depth of 4 meters and a 15meter erodible bed, while all other

parameters were similar to scenario 7. The 3D Closure Curve produced from this set of simulations is shown in Figure 3.

Subsequently, to test this 3D closure surface, we have chosen 7 different variations of inlet cross-sectional areas and initial condition of the simulations and followed the evolution of inlets on the developed 3D closure surface. The outcome of this exercise is shown in Figure 4. This figure illustrates the changes of cross-sectional area due to many possible departures from stability (i.e. perturbations), in which each scenario attempts to find their respective equilibrium state during the 50 years of simulation after perturbations were introduced.

### CONCLUSIONS

The process-based model of a two-inlet tidal system successfully followed the expected evolution pattern. The results showed that for reaching a stable/equilibrium condition sediment import to the inlet from adjacent coast is a necessary condition. The Equilibrium velocity is a function of the amount of sediment imported/exported by the inlet. Model results were verified with the analytical theory of earlier studies (Brouwer, 2013; Escoffier, 1940). The use of expanded Escoffier closure curve (3D closure diagram) proved to be a powerful tool to analyze the behavior of a two-inlet system. Using visual interpretation of the flow diagram and equilibrium flow curves, a reliable prediction can be made for the behavior of a two-inlet tidal system.

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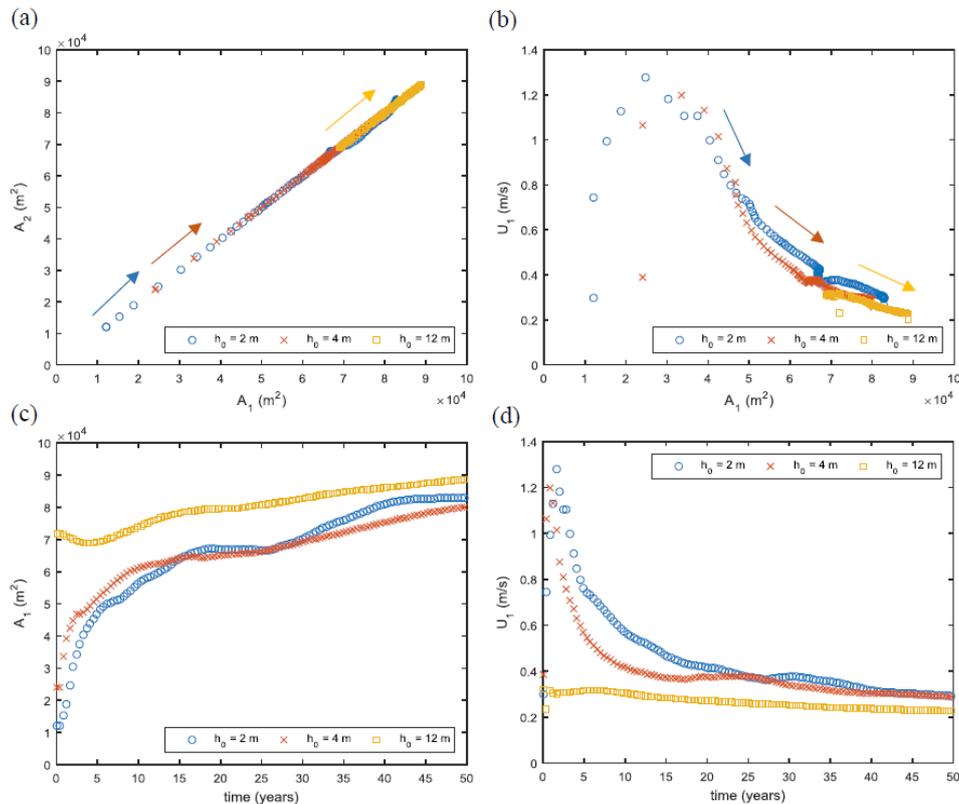


Figure 2. Model output for 2 m, 4 m, and 12 m initial depth (a)  $A_2$  vs  $A_1$ , (b)  $U_1$  (velocity in the inlet) vs  $A_1$ , (c) changes of inlet area during the simulation time and (d) Changes in velocity in the inlet during the simulation time

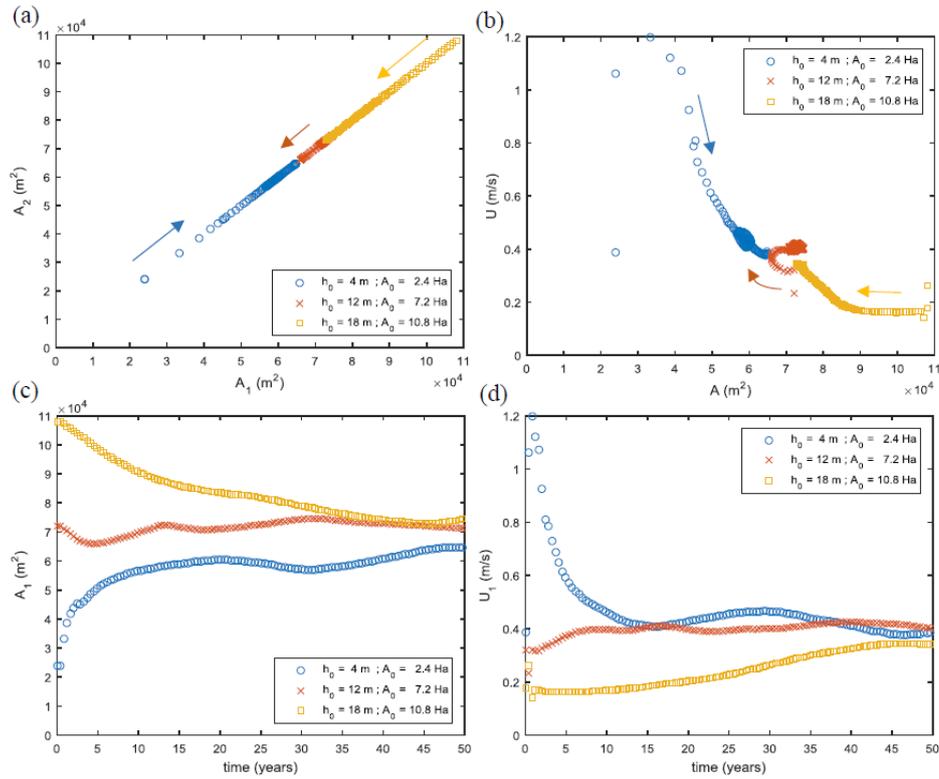


Figure 3. Model output for including sediment import due to littoral drift (a)  $A_2$  vs  $A_1$ , (b)  $U$  (velocity in the inlet) vs  $A$ , (c) Changes of Inlet Area during the simulation time and (d) Changes in velocity in the inlet during the simulation time

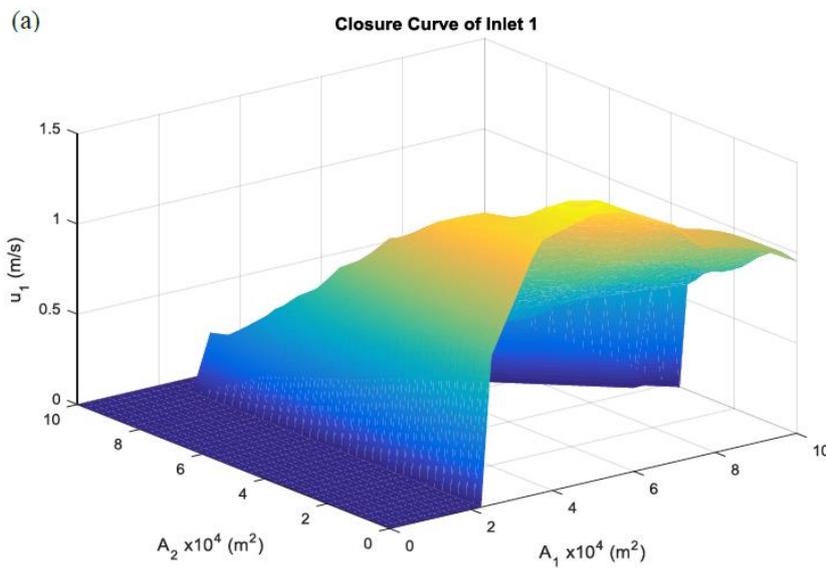


Figure 3. 3D Closure curve for inlets

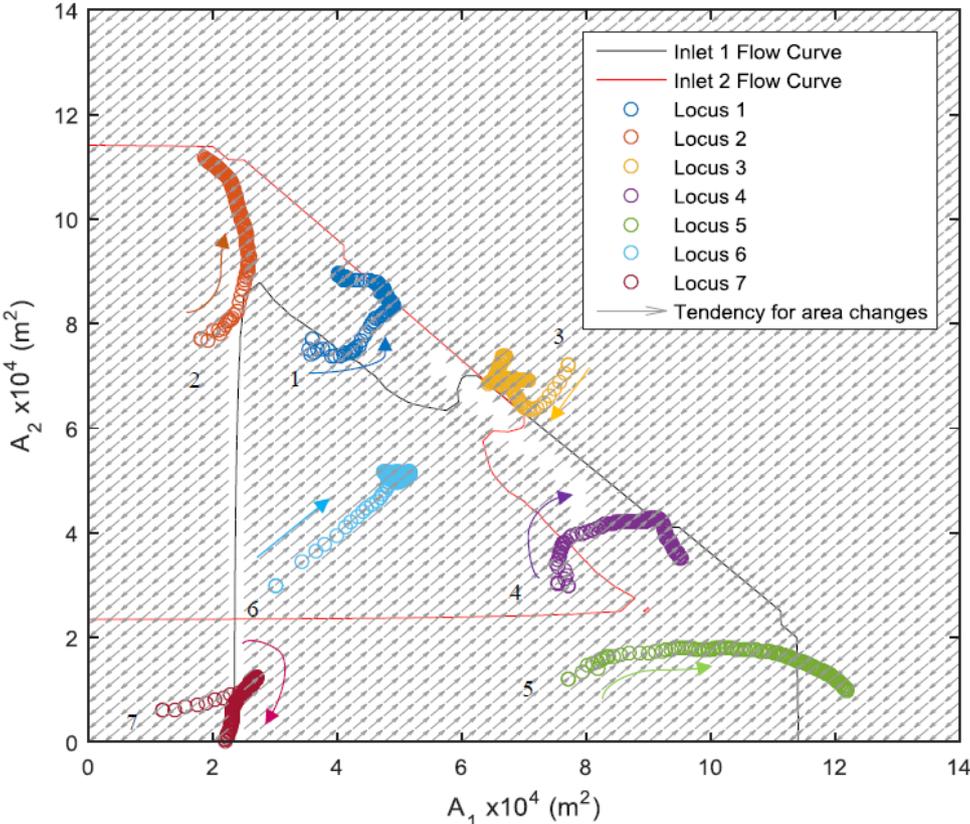


Figure 4. Evolution of inlets starting from an unstable condition (with perturbation)