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Analysis of Different Protocols for the Artificial Opening of the Laguna de Rocha Inlet

Manuel Teixeira* and Sebastian Solari

Facultad de Ingenieria
Universidad de la Republica
Montevideo, Uruguay

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ABSTRACT

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Laguna de Rocha is an intermittent opening and closing lagoon (ICOLL), located on the Atlantic coast of Uruguay. The lagoon closes practically every year during the warm months and, in general, it is artificially opened during the cold months to avoid floods and to facilitate the exchange of water, substances and organisms with the ocean. A consensus among stakeholders has been reached recently for a protocol stablishing when to open the lagoon, as previously there was no protocol at all (Conde *et al.*, 2019). However, an analysis of how the possible opening protocols affect the hydrodynamic response of the lagoon and its exchanges with the ocean in the mid and long term is still required. Following previous researches, a simplified, physics-based model was developed for analyzing time evolution of the hydro- and morpho-dynamics of the inlet. The model resolves the opening and closing processes as well as the water level variations in the lagoon. Sensitivity of the model to several parameters and comparison with available field data was carried out first. Then, the model was used for analyzing how the lagoon responds in the mid to long term (*i.e.* years) to different artificial opening protocols. The response of the lagoon was quantified with several metrics, namely: number of openings per year, amount of water exchanged between the lagoon and the ocean, extent and frequency of flooded areas. Two benchmark protocols are used for comparison purposes: the current protocol defined in Conde *et al.* (2019) and a no-intervention protocol.

ADDITIONAL INDEX WORDS: *ICOLL, coastal lagoon, protected lagoon, breaching, sand barrier.*

INTRODUCTION

Intermittently Closed/Open Lakes and Lagoons (ICOLLs) are a particularly dynamic form of estuary characterized by a periodic entrance and closure to the ocean (McSweeney *et al*., 2017). The estuaries represent the transition between the freshwater and marine environment, and their morphology is defined by the interaction between river outflow, waves and tides (Dalrymple, Zaitlin, and Boyd, 1992).

The connection with the ocean is a key characteristic of an estuary. The physical, chemical and biological interchanges depend on it. Estuaries that present an intermittent connection are usually referred to by a range of terms, one of the most applied internationally is Intermittently Closed/Open Lakes and Lagoons (ICOLLs) (McSweeney *et al*., 2017). The state of an estuary mouth is probably the single most important factor governing the structure and functioning of the resident biotic community (Smakhtin, 2004).

This type of lagoons and lakes are isolated from the ocean for variable periods of time when the waves act to build a sand barrier on the mouth. (Wainwright and Baldock, 2015) The connection occurs when this sand barrier is breached, naturally or artificially (*e.g.*, controlling floods, improving fisheries). The closure is due to the sediment transport associated to ocean waves. It is the balance between freshwater inflows and wave events that determines the opening or closure of the mouth of a particular estuary (Slinger, Taljaard, and Largier, 2017).

The breaching process was described in Gordon (1990) and Wainwrigth and Baldock (2015). The main cause of the breaching is described to be the overtopping induced by catchment filling of the lagoon, generating a narrow channel on the berm. This channel gradually widens and lowers as its slope flattens.

There are several authors that implemented models to reproduce the breaching of the sand barrier at different time scales. Some authors concentrate on the breaching process (at a scale of hours to days) and the modeling of the growth of the inlet channel both vertically and laterally (Tuan *et al.*, 2008; Wainright and Baldock, 2015; Wu and Li, 2017). As an example of a larger time scale model is the one developed by Hinwood, McLean, and Wilson (2012) where the long term evolution of the opening and closure of the sand barrier is evaluated.

The Rocha Lagoon

The study site is the Rocha Lagoon, which can be classified due to its connection to the ocean as an ICOLL. It is a shallow lagoon (average depth: 0.6 m) located on the Atlantic coast of Uruguay (34° 35'S – 54° 17'W, Figure 1), with a surface area of 72 km^2 and a watershed of 1214 km^2 (Conde *et al.*, 2019). It is part of a series

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*Corresponding author: manuelteim@gmail.com

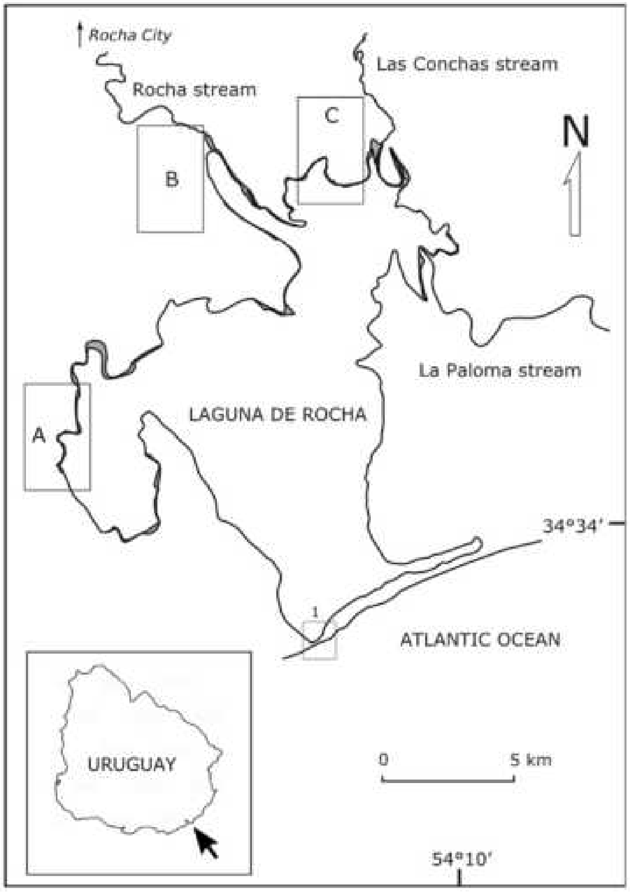

Figure 1. Location of Laguna de Rocha on the Atlantic coast of Uruguay (the black arrow on the bottom right side of Uruguay shows where the lagoon is located). Zone 1: current opening site of the sand barrier; zones A, B, C are the three places referred to in Table 1, where the flooding extent was specifically studied. From Conde *et al.* (2015).

of brackish lagoons that also present an intermittent connection to the ocean.

The lagoon has been declared as a protected area due to its high biodiversity and high biological productivity (*e.g.* Ramsar site, MaB Biosphere Reserve, National System of Protected Areas-SNAP). Breaching of its sand barrier has been a common practice for several decades and is used to reduce flooding in farming areas and in small urban settlements along the floodplains. Breaching is also executed to favor fisheries inside the lagoon, which depend on the influx of larvae of species of commercial value from the adjacent sea (Conde *et al.*, 2019).

A consensus among stakeholders has been reached recently for a protocol stablishing when to open the lagoon, as previously there was no protocol at all (Conde *et al.*, 2019). However, an analysis of how the possible opening protocols affect the hydrodynamic response of the lagoon and its exchanges with the ocean in the mid and long term is still missing.

METHODS

Following Hindwood *et al*. (2012) and Wu and Li (2017), a simplified, physics-based model was developed for analyzing time evolution of the hydro- and morpho-dynamics of the inlet. The model resolves the opening and closing processes as well as the water level variations in the lagoon. Sensitivity of the model to several parameters and comparison with available field data was carried out first. Then, the model was used for analyzing how the lagoon responds in the mid to long term (*i.e.* years) to different artificial opening protocols. The response of the lagoon was quantified mainly with two metrics, namely: number of openings per year and amount of water exchanged between the lagoon and the ocean.

The lagoon was supposed as a reservoir that interchanges water only with the ocean through the connection inlet. It also receives the river inflow. The model solves the mass balance in the entrance channel, the motion equation (integrated along the channel, depth and width integrated), and a sediment balance, along with a sediment transport equation (Equation 5).

The mass balance equation is:

$$A_b \frac{d\eta_b}{dt} = -B\left(\eta_m + h\right)u + Q \tag{1}$$

The motion equation is:

$$\frac{L}{g}\frac{du}{dt} = \left[\frac{FL}{g\left(h+\eta_m\right)} + \frac{m}{2g}\right]u|u| - \left(\eta_0 - \eta_b\right) - \frac{BL\rho_a C_d u_{win}^2 \cos\theta_{win}}{\rho g A} \tag{2}$$

where η_m is the water level at the channel, and is defined as:

$$\eta_m = \frac{\eta_0 + \eta_b}{2} \tag{3}$$

where u is the mean velocity at the channel, L is the channel length, g is the gravity acceleration coeficient, $F = f/8$ where f is the Darcy-Weisbach coefficient, that is determined as a function of the Manning roughness coefficient (n), m is the loss coefficient at the entrance and the exit of the channel, η_o is the water level at the ocean, η_b is the water level at the lagoon, h is the channel depth below the mean sea water level, B is the channel width, Q is the river inflow, A is the cross section area of the channel and A_b is the area of the lagoon surface.

The last term of Equation 2 corresponds to the surface wind stress integrated all along the channel (Wu and Li, 2017). In this term ρ_a is the air density, u_{win} is the wind velocity, θ_{win} is the angle between the wind direction and the channel axis and C_D is the Drag coeficient (computed according to Wu (1982)).

The sediment transport is described by Equations 4 and 5. First, the sediment concentration at the channel is determined (C). Then the sediment balance is solved at the channel, determining the channel depth variation:

$$C = k\left(\left(\frac{u}{u_c}\right)^2 - 1\right) \tag{4}$$

$$L\frac{dh}{dt} = \left(\eta_m + h\right)u\Delta C \tag{5}$$

where k is an empirical constant and u_c is the limit velocity for initiation of motion, determined according to Soulsby (1997). C_o

and C_b represent the sediment concentration at the ocean and at the lagoon respectively.

$$\Delta C = C_0 - C \text{ for flood}$$
$$\Delta C = C - C_b \text{ for ebb} \quad (6)$$

It is possible to identify two stages at the breaching process. A first stage of intensive breaching and a stage of general inlet evolution. In the first stage the flow is faster, and the level of the lagoon is considerably higher than the ocean level. Following Wu and Li (2017) the hydrodynamics of this stage is modelled using a weir equation:

$$Q = 1.7B\left(\eta_b + h\right)^{1.5} \quad (7)$$

The channel cross section was supposed rectangular, where the width B and the water depth at the channel maintain a fixed relation (α). This relation is one of the entrance parameters of the model.

When water depth at the channel approximates to zero, the connection between the ocean and the lagoon is considered interrupted, so the mouth is closed. From this moment a constant growth of the berm is considered at a fix rate, until a maximum height y_{max}.

RESULTS

Sensitivity of the model to several parameters and comparison with available field data was carried out first. Then the model was used to analyze how the lagoon responds in the mid to long term (*i.e.* years) to different artificial opening protocols.

Sensitivity Analysis

Because there is no enough available data to calibrate and validate the model, the parameters of the model where chosen from recommended values of the bibliography. In order to verify the model a sensitivity analysis of each parameter was carried out.

For the parameters C_o and C_b Hinwood and McLean (2015) recommend a value of $C_b = 7.5 \times 10^{-5}$, and conclude that variations in this parameter do not imply significant variations to model results; the same was concluded in this work. The parameter C_o is more significant and represents the main cause for the lagoon closure. Hinwood and McLean (2015) recommend a range from 0 to 10^{-3}, but they specify that this parameter is significantly dependent on the waves climate.

Another relevant parameter is the relation between the channel width and the channel depth (α). There is not a recommend range of values for this parameter, so it is necessary to analyze its sensitivity. Other geometric parameters as the channel length are supposed fixed and are considered known from measurement campaigns.

There are three parameters related to the head loss: the loss coefficient at the entrance and exit of the channel (m), the roughness Manning coefficient (n) and the length of the channel. The sensibility of the head loss was analyzed only for the Manning coefficient (n).

The sensitivity analysis was carried out using annual mean averaged values of the physical drivers (astronomical tide, annual mean river inflow, and annual mean wind velocity). The Figure 2 shows the variations on the channel cross section area when the parameter C_o changes. A value of $C_o = 0.002$ was selected. This value is slightly higher than the range recommended by Hinwood and McLean (2015), but lower values imply a stable channel with no closure of the lagoon.

Figure 3 shows the sensibility analysis result for the α parameter. It can be seen that the influence of this parameter on the area variation is low. The value adopted was $\alpha = 33$.

Figure 4 shows the sensitivity analysis result for the Manning coefficient. For values higher than $n = 0.06$ there is a qualitative change, although this value is unrealistically high for this case. For smaller values the behavior tends to a similar pattern, with small variation for the different values analyzed. The value adopted was $n = 0.016$ (in agreement with the value recommended by Chow *et al.* (1994) for recently dredged channels).

Model Response to Different Artificial Opening Protocols

The period corresponding to the years 1993 to 2008 was modelled, forcing the model with real series of the physical

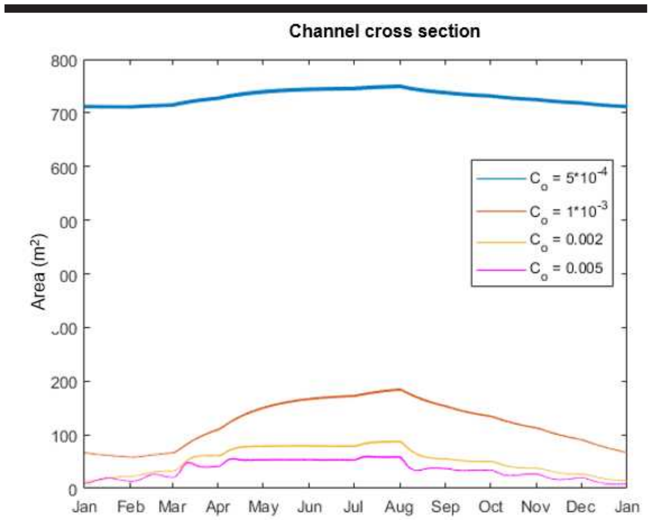

Figure 2. Sensitivity analysis of C_0.

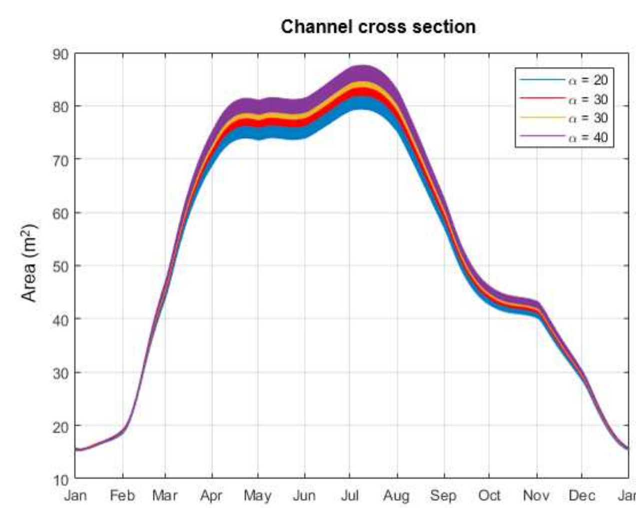

Figure 3. Sensitivity analysis of α.

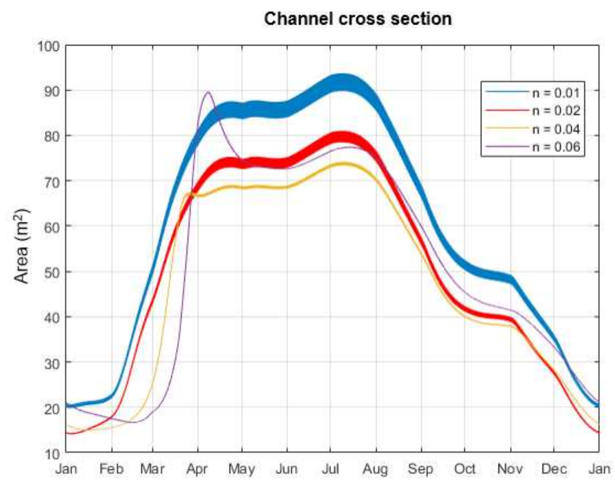

Figure 4. Sensitivity analysis of Manning coefficient (*n*).

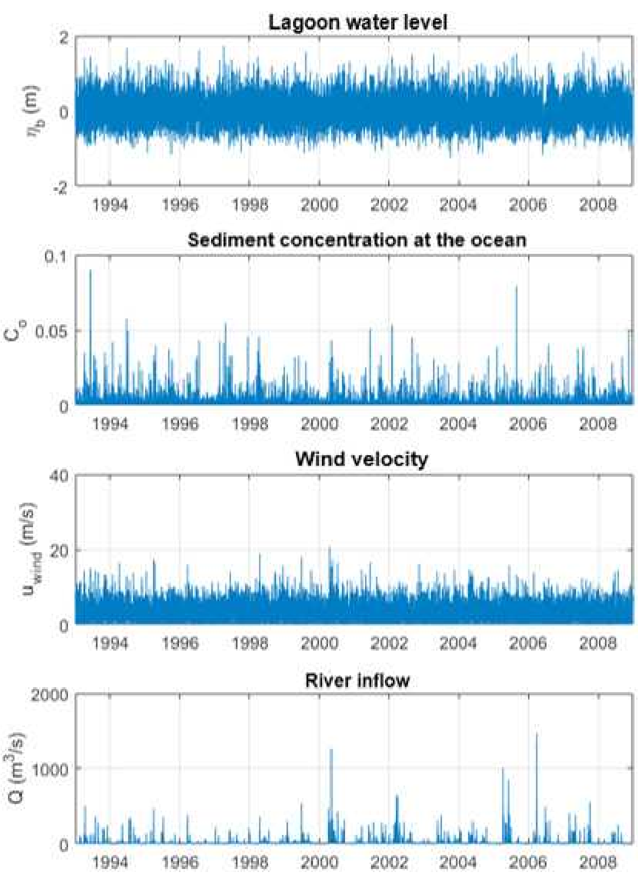

Figure 5. Physical stressor series.

drivers (see Figure 5). The river inflow was obtained from a daily hydrological model of the catchment area. The ocean sediment concentration was supposed to be a function of the longshore sediment transport. The ocean water level was obtained from the hindcast model of Alonso and Solari (2019). The wind data was obtained from the CFSR reanalysis (Saha *et al.*, 2014).

Table 1. *Flooded areas and flooding times for different opening protocols.*

Opening Water Level	Zone A (West)	Zone B (North)	Zone C (North)	
	Flooded Area (ha)	Flooded Area (ha)	Flooded Area (ha)	Averaged days per year flooded
1.4	234.7	161.7	83.7	80.3
1.6	241.7	167.8	85.18	87.6
1.8	248.7	170.5	86.23	102.2
2.0	256.2	172.8	87.3	116.8
2.2	261.8	174.1	88.3	164.25

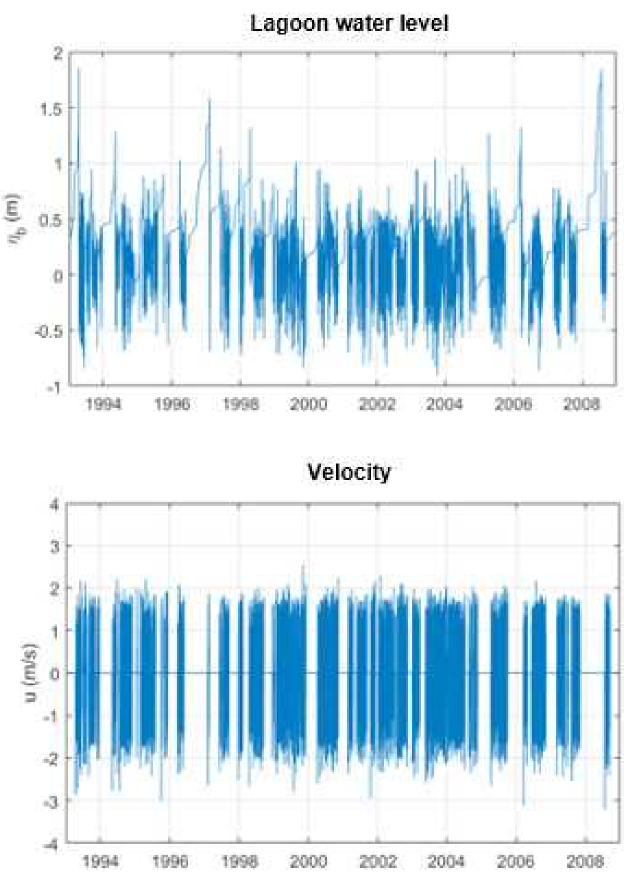

Figure 6. Water level at the lagoon and velocity at the inlet cannel obtained with the physical stressor series.

First the lagoon response without artificial openings was analyzed (*i.e.* not imposing the opening when the lagoon level reaches a specific level). Figure 6 shows the results for the velocity and the lagoon water level for this case. The results are consistent with the reality, as the lagoon mouth closes at least two times a year.

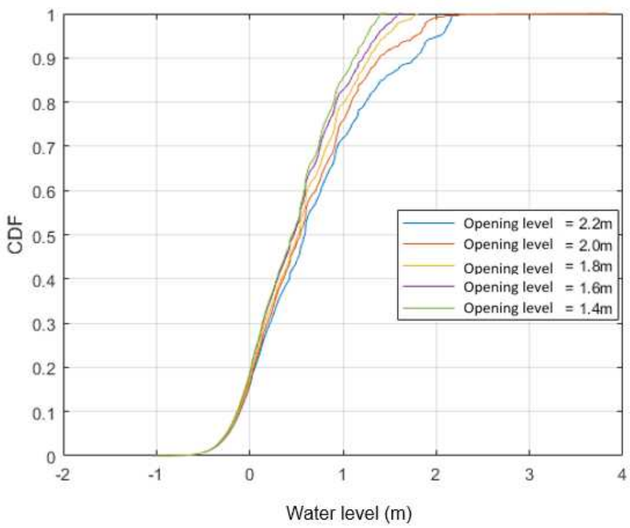

Figure 7. Empirical distribution function of the water levels obtained for the different opening values.

Then, different artificial opening protocols were analyzed imposing the opening of the lagoon mouth when the water level reaches specific values. The levels used include a range of values at which the lagoon was opened in the past (it can be supposed, as a simplification, that the lagoon is artificially opened when the lagoon water level reaches 1.6 m). The values evaluated for the opening were 1.4 m, 1.6 m, 1.8 m, 2.0 m and 2.2 m. In Table 1 the results of the flooding areas for the different opening levels are shown, as well as the averaged number of days per year they are flooded. The flooding was studied in three zones of major interest in Laguna de Rocha (named A, western coast; B and C, northern coast; see locations in Figure 1). These are the same zones analyzed in Conde *et al.* (2015), for which high resolution elevation models are available. The areas were considered flooded when the legal public boundary of the lagoon was exceeded (0.87 m).

Figure 7 shows the distribution function of the lagoon water levels for different opening values. As it was expected, the probability of obtaining higher levels increases as the opening value increase. For example, if the opening value considered is 1.8 m, then the probability of having values higher than 1.5 m is 3%, but if the opening value is 2.2 m, the probability of obtaining values higher than 1.5 m is 12%.

DISCUSSION AND CONCLUSIONS

The velocity and water level series obtained as a result of the application of the model allow to relate the opening and closure events with particular values and events of the physical drivers (*i.e.* high river inflows can be related to opening events, and periods with low river inflows and high ocean sediment concentration can be related to closure events). In particular, river inflow and ocean sediment availability are identified as the main physical drivers associated to the opening and closure of the sand barrier.

The impact of the different opening policies on the persistence of the water levels in the lagoon is quite significant, with variation in the order of tens of days when the opening level variates tens of centimeters. Variation in the extent of the flooding for the studied zones seems to be less dramatic.

The model implemented allowed for the first estimation of water exchanges between the ocean and the lagoon, and for the quantification of the effect that the different opening policies has on it and on the flooding time and extent. In sense, the model is a useful tool for the Rocha Lagoon management; however, proper calibration and validation data is still missing, as a more precise version of the model is desirable for assist decision making.

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