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Fresh Marsh Network Modeling for Ecological Continuity

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Abstract: *In many coastal marshes, hydraulic structures are widely used to prevent from flooding and salt intrusion in coastal areas. However, these structures (tide gate, sluice gate, weir) are an obstacle to fish passage and cause the disconnection of water bodies. In this paper, we investigate the case of a fresh marsh network linked to the sea by a tide gate. The objective is to explore management strategies of hydraulic structures in order to improve fish passability by increasing the duration of "fish-friendly" periods. The study area is located at the mouth of Charente River (France, Atlantic Ocean coast), an area with a high potential for European Eel growth. The marsh consists of ponds separated by sluice gates and weirs, and 4 lateral tributaries used for irrigation and drainage. To determine if a fish can pass through a hydraulic structure (tide gate or sluice gate), local hydraulic conditions need to be considered and compared to maximum swim speed of fish species. If the swim speed of a given chosen fish species (European Eel) is lower than to the mean velocity through the gate, then the gate cannot be passed. A simple management strategy was to put a block on the gate in order to avoid the complete closing of the tide gate, and so let a slot for fish passage. The consequence is an increase of sea water intrusion within the network, causing a decrease of water level difference and then a less efficient drainage.*

Keywords: *Tide gate, sluice gate, water resource management, fish passage*

1. Introduction

Hydraulic control of open-channel networks is investigated for many reasons, first for water conservation (Walhin and Zimbelman 2014), but also for water quality (Feng et al. 2016) and ecological issues (Cox et al. 2006). The hydraulic control is performed because of hydraulic structures. However, these structures may behave as obstacles to fish passage (Wright et al. 2014). Indeed they impose extreme hydraulic conditions (high water velocity, water level jump/drop) unpassable for fish with poor swim capacity. Obstacles induced by hydraulic structures are one of the major causes for the drop of some fish populations (Feunteun 2002) because they cause water bodies disconnection. This disconnection is increased with the number of hydraulic structures on one river or marsh. The cumulative effect of obstacles can restrict access to some parts of the network and fragment the fish habitat. Solutions have been developed to enhance fish passage at hydraulic structures, such as fish ladders (Larinier et al. 2002) and operation strategies (Mouton et al. 2011; Boys et al. 2012). These solutions are applied to a single structure and enhance fish passage locally. Few studies have explored the impact of a single gate management on the continuity at a larger scale (Franklin and Hodges 2015).

The objective of this study is to show how the management of a tidal gate can enable fish passability for remote hydraulic structures of a fresh marsh network. The selected management strategy is to let an opening at high tide. This has been shown in previous studies that it could indeed improve tide gate passability (Boys et al. 2012). The novelty here is to analyze the impact of the management strategy at a larger scale, including the upstream reach and, notably, the passability of upstream control structures. To do so, we selected a canal network in a coastal area with a high potential for European Eel growth, where flow is controlled by a series of gates and downstream conditions imposed by tides. Different conditions of the tide gate opening were applied during a migration period of European Eels. These conditions were analyzed regarding fish passability at different points, thanks to the development of a hydraulic model.

The paper is structured as follows: the study area is first presented; the following section presents a hydraulic model describing the flow conditions that need to be analyzed regarding fish passability and the management rules which are simulated; and the last section presents the analysis of the management strategies and a discussion of the results.

2. Study Area

2.1. Charras Marsh

Charras marsh is located at the mouth of Charente River (France, Atlantic Ocean coast) (45°53'30.2"N, 1° 00'11.8"W). This catchment is divided in 5 drainage basins separated from a main drain by sluice gates (G_3, G_4, G_5, G_6, G_7 – see Fig. 1). G_4, G_5, G_6, and G_7 sluice gates are coupled to flap gates which prevent sea water intrusion during tide. They close when the water level downstream of the gate becomes higher than the water level upstream of the gate. The hydraulic structures downstream of the marsh are composed of a tide gate (P_1) and two parallel sluice gates (G_1). The tide gate is composed of two vertical plates. One can move around a vertical axis due to hydrostatic pressure. A block installed between the two plates can be used to prevent total closure of the tide gate P_1. The objective of this is to let a way for fish passage during high tide; if water flows from sea to marsh, then the fish (such as a Glass Eel) can penetrate the marsh without difficulty. Moreover, this causes an increase of water elevation in Charras marsh, which in turn decreases the water level difference at sluice gate G_2 located upstream in the marsh. As a consequence, the flow velocity at G_2 is decreased, too. This has a consequence for fish passability to the marsh upstream of gate G_2. So, we can say that the opening conditions of gate P_1 and the tide amplitude and duration have an impact on fish passability far upstream in the marsh.

The hydraulic structures' characteristics are provided in Table 1. Flow is always under gate and no overflowing occurs. This choice is motivated by two reasons: to avoid illegal fishing and to allow fish with poor swim capacity to swim near the bottom to take advantage of the lower flow velocity.

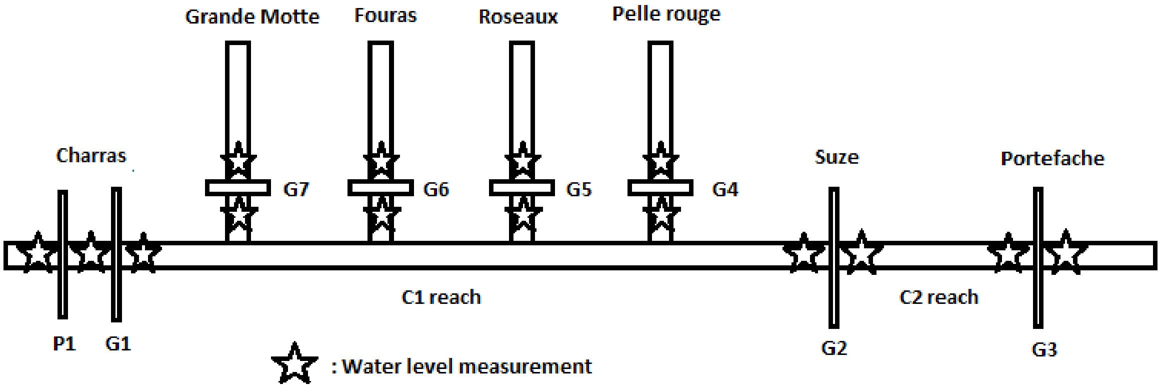

Figure 1. Charras network scheme.

Table 1. Hydraulics structures characteristics. For *P1*, the opening due to the block is 0.1m. When the water flows to the sea, the gate is totally open.

Gate	Name	Gate width (m)	Sill elevation (m)	Gate height (m)
Charras tide gate	P_1	depending on flow direction	2.5	NaN
Charras sluice gate (x2)	G_1	2.2	-0.5	4.5
Suze Sluice gate	G_2	6.5	-0.5	4
Portefache sluice gate	G_3	5.5	0.18	6
Pelle rouge sluice gate	G_4	1.5	0.59	3.403
Roseaux sluice gate	G_5	1.5	0.95	3.042
Fouras sluice gate	G_6	1.2	0.78	1.18
Grande motte sluice gate	G_7	1.2	0.83	4.5

2.2. Glass Eel

According to the International Union for Conservation of Nature (IUCN) red list, *Anguilla Anguilla* (European Eel) is a critical endangered species (Jacoby and Gollock 2014). The *Anguilla Anguilla* population is severely declining since 1980 (Feunteun 2002). One of the major causes of the decline is the presence of hydraulic structures (gate, dam, and weir), which are obstacles to *Anguilla Anguilla* migration (Feunteun 2002). They lock water bodies where *Anguilla Anguilla* grows. Indeed, *Anguilla Anguilla* is a catadromous fish, which spawns in sea and migrates to fresh water to develop and live. So, access to fresh water bodies is a key condition for the species survival. French fresh marshes of the Atlantic coast are a habitat suitable area for European Eel during growth period. However, their access is limited by hydraulic structures, which often impose water speed at gates greater than the swim capacity of elvers, which have a burst swim capacity of 0.6 m/s (McCleave 1980). So, in order to improve European Eel access into Charras marsh, it is necessary to increase periods where water speed at gate is lower than 0.6 m/s.

2.3. Management Rules

The gates were operated according to the following principles (Fig. 3):

- The gates were managed with a maximum frequency of one modification per day, whatever the rapidity of the flow variation.
- Out of the irrigation period, G_3 gate was always totally open. That implied an equal level upstream and downstream of the gate, which could be passed easily.
- G_1 gate and G_2 gate opening is directly linked to flow variation in order to maintain a constant water elevation.
- The opening at the side gate (tributary control) was rarely modified during the period, whatever the upstream flow. Therefore, the levels in tributaries were affected by the flow conditions in reach C_1 (since gates were submerged).

2.4. Measurement Setup

In the following, we describe the network of sensors installed to monitor the flow conditions within the marsh. These conditions vary with time due to the tides and gate movement; therefore, continuous monitoring was necessary. The monitoring period was chosen during the most favorable period for Glass Eel migration (February and March in the area). The objectives of the measurements were:

- To evaluate experimentally the efficiency/impact of tide gate opening conditions on Eel migration capacity; and
- To provide data for the calibration of a model able to simulate alternative management strategies.

Water elevation measurements were monitored continuously between 02/02/2015 and 03/18/2015, with a recording period of 15 minutes (Fig. 2). These measurements were taken upstream and downstream of each gate (Fig. 1). They will be used to estimate flow rate and velocity at the hydraulic structure (sluice gates and tide gate). During the 40 measurement days there were variations in weather and hydrological conditions (rainfall, tide range), imposing changes in gate positions, as shown in Fig. 3.

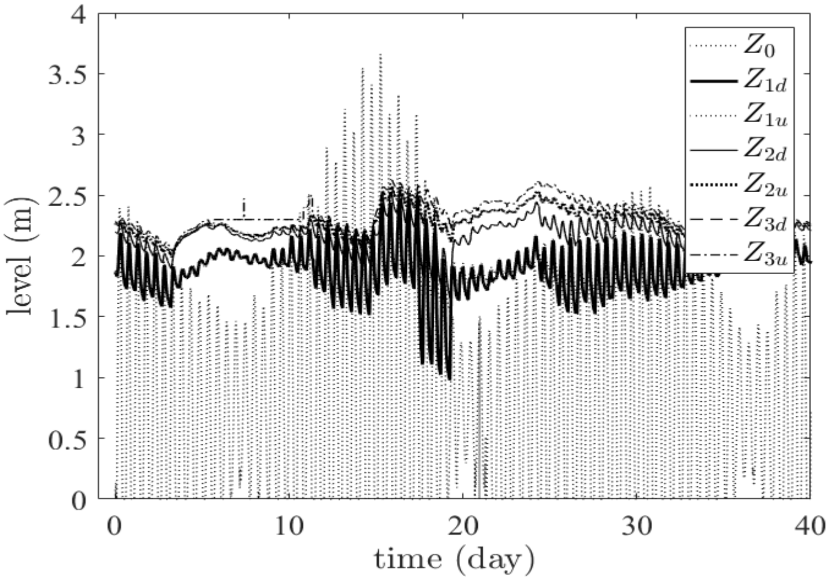

Figure 2. Water level variations during the recording period. Z_0 is estuary water level (downstream of P_1), Z_{id} water level downstream of gate G_i, and Z_{iu} water level upstream of gate G_i.

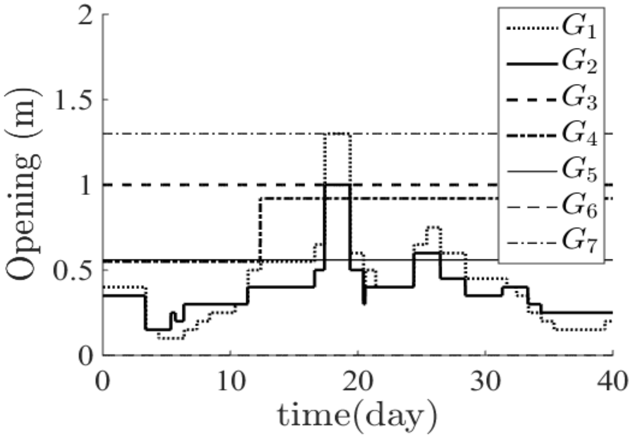

Figure 3. Gate opening variation during the recording period.

In order to calibrate the discharge equations of the hydraulic structures, flow rate measurements were carried out at each gate with an Acoustic Doppler Current Profiler. Due to the size of tributaries, the flow rate measurement in tributaries was impossible by the acoustic method; therefore, the discharge was estimated by difference between flow rates in the main reach, downstream, and upstream of tributary junctions. Four flow rate measurements were made for each gate to ensure flow measurement consistency.

Upstream of G_1 the flow rate evolution was monitored during one tide cycle to focus on the discharge variation during the closing period of the tide gate. Downstream of G_1, because of tide, water level was too low for the recording range of water level sensor, so values were obtained by filtering and extrapolation by a sinusoidal function. However, the extrapolated levels were not used since flow was supercritical, so it was a free discharge condition. Therefore, the extrapolated water elevation could be thresholded at 0 m. This value corresponds to water elevation observed at low tide during free flow. There has been a dysfunction of the water level device upstream G_3 gate (Z_{3u}): between 02/11/15 and 02/16/15, water elevation has been not recorded. Missing data (between 02/11/2015 and 02/16/2015) for the water level sensor upstream gate G_3 have been substituted by a constant value. Important variation can be noted in reach C_1

due to high gate opening. In particular, during the 16th day, the flow was not high enough to compensate for water loss due to too large of a gate opening. This induced water depth decrease for Z_{1d}. During high tide, at Charras sluice gates (G_1), water elevation was larger upstream than downstream, leading to a reversal velocity under the sluice gate and so a passage possibility for fish. For Suze sluice gate (G_2) the water level difference between upstream and downstream decreased down to 2 cm, making fish passage possible at this gate.

The block was installed on tide gate P_1 before and during measurement period. The block size let an opening of 10 cm at high tide. Fig. 2 shows that all reaches and tributaries of the marsh are impacted by the tide, due to backwater effect, even if the tidal range decreases with distance from estuary. As a consequence, we expect that gate G_1 is able to control the flow at a long distance upstream of it in the marsh. The high tidal range implies high water elevation variation in reaches and tributaries.

A decrease of the head loss at all the hydraulic structures (controlling inflow from tributaries) was also observed. At high tide, the water level in canal C_1 can become greater than the water level in the tributaries. This causes a flow from canal to tributaries. Therefore, a block could be used to prevent the total closure of the flap gate and make tributaries accessible for fish. However, the gates may be passed by fish even with a flow from tributary to C_1, provided that the velocity is not too large so the fish can still swim against the current. The following section shows how these velocities were calculated.

3. Velocity and Flow Rate Under Gates

3.1. Gate Modeling

To estimate flow at gates from continuous water level monitoring, the following equations were used for the sluice gates (see Henderson (1966) and Belaud et al. (2009)):

$$Q = C_C L W \sqrt{2g(h_u - C_C W)} \text{ if } h_d < \mathrm{Cc\,W} \text{ (free flow)} \tag{1}$$

$$Q = C_d L W \sqrt{2g h_u} \text{ if } h_d > C_C W \text{(submerged flow)} \tag{2}$$

where h_u the upstream water level, h_d the downstream water level, W gate opening, and C_c contraction coefficient. The transition between both regimes occurs when the tail water depth reaches the depth at the contracted section due to the jet under the gate. When the sluice gate is submerged, the discharge coefficient C_d is calculated as follows:

$$C_d = C_c \frac{\sqrt{1 - \frac{h_d}{h_u}}}{\sqrt{1 - C_c^2 \frac{W^2}{h_u^2}}} \tag{3}$$

The only unknown parameters are the contraction coefficients C_c, which are expected to be close to 0.61. Head losses and gate specificities can be considered by adjusting C_c, which were determined from the flow measurements and water level records. The estimations of C_c for each gate are presented further.

For tide gate modeling, there are two possible cases:

- If the water level downstream of the gate is below the water level upstream of the gate, then the tide gate is open and it has no influence on flow.
- If the water level downstream of the gate is above the water level upstream of the gate, then the tide gate is modeled by a vertical opening with the following equation derived from energy conservation:

$$Q = \mu_g b h_u \sqrt{2g\,\mathrm{Max}(h_d - h_u; 0)} \tag{4}$$

where h_u is the water level upstream of the gate, h_d is the water level downstream of the gate, and b is the opening. This opening can be controlled due to blocks added to prevent them from closing completely. Coefficient μ_g has to be calibrated because of flow rate measurements. The difference between both levels was small enough to consider that the flow was submerged. When tide gate P_1 was active, the flow could be limited either by the sluice gate G_1 (Eq. (1)-(3)) or by the tide gate (Eq. (4)). We assumed that the flow was controlled by the gate causing the highest head loss, so Q is given by the minimum of both calculations (sluice gate and tide gate).

3.2. Gate Calibrations

Charras structures (G_1 and P_1) had to be calibrated separately at low tide and at high tide. At low tide (tide gate open), P_1 is open and G_1 is in free flow. We measured a flow of about 8 m^3/s (Fig. 4). The calibration of Cc gave a good agreement between Eq. (1) and measurements for the whole series of measurements. At high tide, the tide gate was partially closed, with an opening controlled by the block size. A constant coefficient μ_g=0.5 was used to keep a flow rate constant around -1.5m^3/s (Fig. 4) as obtained experimentally.

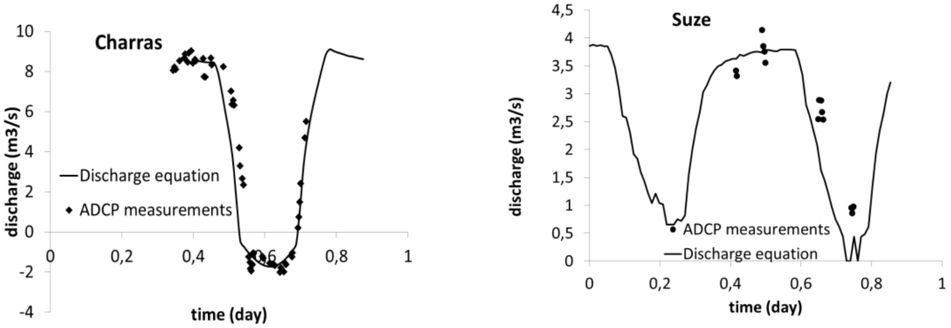

Figure 4. Flow discharge at Charras gates (left) and under Suze gate (right) during the 16th February: c calculated with calibrated discharges equations using water level measurements (Continuous lines), and ADCP measurement.

The calibration of gates G_2, G_3, G_4, and G_5 gave slightly lower values (0.6, 0.6, 0.55, 0.55) for C_c. These variations between coefficients can be explained by their configuration and their submergence (Belaud et al. 2009)

Sluice gate G_7 did not need to be calibrated since it was always fully open, while G_6 sluice gate was always completely closed, so it behaved as a weir. The relationship between upstream h_{ug} and flow above weir is given by:

$$Q = 0.4L\sqrt{2g}\,h_{ug}^{3/2} \tag{5}$$

where h_{ug} is the head above the gate.

4. Results and Discussion

4.1. Flow Variation

Flow rates at each gate were calculated with Eq. (1), (2), (4), and (5). From Fig. 5, we can see large variations during the period, mainly due to tidal effects.

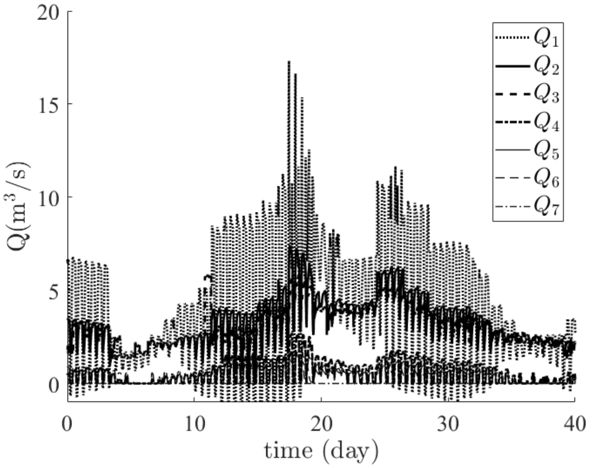

Figure 5. Flow rate calculated during the recording period. Q_i is the flow rate at gate G_i.

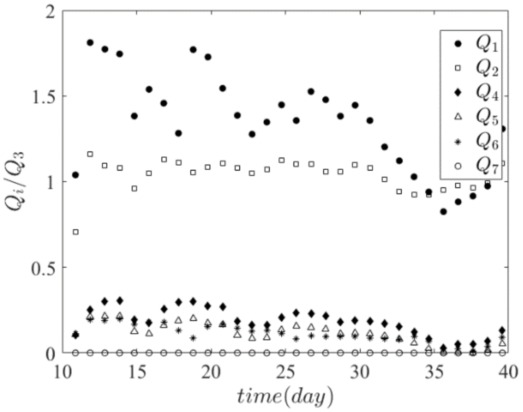

Figure 6. Mean daily flow rate at gates. Q_i is the flow rate at gate G_i. The first 10 days have been removed due to the dysfunctioning of the water level sensor at Portefache gate (G_3).

The flow conservation was verified based on a daily integration in order to take account of transients due to tide (Fig. 6). The daily volume passing through gates G_3 to G_7 was consistent with their respective drained areas

4.2. Velocity Under Suze Sluice Gate (G_2)

The mean velocity under sluice gate G_2 V_m was estimated and compared to front current velocity limit for glass eel (0.6m/s). If V_m <0.6, then glass eels can pass under the sluice gate. The velocity can be obtained from the discharge, considering that the flow is constant in the contracted jet under the gate. Since the jet thickness is C_cW, this velocity is obtained as follows:

$$V_m = \frac{Q}{C_c W L} \tag{6}$$

Flow rate Q is estimated with Eq. (1) or (2), with C_c as a constant contraction coefficient in both regimes (free/submerged flow).

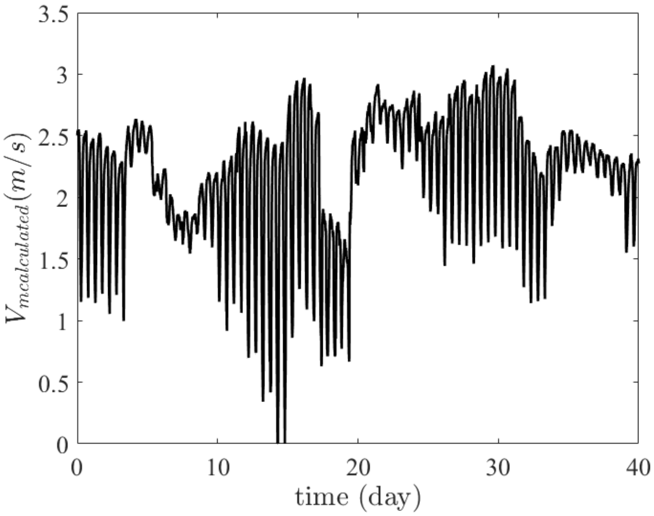

Figure 7. Water velocity under Suze sluice gate (G_2).

Fig. 7 shows the mean water velocity under gate G_2. There are four tides (at days 13 and 14) when fishes can pass under the sluice gate. These periods correspond to high tide at estuary (Fig. 2). G_2 gate is not passable during the following days (days 15, 16, 17), when the tide range is equivalent or greater (Fig. 2) because of rain causing upstream flow rate increase (Fig. 5). To avoid a huge water level increase, the sluice gate opening was increased (see Fig. 3) but not enough to remove the water difference induced by the sluice gate.

So, putting a block on tide gate P_1 was a way to increase the duration of the fish-friendly period for sluice gate G_2, by allowing seawater intrusion in the marsh, therefore decreasing the water level difference at the sluice gate. This solution could only work during high tidal range. The advantage was to increase the time for fish passage at gate G_2.

4.3. Sea Water Intrusion in the Marsh

A counterpart of the above strategy is salt intrusion in the marsh. It is possible to quantify the incoming quantity by integrating the discharge of seawater flowing into the marsh through gate P_1. Fig. 8 shows the ratio of the daily volume of sea water intrusion volume to the daily volume of freshwater inflow into the marsh. The ratios were calculated for three different block sizes (0.1 m, 0.3 m, 0.5 m).

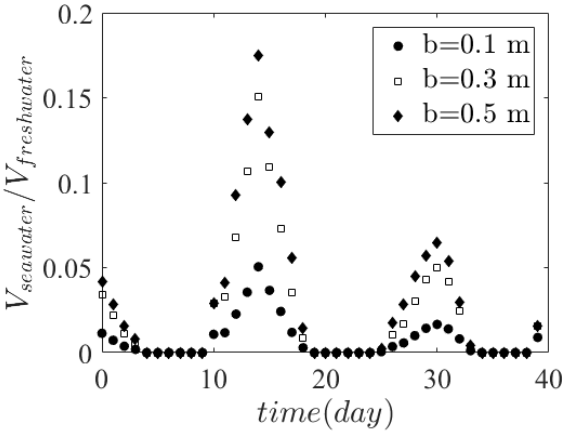

Figure 8. Ratio between sea water daily volume ($V_{seawater}$) inflow to fresh water volume inflow into the marsh ($V_{freshwater}$) for three opening sizes: 0.1 m (circles), 0.3 m (squares), and 0.5 m (diamonds).

As expected, sea water inflow increases with size block. Sea water inflow is strongly correlated with tide amplitude (see Fig. 8 and 2). This sea water intrusion could be limited by moving sluice gate G_1. Here, the gates were operated to keep the mean water level around a target value in C_1 and C_2 reaches, whatever the inflow through upstream gates and tributaries. The volume of saltwater intrusion remained reasonable (5 to 18% of freshwater inflow, depending on the block size), despite the large amplitude of the tide. However, these rates are not negligible, as saltwater intrusion could have an impact on the marsh ecosystem. The modelling of the whole system allows evaluating the impact of the gate management strategies by evaluating the counterbalance between fish passability and water quality.

5. Conclusion

Hydraulic structures have been installed in many coastal areas to control the freshwater outflow. They cause discontinuities for fish habitat and limitations for migration. Based on the study of the Charras marsh at the Charente river mouth, we have shown that:

- Tide gates could be adapted with simple devices in order to increase the duration of friendly periods for European Glass Eel;
- These adaptations could have an impact not only locally, at the tide gates equipped with blocks, but also at a larger scale due to backwater effect; and
- A simple modelling was developed to evaluate the efficiency and the impact of these adaptations at the marsh scale.

This opens the path for the optimization of management strategies of gates in such a context by considering adverse effects, such as fish-passability, water quality, and level control. Through this perspective, marsh models are developing based on continuity equations and shallow water equations.

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