Hydraulic management of coastal freshwater marsh to conciliate local water needs and fish passage

Léo Guiot de La Larochere, Ludovic Cassan, David Dorchies, Pierre Sagnes, Gilles Belaud

Hydraulic management of coastal freshwater marsh to conciliate local water needs and fish passage

L. Guiot[a] and L. Cassan[a] and D. Dorchies[b] and P. Sagnes[c,d] and G. Belaud[e]

[a]Institut de Mécanique des Fluides de Toulouse (IMFT), Université de Toulouse, CNRS, Toulouse, France; [b]UMR G-eau, Univ. Montpellier, AgroParisTech, Cirad, Institut Agro, INRAE, IRD, 365 rue Jean-François Breton, 34196 Montpellier, France; [c]Office français de la biodiversité (OFB), Direction de la recherche et de l´appui scientifique, Toulouse, France; [d]Ecohydraulics team, OFB-IMFT-PPRIME, France; [e]UMR G-eau, Univ. Montpellier, AgroParisTech, Cirad, Institut Agro, INRAE, IRD, 2 place Pierre Viala, 34060 Montpellier Cedex 1, France

ARTICLE HISTORY
Compiled July 10, 2020

ABSTRACT
Water control structures, used to regulate water levels and flow exchange in coastal marshes, act as barriers during fish migration between the ocean and brackish or freshwater ecosystems. Usual fish pass solutions may be unsuitable for obstacles subject to significant water level variations such as tidal range. This study proposes new solutions that were developed, implemented and evaluated on a marsh controlled by a series of hydraulic structures. These solutions were based on soft physical modifications (passive management) of the control gates, and on adaptations of their operation rules (active management). To evaluate the impacts of these adaptations, a hydraulic model of the marsh was built. It solves the one-dimensional Saint-Venant equations and appropriate gate equations. The model was used to identify management rules of control structures in a way to improve fish migration without significantly affecting the initial hydraulic management of the marsh (i.e. targeted seasonal water levels). It was also showed that fish passability of upstream structures could be improved by managing downstream ones. It was concluded that the combination of active and passive management of water control structures could largely increase the passability of these obstacles during glass eel migration, while limiting seawater intrusion in the marsh and maintaining water levels into a range compatible with marsh management needs.

KEYWORDS
Ecological continuity; Sluice gate; Tide gate; Open-channel control; Water management

1. Introduction

In many coastal areas, open marshes have been controlled for centuries in order to increase land-use for agriculture, pasture, and to contribute to flood prevention. This has led to the channelization of the marshes and a flow control based on hydraulic structures, such as sluice gates and weirs in order to maintain water levels around targeted values, to regulate seawater inflows, and to control wetland drainage. In addition, spe-

L. Guiot. Email: lguiotde@imft.fr

cific hydraulic structures have been designed to operate automatically (thanks to the hydrostatic pressure) in response to the tide, to prevent salt intrusion and tidal flood issues (Giannico and Souder 2005). However, these coastal hydraulic structures create physical barriers and, sometimes, subsequent flow conditions which constrain fish passage: sluice gates impose large flow velocities by contracting the flow, tide gates are physical barriers at high tide (Doehring et al. 2011; Wright et al. 2014), while weirs create water falls (Amaral et al. 2016). Therefore, all these structures may have an effect on fish migration either by stopping individuals and preventing them from reaching suitable habitats to spawn or to grow, or by adding a delay in their migration time (Ovidio and Philippart 2002). This delay may result in fish arriving in these habitats under unfavourable environmental conditions. These ecological consequences participate in the decline of some fish populations or species, such as the European eel (*Anguilla anguilla*) (Feunteun 2002; Bult and Dekker 2007)

Since 1980, this species has lost around 90 % of its population (Feunteun 2002), making it a severely endangered specie according to IUCN. During the past decades, various technical solutions have been developed to restore fish passage, such as fish ladders (Larinier 2002; Katopodis and Williams 2012), fish lifts (Travade and Larinier 2002) or rock ramps (Katopodis et al. 2001). Some authors also proposed soft modifications (i.e. that do not require an important upgrading of the structures), like placing blocks in a culvert (Franklin and Bartels 2012; Newbold et al. 2014), installing a bristle or studded ramp on a weir (Kerr et al. 2015; Vowles et al. 2017), or making permanent openings in an existing structure (Boys et al. 2012). Moreover, considering that gates can be actuated based on different rules, management of movable control structures could integrate criteria to improve fish passage (Mouton et al. 2011, 2012).

In a regulated open channel network, there are usually several hydraulic structures, implying a cumulative effect on fish migration processes (Lucas et al. 2009) and a fragmentation of habitats in the concerned water bodies. Therefore, restoring fish connectivity supposes to act on all (or nearly all) the structures acting as barriers in order to achieve a significant increase in connectivity at the network level. The issue of prioritization of barrier removal was studied in river contexts (Mouton et al. 2007; O'Hanley 2011; Shaw et al. 2016), e.g. by mixing economic and ecological criteria, but, to our knowledge, no comparable methodology is available in the context of coastal networks characterized by strong seawater influence on both water level and salinity, which should be considered when designing solutions to improve fish passage (Franklin and Hodges 2015; Roman and Garvin 1995).

In addition, fish passage solutions adapted to river environments may not be adequate for coastal networks, due to highly fluctuating flow conditions due to tide and/or variations of river flow. For example at low tide, a high water level difference between the upstream and the downstream parts of an obstacle may induce harsh flow conditions in the basins of a pool-type fishpass. At high tide, for the same fishpass, the downstream basin(s) would be submerged, making its entrance unattractive for fish. In a regulatory context that imposes effective solutions for restoring ecological continuity in some freshwater bodies, which is currently the case in France, managers have therefore to propose innovative solutions that could be adapted to the particular context of marshes.

In this context, the originality of this study is to consider a series of hydraulic structures, and their cumulative effects on fish passage continuity, in a coastal open-channel network. The goal is to explore and design low-cost solutions to improve this continuity through management operations, while keeping the original purpose of the infrastructure.

More specifically, we intend to show that (i) soft modifications of one control structure (e.g. small alterations such as adding blocks to a tide gate) could improve fish passage both locally and at a larger spatial scale in the marsh, (ii) management strategies could be designed to improve fish passage continuity based on soft modifications of structures and the adaptation of existing rules for gate opening, (iii) these strategies can be explored and optimized using a specific hydrodynamic model that solves the Saint-Venant equations, including models of the structures.

For this purpose, we selected a marsh on the French Altantic Coast comprising a channelised river and some tributaries, where water levels are controlled by hydraulic structures (sluice gates, flap gates) originally installed for agricultural uses (irrigation and drainage). A numerical model was developed and calibrated in order to simulate different management scenarios, and to identify new options to increase fish passage while taking into account hydraulic interactions between structures.

This article is structured as follows. The first section describes the study area, the targeted fish species and the measurements used to calibrate the model. The second section presents the modeling approach and the criteria used to compare diverse management strategies. The results section analyzes different options for the design and operation of control structures. Finally, the discussion section presents the effects of the interaction between structures in a tidal environment, and pathways to improve fish passage continuity by adapting these structures.

2. Ecological and management context

2.1. Study area and targeted species

The freshwater marsh of Charras, on the French Atlantic Ocean coast, serves as case study in which we consider the passage continuity during European eel (*Anguilla anguilla*) migration. Charras marsh (Figure 1) is connected to the Charente river estuary (45°53'30.2"N, 1°00'11.8"), 5 kilometers from the Atlantic Ocean, and drains a watershed of around 300 km^2. The marsh is largely influenced by tidal movements, with a maximal water level amplitude of 5 m. Therefore tide gates have been placed at the confluence between the Charente river and the Charras Canal, the main drain of the marsh. This drain, a former tributary river of Charente River, was channelized between the Middle-Ages and the early nineteenth century.

This marsh (as many others on the French Atlantic coast) represents a suitable habitat for the European eel during its growth period. This species is a catadromous fish that migrates into freshwater to grow and mature after being spawned at sea. The access to suitable fresh water growth habitats is a key factor for the species survival. During the period of their recruitment in French estuaries (mainly between February and April), eels are at a life-stage called glass eel. At this stage, individuals are unpigmented and less than 10 cm in length. It is a transitional stage between the leptocephal larval stage and the pigmented juvenile elver stage. According to McCleave (1980), elvers have a burst swimming capacity of 0.6 m/s. Consequently, flow velocities nearly equal to or higher than 0.6 m/s, often encountered at the level of water control structures (e.g. under sluice gates), may theoretically be impossible to cross by glass eels and elvers. Therefore, all the structures located in the marsh can be suspected to create barriers during young eel migration from the ocean to the marsh habitats.

Currently the most usual solution for glass eel passage at physical obstacles consists of climbing ramps (Porcher 2002). Their efficiency mainly depends on the type of

substrate used (Watz et al. 2019), the water temperature (Linton et al. 2007), the hydraulic conditions on the ramp, and the attraction flow rate (Piper et al. 2012). Unfortunately, such devices concentrate glass eels in small areas and out of the water, which facilitates illegal fishing. Moreover, it seems that, when the air temperature is low, glass eels do not use these ramps (pers. obs.). All these reasons make climbing ramps not well adapted for environments such as Charras fresh marsh, so other types of solutions are necessary to be studied.

2.2. Hydraulic context and infrastructures

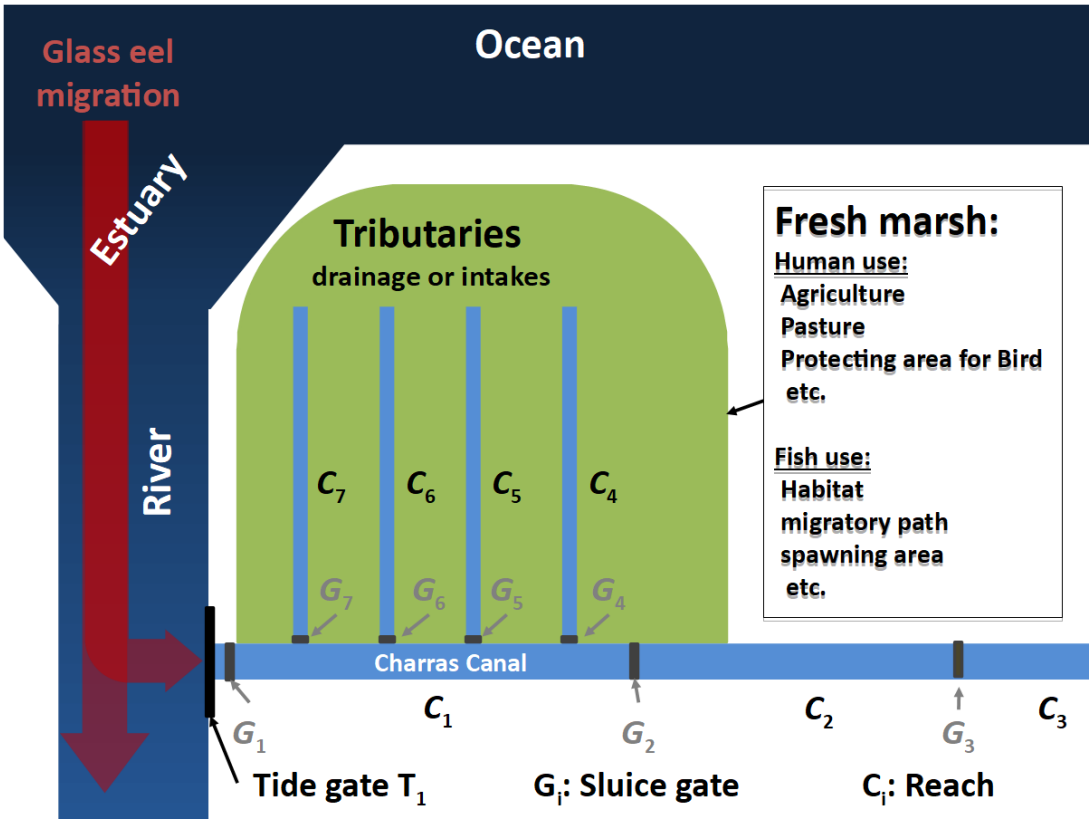

Figure 1. Charras network schematic map and examples of marsh water uses. G_4, G_5,G_6, and G_7 gates are coupled to flap gate to prevent salt water intrusion in tributaries.

The Charras canal is approximately 20 kilometers long. To avoid sea water intrusion in the marsh, a side hinged tide gate (T_1) has been installed at the mouth of Charras marsh (Fig. 1). Water levels are controlled by sluice gates: Charras gate (G_1) at the mouth of the channel, Suze gate (G_2) 7 kilometers upstream, and Portefache gate (G_3) 15 kilometers upstream from the mouth. Four tributaries are connected to Charras canal. The connections are controlled by sluice gates coupled to flap gates (G_4, G_5, G_6, and G_7).

The canal and its tributaries have trapezoidal cross sections; their characteristics are given in Table 1, while those of the gates are given in Table 2. When Charras tide gate (T_1) is open, it does not control the flow. However, when glass eels arrive (i.e. on rising tide), the tide gate T_1 is supposed to close. Therefore, to improve fish passage, since 2010, a minimum opening of 20 cm has been imposed through the presence of

three wooden blocks in order to prevent complete gate closure during high tide. The efficiency of such a soft adaptation has already been documented for estuaries (Boys and Williams 2012; Mouton et al. 2011), with a clear improvement regarding fish migration processes and subsequent local fish assemblages.

Reach	name	length (m)	Bottom width (m)	Side slope (m/m)	bottom elevation (m asl.)
Charras-Suze	C_1	7000	6.5	0.9	no constant
Suze-Portefache	C_2	7400	7.5	0.9	no constant
Upstream Portefache	C_3	10000	5.5	1.13	0.2
Upstream Pellerouge	C_4	15000	8	0.8	0
Upstream Roseaux	C_5	14000	9	1.0	0.5
Upstream Fourras	C_6	3000	10	1.5	0.8
Upstream Grande motte	C_7	3000	10	1.5	0.2

Table 1. Characteristics of the main canal and tributaries of the marsh. For C_1 and C_2 reaches bathymetry measurements, see figure 7. All elevations are above sea level (asl) and are related to the French geodetic system (NGF-IGN1969).

Structure	Name	Gate width (m)	Sill elevation (m)	Gate height (m)
Charras sluice gate (*2)	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

Table 2. Characteristics of sluice gates. The gate heights are given because of possible overflow.

Like tide gate T_1, flap gates coupled to G_4, G_5, G_6, and G_7 sluice gates have been equipped for a few years with blocks to improve glass eel passage. These blocks impose a minimum opening of 20 cm at each flap gate. Thanks to the blocks at T_1, gate G_1 (located 10 m upstream) is passable by eel during high tide, when water flows in the upstream direction. Glass eel passage has been verified through fishing operations and comparisons of individual densities downstream tide gate T_1, and upstream sluice gate G_1 (Rigaud et al. 2014). However, the next structure encountered by eels, gate G_2, may be a barrier to migration as, at water flows downstream, i.e. with a direction opposite the migrating eels. In order to be, at least, passable by a significant number of glass eels, flow velocity at gate G_2 has to be below their 0.6 m/s swimming limit.

Sluice gates usually induce a head-loss from a few centimeters to a few tenths of centimeters. Applying Bernoulli's theorem, one can calculate the velocity in the jet under the gate, following:

$$V_w = \sqrt{2g\ \Delta H} \tag{1}$$

with g acceleration due to gravity, ΔH head difference (which is almost equal to water level difference) between upstream and downstream sides of the gate. Following equation (1), making the gates passable by glass eels (i.e. a flow velocity < 0.6 m/s) requires ΔH value lower than 2 cm, which is a real challenge for marsh managers.

2.3. Water Management Objectives

Hydraulic structures have two purposes in the studied area. The first objective is to drain high rainfall in order to avoid flooding during winter, and the second one

is to keep water level around target values for agricultural needs during summer. These two different objectives, at different times of the year, imply the following water management plan:

- During the period of high rainfall events (usually between December and February), hydraulic structures are used to facilitate drainage. Sluice gates are fully open.
- During wet periods (usually between March and May), hydraulic structure are managed to drain periodic rainfall events. The goal is to drain the water volume in excess while keeping enough water volume storage for the drier periods, expected in spring and summer. In this case, water levels are kept around target values (Table 3). At sluice gates, the water level control is performed by under gate flows, whereas water is flowing over the top of the weirs.
- During dry periods (usually between May and September), there are few rain events, and the marsh is used for water storage. In this case, sluice gates are closed in order to maintain high water levels (Table 3).
- During autumn, first rainfalls occur, usually between October and December. Sluice gates are maintained closed until the marsh is fully filled.

During all these periods, tide gates are not operated manually, they automatically move with the tide to limit seawater intrusion.

Table 4 summarizes this annual cycle of management operations and indicates the most favorable periods for glass eel migrations.

Reach	Level target (m)	
	Summer	Winter
C_1	2.15 - 2.20	1.90 - 2.00
C_2	2.25 - 2.30	2.15
C_3	2.35 - 2.40	2.25 - 2.30

Table 3. Water level target at two seasons in principal reaches of Charras marsh.

Season	Rain	Objective	Gate position	Channel velocity	Glass eel migration
Winter	High	Rainfall drainage	Large opening	High	Increases progressively
Spring	Medium	Water drainage	Daily control	Medium	High
Summer	low	Maintain water level	Close	Null	Low
Autumn	High	Rainfall drainage	Large opening	High	None

Table 4. Summary of the seasonal water managements operations and flows in Charras marsh.

2.4. Hydraulic data

Water level measurements have been monitored continuously at different locations in the marsh, during the period of glass eel arrival from the ocean, between 06/02/2015 and 18/03/2015, using ultrasonic water level sensors, with a recording interval of 15 minutes (Figures 2 and 3). In complement several flow rates were measured upstream of G_1 (18/02/2015) and at each hydraulic structure on 19/02/2015. They were performed with an Acoustic Doppler Current Profiler (RDI StreamPro), allowing a quick measurement compatible with the frequent change in hydraulic conditions due to the tide. These measurements were used to calibrate sluice gates and tide gates discharge equations. Sluice gate openings were also available during the study period (Fig. 4).

For management purposes, the following rules applied:

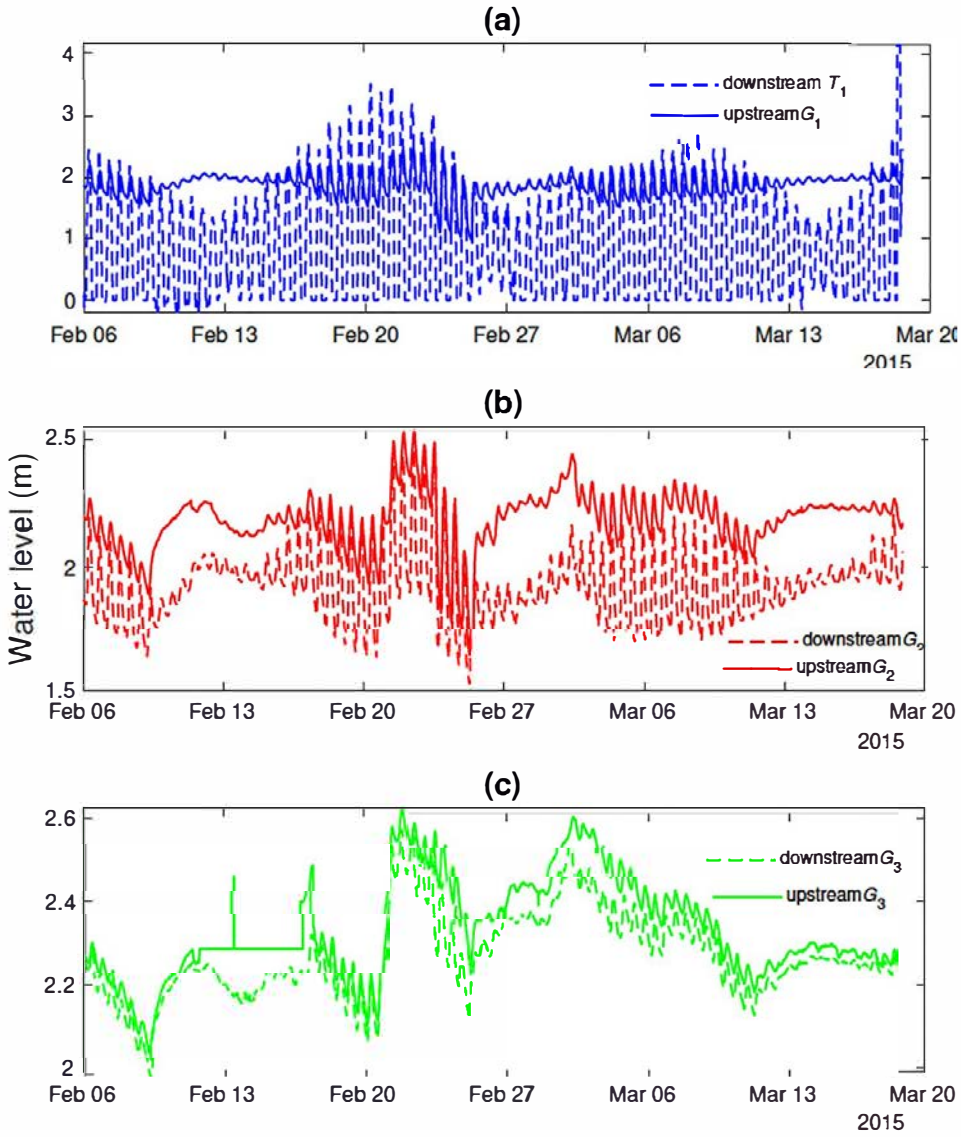

Figure 2. Water level records in different location of the Charras canal. (a) water level downstream T_1 gate (i.e. corresponding to the down-stream constraint) and water level upstream G_1. (b) water levels downstream and upstream G_2. (c) water levels downstream and upstream G_3.

- The openings of sluice gates G_1 and G_2 were modified daily. The opening modification depended on the inflow variation (Fig 4).

- Except during the irrigation period, G_3 was fully open. As a consequence G_3 was not an obstacle during glass eel migration.

- Sluice gates openings on tributaries (C_4, C_5, C_6, and C_7) were rarely modified. During the study, water levels in tributaries were controlled by water level variation in C_1 reach, the gate openings being unchanged.

- G_6 was always closed, but there was usually an overflow (i.e. a flow above the

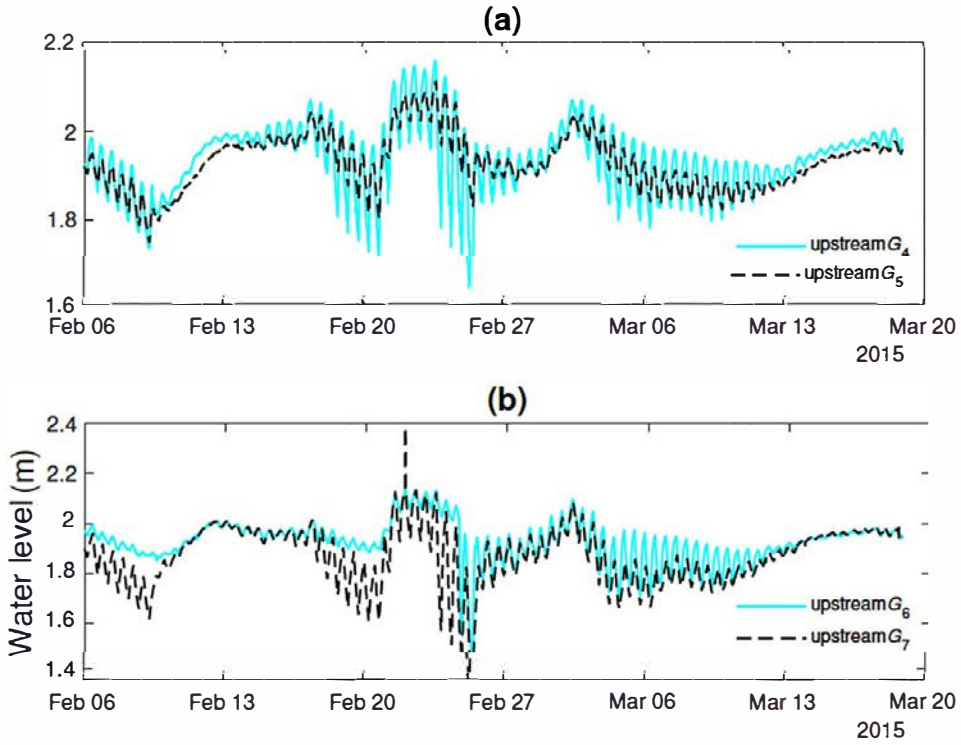

Figure 3. water level records, in different locations of Charras marsh tributaries. (a) water levels upstream G_4 and G_5.(b) water levels upstream G_6 and G_7.

gate).

- G_7 was always open and did not disturbed the flow. However a flap gate controlled water entrance in C_7 at high tide.

These observations show that, during glass eel migration period, daily water management was performed along the marsh with the modification of G_1 and G_2 openings, which led us to focus on these two gates for possible adaptation of management rules in the perspective of eel passage improvement.

As said above, it is possible to place blocks on the gate T_1 to permit the passage of glass eels. However, this operation affects the water levels, and therefore the entire hydraulic conditions in the networks due to backwater effects. The adaptation of G_2 operation (to improve fish passage) should consider this interaction. To maintain sustainable agricultural uses in the area, it is also required to maintain the water level in C_1 near the target value (see Table 3).

3. Modelling strategy

This section describes the hydraulic model developed for the study, its calibration against observations, the management strategies which will be compared and the selected indicators for this comparison.

In this approach, it is important to consider the backwater effects and the time-varying flow conditions due to tides, which cause periodic flow inversions at various locations in the marsh. In this context, a hydraulic model based on the one-

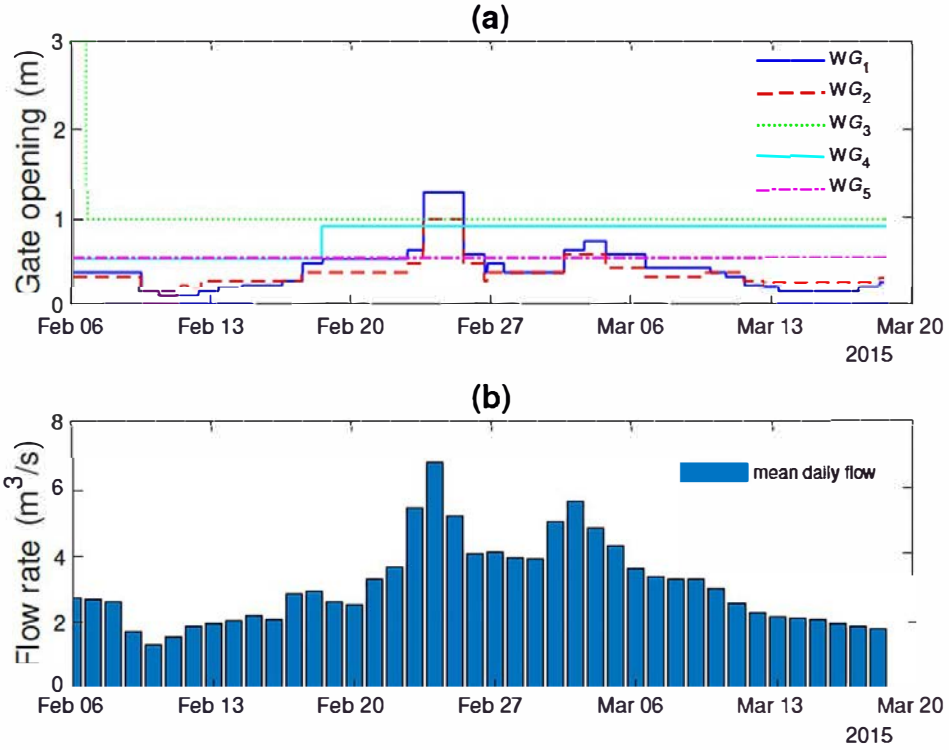

Figure 4. (a) gate openings in Charras marsh during the measurement period. Gate G_6 and G_7 are not presented because: G_6 was closed, and gate G_7 was fully opened during the measurement period. (b) mean daily flow at G_2 gate, calculated from water level measurement and the sluice discharge equation (see text section 3).

dimensional Saint-Venant's equations was used. The software SIC ("Simulation of Irrigation Canals") was selected for its ability to simulate regulated networks, with possible flow inversion, and to implement specific discharge equations in regulation modules (Baume et al. 2005).

The hydraulic model is expected to provide key variables for fish passage assessment, notably the potential constraining flow velocities at structures. Due to tides, the model has to address regular transitions between free flow and submerged flow at sluice gates, and high submergence and flow inversions at sluice gates. There are few gate equations able to deal with such challenging conditions to be included in numerical models. Specific equations based on energy-momentum balance (Belaud et al. 2009) were implemented and coupled with the 1D flow equations.

3.1. Description of the hydraulic model

3.1.1. Saint-Venant equations

The one-dimensional Saint-Venant's equations can be written as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial Q^2/A}{\partial x} + gA\frac{\partial h}{\partial x} + gA(S_f - S_b) = 0 \tag{3}$$

where t is the time, x is the abscissa, Q is the flow rate, A is the wetted Area, h is the water level, g is the gravitational acceleration, S_f is the friction slope, and S_b is the bed slope. Equation 2 and 3 are solved thanks to Preissman numerical scheme, which is unconditionally stable. A time step of 1 minute was selected for the sake of accuracy. The friction slope was calculated with Manning equation, in which Manning coefficient (n) was adjusted by calibration on observed water levels.

3.1.2. Hydraulic structures discharge equations

Sluice gate discharge equation – Water levels are strongly affected by sluice gates. These structures also create flow accelerations that constitute barriers during fish migration. For this purpose, it is therefore necessary to consider the velocity V_{G_j} in the jet under the gates G_j:

$$V_{G_j} = \frac{Q}{C_c W L} \tag{4}$$

in which C_c is the contraction coefficient (between 0.6 and 1 - see Belaud et al. (2012)), W is the gate opening and L is the gate width.

Standard gate equations with fixed discharge coefficient or contraction do not ensure continuity of flow calculation in all possible configurations of water levels and gate openings. The discharge at these structures were calculated thanks to the following discharge equation:

$$Q = \frac{C_c W}{\sqrt{1+k}} L\sqrt{2g}\sqrt{\frac{h_u - h_1}{1 - \frac{C_c^2 W^2}{h_u^2}}} \tag{5}$$

where k is the correction coefficient due to headloss and other real fluid effects, allowing calibration of the equation on discharge measurements, h_u is the upstream water level, h_d is the downstream water level. The momentum equation was used to determine the flow regime. In case of free flow, $h_1 = C_c W$, otherwise $h_1 = h_d$.

To ensure continuity of the equation with increasing opening, C_c varies with the relative gate opening $a = \frac{w}{h_u}$ and the relative submergence $s = \frac{h_1}{h_u}$, starting from $C_c \simeq 0.6$ for small opening to unity in case of a large submergence and a large opening. Iterations (with a fixed point method) are needed to obtain the discharge as function of h_u, h_d and W (Belaud et al. 2012). Equation (4) gives the velocity under the gate. These equations were used for G_1, G_2, G_3, G_4, and G_5, when flowed under the sluice gates.

Flow over closed gates – When sluice gates were closed, they acted as a weirs. During the measurement period, this situation occurred for G_6. Considering that h_{ug} is the upstream head and h_{dg} is the downstream head over the gate, the discharge is given by:

- For the free flow ($h_{dg} < \frac{2}{3}h_{ug}$):

$$Q = \mu_f L\sqrt{2g}h_{ug}^{3/2} \tag{6}$$

with a discharge coefficient, $\mu \simeq 0.385$.

For the submerged flow ($h_{dg} > \frac{2}{3}h_{ug}$):

$$Q = \mu_s L\sqrt{2g}(h_{ug} - h_{dg})^{1/2}h_{dg} \tag{7}$$

with a discharge coefficient, $\mu_s = \frac{3\sqrt{3}}{2}\mu_f$.

Tide gate discharge equation – If the water level downstream of the tide gate was lower than the upstream water level, the tide gate was fully open and therefore had no influence on the flow. In the opposite case, the tide gate was closed, but the blocks maintains a small opening; to calculate the discharge at the gate, we used a vertical fish slot discharge equation (Wu et al. 1999):

$$Q = \mu_g b h_d\sqrt{2g(h_d - h_u)} \tag{8}$$

where b is the opening width due to the block, h_d is the water level downstream of the tide gate, h_u is the water level upstream of the tide gate, and μ_g is a discharge coefficient around 0.8, which can be calibrated with field measurements.

Flap gate discharge equation – The principle is the same as for tide gates.

If $h_d > h_u$, the flap gate was closed, and the gate blocks allowed a small opening, we used the following sluice gate discharge equation to calculate the discharge at the gate, we use a sluice gate discharge equation:

$$Q = C_d b L\sqrt{2g(h_d - h_u)} \tag{9}$$

where b is the opening due to the blocks (b=0 if there are no blocks), L is the width of the flap gate (equal to the width of the sluice gate positioned few meter upstream of the flap gate), and C_d is a discharge coefficient set to 0.8 following results obtained on similar undershot flap gates in submerged flow (Belaud and Litrico 2008). It can be noticed that free flow never occurs for flap gates.

3.1.3. Model calibration

The hydraulic model contains coefficients which are quite sensitive on model results, considering their possible range of variation: the Manning coefficient for the energy loss in canal reaches, and the head loss coefficients at structures (k for sluice gates, and discharge coefficients μ_g, μ_f, and C_d). The discharge coefficients were first calibrated thanks to ADCP flow rate measurements and water level records. The flow rates have been calculated at each hydraulic structure with water level records upstream and downstream of the hydraulic structures. Table 5 reports the calibrated coefficients for each sluice gate. The channel Manning coefficients were calibrated from water level measurements in fields. Fig. 5 illustrates the quality of discharge predictions for G_1, G_2, G_3, G_4, and G_5.

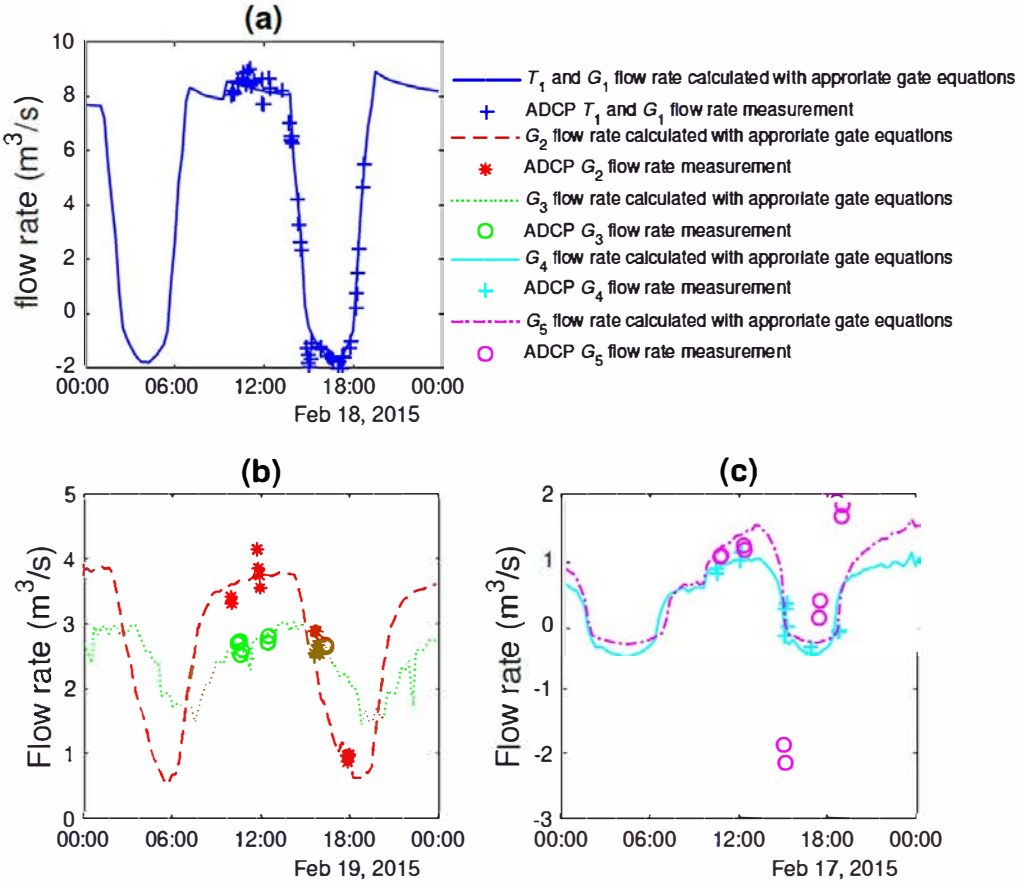

Figure 5. Calibration results for sluice gate G_1 and tide gate T_1 (a). Calibration results for sluice gates G_2 and G_3 (b), G_4 and G_5 (c).

To validate the model, a simulation has been performed with the following boundary conditions:

- Water level measured and corrected downstream of T_1 tide gate.
- Daily flow calculated from water level measurements upstream G_3, G_4, G_5, G_6 and G_7 sluice gates. These daily flows were calculated using water discharge equations and water level measurement.

The root mean square error (Eq. 10) was used to evaluate the performance of the model:

$$RMSE = \frac{\sqrt{\sum (h_{mes} - h_{sim})^2}}{n} \tag{10}$$

where h_{mes} is the water level from field measurements, and h_{sim} is the simulated water level.

Results are summarized in Table 6. There was a good agreement during the 40-day period of observation between the model outputs and the water level observations upstream of gates G_1 and G_2 (Fig. 6). There was also a good agreement between

Gates and reaches	Type	calibrated coefficient
C_1	main reach	n= 0.015
C_2	main reach	n=0.02
C_3	main reach	n=0.025
C_4	tributary	n=0.05
C_5	tributary	n=0.033
C_6	tributary	n=0.022
C_7	tributary	n=0.022
T_1	tide gate	μ_g=0.8
G_1	sluice gate	k=0
G_2	sluice gate	k=0.35
G_3	sluice gate	k=1
G_4	sluice gate	k=0.2
G_5	sluice gate	k=0.2
G_6	weir (sluice gate closed)	μ_f=0.4
G_7	sluice gate	n.a. (sluice gate fully open)

Table 5. Calibrated coefficients for head losses at different locations of the Charras marsh (Manning n and others from discharge equations of the respective gates, see text). For flap gates at structures G_4, G_5, G_6 and G_7, the discharge coefficient was set to 0.8.

water velocities under G_2 calculated with Eq. 1 and measured and simulated water levels (Fig. 6). These velocities will be used afterwards as an indicator for fish passage opportunities under the gate. Figure 7 shows the water level simulated along reaches C_1 and C_2 at three different times. At low tide, there was a significant friction slope in both reaches (Fig. 7). Flow variability was high throughout the system, especially between low tide and high tide conditions, and the mean flow was obviously not sufficient to describe the hydraulic conditions. These results illustrates the importance of using the unsteady Saint-Venant equations to describe water flows in the marsh.

	$\overline{H}$ (measured)	$\overline{H}$ (simulated)	$RMSE$
G_1	1.89	1.88	0.10
G_2	2.19	2.18	0.10
G_3	2.33	2.33	0.12
G_4	1.93	1.94	0.10
G_5	1.93	1.94	0.10
G_6	1.93	1.96	0.10
G_7	1.87	1.84	0.13

Table 6. Calibration evaluation of the hydraulic model: mean water level ($\overline{H}$) upstream of different gates and $RMSE$.

3.2. Alternative management scenarios to improve eel passage

To improve glass eel passage at hydraulic structures, alternative management scenarios can be explored in order to (i) show the impact of management modifications at one gate on the overall open channel network hydraulic conditions; and (ii) provide recommendations about the operation or the design of these gates. Two kinds of strategies were explored:

- A passive management strategy. It consists on a modification of tide gate blocks size, without modification of sluice gate openings. At high tide, the water level in C_1 reach should raise, and the water level difference between the upstream and downstream sides of G_2 gate should decrease. This management scenario does not need any modification in manager work, neither a coordination between different gate managers, but the blocks cannot be removed or changed easily, which implies that this management scenario cannot be adaptative to daily inflow

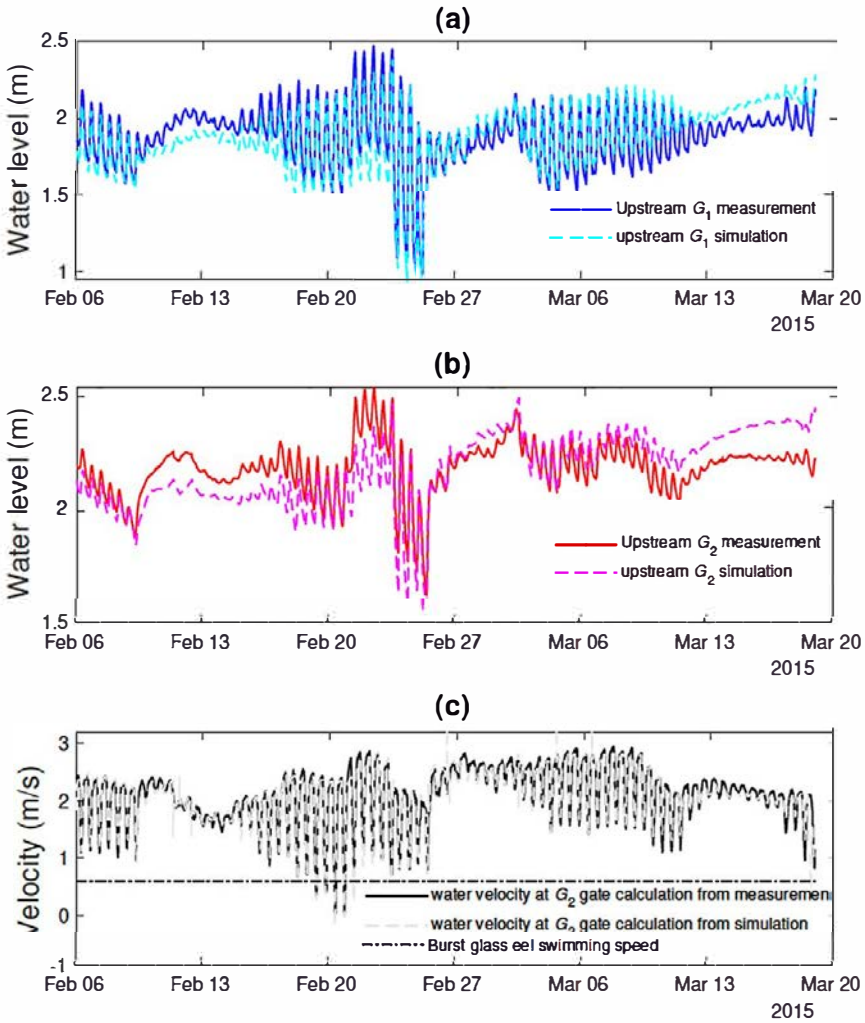

Figure 6. Model outputs over the measurement period. (a) comparison between measured and simulated water level upstream of G_1. (b) comparison between measured and simulated water level upstream of G_2. (c) comparison between water velocities at gate G_2, calculated from measured and simulated water levels; the burst swimming speed of glass eel is given as a reference value of flow velocity above which eel passage should be highly compromised.

and tide variations. The increase of seawater inflow (compared to a scenario upon which T_1 or G_1 are closed) has therefore to be estimated and compared with the amount of (salt)water that can be accepted upstream.

- An active management strategy. Sluice gates opening may be modified daily, the blocks being maintained as in year 2015. The objective is here to temporally reduce the velocity under G_2 in order to increase the duration of gate passability for eels. This can be achieved by reducing the water level difference downstream and upstream the gate, e.g. by opening it for a while. This time should not be too long to avoid an excessive decrease of the water level in pool C_2. This kind of management is more adaptative to inflow and tide variations but sluice gate

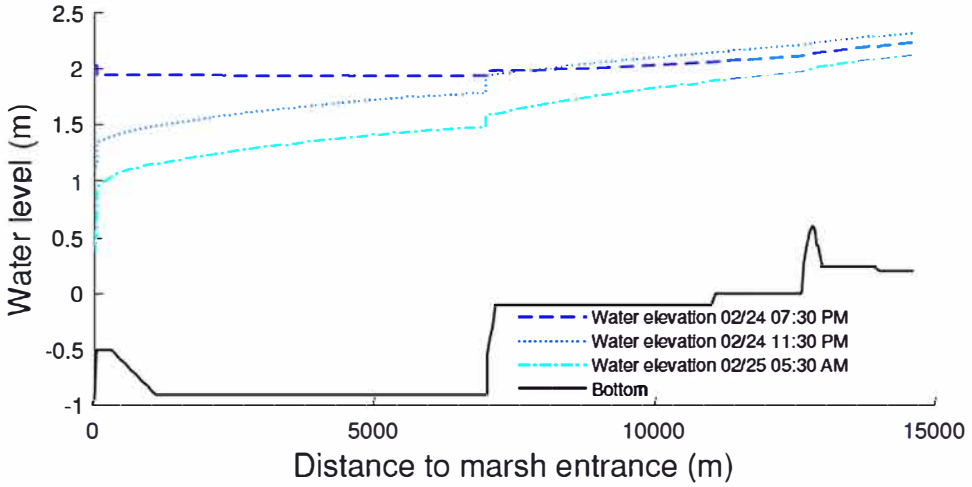

Figure 7. Water elevation along reaches C_1 and C_2. The solid line represents the canal bottom. Dotted lines show water elevations at 3 different hours on 24/02/2015 and 25/02/2015.

openings have to be adjusted daily.

To test the feasibility and the efficiency of the different options, 3 periods were selected with different tide ranges and flow rate inflows. Each period was selected in a way that, during 2 days, the flow conditions were quite stable (i.e. did not vary from more than 10%), and the seven sluice gates G_i had a constant opening (i.e. none has been managed during the 2 days). The corresponding conditions are reported in Table 7. Figure 8 illustrates the capacity of the model to simulate the observed conditions (water levels and calculated velocities) during the 3 selected periods.

Day	name	Inflow (m^3/s)	Tide range (m)	G_1 opening (m)	G_2 opening (m)
07/02/2015	P_1	2.70	2.20	0.40	0.35
19/02/2015	P_2	2.64	3.10	0.55	0.40
07/03/2015	P_3	3.40	2.45	0.45	0.35

Table 7. Periods selected and corresponding parameters for the comparison of alternative management strategies

The comparison between simulated and measured water levels and flow velocities (Fig. 8) showed that the model is accurate. Comparing the flow velocities under G_2 and the burst swimming speed of glass eel (Fig. 8), it seems G_2 can be crossed by glass eel during the four tides of period P_2, but is not passable during the 2 other periods. Due to its higher tide range, it seems logically that salt intrusion is also higher during this period.

Several simulations were performed on P_1, P_2, and P_3 periods (Table 7) in order to evaluate the impact of management strategies:

- For the passive management strategy, simulations were performed with different block sizes, ranging from 0 to 60 cm, on the 3 periods. The used sluice gate openings were those observed in the fields during the periods. The objectives of these simulations were (i) to test the impact of blocks size on both fish passage and hydraulic management needs and (ii) to analyze the influence of the block size on the hydraulic conditions.
- For the active management strategy, simulations were performed with G_1 gate

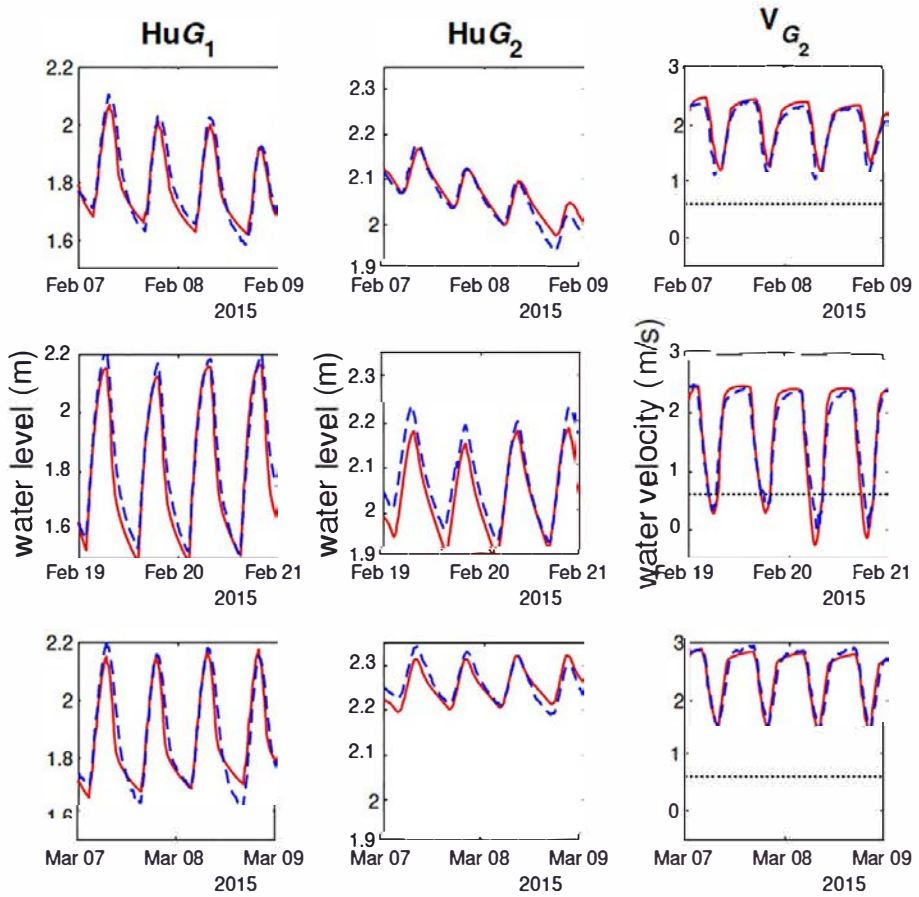

Figure 8. Simulation of water levels and flow velocities at G_1 and G_2, during the 3 P_i periods with constant inflow and stable management. Blue dashed lines corresponds to measurements, red lines to simulations. 1st, 2nd and 3rd rows are for periods P_1, P_2 and P_3, respectively. 1st column is for water level upstream of gate G_1, 2nd column for water level upstream of G_2 and 3rd column is water velocity at gate G_2. Black dotted lines, in the third column, indicates glass eel burst swimming velocity (0.6 m/s).

openings varying from 28 to 52 cm, and G_2 gate openings varying from 35 to 74 cm, by steps of 2 cm (which corresponds to the current ranges and resolution of gate movements). These simulations were performed on period P_1 only, which corresponded to an average flow rate in the system (4) and an average tide range (see Fig. 2 and 3). These simulations were performed with blocks of 20 cm at tide gate T_1 (which corresponds to the current real blocks size). The hydrologic conditions were constant over the period, which led to select a constant gate opening throughout the period, as done in practice in the fields (Fig. 4).

- In order to show how the active management principles can be applied, and how they perform in terms of fish passage opportunities, salt intrusion and water level control, simulations have been done over the whole measurement period of 40 days, with the modified management rules between 18/02/2015 and 25/02/2015. This analysis can also serve to illustrate how the model can be used to evaluate *a priori* alternative management operation strategies.

3.3. Indicators for the evaluation of management scenarii

Four indicators have been selected in order to compare the different management options.

The first one, T_{pass} is the duration when the water velocity at G_2 gate is lower than glass eel swim capacity (0.6 m/s), during one tide. This indicator is useful to quantify the effectiveness of the studied scenarios from an ecological point of view. It was arbitrarily decided that it should be greater than 1 hour per tide to allow a significant passage of eels.

Three other indicators were chosen for their usefulness from an agricultural and flood management points of view.

ΔH_1 is the mean water level deviation from recorded water levels upstream of gate G_1 (H_{u,G_1}). We chose this average water level as a reference (rather than the ones previously given in Table 3 which are average targets), because it is necessary to continuously adapt the water level due to the variations of tide and river flow. For management purposes, ΔH_1 should be lower than 15 cm.

ΔH_2 is the mean water levels deviation from recorded water level upstream of gate G_2 (H_{u,G_2}). For management purposes, ΔH_2 should also be lower than 15 cm.

R_{sea} is the ratio of the sea water volume intrusion through T_1 to the water volume drained out of the marsh. For management purposes, R_{sea} should be lower than 0.2.

The reference values, for each periods P_i, have been calculated from measurement and are provided in Table 8. These values were used to compare the results of tested management with the results of current management.

Period	T_{pass} (H)	H_{u,G_1} (m)	H_{u,G_1} (m)	R_{sea}
P_1	0	1.79	2.06	0.03
P_2	2.6	1.78	2.01	0.17
P_3	0	1.87	2.26	0.05

Table 8. Reference values for the 3 studied periods P_1, P_2, P_3. H_{u,G_i} is the average water level upstream of G_i

4. Results

4.1. Passive management

The passive management strategy was evaluated by calculating the indicators during each period using different block sizes (Fig. 9). With no block, there was obviously no seawater intrusion. Consequently, the water level difference between the upstream and downstream sides of G_2 remained high and thus induced, below gate G_2, a water velocity that was always above glass eel burst swimming speed.

An increase of the block size implied more sea water intrusion and an increase of the mean water levels in all reaches. During period P2, a 10 cm block allowed flow velocities under gate G2 that were theoretically compatible with some eel passage (Fig. 9). With a 20 cm block, during period P_2 the seawater intrusion allowed the passage of glass eels during about 2.6 hours per. However, during periods P_1 and P_3, whatever the block size, passive management scenarii were not sufficient to permit fish passage.

All the indicators linearly reacted to block size in the size range 0–25 cm, while blocks larger than 30 cm induced indicator values equivalent to a situation without tide gate. For larger blocks, R_{sea} seemed excessive for some of the tides during period P_2 (Fig. 9). This should be an issue for the purposes of water management in the

Charras freshwater marsh. In addition, from an ecological point of view, the release of a large volume of salt water during the next tidal cycle could deter fish looking for fresh or brackish water, such as glass eels.

These results illustrate one of the limitations of passive management. Indeed, if the tide gate opening is too high, due to a large block size, then the sea water inflow is no longer controlled by the block, but by the sluice gate only. Therefore, the optimal block size depends on the opening of G_1 and on the hydrological conditions.

This argues to select a unique block size, and to increase the time favorable to fish passage by changing the gate openings according to the hydrological and tidal conditions. These principles of active management are analyzed below.

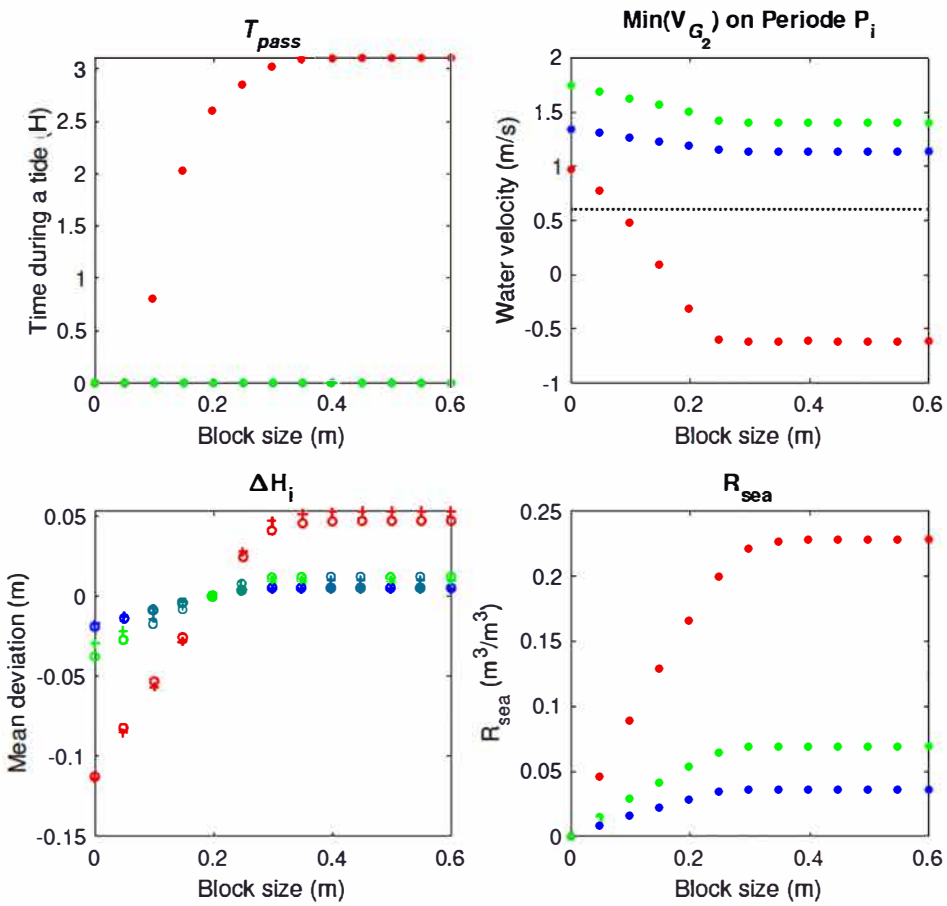

Figure 9. Effects of block size on four indicators (T_{pass} duration when G_2 is passable by glass eel during one tide, ΔH_1 mean water level deviation from water recorded level upstream G_1, ΔH_2 mean water level deviation from water recorded level upstream G_2, and R_{sea} the ratio of sea water intrusion), during the 3 studied periods (Blue P_1 period, red P_2 period, and green P_3 period). On the down left figure, open circles and cross symbols represent respectively the mean water level deviation from reference upstream G_1 and upstream G_2. Black dotted lines, on the top right figure, indicates glass eel burst swimming velocity (0.6 m/s).

4.2. Active management

It was assumed here that 20 cm blocks were installed on the tide gate T_1. Simulations were then performed for a combination of G_1 and G_2 gate openings.

Figure 10 plots the changes in the four indicators for simulated conditions during the studied period P_1. Fish passability of gate G_2 was facilitated by increasing G_2 opening. A limit exists, below which the gate is unpassable. This opening limit depends on the other gate openings (Figure 10) and on hydrological conditions. Indeed, on period P_2, gate G_2 is passable with a fixed block of 20 cm, G_1 opening of 55 cm and G_2 opening of 40 cm (Figure 9). However, on period P_1, gate G_2 is unpassable with the same management (Figure 10).

An increase in G_2 opening emptied reach C_2 and filled C_1, reducing seawater intrusion. The upper limit was defined by the decrease of HuG_2, a too large deviation from target value being prejudicial to the agricultural uses in the marsh.

Increasing of G_1 opening is also a way to enhance fish passage of gate G_2. Such as for G_2 opening, there is an opening limit in order to respect the water level needed for the marsh management.

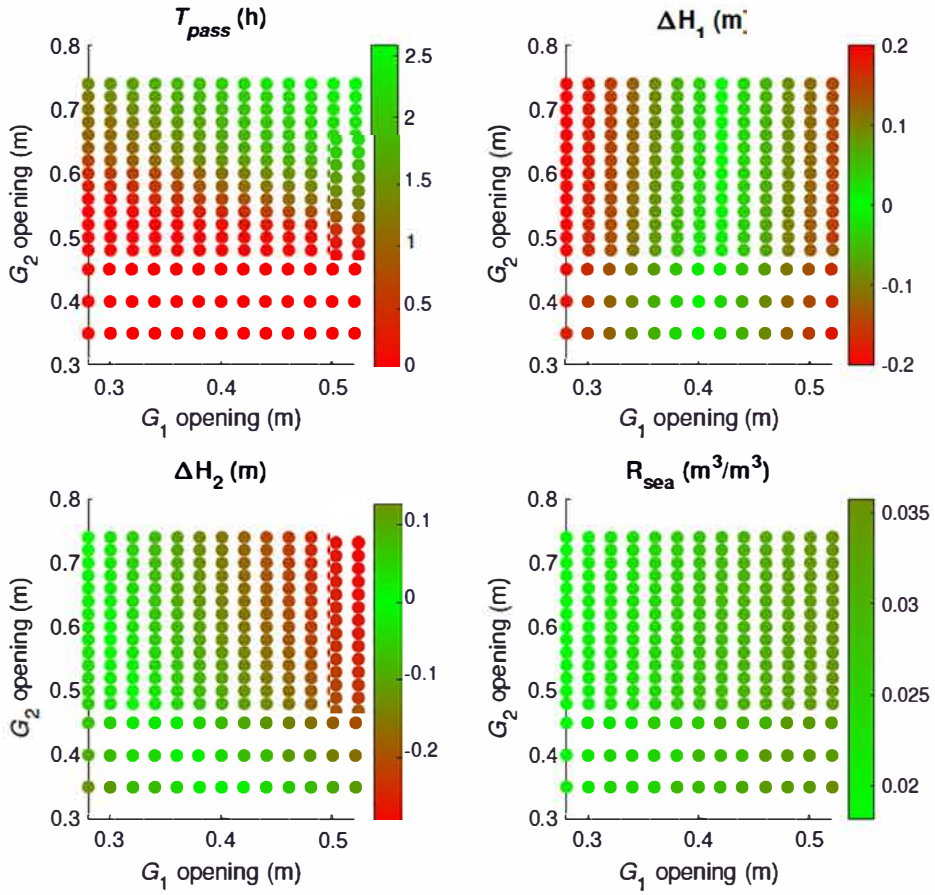

Figure 10. Effects of G_1 and G_2 opening modifications on period P_1. The top left figure shows T_{pass} variations in hours. The top right figure shows mean water deviation ΔH_1 variation in meters. The down left figure shows mean water deviation ΔH_2 variation in meters. The down left figure shows R_{sea} ratio variations.

The best active management for fish passage continuity is, obviously, when gates are open at their maximum. This management rule made G_2 passable during more than 2 hours per tide. But this strategy appeared unacceptable regarding hydraulic management indicators: the mean water level in reach C_2 was 1.77 m, a value far

below the target level of 2.06 m (i.e. water level is 30 cm too low). From Figure 10, it was possible to find a management strategy that should improve fish passage continuity while respecting the constraints on the other indicators. Figure 11 shows the period suitable for fish passage using an active management scenario that respects the different constraints on indicators. Ten combinations appeared relevant, and the best active management for fish passage continuity was obtained with a G_1 opening of 38 cm and a G_2 opening of 74 cm. In these conditions, gate G_2 was passable during more than 1.5 hour per tide, and the salt intrusion ratio was limited to $R_{sea} = 2.5\%$.

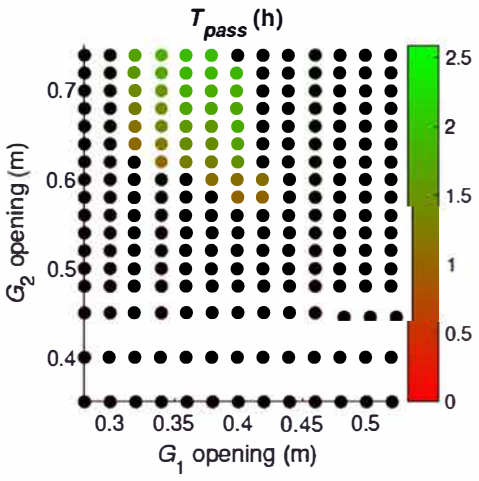

Figure 11. Optimization of T_{pass} with an active management scenario during period P_1. The operating conditions which do not respect the constraints on indicators have been fill in black.

Figure 12 illustrates the impact on water level and water velocity under gate G_2 for three active management scenarii, including the observed (i.e. real, current) one. With a G_1 opening of 52 cm and a G_2 opening of 74 cm, the gate was passable at each high tide. There was no difference in T_{pass} between the four tides of period P_1, but the water level in marsh decreased continuously during the 2 days, implying large fluctuations of water level upstream of G_2 due to the tide.

With a G_1 opening of 38 cm and a G_2 opening of 74 cm, the water level in the marsh was higher, reaching the targeted levels for marsh management, and the gate was passable at each high tide. There was no difference in T_{pass} between the four tides. The tidal influence upstream of G_1 decreased.

The search of an optimal active management scenario over the period P_1 suggested the following improvements compared to the reference situation: gate opening of G_1 should be slightly decreased, while gate opening of G_2 should be significantly increased. This philosophy was applied on the period between the 18/02/2015 and the 25/02/2015, which included successive tides with large amplitudes (Fig. 2). Figure 13 compares the water levels and the velocities under gate G_2 between current management parameters and two management scenarii increasing eel passage (the best management for glass eel tested with, and without, management constraint in ΔH_1, ΔH_2 and R_{sea}). With the new proposed values of openings, the number of tides where the velocity at gate G_2 was under 0.6 m/s was increased from 5 (total duration of 11.5 hours) to 14 (total duration of 50.25 hours). However, this caused some variations on the water levels, notably an increase of levels at gate G_1. The mean water level upstream G_1 was increased by about 20 cm in comparison with the mean water level upstream G_1 simulated with recorded management (Fig. 13). This is more than the

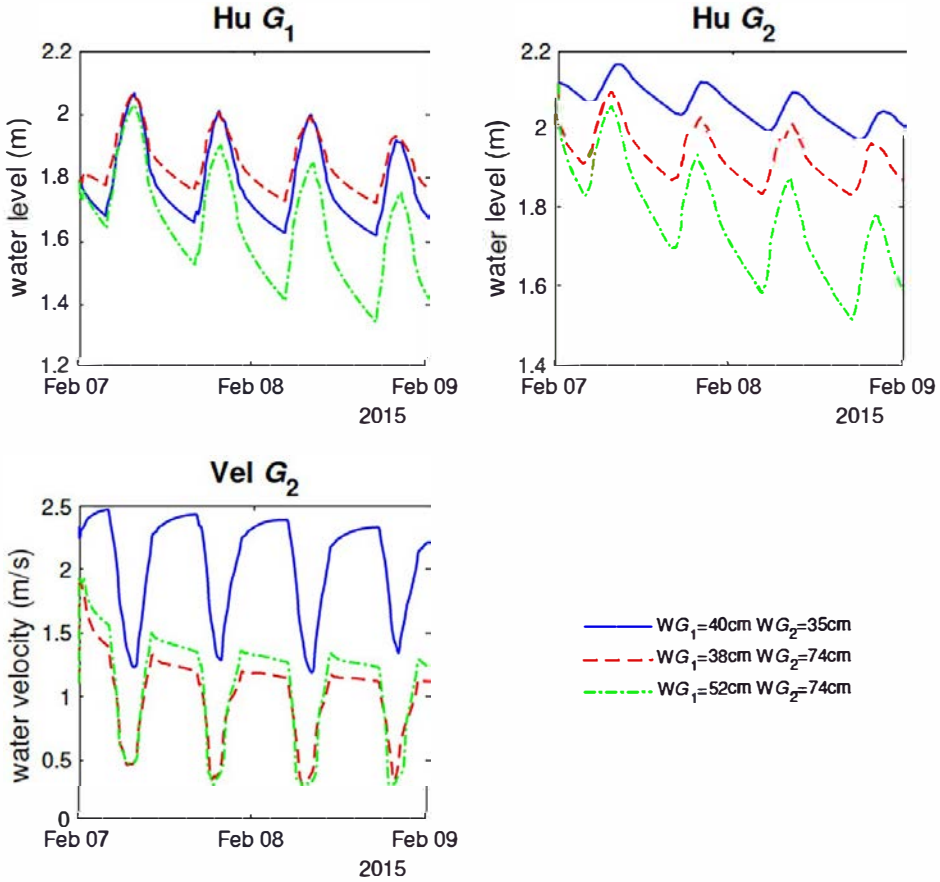

Figure 12. Simulation of water levels and water velocities for 3 different active management scenarii during period P_1. Blue continuous line: current management (G_1 opening = 40 cm, G_2 opening = 35 cm). Red dashed line: best management scenario to improve fish passage (among those that have been tested), with respect of other constraints (G_1 opening= 38 cm and G_2 opening= 74 cm). Green dash-dot line: best scenario to improve fish passage (among those that have been tested), other constraints not considered (G_1 opening= 52 cm, G_2 opening= 74 cm).

15 cm, because this scenario was optimized for tides and flow condition (tide and flow which occurred during P_1 period), whereas variable flow and tidal conditions occurred between 18/02/2015 and 25/02/2015. The level returned to the normal after 6 days, and there is almost no difference between scenarios after 02/03/2015 (Figure 13).

5. Discussion

5.1. From local to network scale: dealing with backwater and unsteady flow

The optimization of fish passage continuity through management measures is generally understood at the obstacle scale, by managing its opening or by building a structure making it passable. In the case of low-slope networks, the "backwater effect" implies an influence of the management of structures on the upstream part of the networks.

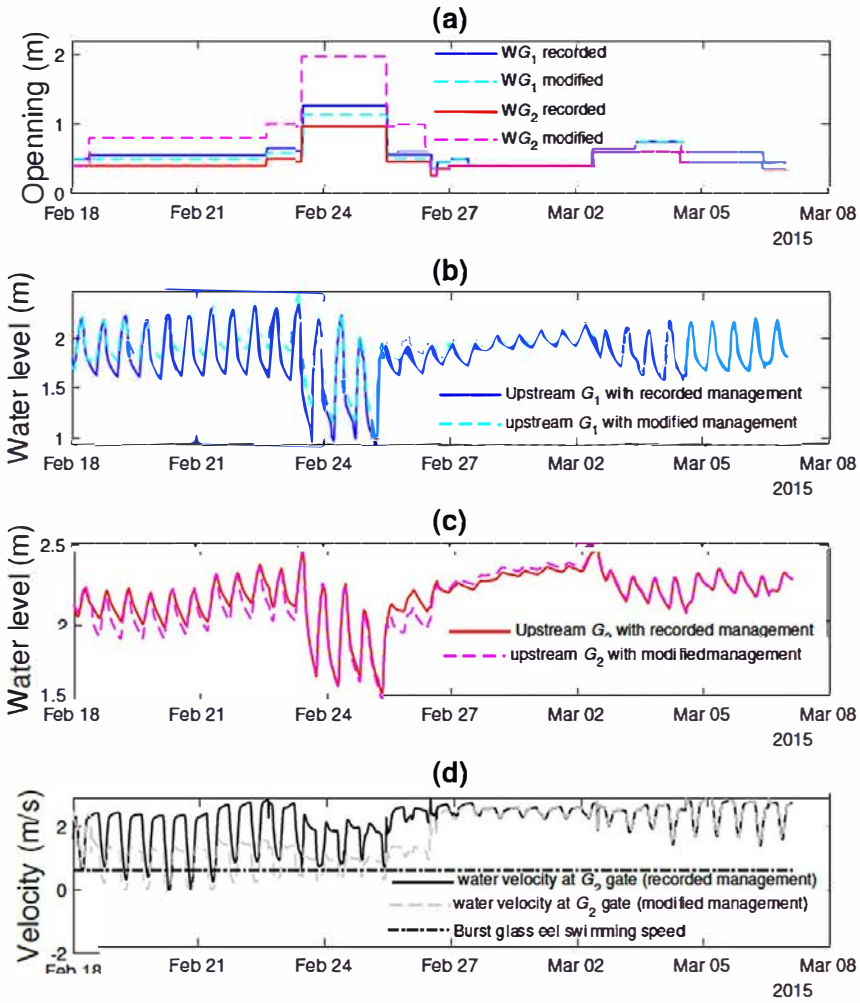

Figure 13. Simulations of water levels and water velocities following management adaptations between 18/02/2015 and 26/02/2015. (a) comparison of G_1 and G_2 openings for recorded management and modified management. (b) and (c) comparison of simulated and measured water levels between reference and modified management rules. (d) comparison of velocities under gate G_2 between reference and adapted management rules.

This makes it possible, through the management of a single structure, to promote fish upstream migration at the next upstream structures. However, this influence is complex to understand, particularly in coastal environments subject to the tide influence. The implementation of a 1D model with unsteady flow, backwater effect and specific gate equations was essential to quantify and to optimize these longitudinal interactions between structures subject to varying hydraulic conditions. Under coastal marsh conditions, changes of hydraulic regime at the structures are very frequent (at each tide), presenting free to submerged flow transitions and flow inversions.

Specific structure equations, ensuring the continuity of the calculations during these hydraulic transitions, have been implemented in the software SIC, thus allowing flow

rates and height variations to be simulated accurately. The tool developed could then be used to explore management strategies based on the addition of blocks or modifications to structure openings.

The method developed above makes it possible to explore the interactions between different constraints considering the hydraulic complexity of a tidal marsh environment, with backwater effects and constantly varying boundary conditions.

In our case, there have been two major interests of using the hydrodynamic model:

(1) We were able to find an optimum management strategy for each hydrological inflow condition, by following the method used for period P_1. However, note that it could be time-consuming, due to numerous possible combinations of boundary conditions and initial water levels in the marsh. This complexity also increases with the number of gates to consider.
(2) This model allowed to diagnose operating conditions, in order to adjust gate opening in near real-time. For instance, whereas a combination of gate openings was found satisfying for fish passage continuity, the model was useful to evaluate the impact of this management rule on water levels, and the time after which the water level would return to a target level.

5.2. Passive management: a soft solution to improve fish passage continuity

Passive management could, at a low cost, help to increase fish passage continuity in a the tidal marsh. Simulations have shown that adding blocks to the downstream tide gate (T_1) may make an upstream sluice gate (G_2) passable for fish during some tide cycles (Figure 9). However, the choice of block size influences various indicators, such as salt water inflow, water levels, maximum velocities at structures and therefore the duration of favorable hydraulic conditions for fish migration.

Nevertheless, modifying one control structure appeared to be insufficient to allow fish passage during all tides, and the block efficiency depends on the tidal range and on other instantaneous hydrological conditions. For example, if the tidal amplitude is too low to obtain sufficient seawater entry into the marsh, then the presence of a block will have little impact on the flow level in the marsh and, subsequently, on the optimization of hydraulic conditions for eel passage. In addition, the overall efficiency of the blocks was shown to be highly dependent on the management conditions of the other hydraulic control structures.

5.3. Toward advanced control strategies

Passive management has the advantage of minimizing interventions, but it allows salt water to enter the marsh during periods when there is no clear ecological needs (at least in this study, e.g. no passage of target species). Thus, a strategy based on frequent gate operations makes it possible to go further in meeting the objectives of fish passage continuity, salinity and water levels control. In our case study, we were able to identify gate operation strategies that could largely increase the time duration suitable for fish passage. This type of solutions may be a good way to improve fish passage in marsh systems, where flow conditions are highly variables and depend both on tide ranges and on the outflow from freshwater network. In some conditions, the management of gate opening could therefore advantageously replace traditional solutions such as eel ramps, which could be easily poached and are not always efficient for glass eels in such

varying hydraulic conditions and/or when air temperature is low.

The modelling procedure allowed quantifying performance of operation scenarios a priori, and thus to define management procedures for different hydraulic structures, during the favorable periods for fish migration and under various hydrological conditions. In this case study, we limited the number of gate operations, corresponding to the usual management practice of this type of environment (daily maneuvres requiring human intervention). Increasing performance is possible with finer management, based on frequent actuations of gates openings, which could be possible with automatic management procedures as done for irrigation canals in order to achieve minimum water losses (Wahlin et al. 2014). The automation of the structures has enabled significant progress in terms of hydraulic management (compliance with flow rates and set-point levels), using methods based on the automation and simulation of hydraulic dynamics. The application of such methods to the biological quality of environments is more recent, such as the management of algal populations in water distribution channels for irrigation supply (Fovet et al. 2012). The approach developed here could be extended to evaluate the contribution of automatic control on the optimization of gate operation of all structures, aimed at maximizing the passability of structures for fish while limiting salt inputs and level variations.

5.4. Hydraulic modelling for water management and ecological issues

The hydraulic model allows to simulate the water level and the flow rate at any position of the network and any time, then to evaluate management scenarios based on a large number of criteria:

- Water levels for management: maximum levels for submersion issues, minimum levels for freshwater availability. It is also possible to quantify the tidal range for bank stability issues. We have used an average level as a reference.
- Drainage and water supply: water volumes exchange within the marsh, or between the marsh and other connected water bodies (e.g. the estuary, the upstream river system), is a key information for some human activities (e.g. irrigation). In our example we used the volume ratio at the mouth of the marsh.
- Fish obstacle and fish habitat issues: as shown in our study, 1D-modelling can be used to estimate velocities at obstacles, and water level and mean flow velocity along the system which are essential variables for habitat modelling.
- Tidal range as an ecological criterion: in some coastal marshes, the appearance of particular flora is conditioned by the tidal range.

Models based on Saint-Venant equation can be coupled with other equations to estimate the evolution of temperature or the transport of solute (e.g. salt) in a hydrographic network. It is then necessary to develop the monitoring network (e.g. salinity or temperature sensors) for the calibration of the specific models.

6. Conclusion

Among the causes of fish population decline, the fragmentation of habitats and a limited access to suitable ones may be partially addressed with cheap and acceptable adaptations, based on a better understanding of fish behavior and soft solutions for the management of hydraulic structures. Here, we have considered tide-influenced

marshes which are key areas for the growth of numerous fish species such as the European eel. By developing a 1D hydrodynamic model, we have been able to identify soft modifications of control structures, from the presence of blocks on tide gates (eventually installed once during the migration season) to more active gate opening strategies. The example of the Charras marsh showed that:

- It is possible to increase fish passage continuity at a medium spatial scale in a regulated open-channel network by managing a few (eventually one) control structure(s);
- Simple modifications of control structures could increase fish passage continuity under tidal influence;
- In a tidal environment, control structure management strategies should consider multiple objectives such as ecological continuity, water level control and salt intrusion control;
- A site-specific 1D-model could be developed in order to calculate the indicators necessary to evaluate the compromises between the 3 objectives mentioned above.

This methodology can be easily extended to other species, other indicators that could be relevant for the restoration of ecosystems functioning, or for economical purposes (e.g. agriculture, pasture, navigation).

Acknowledgements

This study was funded by the French Office of Biodiversity (OFB). It was carried out with the support of UNIMA, which provided a free access to the Charras marsh.

The authors would also thank the people who participated in the February and March 2015 measurements: Alain Alric, Sylvie Tomanova (OFB), François-Xavier Robin (UNIMA) and Christian Rigaud (INRAE).

References

Amaral, S. D., Branco, P., Teixeira da Silva, A., Katopodis, C., Viseu, T., Ferreire, M. T., Nascimento, A., and Santos, J. M. (2016). Upstream passage of potadromous cyprinids over small weirs: the influence of key-hydraulic parameters. *Journal of Ecohydraulics*, 1:79–89.

Baume, J.-P., Malaterre, P.-O., Belaud, G., and Le Guennec, B. (2005). SIC: a 1D hydrodynamic model for river and irrigation canal modeling and regulation. *Métodos numéricos em recursos hidricos*, 7:1–81.

Belaud, G., Cassan, L., and Baume, J.-P. (2009). Calculation of contraction coefficient under sluice gate and application to discharge measurement. *Journal of Hydraulic Engineering*, 135(12):1086–1091.

Belaud, G., Cassan, L., and Baume, J.-P. (2012). Contraction and correction coefficient for Energy-Momentum balance under sluice gates. In *World Environmental and water Resources Congress 2012*, pages 2116 – 2127. ASCE.

Belaud, G. and Litrico, X. (2008). Closed-form solution of the potential flow in a contracted flume. *Journal of Fluid Mechanics*, 599:299 – 307.

Boys, C. A., Kroon, F. j., Glasby, T. M., and Wilkinson, K. (2012). Improved fish and crustacean passage in tidal creeks following floodgate remediation. *Journal of Applied Ecology*, 49:223–233.

Boys, C. A. and Williams, R. (2012). Succession of fish and crustacean assemblages following

reinstatement of tidal flow in a temperate coastal wetland. *Ecological Engineering*, 49:221–232.

Bult, T. P. and Dekker, W. (2007). Experimental field study on the migratory behaviour of glass eels (*Anguilla anguilla*) at the interface of fresh and salt water. *ICES Journal of Marine Science*, 64(7):1396–1401.

Doehring, K., Young, R. G., Hay, J., and Quarterman, A. J. (2011). Suitability of Dual-frequency Identification Sonar (DIDSON) to monitor juvenile fish movement at floodgates. *New Zealand Journal of Marine and Freshwater Research*, 45:413–422.

Feunteun, E. (2002). Management and restoration of European eel population (*Anguilla anguilla*): An impossible bargain. *Ecological Engineering*, 18:575–591.

Fovet, O., Belaud, G., Litrico, X., Charpentier, S., Bertrand, C., Dollet, P., and Hugodot, C. (2012). A model for fixed algae management in open channels using flushing flows. *River research and applications*, 28(7):960–972.

Franklin, P. and Bartels, B. (2012). Restoring connectivity for migratory native fish in a New Zealand stream: effectiveness of retrofitting a pipe culvert. *Aquatic conservation: Marine and freshwater Ecosystems*, 22:489–497.

Franklin, P. and Hodges, M. (2015). Modified tide gate management for enhancing instream habitat for native fish upstream of the saline limit. *Ecological Engineering*, 81:233–242.

Giannico, G. R. and Souder, J. A. (2005). Tide gates in the Pacific Northwest: operation, types, and environmental effects, volume 5. Oregon Sea Grant, Oregon State University.

Katopodis, C., Kells, J., and Acharya (2001). Nature-like and conventional fishways: alternative concepts? *Canadian Water Resources Journal*, 26:211 – 232.

Katopodis, C. and Williams, J. G. (2012). The development of fish passage research in a historical context. *Ecological Engineering*, 48:8–18.

Kerr, J. R., Karageorgopoulos, P., and Kemp, P. (2015). Efficacy of a side-mounted vertically oriented bristle pass for improving upstream passage of European eel (*Anguilla anguilla*) and river lamprey (*Lampetra fluviatilis*) at an experimental crump weir. *Ecological Engineering*, 85.

Larinier, M. (2002). Fishway - general considerations. *Bulletin Français de la Pêche et de la Pisciculture*, 364:21–27.

Linton, E. D., Jonsson, B., and L.G., N. D. (2007). Effects of water temperature on the swimming and climbing behaviour of glass eels, Anguilla spp. *Environmental Biology of Fishes*, 78:189–192.

Lucas, M. C., Bubb, D. H., Jang, M. H., Ha, K., and Masters, J. E. G. (2009). Availability of and access to critical habitats in regulated rivers: Effects of low-head barriers on threatened lampreys. *Freshwater Biology*, 54(621-634).

McCleave, J. D. (1980). Swimming performance of Europen eel (*Anguilla anguilla* (L.)) elvers. *Journal of Fish Biology*, 16:445–452.

Mouton, A., Schneider, M., Depestele, J., Goethals, P., and De pauw, N. (2007). Fish habitat modelling as a tool for river management. *Ecological Engineering*, 29:305–315.

Mouton, A. M., Huysecom, S., Buysse, D., Maarten, S., Van den Neucker, T., and Coeck, J. (2012). Optimisation of adjusted barrier management to improve glass eel migration at an estuarine barrier. *Journal of coastal conservation*, 18:111–120.

Mouton, A. M., Stevens, M., Van den Neucker, T., Buysse, D., and Coeck, J. (2011). Adjusted barrier management to improve glass eel migration at an estuarine barrier. *Marine ecology progress series*, 439:213–222.

Newbold, L. R., Karageorgopoulos, P., and Kemp, P. (2014). Corner and sloped culvert baffles improve the upstream passage of adult European eels (*Anguilla anguilla*). *Ecological Engineering*, 73:752–759.

O'Hanley, J. (2011). Open rivers: barrier removal planning and the restoration of free-flowing rivers. *Journal of Environmental Management*, 92:3112–3120.

Ovidio, M. and Philippart, J. C. (2002). The impact of small physical obstacles on upstream movements of six species of fish. *hydrobiologia*, 483:55–69.

Piper, A. T., Wright, R. M., and Kemp, P. (2012). The influence of attraction flow on upstream

passage of European eel (*Anguilla anguilla*) at intertidal barriers. *Ecological Engineering*, 44:329–336.

Porcher, J. (2002). Fishways for eels. Bulletin Français de la Pêche et de la Pisciculture, 364:147–155.

Rigaud, C., Alric, A., Robin, F. X., and Courret, D. (2014). Les civelles face à deux ouvrages latéraux de l´ estuaire de la Charente. Tests de modalités de gestion ou d aménagement visant à améliorer la franchissabilité de ces ouvrages. Bilan des suivis 2010-2013. *Rapport du Pôle éhydraulique (Onema-Irstea-Imft)*, 92pp.

Roman, R. and Garvin, R. andPortnoy, J. (1995). Hydrologic modeling as a predictive basis for ecological restoration of salt marshes. *Environmental M*, 19(4):559–566.

Shaw, E., Lange, E., Shucksmith, J., and Lerner, D. (2016). Importance of partial barriers and temporal variation in flow when modelling connectivity in fragmented river systems. *Ecological Engineering*, 91:515–528.

Travade, F. and Larinier, M. (2002). Fish locks and fish lifts. *Bulletin Français de la Pêche et de la Pisciculture*, 364:102–118.

Vowles, A. S., Don, A., Karegeorgopoulos, P., and Kemp, P. (2017). Passage of european eel and river lamprey at a model weir provisioned with studded tiles. *Journal of Ecohydraulics*.

Wahlin, B., Zimbelman, D. D., et al. (2014). *Canal automation for irrigation systems*. American Society of Civil Engineers.

Watz, J., Nilsson, P., Degerman, E., Tamario, C., and Calles, O. (2019). Climbing the ladder: an evaluation of three different anguillid eel climbing substrata and placement of upstream passage solutions at migration barriers. *Animal Coservation*.

Wright, G., Wright, R., and Kemp, P. (2014). Impact of tide gates on the migration of juvenile sea trout, *Salmo trutta*. *Ecological Engineering*, 71:615–622.

Wu, B., Rajaratnam, N., and Katapodis, C. (1999). Structure of flow in vertical slot fishway. *Journal of Hydraulic Engineering*, 125.