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Modeling of a managed coastal Mediterranean wetland with TELEMAC-2D: the Vaccarès lagoons system (Rhone delta, Camargue, France)

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***Abstract*— The "Ile de Camargue", the central part of the Rhône delta (Fig. 1) delimited by the two embanked branches of the Rhône river, is a complex hydrosystem submitted to high natural hydrological variability due to the combination of a Mediterranean climate and the artificial hydrological regime imposed by human water management. It includes agricultural drainage with low elevation gradient, marshes and the brackish shallow Vaccarès lagoons system whose connection with the sea is managed. During rice cultivation, large amounts of water are pumped from the Rhône river for irrigation, generating significant water fluxes. This complex hydrosystem is particularly representative of human influence on water and salinity regimes in a lagoon system. It has been listed as an area for nature conservation since 1927, and provides critical habitats for a wide range of terrestrial and aquatic wildlife. This study presents a two-dimensional hydrodynamic modeling of the "Vaccarès lagoons system" using TELEMAC-2D, with special attention to water fluxes and salinity. Rain and evaporation, which have a great influence on water levels and salinity in this area, were implemented in the code. Water circulations in the lagoons are mainly induced by the wind, thus a spatial interpolation of the wind was tested. Water depths and salinities were simulated on four months. Results were compared with experimental data acquired on several stations for water levels and salinities. TELEMAC-2D appears to be a promising tool to simulate the Vaccarès lagoon system. However this paper presents preliminary results and further studies are needed to calibrate and validate the model.**

I. INTRODUCTION

The Ile de Camargue basin is the central part of the Rhône Delta in the South of France, included between the two branches of the Rhône river (see Fig. 1). The higher parts of this area of about 800 km² are devoted to agricultural land (420 km²), mainly rice fields, whereas wetlands, brackish lagoons and marshes occupy lands of lower elevation [1]. This system includes three interconnected lagoons, which form the "Vaccarès lagoons system". These interconnected lagoons are the Vaccarès lagoon, the "Impériaux" lagoon (IL), and the complex "Lion/Dame" lagoon (LDL) (Fig. 1). The Vaccarès lagoon is the only one receiving runoff from rice farming. "Impériaux" is the only lagoon exchanging water with the sea, through the sea connection at "La Fourcade" (see Fig. 1).

The aquatic ecosystem in the center of the "Ile de Camargue" is internationally recognized as a biosphere reserve within the framework of the UNESCO's Man and Biosphere Programme. The "Ile de Camargue" is an important area of reproduction of a wide variety of aquatic organisms and birds, and in addition an important resting area for migrating birds.

Tourism activities prevail in the western part of the delta. In the low lands surrounding the lagoons, large freshwater marshes (25 km²) are managed for waterfowl hunting, nature conservation or exploited for their reed beds. Agricultural land borders the park to the North and South-East, and most of it is devoted to intensive flooded rice cultivation. The rice parcels are irrigated during the crop period (from mid-April or early May, to September) by irrigation pumping stations taking water from both arms of the river Rhône. On an unpolderized agricultural area of 112 km² in the north-eastern part of the Ile de Camargue and around the Vaccarès lagoon, the runoff of rice paddies is directly discharged to the lagoon system through two drainage channels ("Fumemorte" (FUM) and "Roquemaure" (ROQ), see Fig. 1), whereas in the northern and south-eastern parts, the runoff of 310 km² of polderized rice paddies is pumped back to the Rhône River or to the Mediterranean sea [1]. The discharge of irrigation induced drainage water to the lagoons is about 480,000 m^3 per day during the crop period. This counterbalances partially the salinity increases in the lagoons due to high evaporation rates and due to seawater intrusion, but carries a load of anthropogenic substances into the protected area [2-3]. Therefore, there is an ongoing debate on the management of water in this area.

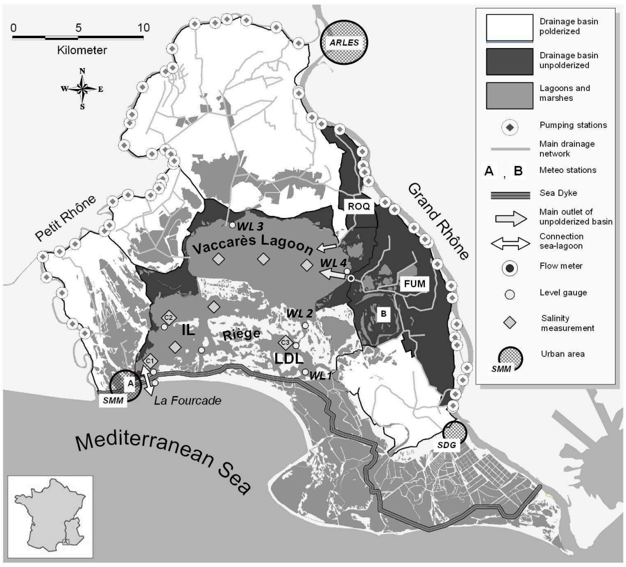

Figure 1. Map of the "Ile de Camargue" hydrosystem delimited by the two branches of the Rhône river ("Petit Rhône" and "Grand Rhône"). "SMM" and "SDG" are the cities of "Saintes-Maries de la Mer" and "Salins de Giraud".

The Camargue regional nature park is separated from the Mediterranean Sea by a sea dike. Sea-lagoon exchanges through the sea connection at "La Fourcade" (see Fig. 1) are managed by 13 manual sluice gates. In autumn and winter, the gates are opened during northerly wind to decrease water level in the lagoons. In spring, one to three gates are opened to allow fish recruitment into the lagoons [4]. Water exchanges through the gates are mainly seawards. During sea storms, sluice gates are closed. The exchange of water from the lagoons with the Mediterranean Sea is then limited [1], and the major pathway for water loss from the Ile de Camargue is evaporation during the summer months. Water circulations in the lagoon are mainly induced by the wind [1]. Frequent strong winds tend to homogenize salt concentrations within each lagoon and force water exchanges between the lagoons.

This study aims to model water and salt fluxes on the Vaccarès lagoons system at short time period with great spatial resolution. Results of hydrodynamic simulations are also used in conceptual models used for long term runs and prospective analysis, to help stakeholders for water and salt management in this area.

II. METHODOLOGY

A. *Monitoring data*

1) *Hydro-meteorological data*

Wind (speed and direction), temperature, precipitation data were measured continuously at stations A and B (see Fig. 1), and averaged on a 60 minutes basis. Hourly potential evaporation was calculated at the same sites as described in detail by P.W. Brown (http://ag.arizona.edu/azmet/et2.htm).

2) *Water Levels and salinity*

Water levels have been monitored continuously at 9 sites (see Fig. 1), on a 15 minutes basis, since 2002. Water conductivity is measured monthly (converted to salinity) at five locations (see Fig. 1) in the Vaccarès lagoon and the southern lagoons since 1970. In addition, conductivity data are acquired at a time step of 30 minutes at stations C1 since 2003 and C2 and C3 since March 2011) (see Fig. 1).

3) *Flow data*

At the outlet of the Fumemorte canal, discharge was monitored continuously on a 30-min basis from 1993 to August 2008 using an automatic ultrasonic flow meter, which became out of order afterwards. Since August 2008, we then used a rainfall runoff model to estimate the discharge at the outlets of the Fumemorte and Roquemaure canals [5].

At the Fourcade (lagoons-sea connection, see Fig. 1), the discharge Q (m3/s) through the gates is calculated using the following hydraulic equation:

$$Q = N\left(\frac{2H}{3}\right)^{3/2} KL\sqrt{g}\left[1-\left(\frac{H'}{H}\right)^{3/2}\right]^{0.385} \tag{1}$$

where L is the width of one sluice gate (m), N is the number of opened sluices, H the experimental upstream water height above the sill (m), H' the experimental downstream water height above the sill (m) and K the discharge coefficient depending of the characteristics of the sluices (–).

4) *Bathymetry and vegetation*

The bathymetric data used came from echo-sounding campaigns for the Vaccares lagoon and from manual depth measurements for the lower lagoons and the marshes. Maps of the sea grass bed from 2004 were used to describe the hydraulic roughness in the hydrodynamic model (Réserve Nationale de Camargue, unpubl. data).

B. *The numerical model*

The two-dimensional mathematical model computing transient flows in the Ile de Camargue was constructed with TELEMAC-2D [6]. The TELEMAC-2D code solves the following four hydrodynamic equations simultaneously:

$$\frac{\partial h}{\partial t} + \vec{u}.\vec{\nabla} h + h\vec{\nabla}\cdot\vec{u} = S_h \tag{2}$$

$$\frac{\partial u}{\partial t} + \vec{u}.\vec{\nabla}(u) = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}\vec{\nabla}\cdot\left(h\nu_t\vec{\nabla} u\right) \tag{3}$$

$$\frac{\partial v}{\partial t} + \vec{u}.\vec{\nabla}(v) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\vec{\nabla}\cdot\left(h\nu_t\vec{\nabla} v\right) \tag{4}$$

$$\frac{\partial T}{\partial t} + \vec{u}.\vec{\nabla}(T) = S_T + \frac{1}{h}\vec{\nabla}\cdot\left(h\nu_T\vec{\nabla} T\right) \tag{5}$$

where h is the depth of water (m), t the time (s), u and v the velocity components (m/s), S_h the source or sink of fluid (m/s), g the gravity acceleration (m/s^2), x and y the horizontal spatial coordinates (m), S_x and S_y the source or sink terms in the dynamic equations (m/s^2), Z the free surface elevation (m), ν_t the turbulent viscosity coefficient (m/s^2), T the passive tracer (salinity in this study) (g/l), ν_T the diffusion coefficient of tracer (m^2/s), and S_T the source or sink of tracer (g/l/s).

C. *Rain and evaporation modelling*

Rain and evaporation, which have a great influence on water levels and salinity in the Ile de Camargue, were calculated in equation (2) with:

$$S_h = R - E \tag{6}$$

where R is rain intensity (m/s) and E the evaporation rate (m/s), derived from experimental data.

D. *Salinity modelling*

S_T is determined considering a constant mass of salt, with a variation in the volume of water due to the rain and/or the evaporation.

E. *Spatial wind interpolation*

To take into account spatial variability of wind, we used the spatial interpolation as described in equations (7−12):

$$S_x = \frac{1}{h}\frac{\rho_{air}}{\rho_{water}} a_{wind} U_{wind} \sqrt{U_{wind}^2 + V_{wind}^2} \tag{7}$$

$$S_y = \frac{1}{h}\frac{\rho_{air}}{\rho_{water}} a_{wind} V_{wind} \sqrt{U_{wind}^2 + V_{wind}^2} \tag{8}$$

$$U_{wind} = U_A \frac{D_B}{D_A + D_B} + U_B \frac{D_A}{D_A + D_B} \tag{9}$$

$$V_{wind} = V_A \frac{D_B}{D_A + D_B} + V_B \frac{D_A}{D_A + D_B} \tag{10}$$

$$D_A = \sqrt{(X_A - X)^2 + (Y_A - Y)^2} \tag{11}$$

$$D_B = \sqrt{(X_B - X)^2 + (Y_B - Y)^2} \tag{12}$$

where S_x and S_y are the source or sink terms in the dynamic equations (m/s^2), a_{wind} the wind forcing coefficient (–), U_{wind} and V_{wind} the components of wind velocity (m/s), ρ_{air} and ρ_{water} the densities of air and water (kg/m^3), X_A, Y_A, X_B and Y_B the horizontal space coordinates of the two meteorological stations A and B (Fig. 1), D_A (m) the distance from the meteo station A (X_A,Y_A) to a point of coordinates (X,Y), and D_B (m) the distance from the meteo station B (X_B,Y_B) to a point of coordinates (X,Y).

F. *Mesh and altitude*

The non-structured grid consisted of some 17767 triangular elements of varying sizes and 9745 nodes (Fig. 2). The triangular elements ranged in size from 250 meters in the different lagoons to 2 meters in the different channels between IL and LDL lagoon sub units, and between the Vaccarès lagoon and LDL.

The resulting altitude is shown in Fig. 3. The different lagoons of the Vaccarès lagoons system are characterized by a minimum altitude of -2mNGF with a maximum altitude of 1.9mNGF. For a mean water level in the Vaccarès lagoons system of 0 mNGF, the area covered is about 110 km2, and the volume of water is about 108 10^6 m3. For a mean water level of 0.5 mNGF, the lagoons store a total volume of about 163 10^6 m3. The French topographic datum (zero NGF) was fixed in Marseille at the end of the 19th century by averaging local maregraphic records between 1885 and 1897 [7].

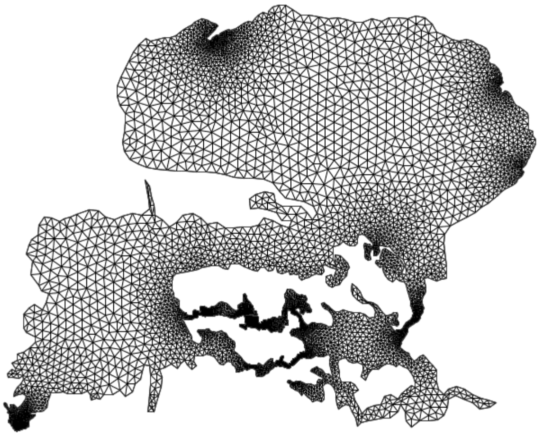

Figure 2. Resulting global Mesh of the Vaccarès lagoons system's model.

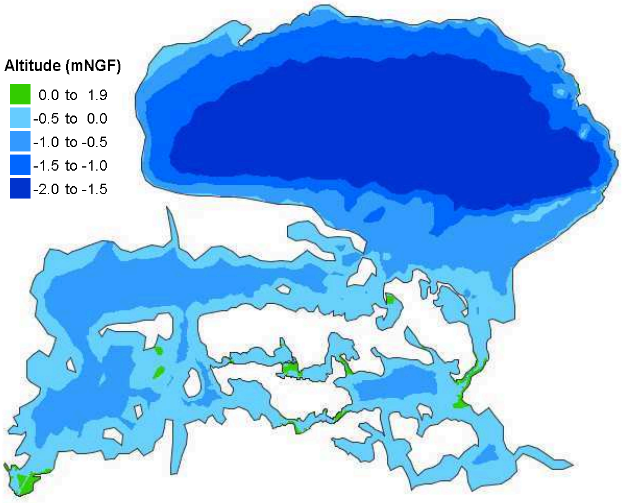

Figure 3. Resulting altitude of the Vaccarès lagoons system's model.

G. *Bottom friction*

Bed roughness was represented by using the Strickler law. In a first approach, we used maps from 2004 of the sea grass bed to describe hydraulic roughness in the hydrodynamic model. In a first step, we chose a Strickler equal to

55 m$^{1/3}$/s for a bed with vegetation and equal to 120 m$^{1/3}$/s when no vegetation was observed.

H. Boundary and initial conditions

Three liquid boundaries were considered for i) the lagoons-sea connection ("Fourcade", see Fig. 1), ii) the FUM canal and iii) the ROQ canal. At the "Fourcade" boundary, semi-experimental water flow (see (1)) and experimental salinity (see gauge C1 in Fig. 1) were imposed. At the FUM and ROQ boundaries, water flows estimated with the rainfall runoff model [5] were imposed. Other boundaries are rigid boundaries.

Initial salinities and water levels were derived from experimental data routinely acquired each month at six locations (see "salinity measurement" in Fig. 1) during five field campaigns (16/03/2011; 14/04/2011; 18/05/2011; 10/06/2011 and 30/06/2011). The punctual measurements were extrapolated to the different lagoons to obtain the initial conditions of water level and salinity.

I. Events simulated

According to available data, simulations were conducted from March 2011 to June 2011. In accordance with the field campaigns, four runs were performed:

- Run 1: from 16/03/2011 to 14/04/2011
- Run 2: from 14/04/2011 to 18/05/2011
- Run 3: from 18/05/2011 to 10/06/2011
- Run 4: from 10/06/2011 to 30/06/2011

III. PRELIMINARY RESULTS

This study is a preliminary work, more experimental data are needed to calibrate and validate the model. However, preliminary results are presented here.

A. Model performance criteria

To measure the model performance for each stations, two criteria were used, the mean absolute error (MAE) and the root-mean-square error (RMSE) of difference between simulated and measured water levels and salinities.

B. Water levels

Experimental and simulated water levels where compared for stations C2, C3 and WL1, as shown in Fig 1. An example of comparison is given Fig. 4 for the station C2 for Run 2.

MAE and RMSE of difference between simulated and measured water levels are given in Table 1 for Runs 1, 2, 3 and 4. It can be seen that the corresponding MAE values range from 0.01m for station C2 and Run 1, to 0.05m for station C3 and Runs 2 and 3. RMSE values range from 0.02m for stations C2 and WL1 for Runs 1 and 4 respectively, to 0.06m for station C3 and Run 2. Higher values are generally observed for stations C3 and WL1. This can be explained by problems with experimental water levels monitored at station WL2 (South-East of the Vaccarès lagoon, see Fig. 1). We could not use these data to determine the initial water levels conditions in the model for the Vaccarès lagoon. In a first approach initial water level in the Vaccarès lagoon was chosen as equal to water level monitored in station WL3. However at the beginning of Runs 1, 2, 3 and 4, wind conditions induce higher water levels in the western part of the Vaccarès lagoon than in the eastern part. This implies lower simulated flow from the Vaccarès lagoon to the LDL lagoon than the observed one, and lower simulated water level in the LDL than the observed one.

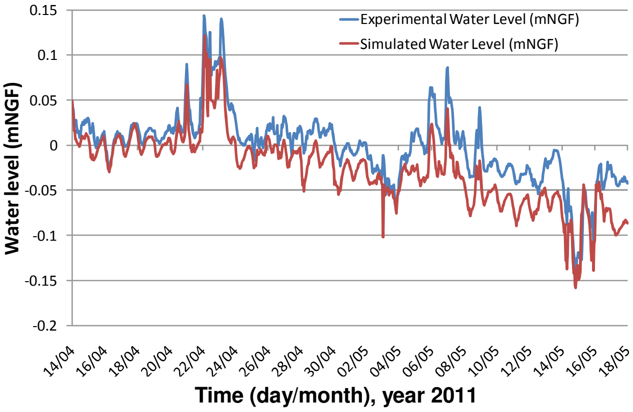

Figure 4. Experimental and simulated water levels in the station C2 (see Fig. 1) for Run 2 (from 14/04/2011 to 18/05/2011).

TABLE I. MEAN ABSOLUTE ERROR (MAE) AND ROOT-MEAN-SQUARE ERROR (RMSE) OF DIFFERENCE BETWEEN SIMULATED AND MEASURED WATER LEVELS FOR RUNS 1, 2, 3 AND 4.

		Water level			
		Run 1	***Run 2***	***Run 3***	***Run 4***
C2	MAE (m)	0.01	0.03	0.02	0.04
	RMSE (m)	0.02	0.03	0.03	0.04
C3	MAE (m)	0.04	0.05	0.05	0.03
	RMSE (m)	0.05	0.06	0.05	0.03
WL1	MAE (m)	0.04	0.04	0.04	0.02
	RMSE (m)	0.05	0.05	0.05	0.02

New initial conditions for water levels have to be used, using data of stations WL3 and WL4, and using a new station in WL3.

C. Salinities

Experimental and simulated salinities where compared for stations C2 and C3, as shown in Fig 1. Examples of comparisons are shown for Run 2 for stations C2 (Fig. 5) and C3 (Fig. 6).

MAE and RMSE of difference between simulated and measured salinities are given in Table 2 for Runs 1, 2, 3 and 4. MAE values range from 1.5g/L for station C2 and Run 4, to 5g/L for station C3 and Run 4. RMSE values range from 2g/L for station C2 and C3 for Runs 4 and 1 respectively, to 5.6g/L for station C3 and Run 4. These rather high values can be again explained by a lack of experimental data to describe the initial conditions for salinities in the model. Additional salinity data are then needed to calibrate and validate the model.

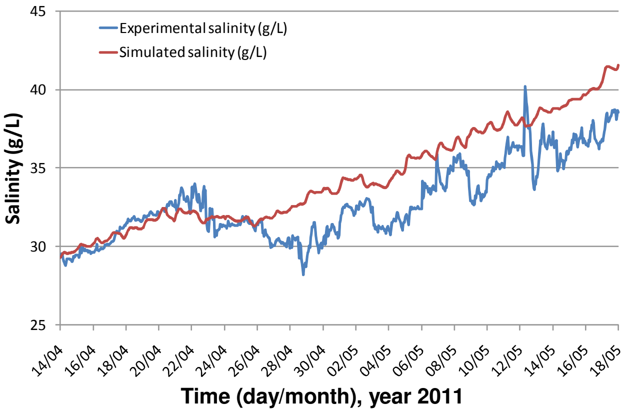

Figure 5. Experimental and simulated salinities at the station C2 for Run 2 (from 14/04/2011 to 18/05/2011).

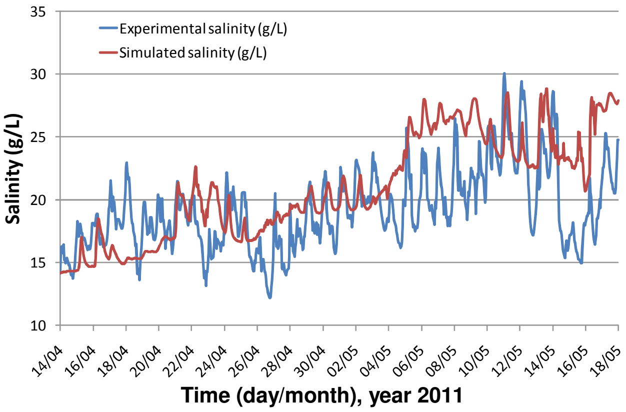

Figure 6. Experimental and simulated salinities at the station C3 for Run 2 (from 14/04/2011 to 18/05/2011).

TABLE II. MEAN ABSOLUTE ERROR (MAE) AND ROOT-MEAN-SQUARE ERROR (RMSE) OF DIFFERENCE BETWEEN SIMULATED AND MEASURED SALINITIES FOR RUNS 1, 2, 3 AND 4.

		Salinity			
		Run 1	***Run 2***	***Run 3***	***Run 4***
C2	MAE (g/L)	2.6	1.8	2.7	1.5
	RMSE (g/L)	3.4	2.2	3.5	2.0
C3	MAE (g/L)	2.0	3.1	4.1	5.0
	RMSE (g/L)	2.7	3.9	5.0	5.6

IV. CONCLUSION

TELEMAC-2D appears to be a promising tool to simulate the Vaccarès lagoons system. However this paper presents preliminary results. Further studies are needed to calibrate and validate the model.

First, it appears necessary to acquire more experimental data. Continuous salinity data are indeed only available for three stations (C1, C2 and C3, see Fig. 1). New stations are planned in 2011 to have more spatial continuous data for salinities and water levels. In addition, water discharges at the outlet of the Fumemorte and Roquemaure canals are estimated with a rainfall runoff model. Installation of flow meters are planned to have physical measurement of these discharges.

Another important point would be to measure flows in the channels between the Impériaux lagoon (IL) and the Lion/ Dame lagoon (LDL), and between the Vaccarès lagoon and the Lion/Dame lagoon, to calibrate and validate the model considering flows.

It would also be interesting to have data of another meteo station, to test other spatial interpolation for the wind effect.

In the presented simulations, maps of the sea grass bed from 2004 were used to describe the hydraulic roughness in the hydrodynamic model. New maps are planned for 2011 and 2012 to have a better description of the hydraulic roughness.

It would also be interesting to test TELEMAC-3D in this area as we expect a vertical variation of the salinity in the different lagoons.

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