Simulating hydraulic management of the Rhone delta under flood and sea surge conditions

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Abstract

This work was part of the IMPLIT project ("Impact of extreme events (storms and sea surges) linked to climatic change, on the French coastal Mediterranean hydro-systems") developed within the framework of the GICC program ("Management and impact of climatic change"), (Ministry of Ecology and Sustainable Development).
The objective of the Rhone delta hydrosystem modelling task was to analyse hydraulic management constraints of the "Ile de Camargue" in extreme hydro-climatic conditions; to develop a simplified and adaptive simulation tool for hydrologic and hydraulic functioning of the Vaccarès lagoon system, in order to provide decision support for flood management and prospective. An analysis of existing hydro-climatic data was made (precipitations, wind, flood discharges and management of Camargue drainage basins; Rhone river floods at Beaucaire, effects of wind on lagoon water levels), in order to derive crisis scenarios used for simulations. After calibration and validation on autumn-winter periods (September to March) 2003-2004 and 2005; simulations were made with a conceptual model, combining observed data (wind, evaporation, sea level) and forcing by drainage hydrographs from the North delta flooded area (1993 or 1994 flood event type). Impact of additional works: drainage pumping station on the basin, increased capacity for discharge by gravity to the sea; with sea level rise, were also simulated, using scenarios based on data from 1996-97, 2002 and 2003, corresponding to the last major floods of the Rhone river.
Statistical analysis of maximum annual discharge shows that the last strong flood of the Rhone river in 2003 may have only a 50 year return period, revisiting former risk analysis knowledges. The simulations made with the simplified model (developed with Vensim TM) show that in order to maintain water levels in the lagoon under 0,5 m NGF less than 20 days after a flood, new management rules and hydraulic works must be made.

Abstract keywords: Rhone delta, floods, simulation tool, climatic change, lagoon

Introduction

The IMPLIT project ("Impact of extreme events (storms and sea surges) linked to climatic change, on the French coastal Mediterranean hydro-systems") is based on a multidisciplinary approach with hydrologists, coastal geomorphologists and climatologists. Our objective in the hydrology work package is to analyze the limits of hydraulic management in the " Ile de Camargue " hydrosystem, central part of the delta, between the two branches of the Rhone , in critical situation (strong rains, river floods and sea storms). The task does not include a full hydrodynamic modelling of delta flooding, but focus on how the water arriving to the lagoon system could be managed under extreme current or foreseen hydroclimatic conditions. The impact of water transfer coming from flooded areas North of the lagoons, due to dyke breaching will be introduced under the form of hydrographs (data acquired on 1993, 1994, 2003) corresponding to the maximum flow of occasional outlets. No hydrodynamic modelling of water from breaches to the entry of lagoon will be made at the moment. Upstream the lagoon system, deltaic area may be affected by several dyke breaches, particularly on the Petit Rhone (Chauvelon et al., 2005), the pumping stations being already saturated by drainage of local rainfall, or not operational because their electric devices were sometimes positioned outside the dykes! It was therefore unavoidable to use the lagoons as a flood expansion area. The main limitation for water management lies in the fact that drainage from lagoon to the sea is only made by gravity and therefore not applicable during sea surges.

Materials and methods

Diagnostic of the Vaccarès hydrosystem hydraulic functioning

In the north and south-east (310 km^2) of IDC (total drainage area of 422 km^2) irrigation water is pumped from the river and drainage water is returned back (or to the sea) by pumping. The east delta (fig. 1) is drained into the Vaccares lagoon by low slope canals, the Fumemorte basin (FUM) canal being the main one. In this "unpolderized" zone (87 km^2) agriculture is mainly flooded rice cultivation. A dyke protects the IDC from floods and sea surges; the lagoon system is isolated from salt works area, and connected to the sea at the "Grau de la Fourcade" (GDF). The lagoon system, 105 km^2 and 101 10^6 m^3 for a water level at 0 cm NGF (NGF for "Niveau Général Français", present mean sea level being approx. 14 cm NGF), can be divided in: the Vaccares lagoon itself, and the lower lagoons, separated themselves into two temporarily connected sub units (EI and EL in fig. 1). Annual precipitation for the last 30 years in the delta was 620 mm, occurring mainly in autumn and winter during short and intense rain events; whereas open water evaporation is estimated around 1400 mm. Water circulations in the lagoons are mainly induced by wind, whose speed and direction are measured at stations A and B (fig. 1). Water levels are continuously monitored within the lagoons and on each side of the sea wall at GDF. Sea-lagoon exchanges at GDF are controlled by thirteen manually operated sluice gates. In autumn and winter, they are opened under northern winds to evacuate water to the sea. In spring, one to three gates are opened, to allow fish recruitment. An ultrasonic flow meter measured continuously the discharge at the outlet of the FUM basin. The whole catchment discharge is extrapolated using a multiplying factor of 1.9 (ratio of total unpolderized area to FUM area).
The discharge from lagoon to the sea was calculated from limnimetric data and sluices status. During drainage of flooded area, flow measurements were made at the temporary northern lagoon inlet on a quasi daily basis. Hydrograph was interpolated between these measurements (1994) or extrapolated from limnigraphic data (1993).

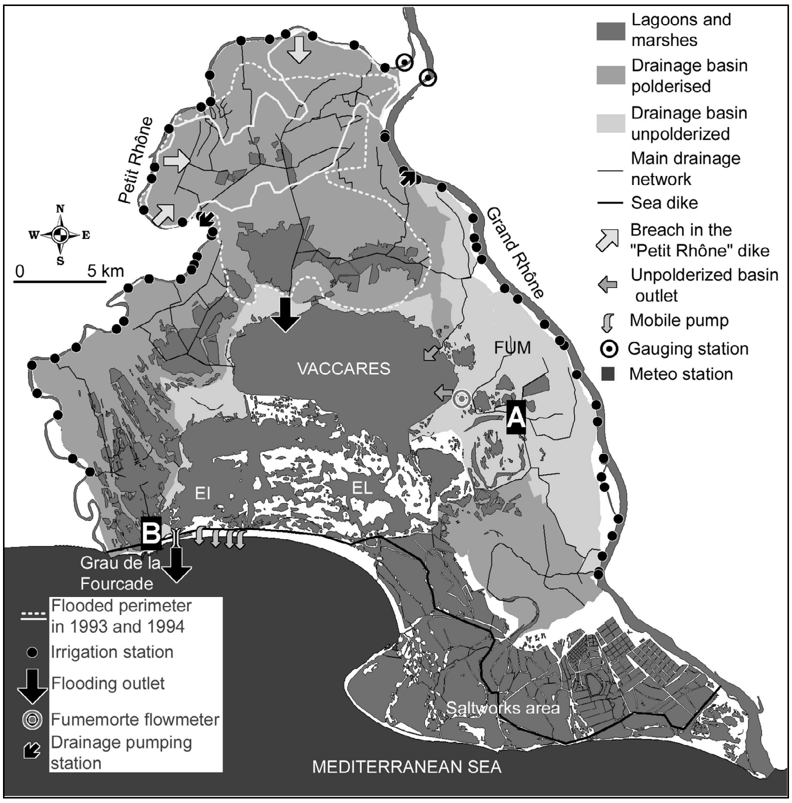

Figure 1 : Map of the « Ile de Camargue », with description of flooding conditions in 1993 and 1994.

The discharge measured at the North basin outlet (Rousty canal) to the lagoon varied from 2 to 42 m^3/s. There is also a possibility of transfer from polderized to unpolderized ROQ basin (3 sluices) North of the FUM basin outlet. The maximum capacity for drainage to the river in the North basin is 26 m^3/s if all pumps are operational, which was not the case during several days during the major flood of December 2003. When a massive water transfer occur from the flooded North basin, combined with floods from the unpolderized basins and sea surge, there may be a ratio of 3:1 between the input to the lagoon and the possible delayed discharge through the outlet to the sea (figure 2).

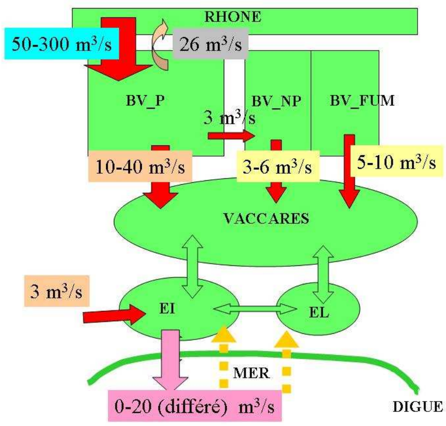

Figure 2 : Schematic diagram of the hydrosystem in crisis : dyke breaches on the « Petit Rhone", with intense rainfall (P, NP : (un) polderized ; EI « Etang de l'Impérial » ; EL « Etang du Lion »)

Precipitations and input from the catchment area

We used 3 series of daily precipitations (TDV : 1963-2006; SDG: 1968-2006; SMM: 1968-2006) in order to estimate return periods (1 to 10 yrs) of daily maximum precipitation by adjustment of probability density function (PDF) (Gumbel or Weibull laws fitting best) using software HYFRAN ™ (50 mm and 100 mm of daily rainfall have respectively a return period of 1 and 10 yrs). We analysed hydrographs from the Fumemorte, gauged since 1993 with a ultrasonic flowmeter. During this period were measured discharges corresponding to the strongest observed rain events at TDV over the last 40 years. It appears that the sluice gates at its outlet are limiting the maximum discharge at about 10 m^3/s. We retained for simulations, reference hydrographs, corresponding to 1 and 10 years return period of daily precipitations, and to the most intense measured rain events.

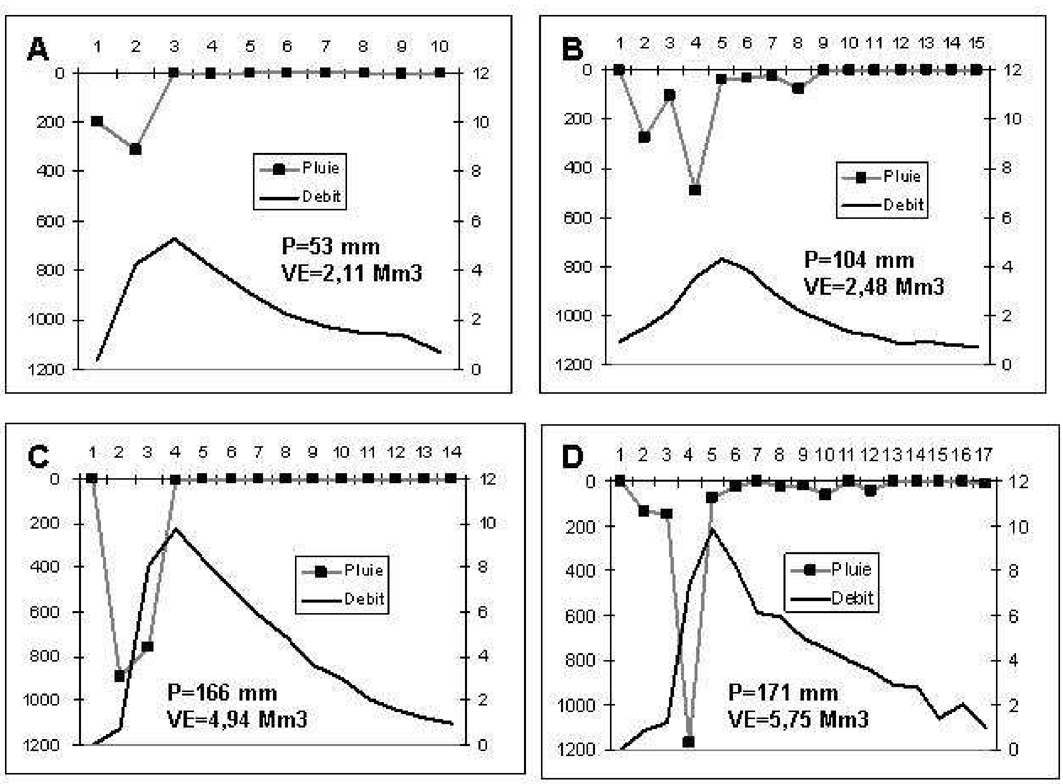

Figure 3 : Reference floods at daily time step (rainfall 1/10 mm, discharge in m^3/s) for the Fumemorte drainage basin (P : rainfall ; VE : runoff volume). A : from 4 to 14/10/95 ; B : from 17 to 30/09/96 ; C : from 18 to 30/09/95 ; D : from 14 to 30/11/96.

Rhone river discharge extreme values

Our modelling approach does not take explicitly the simulation of breaches in function of the river flood discharges in the delta. Nevertheless it appeared interesting to us to re-visit and update analysis of extreme values for discharge at the Beaucaire gauging station. During a strong flood, water level of the river is a boundary condition inducing a risk of dyke breach

and a constraint of functioning for drainage stations pumping back to the Rhone. The daily series is available since 1920, and we obtained annual hourly maximum discharges for the 1977-2005 period (data from “Compagnie Nationale du Rhône”).
Because of the controversy about the December 2003 maximum flood discharge and the consensus conference that concluded for a maximum of 11,500 m^3/s, we re calculated from hourly water levels, mean daily discharges for floods since 1994 previously estimated to be above 8,000 m^3/s. For this purpose, we used the rating curve proposed by Duband and Bois (2005), that provide lower estimated discharges for high water levels at the Beaucaire station (last gauging station between the separation of the Rhone river on two branches in the delta). Both from hourly and daily annual maximum series we try to adjust several PDF, the Gumbel GEV law fitting best.

T	1920-05-MV	1920-05-MM	1977-05-MV	1977-05-MM
100	11403	10689	11597	11643
90	11256	10559	11455	11500
80	11092	10414	11295	11340
70	10906	10250	11114	11158
60	10691	10060	10905	10948
50	10436	9835	10658	10699
40	10123	9559	10354	10393
30	9719	9201	9961	9999
20	9146	8695	9404	9438
10	8149	7815	8435	8465
5	7110	6897	7426	7450
3	6283	6166	6622	6642
2	5541	5510	5900	5916

Table 1 : Fitting a Gumbel distribution on annual mean daily maximum discharge values (m^3/s) at the Beaucaire station, considering the series since 1920 or 1977 (hydraulic works completed on the catchment) (MM and ML respectivevely for fitting usind Method of the moments, or Maximum Likelyhood).

The return period of December 2003 flood peak is about 50 years, to be compared to the provisional estimate given during the crisis of more than 300 years for a discharge of 12,700 m^3/s. Considering the annual daily maximum discharge analysis, the return period in less than 50 years.

We are aware of the limits of using a GEV law on annual maximum discharges of the Rhone river. This basin has a complex functioning and its floods can be generated by very diverse rain events, given the relative contributions of tributaries in function of the flood hydrometeorological characteristics (oceanic, “cévenole”, extensive Mediterranean). It would be interesting to work on peak over threshold (Lang et al., 1999 ; Mitosek et al., 2006) or intensity-duration-frequency analysis (Cunderlik et Ouarda, 2006). For a mean daily discharge (MDD) of 7500 m3/s at Beaucaire (return period about 5 years from the 1977-2005 data set)a water level higher than 5 m NGF is reached on the “Petit Rhone” on the Northern part of the delta. This water level is enough to provoke dyke breaches and flooding, like it happened in 1993 and 1994. It is worth mentioning that the day before the flood peak in December 2003, a fissure in the “Grand Rhone” dyke was repaired in emergency. Without that, the formed breach should have rapidly reached a size greater than 50 m in this place, the river following this way one of its former branch. Such a partial river diversion would have caused serious security problems and complete flooding of the southern delta.

Impact of breaches on the transfer from Northern basin to the lagoon.

We do not simulate breaches and flood propagation and the hypothesis is that the sea wall does not collapse anywhere. In the data set used, there is a river flood strong enough to induce dyke breaching, the sea surge prevents the lagoon waters to discharge into the sea. The river water level is not a boundary condition taken into account in the simulator, but it allows to justify the occurrence of breaches in the simulation scenario, causing massive water input in the North basin, and consequently into the Vaccares lagoon via the Rousty canal outlet. We used hydrographs obtained by gauging in 1993 and 1994 to characterize these inputs. We choose very unfavourable breach and water transfer hypothesis (Oct.-Nov. 1993) that could have occurred during the flood events of 1996, 2002 and 2003.

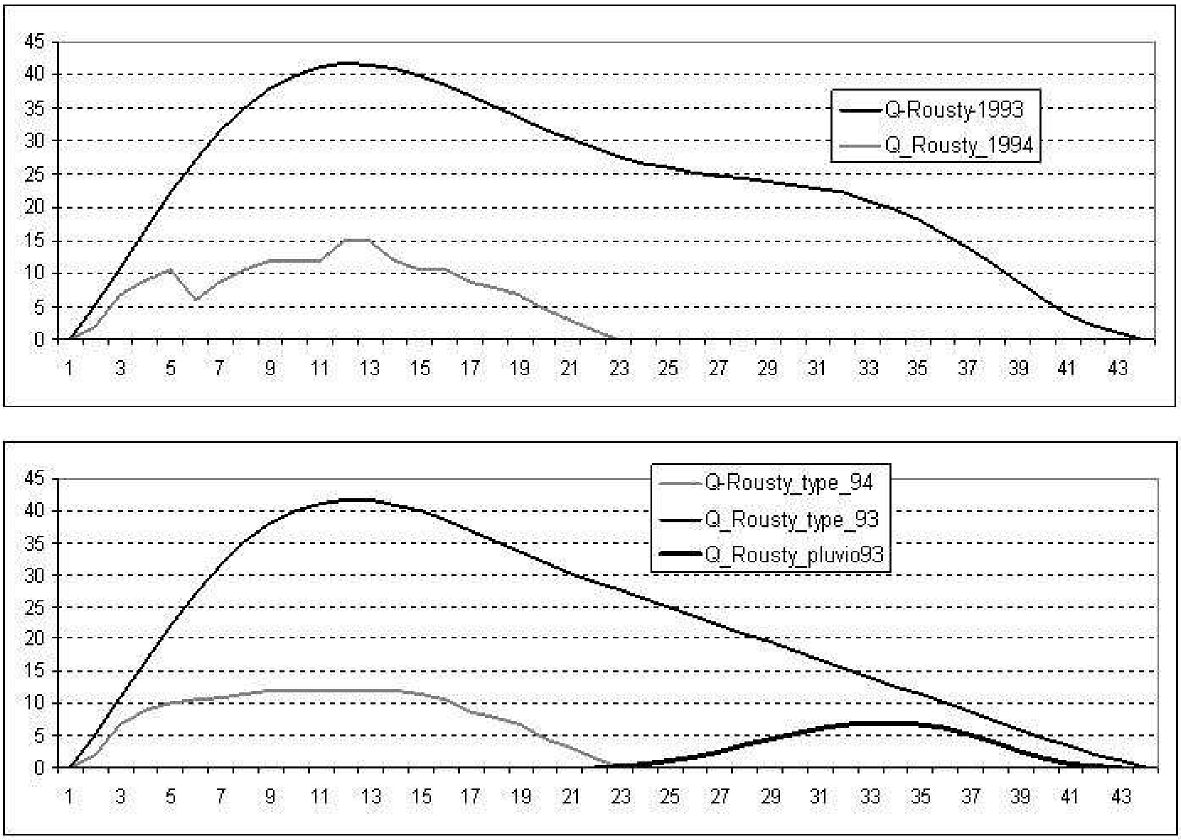

Figure 4 : Hydrographs (daily discharge in m^3/s) of transfer from the North basin in 1993 and 1994 via the Rousty canal to the Vaccares lagoon, and those used in the simulations.

Impact of wind on lagoon water levels

A large enough set of simulation from the new version of the hydrodynamic model (Chauvelon,et al, 2003) being not available, we opted for another modelling strategy. To derive an empirical function of the impact of the wind on water levels, to be used in the conceptual model used at a daily time step, we considered observed series of wind and water level variations. Information is extracted from hourly data of wind speed and direction (TDV station). The distance run by wind from northern directions (290° to 60°) is cumulated for the day, than divided by 24 to obtain a mean wind speed of N sector in km/h.

From the lagoon hourly limnigraphic data that are available since 2002, we extracted selected events. From a calm situation where the water body is quasi horizontal, wind increase and remain stationary for several hours in speed and direction. We measured the water level variation that occurred in the lagoon just upstream the sea wall at SMM, because we are interested in obtaining the difference of water level between lagoon and sea to calculate discharge to the sea. The range of initial water level was 0,1 to 0.45 m NGF and the N wind speed 10 to 65 km/h. We calculate by regression an exponential function (R^2= 0.82) on the combined data set (0,1 to 0.35 m for level and) giving the increase of water level with N wind speed. For a water level above 0.4 m NGF, corresponding to large over bank flow in the surrounds and islands of the lagoon, the variation of water level is calculated to be 1 cm for and increase of 10 km/h wind speed.

Data sets used to create crisis scenarios

The basic hydro-climatic scenarios are extending on a period of 212 or 213 days, from September 1st to March 31. The choice of real data sets (2002-2003, 2003-2004, et 1996-1997) to be used for the simulator appeared us adequate to insure the hydro-meteorological coherence of values (river discharge, sea level, precipitation, wind). Apart the hypothesis of water transfer and hydraulic management (simulated) we only possibly modified the cumulated rainfall for a particular event: the rain event occur at the same date, with the same duration, but with more intensity, increasing in the scenario the direct and runoff input from the deltaic drainage basin. Only the 2002-2003 and 2003-2004 basic data set are presented on figure 5.

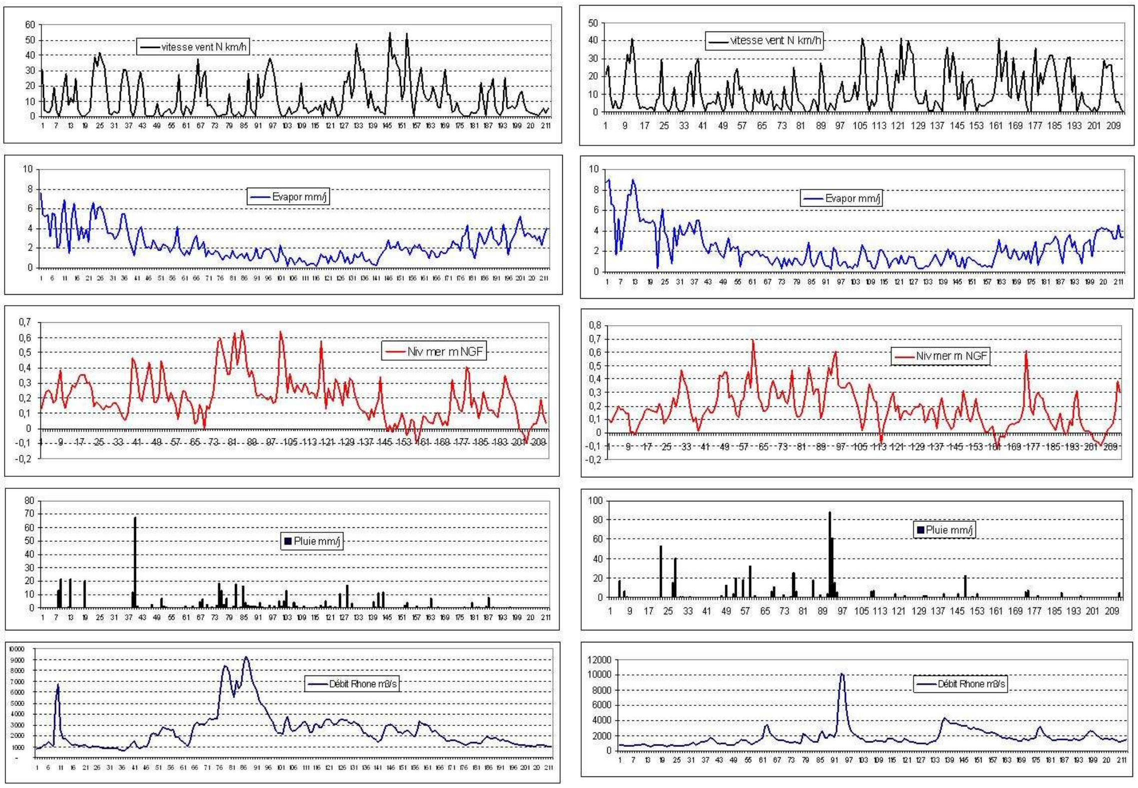

Figure 5 : Basic data set (N sector wind (km/h), evaporation (mm/d), sea level (m NGF), precipitation (mm/d), Rhone river discharge (m^3/s) used fo scenarios based on a situation of the type September 2002 – March 2003 (left) and Sept. 2003 – March 2004 (right).

The structure of the conceptual model

The model was developed using Vensim ™ software, like the model from which it is inspired (Chauvelon et al., 2003). This kind of dynamic system simulation software (Rizzo et al., 2006) are increasingly being used in hydrological (Lee, 1993 ; Li and Simonovic, 2002; Hreiche et al., 2002; Hreiche et al., 2006) or water resources modelling (Argent and Houghton, 2001, Caballero et al., 2004). This version of the model is simplified because it does not take into account the different sub units of the lagoon system and does not attempt to model dynamics and spatial variability of salinity like in the former HIC model version (Chauvelon et al., 2003). The lagoon is considered as a single water body, managed in the model as a stock which variate in function of inputs (from normal basin and exceptional flood transfers, direct precipitation) and outputs (evaporation, discharge to the sea). The wind effect (apart for calculation of evaporation by the Penman method) is not considered during the filling phase when the sea surge prevents from drainage to the sea. The level/volume relationship for the lagoon is used to calculate water level; from this horizontal level, water level upstream the dyke is calculated from the wind effect. When calculated water levels in the lagoon is superior to sea level, then emptying phase are allowed in the model, with opening of sluices. Calibration parameters are used to adjust the contributive areas from lagoon surrounding areas (outside the agricultural catchments) and the daily discharge to the sea. All other parameters and coefficient used in computing are estimated before integration in the simulator.

Results and discussion

Calibration and validation

Because of the lack of knowledge of management options during some events, data set used for calibration and validation of the model cover a period of about 120 days.

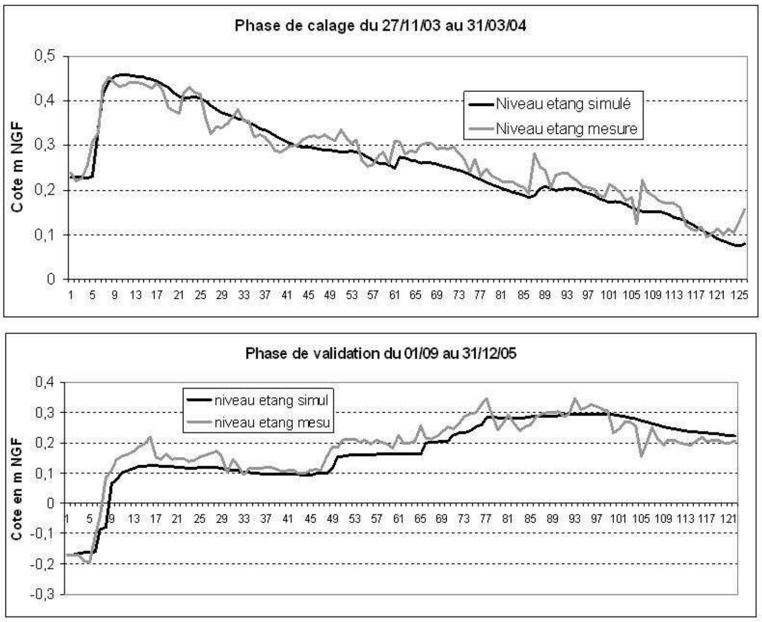

Figure 6 : Comparison between measured and simulated lagoon system mean water levels, in calibration (top) and validation (down) phase of the conceptual model.

Descriptive summary of simulated scenarios

In all scenarios : the « M » option is for a real sea level increased by 10 cm; the "A" option signifies that a supplementary drainage station can disminish up to 10 m3/s of input, no transfer from ROQ basin and that there is 10 more sluices at the sea outlet.

<u>Scenarios of the 2003-2004 type</u>

Scenario 2003-1 : real precipitation, real management up to the flood peak ; dyke breach with transfer (1993 type, 83 Mm^3) from N basin, transfer from ROQ basin, except « A » option.
Scenario 2003-2 : same as 2003-1, except : increased precipitations in september (rain event of 166 mm, like the 18/09/95).
Scenario 2003-3 : same as 2003-1, except: limited breach on the Grand Rhone and transfer (16 Mm^3) in December by the Fumemorte.

<u>Scenarios of the 2002-2003 type:</u>

Scénario 2002-2 : real precipitation, breach with limited transfer (1994 type, 16 Mm^3) from North basin Nord in September, breach and transfer (1993 type, for 83 Mm^3) in November.
Scénario 2002-3 : real precipitation, important breach with increased transfer (enlarged hydrograph from North basin due to rain event ; 89 Mm^3), breach with limited transfer in November (1994 type; 16 Mm^3).

<u>Critical scenarios:</u>

Scenario 2002-max : increased precipitations in September (rain event of 166 mm, like the 18/09/95 important breach with increased transfer (« enlarged » 1993 type ; 110 Mm^3), breach with important transfer in November (1993 type; 83 Mm^3).
Scenario 1996-max : real precipitations (the most important on the period from September to January since 1963, 582 mm),), breach with important transfer in November (1993 type; 83 Mm^3).
Only a sub-selection of simulated scenarios is presented on figures 7 and 8.

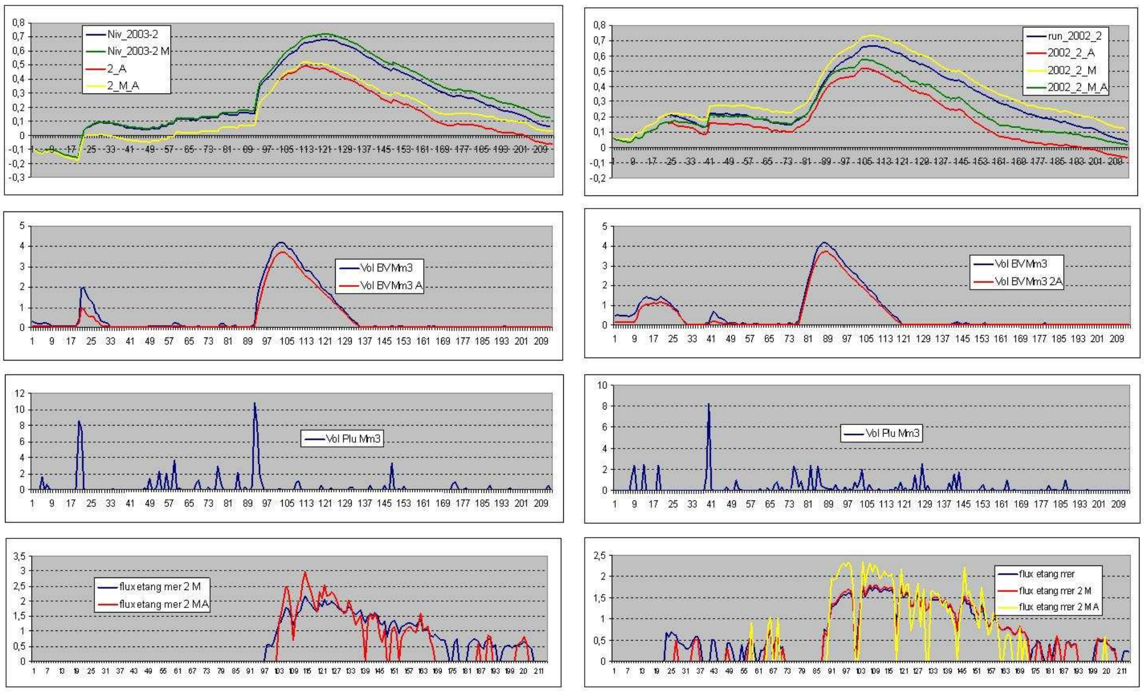

Figure 7 : Results of simulations for the set of scenario 2003-2 and 2002-2 (from top to down, computed daily values for: water level in the lagoon (m NGF); runoff volume from the catchment (Mm3); precipitations (Mm3); output volume to the sea (Mm3)).

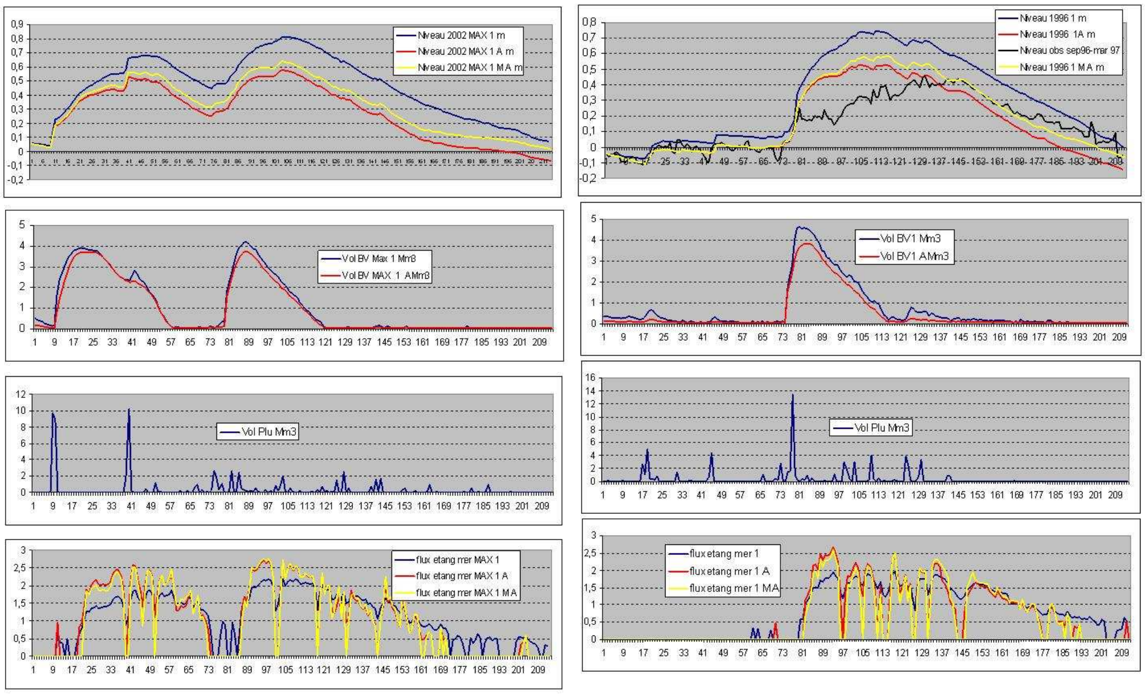

Figure 8 : Results of simulations for the set of critical scenario 2002-max (left) and 1996-max (right) (from top to down, computed daily values for: water level in the lagoon (m NGF); runoff volume from the catchment (Mm3); precipitations (Mm3); output volume to the sea (Mm3).

Simulations results, corresponding to crisis situation combining river floods (with supposed dyke breaches on the Petit Rhone), sea surges and high precipitation shows that it is possible to obtain in all simulated cases a water level considered as acceptable (inferior to 0.2 or even 0.1 m NGF) by the end of March, even with the worst scenario on actual management conditions. But it is clear that in order to reduce the time when water levels are superior to 0.5 m NGF, new management rules are necessary. When water level is superior to 0.5 m NGF in the lagoon, problems appear on the drainage basins: water logging on agricultural soils, flooding of some secondary roads and isolation of some habitations. And of course these problems are more important when lagoon water level increase above this value. So it is important to reduce the time when water level is above 0.5 m NGF. Acceptable hydraulic conditions can be reached only if new management options are considered. Above the possible options, we retained in the model, one example in which a new drainage pumping station (4 units of 2.5 m3/s) is settled in the formerly unpolderized FUM+ROQ basins. In parallel, exceptional transfer from polderized basins are limited to the Rousty canal, and the discharge capacity of the outlet to the sea is increased (10 more sluices of the present type). Given these new conditions with the worst simulated scenario, the water level of 0.5 m NGF will be exceeded only 18 days (38 days if we consider the hypothesis of a sea level 10 cm higher than real series) instead of 69 days for present hydraulic management conditions.

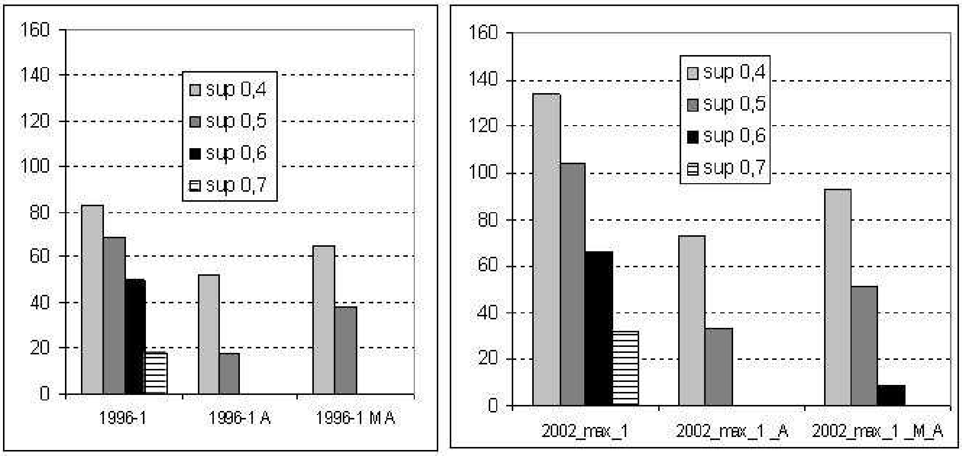

Figure 9 : Number of days with lagoon water level exceeding a given value (0.4 to 0.7 m NGF) for scenarios of the type 1996-max et 2002-max. (M: present sea level increased of 0.1 m ; A : extended polderization and increased capacity of outlet to the sea).

Conclusion

The developed simulation tool is used at a daily time step, based on really observed data combined in a plausible way during the period from September to March, and gives rather good results. To enlarge its prospective domain of use, it will be necessary to establish scenarios based on coherent synthetic series of wind, tide, sea surge derived from the work made by other teams within the framework of this project (Gaufres et Sabatier, 2006 ; Ullman et al., 2007).

The currently under development 2D hydrodynamic model of the lagoon system, allowing strong wind forcing, is a difficult task, and must be based on good topo-bathymetric data recently available. In fact it is mainly for the hydro saline modelling taking into account the different lagoon water bodies that this hydrodynamic approach will be necessary. This work is currently developed within the GIZCAM project ("Constraints, limits and perspectives for Integrated Coastal Zone Management in the Rhone river delta"), from the LITEAU program (Ministry of Ecology and Sustainable Development).

Under increased uncertainty due to climatic change, stakeholders need operational simulating tools based on accurate data bases in order to manage current or foreseen hydro climatic crisis.

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