DESIGN OF A LOCK TO REDUCE SALT INTRUSION IN THE VILAINE ESTUARY

by

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ABSTRACT

The Vilaine estuary is located in South Brittany, along the French West coast. Arzal dam is located eight kilometers upstream from the mouth of the Vilaine in the Atlantic Ocean. It is primarily intended to regulate the flow of the Vilaine and provide drinking water during the tourist season.

In order to reduce the salt intrusion upstream of the Arzal dam, the solution proposed by Artelia and its partners consists essentially in reducing very considerably the quantities of sea salt that enter the reservoir at each lock operation. The tests on the 3D physical model showed that this abatement can be obtained operating the substitution of the brackish waters contained in the lock by fresh water taken from the reservoir before the opening of the upstream doors. The effectiveness of this substitution was confirmed by the physical model of the new lock, which allows to refine the design and operating rules of the lock. A 3D numerical model has also ensured that the residual salinity of the lock operation could not cause any problem in the future in the reservoir.

The substitution of brackish water by fresh water in the lock is fundamental for the proper functioning of the new lock. A withdrawal of the brackish waters near the bottom of the lock chamber combined with a soft introduction of fresh water in the upper part makes it possible, by minimizing the mixing between the two flows thanks to the difference of density. The physical model at scale 1/12 allowed assessing the lock water supply system, the duration of the lock chamber emptying, the crest level setting of the outlet ports, the curves of decay of the salinity in the lock as a function of time. The model also assessed the impact of door opening on freshwater and brackish water trapped below the upstream lock's threshold.

The numerical model of the whole reservoir upstream of the dam allowed evaluating the impact of the new lock on the saline intrusion. The 3D model in place allows to analyse all the processes and to test different configurations of operation of the structures.

1. INTRODUCTION

The Vilaine estuary (Figure 1) is located in South Brittany, along the French West coast. The Vilaine River has a flow discharge ranging between 2 and 1500 m3/s. Arzal dam is located eight kilometers upstream from the mouth of the Vilaine in the Atlantic Ocean. It is primarily intended to regulate the flow of the Vilaine and provide drinking water during the tourist season. This is one of the rare estuarine dams in the world.

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Figure 1: the Vilaine estuary (sea on the left; from the left riverbank to the right: the dam, sluice gates and the lock)

The “Institution d’Aménagement de la Vilaine” (public organization created to carry out the necessary structural adjustments) has initiated design studies for the construction of a second lock at the Arzal dam. This lock must fulfil different and sometimes even contradictory set of functional objectives (protection against floods, drinking water reservoir, river navigation, road crossing, fish crossing, hunting ...). Among these, maintaining and preserving a water resource for the production of drinking water is the major objective of the project. Currently, desalination is carried out by a siphon system which pumps the brackish water in a pit located upstream the dam and evacuates water further downstream. This system is highly water consuming and poses problems especially during the summer.

In order to study the feasibility of the project, two complementary models were used:

- A physical model of the lock to evaluate its efficiency and to optimize some components,
- A numerical model to analyse the saline intrusion in the Vilaine.

2. THE PHYSICAL MODEL OF THE LOCK

2.1 Objectives

The principle of the substitution was developed on the basis of a preliminary 3D numerical model of the lock chamber, which allowed to show that an extraction of brackish water associated with an introduction of fresh water in the upper part would enable to rapidly lower the salinity present in the lock.

However, the complexity of the process requires that a physical scale model be built in order to:

- validate the operating principle and its effectiveness,
- set up the inlet ports crests,
- confirm dimensioning of the inlet and outlet aqueducts,
- define the pumping times according to the desired abatement,
- if necessary, define any rules for valve opening,
- assess any risk to the boats moored in the lock chamber caused by the fresh water filling.

This modelling should also allow a better understanding and visualization of the velocity field within the fresh water flow introduced into the lock chamber, above and after the lateral water gate.

2.2 Conception of the model

Flow dynamics at the scale of the physical model should follow the Froude similitude. This similitude ensures the conservation of the main forces involved in the flow (gravity, inertia, turbulent friction). The densimetric Froude number is also conserved because salt water on the sea side is represented with salt concentrations equal to those of nature. Thus the dynamic effects related to the freshwater/saline water density gradient, whatever the value of this gradient, are also well reproduced in the model.

It is also important that the friction forces in aqueducts and lateral water gate are correctly reproduced, which assumes that the Reynolds number is high enough and that the universal coefficient of friction is conserved. This imposes a fairly large scale.

The geometric similitude and the Froude similitude lead to the following scales:

- Scale of lengths, heights and pressures: 1/12
- Volume scale: $1/12^3$, or 1/1728
- Time and speed scale: $1/12^{1/2}$, or 1/3.46
- The salt concentration scale is 1.

2.3 Model construction

The model represents all the hydraulic components of the lock:

- The lock chamber
- The upstream radial gate of the lock chamber
- The upper and lower aqueducts on each side of the lock chamber: lower aqueduct for salt water intake by gravity or for pumping of brackish water from the lock chamber, upper aqueduct for fresh water supply from the reservoir
- The bottom outlet ports between the lock chamber and the lower aqueducts (9 on each side)
- The upper inlet ports between the upper aqueduct and the lock chamber (10 on each side with adjustable crest)
- The intake radial gates of the upper aqueducts
- Pumps of the lower aqueducts

2.4 Lock operation

The model works like the prototype (the real size lock). During lock operation, salt water is pumped by adjustable pumps at the downstream end of the lower aqueducts to a storage basin (representing the maritime estuary). At the same time, the fresh water is brought into the lock chamber by gravity by opening the gates of the upper aqueducts.

The initial salinity in the lock is adjusted according to the characteristics of the test (3 salinities tested): the salinity is prepared in the storage basin and introduced into the lock chamber by the aqueducts and bottom gates. The salt water is firstly mixed to obtain a good homogenisation.

Each test is initialized in terms of initial water level and salinity in the lock chamber before the gate operation (Figure 2).

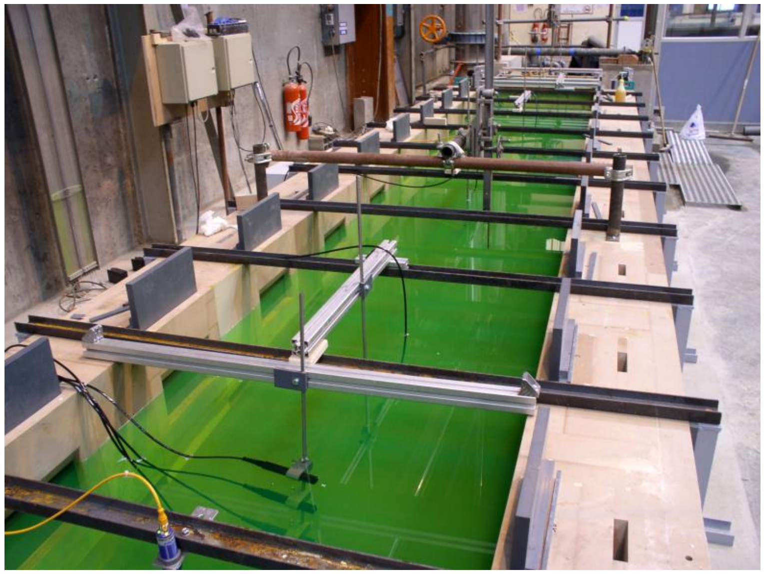

Figure 2: impoundment of the physical model

The measurements concern:

- the discharge of each lower aqueduct: these variable flows are measured downstream of each pump by means of an electromagnetic flow meter
- Water levels: these water levels are measured at four points by echo-sounding sensors: in the upstream basin representing part of the reservoir upstream of the dam, in the lock chamber (upstream, central, downstream)
- Salinity is measured in twelve points distributed vertically and along the lock chamber

All the measurements are recorded at the required frequency and stored in a computer. The radial gates and pumps are also computer-driven (open and closing time of each device, opening and closing velocity, discharge variation)

2.5 Tests

The variables that it was necessary to test are:

- The upstream level (in the fresh water reservoir) which is a boundary condition of the model.
- The downstream level (tidal range downstream the dam). In practice, it can be seen that these levels have no effect on the substitution mechanisms since they are only engaged after the equilibrium of the levels with the upstream reservoir.
- The salinity of the water introduced into the lock chamber (initial condition). The minimum value is 2.50 PSU and the maximum value is 35 PSU, intermediate values are 15 and 32 PSU.
- The position of the crest of the small vertical gates of the inlet ports which has been pre-dimensioned to satisfy two objectives:
    - Minimize turbulence associated with the introduction of fresh water into the lock chamber so as to reduce the risk of mixing fresh and brackish water. This condition is linked in particular to a minimisation of the fresh water introduction with a most possible laminar flow and with the lowest possible vertical velocity field component.
    - Minimize transverse currents on the hulls of boats in the lock chamber by trying to keep velocities below 30 cm/s.

- The pumping rate. By default Q_{max}=4 m^3/s per aqueduct in the prototype (possible variation +/- 1.6 m^3/s) during around 15 mn with a slow rising from 0 to Q_{max} to prevent the mixing.
- The opening rate and the closing rate of the radial gates at the upper aqueduct intake.

2.6 Results

The results are:

- The head losses in the aqueducts between the reservoir and the inlet ports: around 0.36 m for a supplied discharge of 8 m^3/s
- The opening height of the inlet ports according to the discharge and consequently the crest level setting: 0.7 m up to 0.9 m according to the discharge. An opening of 0.6 m appears to be insufficient
- The minimal substitution time to avoid water mixing according to the discharge of the operation: between 15.1 mn and 16.6 mn
- The value and repartition of the salinity at the end of the test: the final salinity remains always below 2 g/l, and mainly below 1.6 g/l, between the water surface and the crest of the sill of the upstream lock chamber gate, whatever the initial conditions with the defined gate opening und pumping conditions
- The influence of the upstream and downstream water levels, initial salinity, pumping rate on the final salinity: the pumping rate is to be between 8 and 9.6 m^3/s. A discharge less than 8 m^3/s is insufficient to lower the salinity. Initial salinity has almost no influence on the final salinity
- The influence of the upstream lock chamber gate opening after a test on the residual salinity dispersion into the reservoir: the opening of the gate does not increase the salinity upstream of the lock above 2 g/l. However a 9.6 m^3/s discharge gives a better security on this residual salinity as the limit between fresh water and brackish water stabilises at the end of the test 1 m below the gate sill. This limit stabilises only at the sill level with 8 m^3/s substitution rate. For that reason, the impact of the boats propellers (not studied in the model) on a local re-mixing, when the boats sail out of the lock, will be much better controlled by a 9.6 m^3/s rate.

The following Figure 3 presents the salinity sensor records of one of the tests with the following conditions: pumping discharge 8 m^3/s, initial reservoir level equal to the mean reservoir level observed in summer season, initial salinity of the water in the estuary 32 g/l, outlet port opening 0.70 m, appropriate opening and pumping increase velocity at the beginning of the substitution. Sensors Sonde 1, Sonde 8, Sonde 9 are located around 1 m above the bottom of the lock chamber.

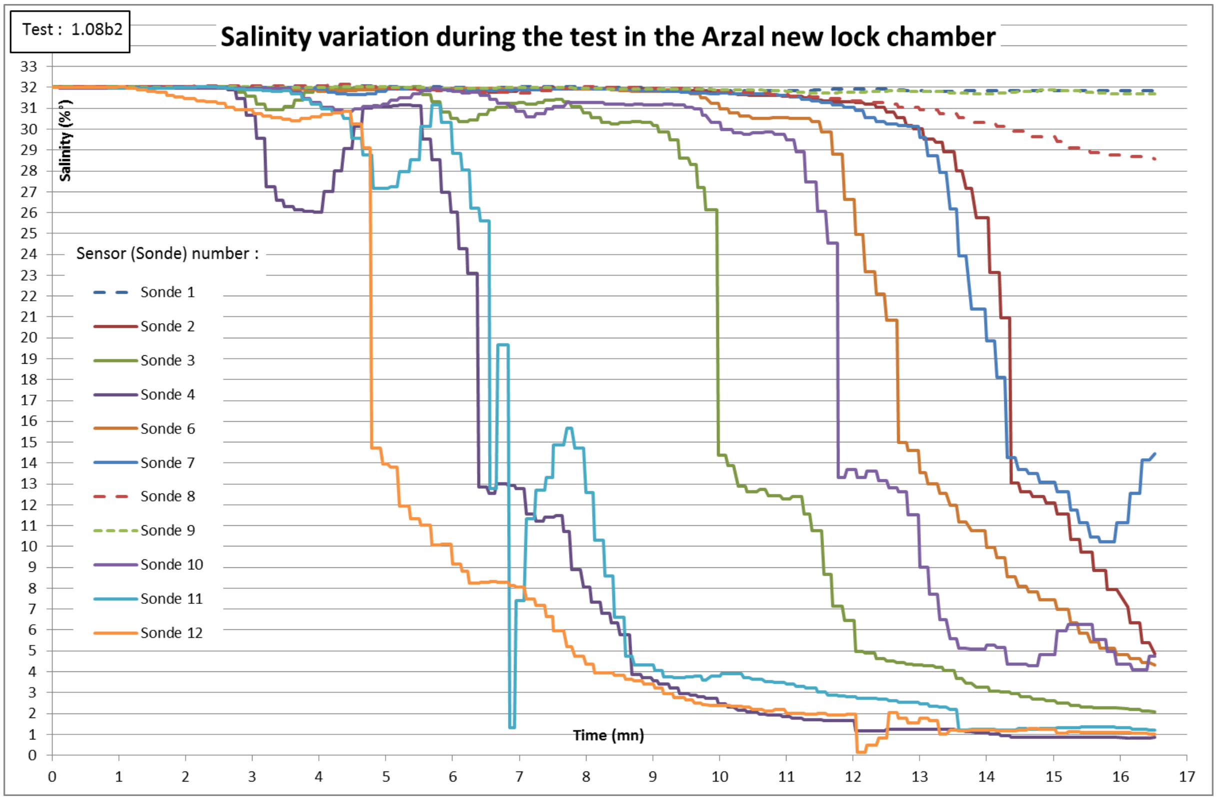

Figure 3: salinity variation during a test – physical scale model

All these variables and the tests carried out allow to specify the characteristics of the lock. The work obtained meets well the requirements of saline water substitution. The impact of the structure on upstream reservoir is then studied by numerical modelling.

3. THE NUMERICAL MODEL OF THE RESERVOIR

The built model allows the calculation, at all points of the reservoir, of the water flow patterns under the influence of upstream water inflows, water outlets at the dam as well as withdrawals and losses (evaporation, water intake from the Férel plant, leaks...), the effects of wind on the surface but also under the influence of the quantity of salt dissolved in the water which is variable.

This variation of dissolved salt causes water density differences and thus internal currents, the saltiest waters, and consequently the densest, tend to flow under fresh water and thus accumulate at the bottom. It is the amount of salt dissolved (its concentration) that is the main concern of the process to answer the questions asked.

For all these reasons, the model is a three-dimensional (3D) one and we have used the TELEMAC-3D software. It covers a territory which, initially limited to a length of about 4 km upstream from the dam, has been extended to the Cran bridge to ensure a more accurate representation of the phenomena and allow a better understanding (Figure 4).

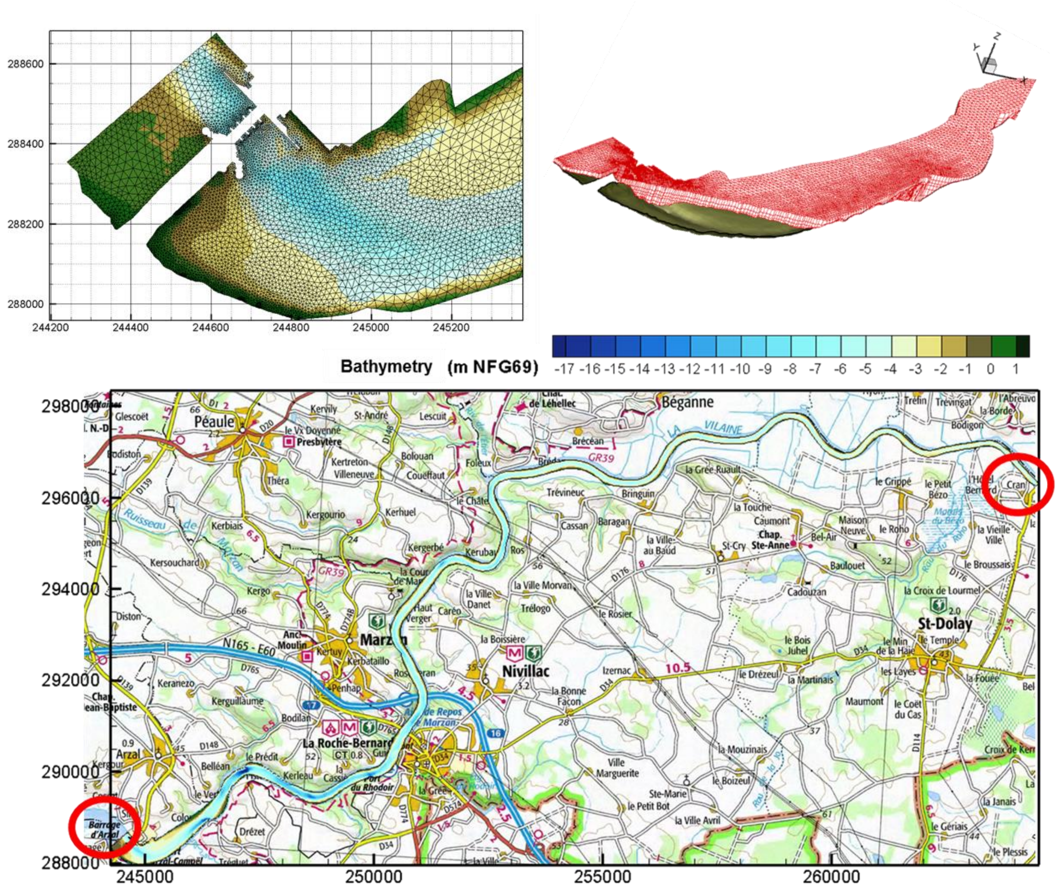

Figure 4: extend and mesh of the numerical model

One of the difficulties of the project is that the precision of certain data is of the same order of magnitude as certain expected results.

2.3 Boundary conditions and calibration

<u>Boundary conditions</u>

Different conditions are imposed at the model boundaries. What goes into the reservoir:

- The natural flow of the Vilaine, upstream from the reservoir and measured at the Pont de Cran, with some secondary inflows. These data are provided by the Pont de Cran station which, since its creation, has contributed to the knowledge of the estuary but which is inaccurate for measuring low flows in summer. Winter floods (slow plains floods due to heavy rains) show flowrates greater than 400 m3/s, whereas in summer low flow is almost null (flowrate less than 2 m3/s).
- Brackish water from the estuary that flows through the dam through the lock at each lock opening (fairly easy to determine) or through leaks at the sluices gates when the sea level is higher than the level in the reservoir. These last are not known and can only be very roughly estimated at a few hundred l/s at most.

What comes out:

- The overflow at the dam. Almost null in summer, these surverses aim to manage water levels in the Arzal reservoir. They are highly variable depending on upstream water contributions. They are not measured but can be approximated based on the recorded levels and the position of the dam gates.
- The locks. These quantities of water leaving the lock can be calculated with correct accuracy. During the year 2005 corresponding to the calibration period, the average flow discharged at the lock is estimated at 9,500 m^3/d (0.11 m^3/s).
- Siphoned waters. The two siphons capture most of the parasite salt water brought by the sluices and redirect it towards the estuary. In low water, a large part of the resource is thus lost by siphons (300,000 to 400,000 m^3/d) at a time when drinking water needs are most high.
- The fish pass. The fresh water flow lost by the fish channel averaged 0.9 m^3/s (over 80 000 m^3/d) in 2005 and 0.3 m^3/s in the summer months alone.
- Evaporation. Over the 2005 calibration period, the volume of water evaporated is greater than the volume of water brought by precipitation. Water loss (obtained by subtracting the volume brought by precipitation from the volume of water evaporated) can reach 42 000 m^3/d (July 11, 2005).
- The Drezet plant has expanded its drinking water production capacity from 30,000 m^3/day in 1972 to 100,000 m^3/day today. This growth is linked to tourist pressure and the development of the industrial basin of the Lower Loire. The plant produces between 15 and 20 million m^3 of drinking water each year. For 2005, the volume of untreated water pumped at Drezet averaged 66,000 m^3/d (0.77 m^3/s) with a peak of over 92,000 m^3/d (July 15) and a minimum of 39,500 m^3/d (January 31). Peak demand is therefore in the middle of the summer period, which obviously corresponds to the low flow period of the Vilaine.

<u>Water levels</u>

Knowledge of the levels in the Vilaine and in the estuary is essential because it makes it possible to establish exchanges through the dam and also to take into account the variability of the quantity of water stored in the upstream reservoir.

The water level in the Arzal reservoir is controlled by opening the gates and dam sluices. It is between +2 and +2.4 m NGF (general levelling of France) during low-water periods (during floods, this level can be much lower). The water level downstream of the dam is influenced by the tide. It varies between -3 and +3.5 m NGF. The data provided by the IAV are measurements taken on both sides of the dam.

<u>Salinity</u>

Salinity varies according to several parameters including:

- the natural flow of the Vilaine (the higher this flow is and the more salinity is pushed towards the sea),
- wind, time and tide level...

This salinity can vary greatly between the surface of the water body and the bottom. Various measurement campaigns have been carried out to better understand these values, one of which was carried out in 2007.

To summarize, we can consider that this salinity varies in very important proportions from 0 to 35 g/l thus passing from a freshwater profile to a seawater profile and that an average value of the order of 13 to 18g/l is representative of the salinity of the waters at the base of the dam without that we can put in evidence a relation with the parameters that influence it.

The "drinking water" requirement involves a normative concentration value for chlorides of less than 200 mg/l (0.2 g/l for approximately 20 g/l for sea water). Local industrial uses may require values below 100 mg/l.

The calibration was carried out by optimizing the setting and the tuning of a set of phenomena such as the refined evaluation of the mass flow of salt rejected by the siphons, a better treatment of the density effects reflecting the mobility of the water masses as a function of their saline concentration, the representation of the volume of salt entering each sluice, the average salinity of the estuary which is representative of the period, the extrapolation of the upstream flowrate for periods without data... By adjusting all these parameters, we obtain, in fine, a simulation of the phenomena rather close to the measurements available at the plant (Figure 5 below).

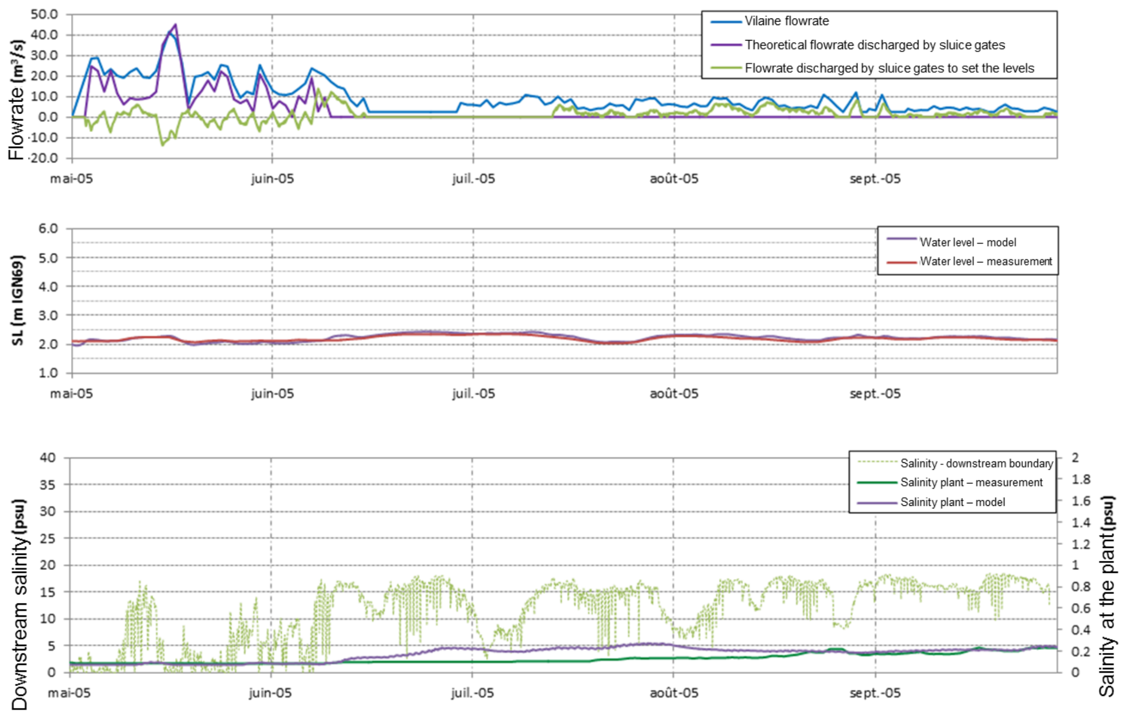

Figure 5: calibration of the numerical model

For the later tests, however, we retained a more unfavourable situation and in particular one where siphons played a more active part. This allowed us to place ourselves in a conservative situation to evaluate the impact of the siphon shutdown.

2.3 Exploitation

The longitudinal profile and the horizontal view of the reservoir, Figure 6 hereafter, show the extent of the salinity front for the configuration selected at the end of the calibration.

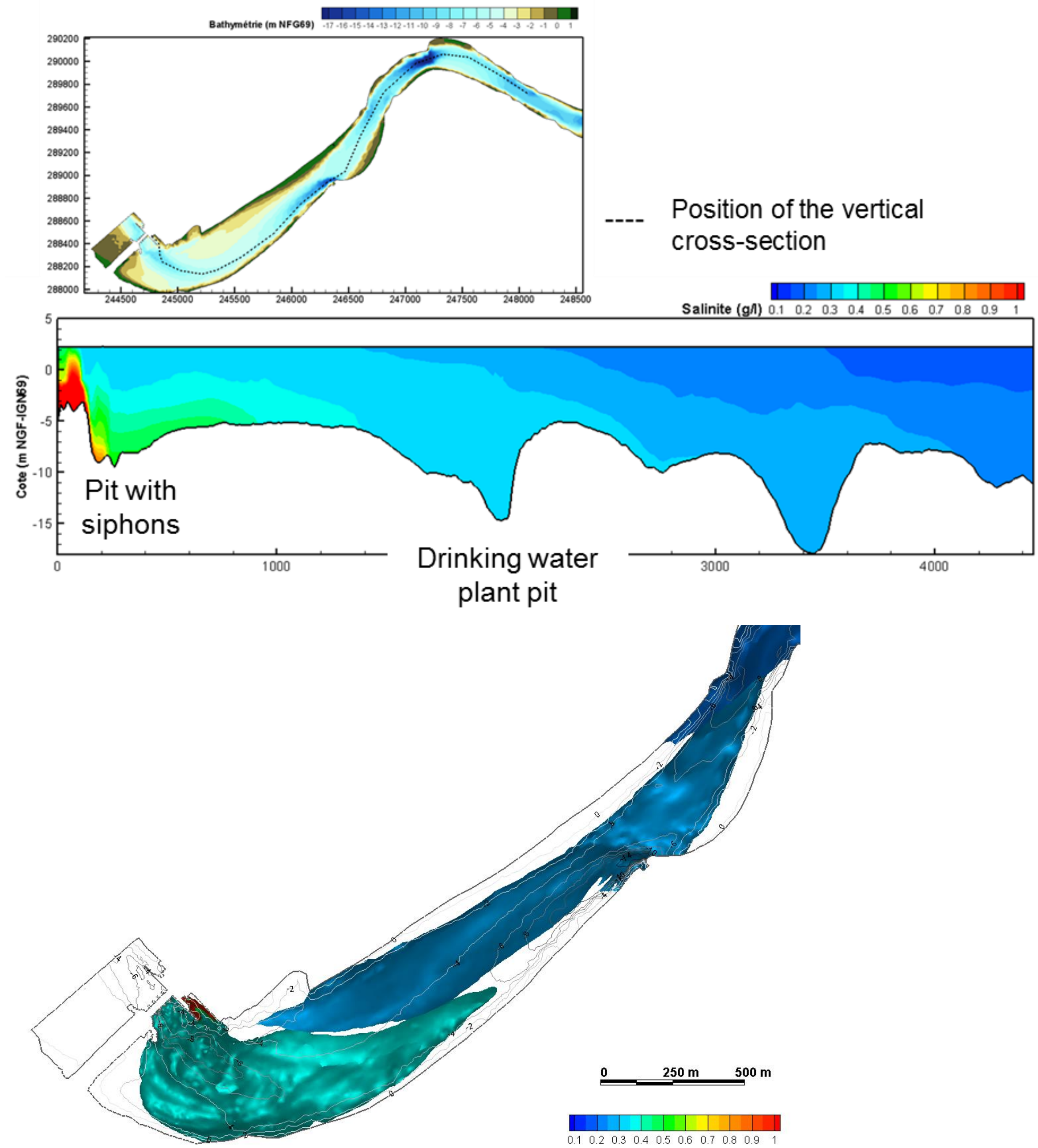

Figure 6: salt intrusion cartography – present state (iso-concentrations fixed at 1 - 0.5 - 0.4 - 0.3 - 0.25 psu)

The figures show that there is a brackish wedge downstream of the reservoir that reaches its maximum concentration near the dam (in red on the longitudinal profile). This high salinity is maintained by saline intrusions linked to the locks opening. Away from the dam, concentrations decrease quite rapidly over the first few hundred meters and then more slowly, even very slowly. Water extends with concentrations above 0.05 g/l upstream from the Roche-Bernard (first town upstream the dam), at least near the bottom, as the salt concentration spreads under the effect of density currents.

The projected lock will significantly reduce the quantities of salt that will enter the upstream reservoir. It remains to determine whether its effectiveness will be sufficient to achieve the fixed objectives.

Tests on the mathematical model of the lock enabled a correlation to be established between the substitution pumping times of the water in the lock and the salinity reduction obtained. To test the effectiveness of the solution, a pumping time of 11 minutes at each ascending lock was assumed. This corresponds to a coherent time with regard to the constraints of passing ships through the structure. The tests were carried out with the siphons maintained (because we know they are effective), then we wanted to know if the new lock would allow us to do without them.

<u>New lock with siphons</u>

The above cross-sections (Figure 7) and graphs (Figure 8) show the efficiency of the new lock with very high salinity reductions in the reservoir.

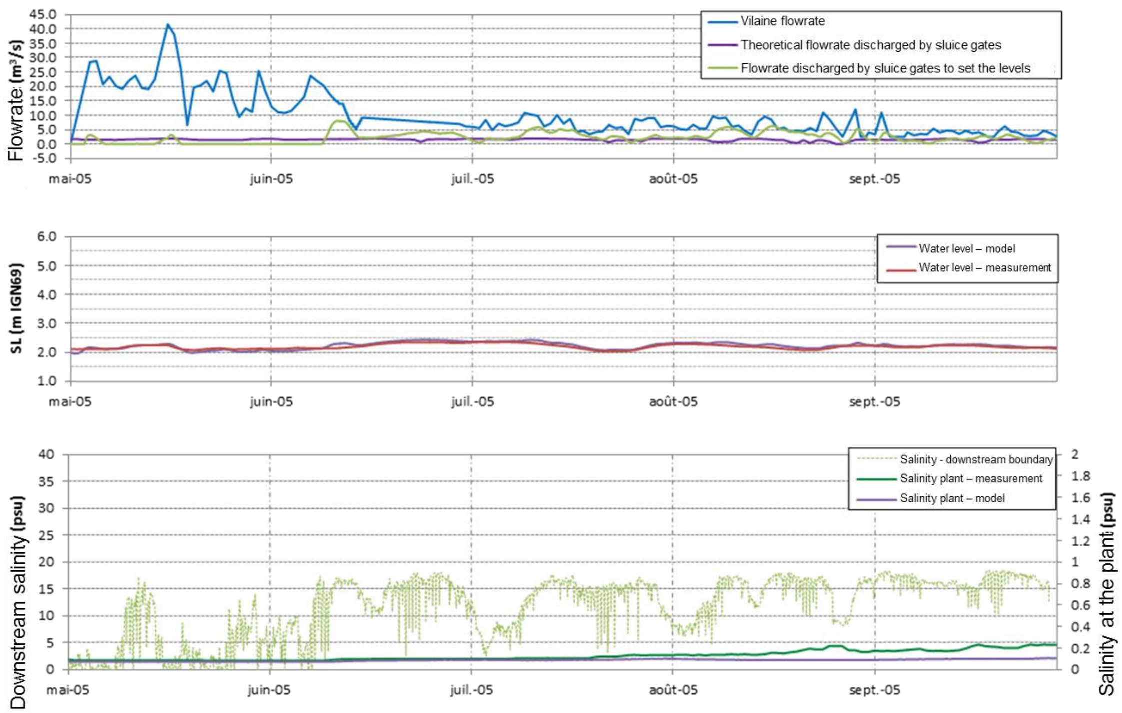

Figure 7: results obtained with the new lock with siphons

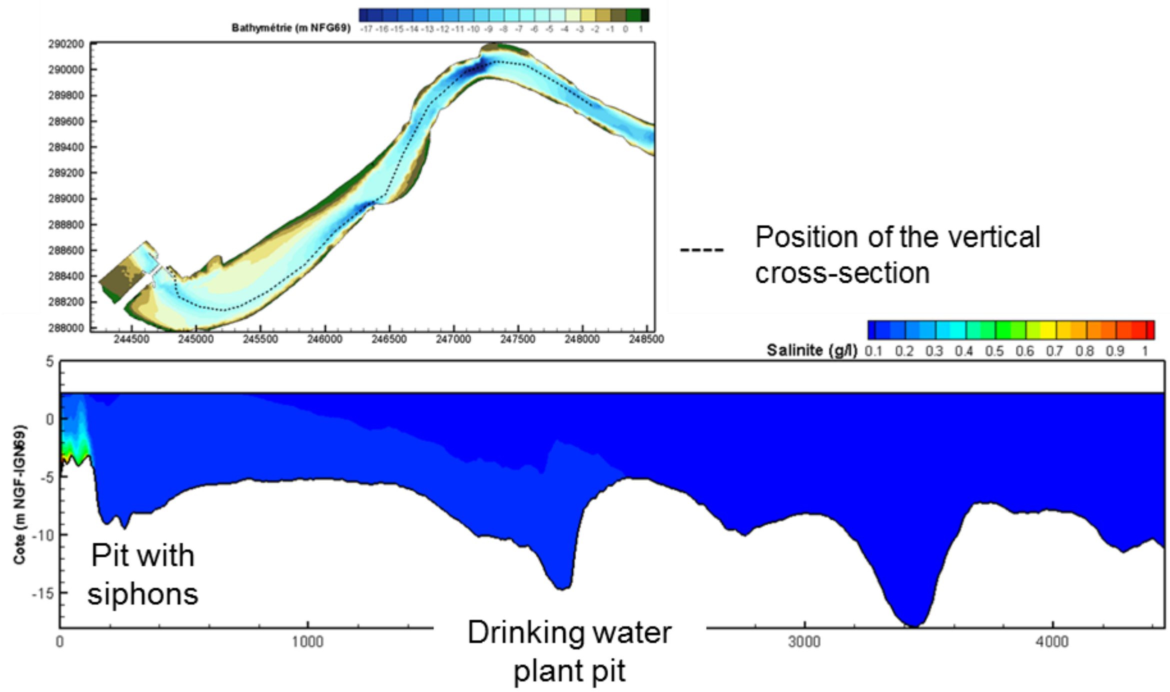

Figure 8: salt intrusion cartography – new lock with siphons

<u>New lock without siphon</u>

Having noted the effectiveness of the system, it is a legitimate question to know whether the new lock can be sufficient to obtain the expected result without having to use siphons that consume water.

The same calculation was done, assuming this time that the siphons are stopped (Figure 9 & Figure 10).

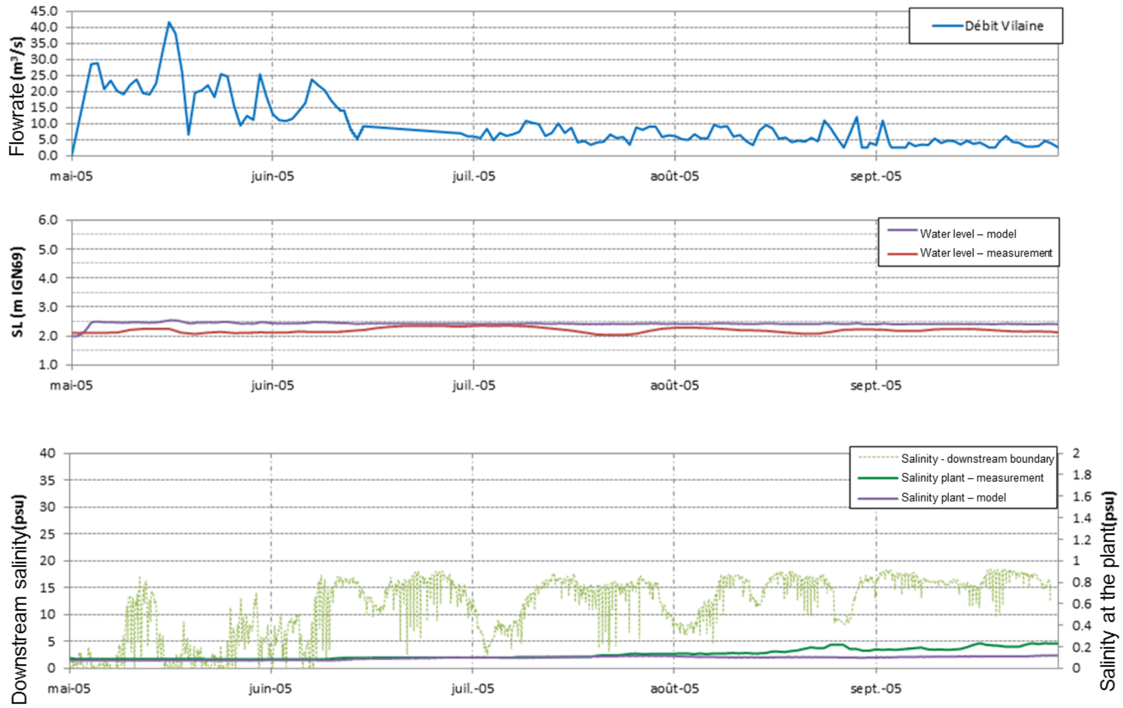

Figure 9: results obtained with the new lock without siphon

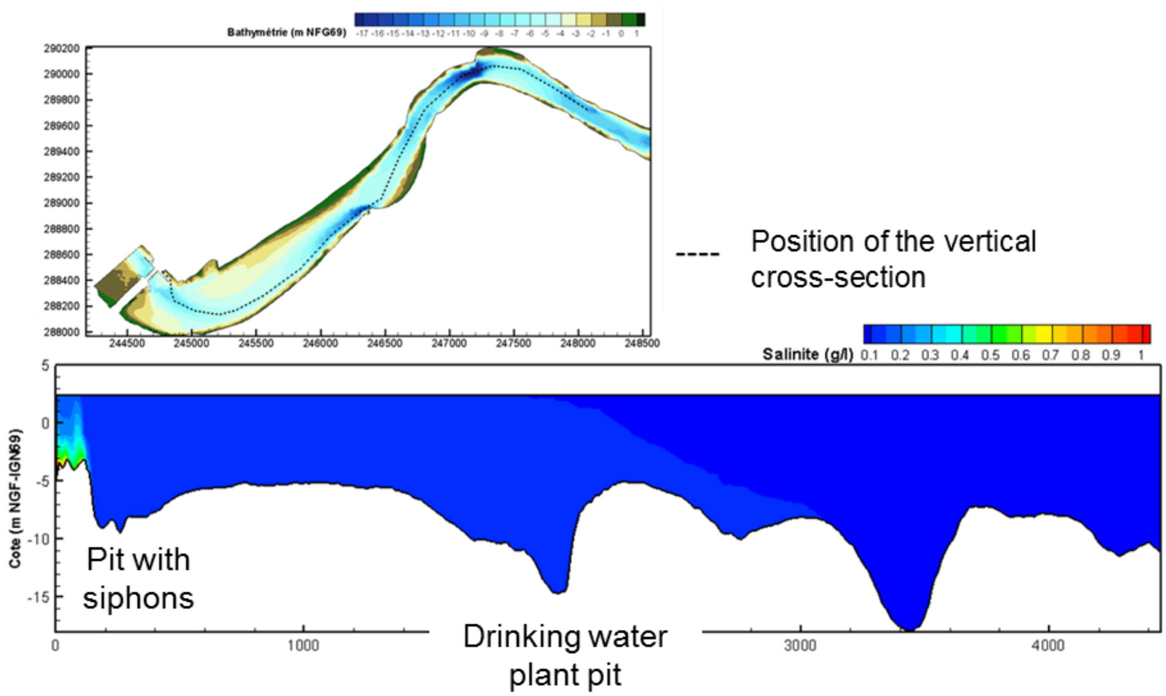

Figure 10: salt intrusion cartography – new lock without siphon

The differences between these two series of graphs do not appear clearly and show that the contribution of siphons remains marginal if the new lock is built.

This clearly indicates that, under conditions similar to those in 2005, the installation of the proposed lock alone would be sufficient to contain the salinity in the reservoir at very low levels without the need to use siphons or move the drinking water intake.

4. CONCLUSION

The Arzal dam is one of the rare estuarine dams in the world. In order to reduce the salt intrusion upstream the dam, two complementary models were used:

- A physical model of the new lock to evaluate its efficiency and to optimize some components,
- A numerical model to analyse the saline intrusion in the Vilaine.

The physical scale model represents all the hydraulic components of the lock and works like the prototype (the real size lock). During lock operation, salt water is pumped by adjustable pumps at the downstream end of the lower aqueducts, at the same time the fresh water is brought into the lock chamber by gravity by opening the gates of the upper aqueducts.

The studies realised shows that the lock meets well the requirements of saline water substitution. The impact of the structure on upstream reservoir is then studied by numerical modelling.

The three-dimensional numerical model covers a large territory upstream from the dam to ensure a more accurate representation of the variation of dissolved salt and the water flow patterns. After a calibration on the current situation, the exploitation of the model for the project state differs by taking into account the new lock which reduces saline intrusions.

The use of the new lock makes it possible to limit saline intrusions very strongly. Two calculations in this project state were performed. These two calculations are distinguished by the use of siphons as is currently the case or the complete stop of siphons during the whole simulated period. It is difficult to differentiate between the two calculations performed, especially given the uncertainty on all input data. This shows that, with the new lock, maintaining the siphons in operation does not bring any significant gain on the salinity reduction.

In conclusion, the proposed solution, i.e. the anti-salt lock, seems relevant and self-sufficient since it addresses the problem of salt intrusion into the reservoir even when the siphons are stopped. However, it seems reasonable to keep and maintain the siphons as they are, which would provide the additional efficiency that may be necessary in the case of a shutdown of the new lock or to compensate for the operation of the existing lock. Indeed, it was recognized that it could be used, on an exceptional basis, on peak summer days.

5. ACKNOWLEDGEMENTS

The authors would like to thank the IAV “Institution d’Aménagement de la Vilaine” for the funding of the studies, the technical exchanges and the sharing of field data.