# IMPROVING THE RELIABILITY OF CANAL DE PROVENCE HYDRAULIC MEASUREMENTS BY DATA RECONCILIATION

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## ABSTRACT

Measurement network on hydraulic system includes many sensors subject to failure or deviation, and spread over a huge area. In addition discharge and volume measurements in open channel hydraulic networks are characterized by large uncertainties. To overcome this kind of problem, in process control industrial applications, data reconciliation is more and more used. The objective of the data reconciliation is to take advantage of information redundancy on a system to make a cross-checking of real-time measurements.

Using this information redundancy, a data reconciliation module allows to detect inconsistent measurements, measurement deviations and provides corrected values whether the initial measurements are valid, biased or invalid. A derived consequence is to better schedule the maintenance of sensors.

A data reconciliation module, based on the measurements from the hydraulic network, has been recently developed and implemented in the SCP's supervisory system. The software has initially been used on a daily basis to check the measured flow on the main canal. It has then been adapted in order to run every 15 minutes on a distribution network including pipes, canals, and tanks.

The paper presents first the theory of the Canal de Provence data reconciliation application. The basic model is an hydraulic network with a series of nodes corresponding to balance equations (inflows, outflows, and storage). Constrained data reconciliation is used in order to satisfy the non-negativity of the hydraulic variables and the mass balance relations. The results are corrected values for measured variables and proposed values for non-measured quantities. A statistical

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analysis of the results is performed. This analysis allows to evaluate the uncertainties attached to the estimated flows and volume values. It allows also to detect invalid measurements, drift of sensors and to decide which maintenance operations to perform. Secondly, field examples are presented : measured and re-estimated flow values with their standard deviations, detection of invalid sensors, performed maintenance operation. The data reconciliation is situated just after the measurement process and takes place in the decision process for diagnosis, identification and control.

## INTRODUCTION

The Canal de Provence is situated in the South-East of France. It supplies water to 80,000 ha of farmland, 110 towns and villages and 400 industries. The water distribution strategy is user oriented, without resorting neither to rotations nor to any sort of priority allocation.

All the main structures are monitored and remote controlled from the General Center by a SCADA system including a module of "Dynamic Regulation" which provides automatic and permanent control of canal flows and safety systems.

A data reconciliation procedure can be implemented as long a redundancy among measurements exists. This redundancy can come from multi-measurements of some physical quantities in the system. It can also come from system equations linking the measured variables due to the existence of a model of the system. In our application, we are essentially concerned by this last case, which is closely connected with the concept of system observability.

Usually one distinguishes two main cases. The static case, where the model equations concern only measured quantities at the same instant. The dynamic case, where the system equations concern measured quantities on different instants. In the dynamic case, the model equations are most of the time those of the dynamic modeling of the system. In any case the relevance of the resulting re-estimated data will depend , of course, on the accuracy of the model.

The first implementation of data reconciliation on the hydraulic system of Canal de Provence, concerns daily volumes on the canal, see figure 1. Therefore, the model equations can be the static volume conservation equations at the nodes of the hydraulic network, since propagation time can be neglected.

More recently, it has been extended to a distribution network of pipes and canals, where it runs every 15 minutes. This second project required to take into account the storage in canal and tanks and the transit time of water along canals.

The next section is devoted to a presentation of the data reconciliation basic principles. The third section presents typical and illustrative field cases.

## DATA RECONCILIATION PROCESS

The model equations can be presented as follow. First we number the daily measured discharges. Let us call $v_i^*$ the true ( unknown ) value of the discharge on branch number i and $v_i$ the value from sensor. Let us call $V^*$ and $V$ the respective vectors. The volume conservation relations at the nodes of the network lead to linear mass balance relations between these branch discharges:

$$MV^* = 0 \tag{1}$$

where $M$ is the network matrix the elements of which have the values 1, -1 or 0. To each node of the network corresponds a row of $M$. The value of an element of a given row is 0 if the corresponding discharge $v_i^*$ does not appear in the node relation, +1 if it is an entering discharge (inflow) and –1 if it is an outgoing one (outflow).

Of course this relation does not hold for the vector $V$. We rather get:

$$MV = E$$

generating then a vector of residues $E$.
At this stage some statistical hypotheses must be done. The $v_i$ are considered as Gaussian, independent random variables, the standard deviations $\sigma_i$ of which characterize the measurements precision. Therefore the covariance matrix W of the random vector V is

$$W = \mathrm{diag}\left(\sigma_i^2\right)$$

The data reconciliation problem is now : find the best estimate $\hat{V}$ of $V^*$, which minimizes the quantity

$$\frac{1}{2}\left(V - \hat{V}\right)^t W^{-1}\left(V - \hat{V}\right)$$

subject to the equality constraints:

$$M\hat{V} = 0$$

and to inequality constraints:

$$\hat{V} \geq 0$$

Numerical solution of this problem is obtained in the framework of the Lagrangien multipliers method (Ragot 1992).The inequality constraints are taken into account using an heuristic method (Gill 1981).

We call $D = V - \hat{V}$. Four statistical tests have been implemented in order to detect a value of D outside the confidence interval, a jump of mean value of D on a sliding window, a too large variance of D, and a value of $\hat{V}$ outside its confidence interval.

We check also for some points that value of $\hat{V}$ does not exceed physical known thresholds for these points.

In addition, in order to test the global consistency of measurements, a khi2 test is performed on the quantity

$$K = E^t M \, W \, M^t E$$

Ill-conditioned numerical problem can occur when measured values are missing in the database. In order to deal with this problem we have implemented an independent method of reconstruction of missing values based on a Principal Component Analysis (PCA) of a complete historical sample of measurements (Fenelon 1982, Canivet 2002)

## FIELD EXAMPLES

The data reconciliation module runs actually on the main canal network on a daily basis and on a hourly basis on the Aix-Nord distribution network including pipes, canals and tanks. The next paragraphs will present these two cases, with a short description of the networks and the constraints.

### The main canal application

The geographical location of Canal de Provence is shown in Figure 1.

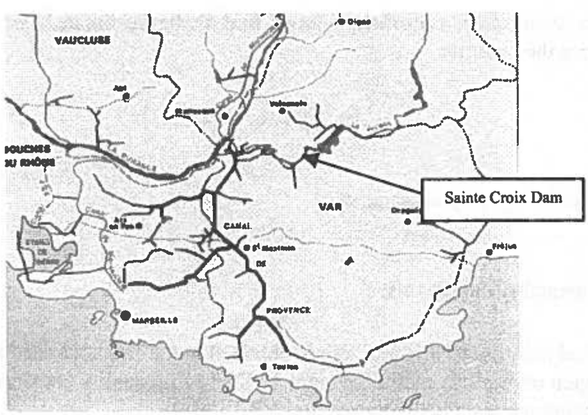



Figure 1: Canal de Provence, location map

The water is taken from Sainte-Croix dam at Boutre intake. The Canal de Provence supplies the Provence and Côte d'Azur region (PACA region). One can distinguish three main areas: the Aix-en-Provence, Marseille and the French Riviera areas.

Figure 2 shows the diagram of the network with the location of measurements. Different categories of sensors are used in order to measure the discharge. Ultra-sonic and electromagnetic flow meters are essentially implemented at the head of distribution networks. At cross structure locations gate formulas are used for the discharge calculation. In addition, calibrated weir, flumes (venturis), pumps tabulated formulas and an open-channel ultra-sonic sensor at the Boutre intake, are also present on the Canal.

The data reconciliation software is executed every morning by the control operator to check the overall discharge coherence of the previous day. This procedure is operational since 1999. Previously, discharge measurements were used for control purpose which needs only relative knowledge of discharge variations. This implementation represents the first step to the final absolute knowledge of the discharge values.

In the following we choose to present three typical examples: the abnormal Saint-Maximin and Pourcieux cross structures behavior and the Boutre discrepancy between two different flow measurements.

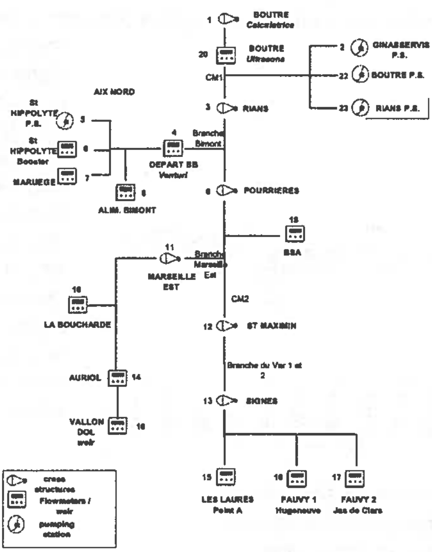



Figure 2: Diagram of network

The Saint-Maximin cross structure consists of two gates which are used alternatively on a monthly basis, for maintenance reasons. The discharge value is obtained from gate opening and upstream level since the structure works in a free flow condition. The software detects inconsistencies depending on the gate used. Figures 3(a) displays the differences between reconciled and measured discharge values, together with the gates status.

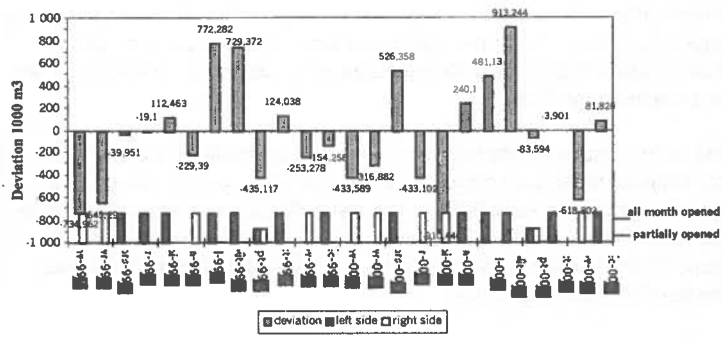



Figure 3(a):Deviation between reconciled and measured values at St Maximin cross structure, year 1999/2000

Inconsistencies correlated with the gate used appear very clearly. A field investigation, point out a slight error on position measurement of the right side gate. This error was small in comparison of the total gate opening. However, since the structure operates at low rate, it has a large effect on discharge calculation. Figure 3(b) shows the actual situation, after the correction mentioned above.

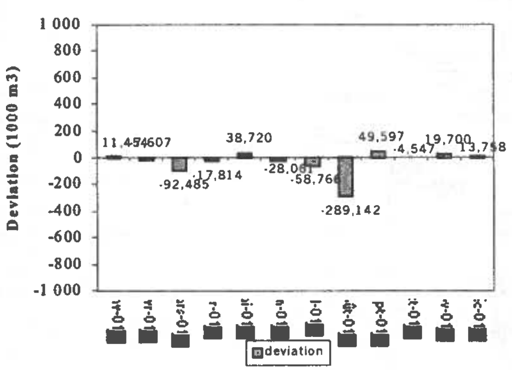



Figure 3(b):Deviation between reconciled and measured values at St Maximin cross structure after correction

At Pourcieux the structure was initially designed for free flow condition operation. The software detected that the discharge calculated at this point was to low in comparison to reconciled value. This was confirmed by a gauging based on flow velocity measurement. We then diagnosed that the canal downstream has an effect on the gate, although the canal slope was high. Now, the discharge calculation formula takes into account submerged condition.

Boutre is the main intake of the canal. The discharge at this point was previously calculated from a gate formula established from a scale model thirty years ago. On one hand the accuracy of this system has been improved by replacing the gate opening measurement. On the other hand, the operating staff decided to add at this point an ultrasonic flow meter located 150 meters (492 ft) downstream.

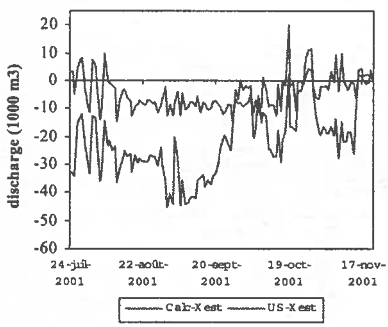
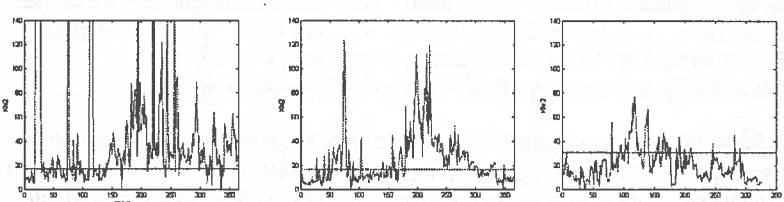



Figure 4:Boutre:deviation between measured and reconciled values

The calibration of this sensor happened to be hard due to backwater effect. Unexpectedly, the software established that the renewed method gives values closest to the reconciled ones. Figure 4 shows the ultrasonic-reconciled and formula based-reconciled discharge deviations. A new calibration of the ultrasonic sensor is now in progress.



(a) year 1999 (b) year 2000 (c) year 2001

figure 5: Evolution of the khi2 value

These previous examples illustrate the various improvements, which have been undertaken on the canal. As presented before, the global khi2 test is a valid indicator of consistency of measurements. Figures 5(a), 5(b) and 5(c) display the evolution of the khi2 values for the last three years, evidence of consistency enhancement is clearly seen in the consecutive graphs.

## Aix-Nord application

Figure 6 shows the Aix-nord network. It consists of two sub-networks the intakes of which are respectively the Saint Hippolyte pumping station (SHPS network) and the Saint-Hippolyte booster (SHB network).

SHPS supplies two reservoirs which feed pipe networks for agricultural and domestic users.

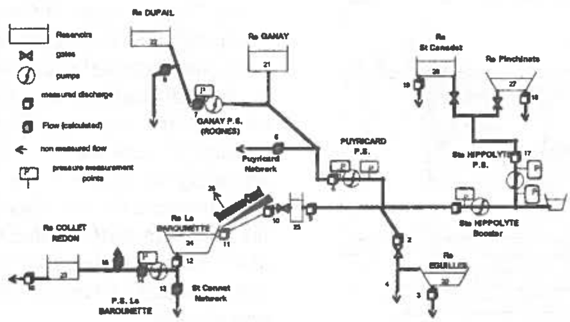



Figure 6:Aix-Nord network

The SHB net work is more complex. It includes pipe networks, pumping stations, reservoirs and the Trevaresse canal which behaves as a pure water transit delay.

In this case, the reconciliation software is automatically executed every fifteen minutes. This application requires to take into account the storage in canal and tanks, and the transit time of water along the canal. To avoid measurements noises, especially on level measurements, the reconciliation has been performed on an hourly basis (mean flow for the last hour, difference in stored volume for the last hour). The Aix-Nord application is running since July 2001. It automatically activates alarms on detection of abnormal situation.

In the following, three typical examples are described: an abnormal backward discharge when the Puyricard pumping station is stopped, the estimation of Saint Hippolyte booster discharge during a period of lack of information at that point, the detection of an abnormal increase of Eguille tank outflow.

Puyricard pumping station lifts the water into Ganay reservoir which supplies the Ganay pumping station. The Puyricard network is supplied with water at a position between Puyricard pumping station and Ganay reservoir. Discharges of the Puyricard and Ganay pumping station are measured by flow meters, a sensor measures the level in Ganay reservoir, whereas the Puyricard network discharge is not measured but deduced from other measurements. Figure 7 shows, when Puyricard pumping station is stopped, a deviation of 20 l/s between measured and reconciled discharge, before 9 January 2002. This was due to backflow measured by the flow meter and send to the supervisory system as pumped. The maintenance department corrected the flow meter configuration to eliminate backflow measurement and eliminated the source of error that caused the deviation mentioned above. The physical malfunction itself may come from leakage through exhaust valves, and the correction is now in progress.

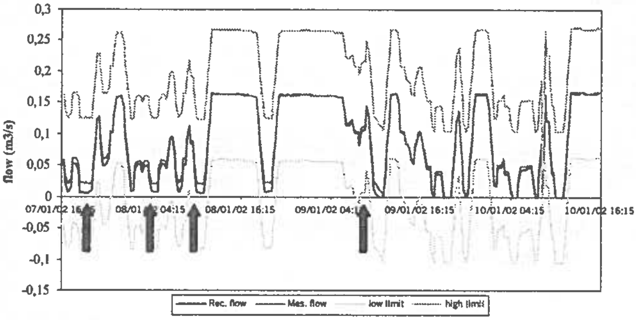



Figure 7:Deviation appearing in Puyricard site with no pump in operation

Because of renewing works, we haven't been able to measure the Saint Hippolyte booster discharge. As presented before the software has estimated this value using

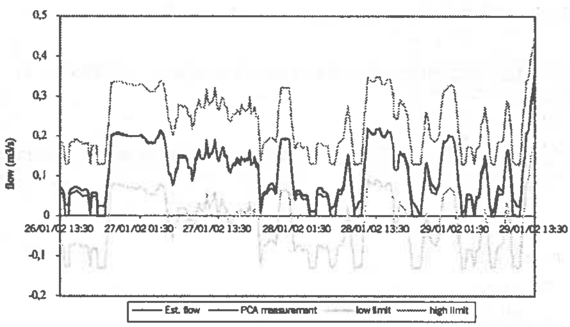



Figure 8: Reconciled values in absence of measurements

PCA method and reconciliation with the remaining measurements of the network. Figure 8 display the behavior of the reconciled values in absence of measurement, reconciled values are closed to initial calculated PCA values.

The software is able to detect abnormal variation in time of reconciled discharge. Particularly, the goal of this function is to alert the operator in case of a pipe breaking on the network. Figure 9 presents the trigger of an alarm on December 20th because of an abnormal increase of discharge flowing from Eguille tank Although on that day the discharge increase was linked to the filling of a pipe which had been emptied for maintenance reason, this confirms the effectiveness of that mode of detection.

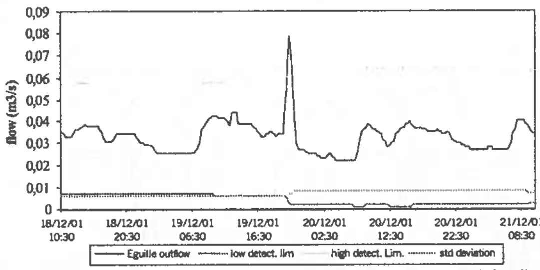



Figure 9:Abnormal time variation of Eguille flow

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