CRISIS MANAGEMENT IN WATER DISTRIBUTION NETWORKS

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Abstract. In this article, we present a strategy for managing crisis in water distribution network based on simulation and optimal control tools. First we give some details about the physical problem and the modelling hypothesis; then, we explain how the management of water network can be seen as a mathematical programming problem. Hence, we give an example of anticipating drinking water consumption and detecting network leaks. Optimising the management of a drinking water distribution network means planning how to use the different installations (treatment works, pumping stations, and valves) in order to convey water from many sources (rivers, borings, springs...) to supply areas, while minimizing operating costs (treatment and electricity). SAPHIR is a tool designed to help managers make decisions regarding the optimal operation of the water supply and distribution system. According to daily consumption estimates and operational constraints, SAPHIR calculates, over a 24 h period, volumes to be produced, flows to be transferred and changes in storage levels. Based on the SAPHIR principle, EMERAUDE is designed to monitor and control in real time all the equipment of the network.

Keywords: Drinkable water network, leaks in distribution networks, reservoir safety levels, network flow algorithms

1. Introduction

Classical approach for computing hydraulic networks is classically based on Hardy Cross method (Cross, 1936; Mays, 1999; Munson et al., 1998; Streeter et al., 1998; Viessman and Hammer, 1993; Harel, 1987). This approach requires iterations of

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the nonlinear flows-pressures system. The properties of the pipes (geometry and roughness) have to be well known and the computational time may be excessive for a huge network.

In this work, we are focusing on special types of networks. Their particular topology and their physical properties allow us to use simplified models. In fact, because of the small number of circuits in the graph and, also because we have the transient behaviour, we can consider only the conservation law (Kirchoff's law) in a strong sense and make an approximation about pressure. Then, we obtain a model based on flow network theory. In this context, the system management becomes a linear network optimisation problem (Fulkerson, 1961; Gondran et al., 1984). The methods of this kind have been originally developed for communication networks (Balakrishnan and Altinkemer, 1992), so is not classical in hydraulic engineering. Their performance is so good that we can use it in real time applications. This is the core of the package SAPHIR developed by CIRSEE and Laboratoire Roberval. However, we also need a tool for forecast consumption. For that, we have developed EMERAUDE software, which is based on Dynamic Programming (Barto et al., 1991), with a moving time window (for more details, see Loubeyre et al. [1991], Footohi et al. [1992], Kora et al. [1987]). Combined with EMERAUDE, SAPHIR can be used as a daily management tool to support system operators.

The most important application fields of SAPHIR are computer aided design, daily pumping scheduling, crisis management and future planning on the water supply and distribution systems. The aim of all optimisation studies is to identify potential savings and to find technical improvements (partial automation, tariff modifications...). It can also be utilised to define and schedule maintenance work and evaluate their consequences on the supply management. Furthermore, in this article, we show how SAPHIR can simulate and anticipate crises situations.

2. Problem Formulation

To establish the mathematical model of the water supply and distribution system, a functional schematic is defined. Containing only operator controllable components (valves, pumps, main reservoirs) and based on available technical data, this schematic includes some hydraulic simplifications. Figure 1 shows an example of an established schematic for a small system.

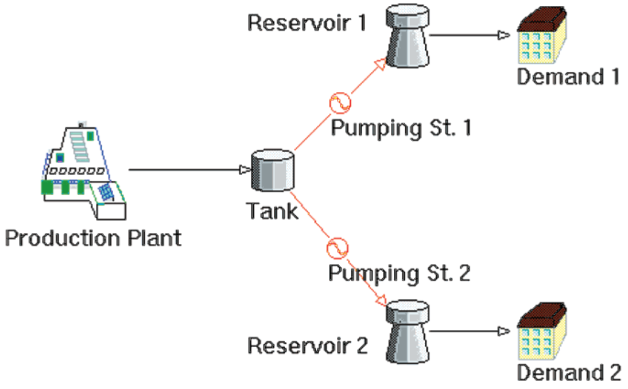


Figure 1. A simple water distribution system

The functional schematic of the water distribution network can be represented by graph where nodes are productions sites, reservoirs or demand areas, and arcs are pumping stations, valves or transfers (Fig. 2).

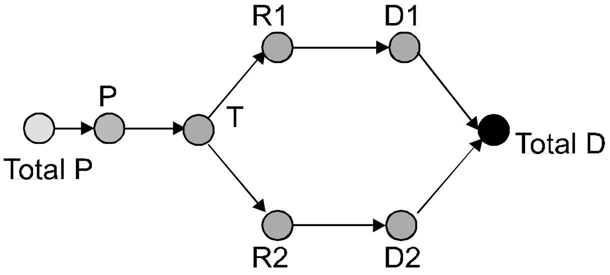


Figure 2. Graph representing the supply system

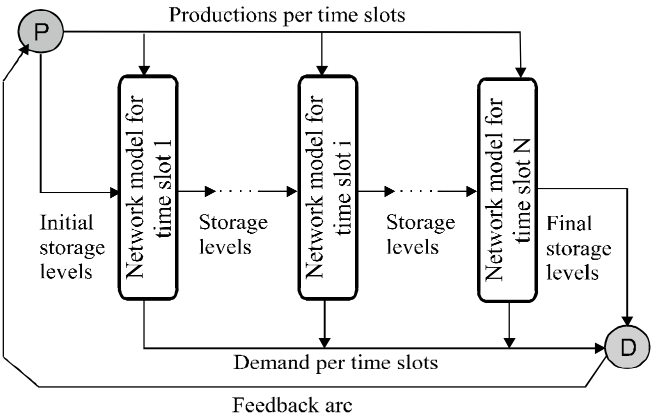


Figure 3. Global graph of the network

In order to represent the water storage on reservoirs and system demand charges during the day, this graph is deployed over 24 time periods. Figure 3 shows the construction and principal of the new graph. Some supplementary nodes and arcs are added to respect mass balance at each node over time.

Finally, the optimal scheduling can be formulated as follows: (problem P)

$$Min \sum_{u \in U1} \alpha_u(\varphi_u)\varphi_u + \sum_{u \in U2} \alpha_u(\varphi_u - \overline{\varphi}_u)^2$$

$$\begin{cases} \forall u \in U, & b_u \le \varphi_u \le c_u \\ \forall i \in X, & \sum\limits_{u \in U^+(i)} \varphi_u = \sum\limits_{u \in U^-(i)} \varphi_u \end{cases}$$

$$U_1 \bigcup U_2 = U$$

$$U_1 \bigcap U_2 = \Phi$$

where X are the nodes and U are the arcs on the graph. U_1 contains piecewise linear cost arcs such as productions, pumps and transfers. U_2 contains quadratic cost arcs used to match final levels of reservoirs. The constraints represent the boundary flow limits on the arcs and the conservation laws on each node. The main difference between our approach and the classical network analysis methods, is that we do not determine system pressures. These are taken into account by using constraints applied to the flows and volumes. On the other hand, we also assume that reservoirs levels do not have a significant influence on transfer flows. In real operations mode, this approximation is acceptable according to demand forecast accuracy.

3. The Solver

The problem (P) is resolved using a primal dual-method, the "Out of kilter" algorithm (Bertsekas, 1991; Edmonds and Karp, 1972; Minoux, 1984). This method was adapted to piecewise linear and quadratic cost functions in order to take into account non-linear pumping costs. As the calculation algorithm has a polynomial complexity, the response time is satisfactory, which allows SAPHIR to be used on large distribution networks.

3.1. THE OUT OF KILTER ALGORITHM

For simplification, we present the method in the case of the standard minimum cost flow problem: find the vector $\varphi = (\varphi_u)_{u \in U}$ which minimizes the cost function $J(\varphi)=\sum_{u\in U}\alpha_u\varphi_u$ (1) under the conservation constraints $\sum_{u\in U^+(i)}\varphi_u=\sum_{u\in U^-(i)}\varphi_u$ (2) for every node $i\in X$ and the bound constraints $\forall u\in U$, $b_u\le\varphi_u\le c_u$ (3).

$$Min\sum_{u\in U}\alpha_u\varphi_u$$
$$\begin{cases}\forall u\in U, & b_u\le\varphi_u\le c_u\\ \forall i\in X, & \sum_{u\in U^+(i)}\varphi_u=\sum_{u\in U^-(i)}\varphi_u\end{cases}\tag{1, 2, 3}$$

The α_u coefficients correspond to the unitary cost flow on the arc u.

If we introduce A, the convexity node-arc matrix, b (respectively c) the lower bound vector (respectively upper bound) vector associated to φ, α the costs vector, the problem (1, 2, 3) becomes:

$$Min\ \alpha^T\varphi\tag{4}$$
$$b\le\varphi\le c,\tag{5}$$
$$A\varphi=0\tag{6}$$

The linear program (4, 5, 6) has a unique solution (Gondran et al., 1984). If we note τ, the Lagrange multiplier associated to the conservation constraints (6), then τ is solution of the dual linear program (7, 8, 9, 10)

$$\tau A-\lambda+\mu\le\alpha^T\tag{7}$$
$$\lambda\ge 0,\tag{8}$$
$$\mu\ge 0\tag{9}$$
$$Max\{-\lambda c+\mu b\}\tag{10}$$

where λ and μ are the Lagrange multipliers associated to the bounds constraints (5).

For any vector τ, let be v and w, vectors associated to the arcs such that

$$\alpha_u<[\tau A]_u\Rightarrow\left(\left(v_u=\alpha_u-[\tau A]_u\right)\wedge w_u=0\right)$$
$$\alpha_u>[\tau A]_u\Rightarrow\left(\left(w_u=\alpha_u-[\tau A]_u\right)\wedge v_u=0\right)$$
$$\alpha_u=[\tau A]_u\Rightarrow\left(w_u=0\wedge v_u=0\right)$$

Then, we have, in any case, $\alpha - \tau A = v - w$ and, if φ is a flow vector such that (6) occurs, then
$\alpha^T \varphi = v^T \varphi - w^T \varphi$.

If φ verifies (5), and thanks to the fact that v and w are nonnegative, then $\alpha^T \varphi \geq v^T b - w^T c$.

Hence, if φ satisfies (5) and (6) and τ is such that $\alpha^T \varphi = v(\tau)^T b - w(\tau)^T c$, then φ is an optimum flow for the problem (4, 5, 6). The existence of the couple (φ, τ) is a consequence of the complementary slackness theorem.

We can also write $0 = \alpha^T \varphi - \left(v^T b - w^T c\right) = v(\varphi - b) + w(c - \varphi)$. Then, if we introduce the tension vector by $\theta = \tau A$, the optimality conditions can be expressed, for the couple (φ, θ):

$$\alpha_u < \theta_u \Rightarrow \varphi_u = c_u \tag{11}$$

$$\alpha_u > \theta_u \Rightarrow \varphi_u = c_u \tag{12}$$

$$\alpha_u = \theta_u \Rightarrow b_u < \varphi_u < c_u \tag{13}$$

When the couple (φ_u, θ_u) verifies (11, 12, 13), we say that the arc u is **in kilter**. The out of kilter algorithm consists of:

(0) initialise (φ, θ)*;*
(1) while there exists an arc u out of kilter repair(u);

The procedure repair(u) modifies (φ, θ) such that u is in kilter and preserves the conformity of the others arcs. It is based on Minty's lemma (for more details, see Edmonds and Karp [1972]). The most important property is that it works in polynomial computational time. The extension to a quadratic cost function is easy.

4. General Software Description

A water distribution network is composed of different installations. Raw water coming from various sources is treated at treatment plants. It is conveyed through pipes by gravity, or by using pumps, to storage reservoirs to meet user demands.

The main objective of water distribution managers is to satisfy all supply area demands, to respect water quality standards and to reduce the operating costs.

Optimal operation should take into account the variations in electricity costs at different moments in the day as well as the treatment costs of each plant and the energy consumption of each pump. On the other hand, operational constraints such as minimum and maximum reservoir water levels, maximum power demands and maximum flow rate variations, must be respected.

In order to improve the operation performances, Lyonnaise des Eaux had developed two optimisation tools for the production and distribution management.

SAPHIR is an off-line system that assists managers in making better decisions regarding optimal scheduling on the distribution network. It calculates production and pump volumes and reservoir levels over a 24 h period, according to the daily demand forecast.

EMERAUDE is an on-line real time control system. Using the last updated water demand forecast and the state of the water network, EMERAUDE calculates the best pumping strategy and sends the controls to the process (Fig. 4).

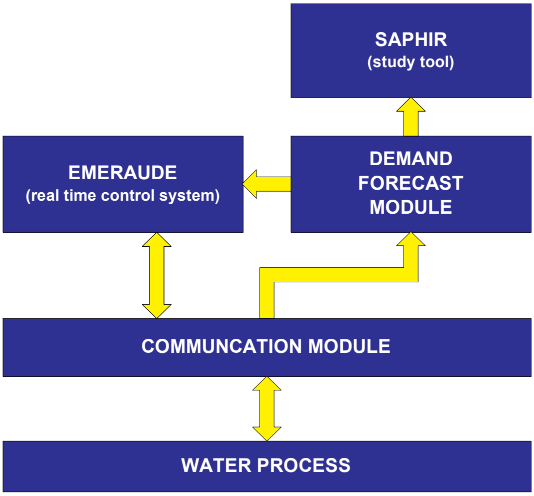


Figure 4. EMERAUDE and SAPHIR main components and process

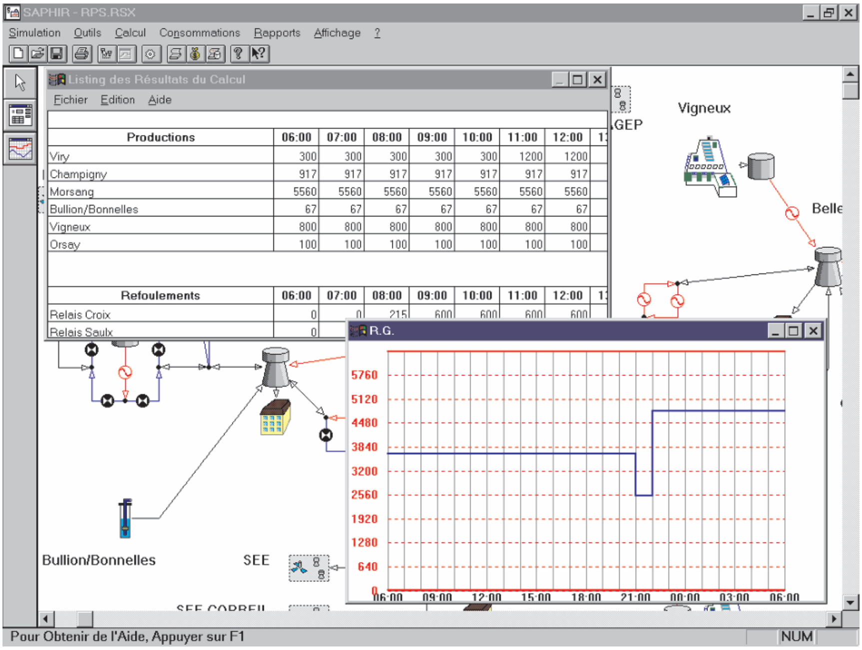
4.1. SAPHIR

4.1.1. *Overview*

SAPHIR is organized in two main modules: the editor and the simulator. The editor program is used to define the network functional schematic and to describe specific system characteristics. The simulation program allows users to enter constraints related to real situations and to develop optimal production and pump scheduling.

Figure 5 shows SAPHIR input and output data: the horizontal entries represent static data and are entered into the editor program while the vertical data change from day to day and are entered through the simulation program.

Figure 6 shows the various steps involved in the editor and simulation programs.



Productions	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Viry	300	300	300	300	300	1200	1200
Champigny	917	917	917	917	917	917	917
Morsang	5560	5560	5560	5560	5560	5560	5560
Bullion/Bonnelles	67	67	67	67	67	67	67
Vigneux	800	800	800	800	800	800	800
Orsay	100	100	100	100	100	100	100

Refoulements	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Relais Croix	0	0	215	600	600	600	600
Relais Saulx	0						

Figure 5. SAPHIR Simulator and results

4.1.2. *Network Description*

The functional schematic of the network is described via the editor. Using a graphical user interface, the operator constructs the network model by first setting network nodes (treatment plants, boreholes, reservoirs, demand areas) and next by linking the nodes with arcs (pipes, pumps and valves).

Each element is then described by the user who enters specific system design data (reservoir volumes and surface areas, pipe capacities...), operational constraints (reservoir minimum and maximum levels, maximum flows in accordance with each electric tariff period,...) and information concerning management criteria (electricity tariffs, energy consumption per pumping rate,...). Furthermore, data modifications and file facilities are available during the editing session.

Figure 7 shows the editor screen: the network schematic is displayed in the background and the editor window in the foreground concerns the pumping station configuration.

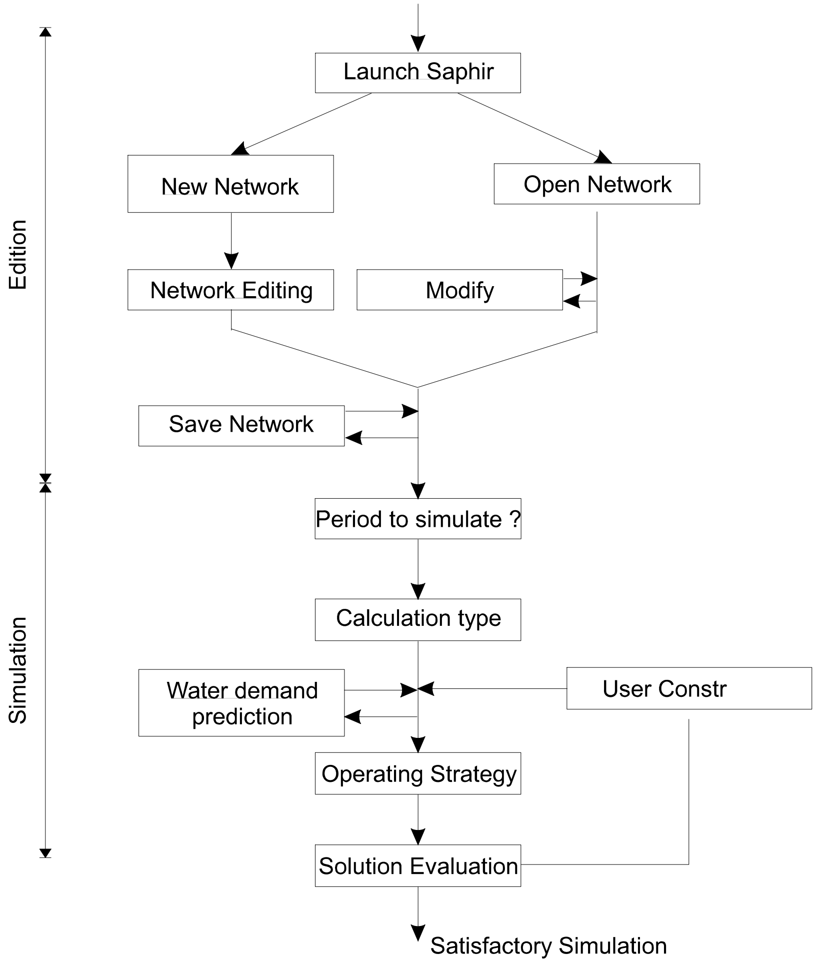


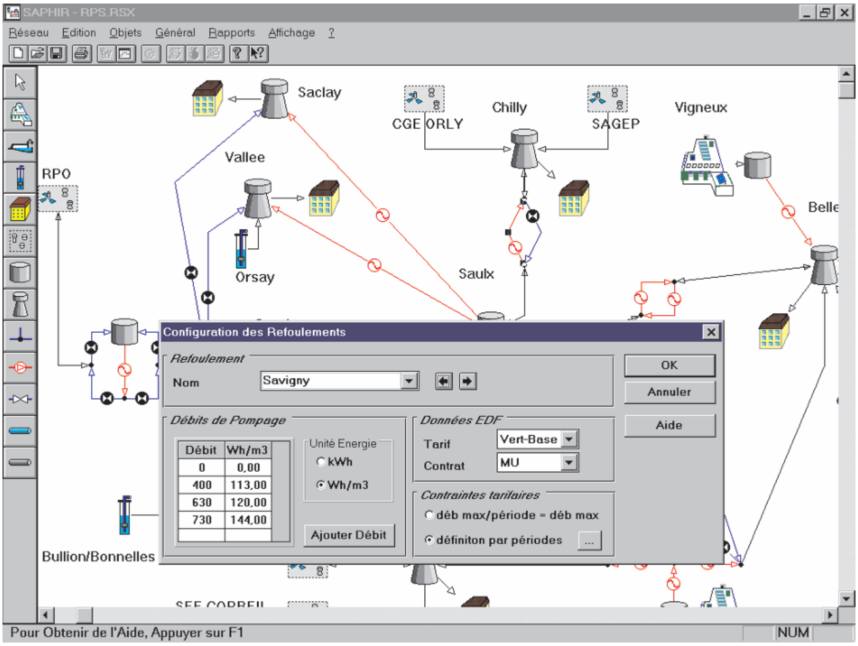
Figure 6. Utilisation schematic

4.1.3. *Defining a Network Situation*

During this phase, the operator enters management constraints and other data in order to define a specific system situation:

Electric tariff periods
Consumption estimates
Additional operating constraints
Initial reservoir levels

The consumption estimates might be set either by the user or could be retrieved from available text files. These files can be generated by an demand



Nom: Savigny

Débit	Wh/m3
0	0,00
400	113,00
630	120,00
730	144,00

○ kWh
● Wh/m3

Tarif: Vert-Base
Contrat: MU

○ déb max/période = déb max
● définiton par périodes

Figure 7. SAPHIR Network Editor

forecast system or by SCADA. Facilities are also provided to retrieve actual reservoir levels for use in the simulation.

Operating constraints, such as component unavailability are entered using the simulator dialogue box.

4.1.4. *Optimisation*

Once the network situation is defined, the user runs the simulator program which calculates the optimum solution for the daily schedule. The calculation takes into account the operating costs and user defined constraints and safety criteria. When a crisis situation is detected by the program, SAPHIR provides information regarding the absence of water per demand point.

Two types of calculation are available:

Daily profile: SAPHIR will find a cyclic operating strategy: initial and final reservoirs levels are calculated by SAPHIR, the objective is to maintain the same reservoir levels at the initial and final stages from day to day.

Follow-up: Users entered into SAPHIR initial and final target reservoir levels. This mode is useful for adapting the programmed schedule to the real situation.

Several outputs are provided to facilitate interpretation and exploitation of optimisation results:

A summary of information such as total production and consumption on the network, treatment and electricity costs

Detailed listings describing the management schedule hour by hour and over 24 h

Analysis listings containing detail information on economic costs

Result curves per system component

Figure 7 shows the calculation results presented on the simulator program screen with typical 24 h pump operation.

4.1.5. *Application Fields*

SAPHIR's most important fields of application are optimisation studies, daily pumping scheduling, crisis management and future planning on the water supply and distribution system.

The aim of all optimisation studies is to identify potential savings and to find technical improvements (partial automation, cost modifications ...).

Combined with a demand forecast system, SAPHIR can be used as a daily management tool to support system operators.

It can also be utilised to help define and schedule maintenance work and evaluate their consequences on the supply management. Furthermore, SAPHIR enables the user to simulate and anticipate crisis situations.

4.2. EMERAUDE

EMERAUDE is a real time system designed to optimise the water network management. It has two main modules:

A water demand forecast (WDF) module. This forecast is auto-corrected in real time, according to the real demand.

An optimisation module which uses the latest updated forecast and computes the best pumping strategy.

An communication module which makes the connection with the water network.

4.2.1. *Water Demand Forecast System*

The goal of this module is to predict the daily consumption curve for each specific consumption site. The calculation of the forecast is performed in two steps:

A initial prediction for the entire day is calculated at the beginning of the day (generally at 4 a.m.).

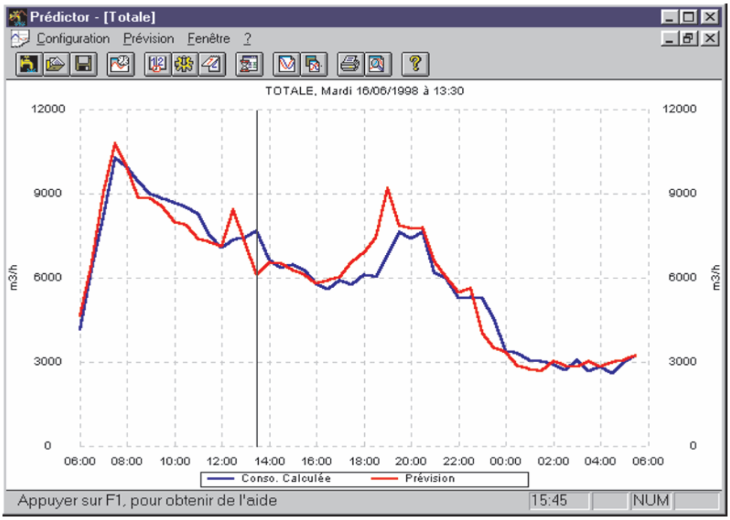
The forecast is corrected every a quarter of an hour according to the observed water demand.

The first step of the water demand calculation is based on recent historical data (last 2 weeks). A choice of possible prediction methods is proposed and they are chosen according to the specific demand of each site:

An Artificial Neural Network method

Simple Statistical Methods (using the demand of the previous day, day-14, day-7 and day-8)

The second step concerns the real time correction of the original forecast. The prediction module is connected with the state process and calculates in real time the observed water demand. The system analyses errors made and computes a new water demand forecast using a least squares method. The new demand forecast is calculated as a linear combination of independent shape functions defined over a 24 h interval. The principal is based on the fact that consumption curves for each day of the week have a particular shape. Consumption curves for Sundays are different from those on Saturdays. For a fixed day (i.e. Saturday) consumption peaks occur at same instant but with a different amplitude. Everyday, the water demand module constructs, from the previous weeks, the typical profile of the day concerned. Shape functions are based on a calculated typical profile. Demand forecast are then auto-corrected every 15 min, according to errors recorded on the previous forecast. Figure 8 shows an EMERAUDE WDF screen where readers can distinguish between real and predicted consumption.



Appuyer sur F1, pour obtenir de l'aide

Figure 8. EMERAUDE’s WDF screen

4.2.2. *Optimisation System*

The goal of the optimisation module is to produce an optimal scheduling for all main equipment.

With the latest update forecast and the real state of the water network (pump and reservoirs availability), it calculates the best pumping strategy and sends the controls to the process through the communication module.

Every hour, EMERAUDE reconstructs its pumping strategy according to the real state of process.

Monitoring in real time all main equipment (pumps availability, reservoirs level,...), EMERAUDE can decide to start a non-planned optimization if important malfunctions occur.

The Optimisation system shows what it has done and the scheduled pumping strategies.

Figure 9 shows the Morsang sur Seine treatment plant where EMERAUDE was first installed.

Figure 10 represents the Optimisation module's interface where a pumping strategy for a treatment plant with three pumping stations and their associated tank levels are shown.

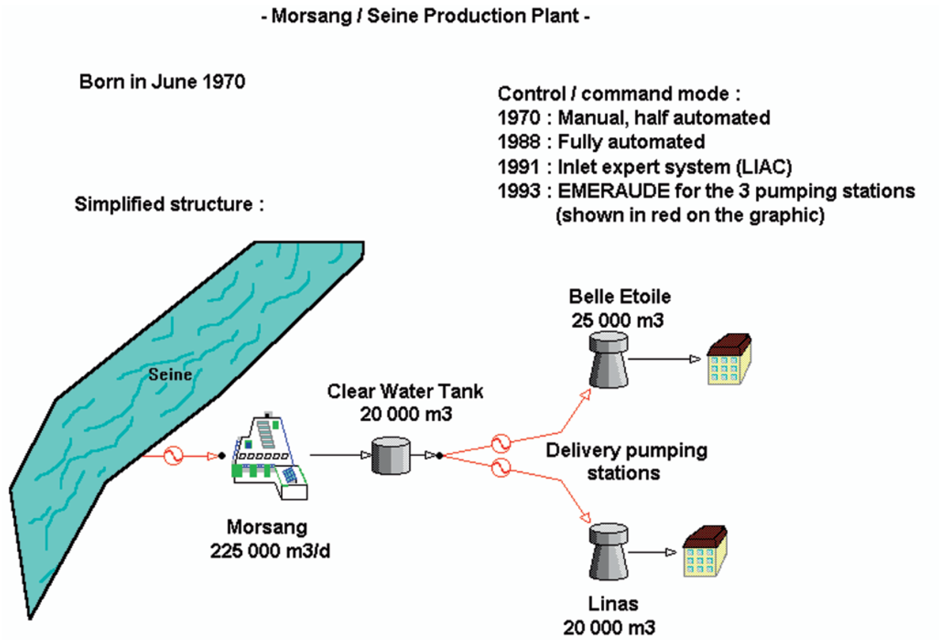


Figure 9. The Morsang sur Seine water treatment plant

Also, EMERAUDE respects the following operational constraints:

Water demand

Minimum and maximum reservoir levels

Maximum power demand

A maximum number of flow variations

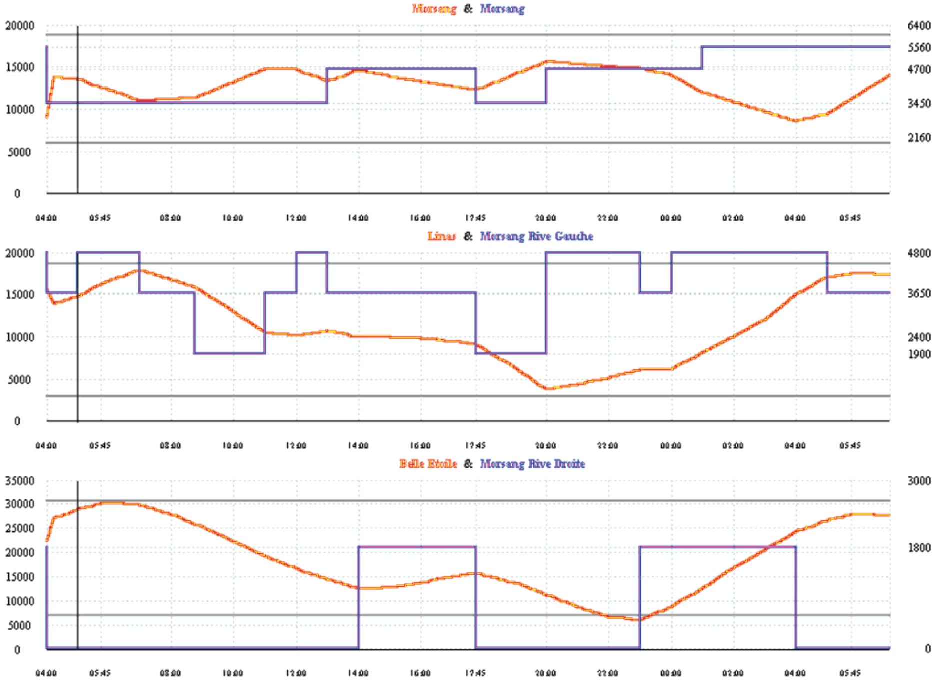


Figure 10. EMERAUDE's graphical interface

Additional constraints are taken into account on the sites where EMERAUDE is installed.

4.2.3. *Method*

The calculation algorithm is a mix of dynamic programming and branch and bound algorithm. The first step is the linear programming algorithm that runs to impose limit conditions on the second step. The branch and bound algorithm solves the optimising problem with discrete variables and equations.

We use this method to reduce the complexity of problem and to have discrete solutions for the schedule of all the equipment on the water network.

In the second step, the hydraulic model is the same as in the SAPHIR tool.

The cost function, used in both steps, takes into account the treatment cost, the electric costs and flow variation penalties. The treatment cost concerns the chemical and biological products used during the treatment process. The electric cost concerns the pumping stations. The unit cost varies during the day and the cost coefficients vary during the year.

4.2.4. *User Intervention*

EMERAUDE is a autonomous system and works without human interventions. But the user can interact with EMERAUDE as follows:

Schedule events on the network like works on pump units (all pumps are stopped), an objective level on a reservoir, decrease the maximum power demand

Indicates an availability of a pump or a reservoir

Schedule a wholesale draft

4.2.5. *Managing Malfunctions*

The following sub-sections describe some of the activities handled by EMERAUDE concerning events that need corrective actions or a new schedule.

When a communication failure comes up, EMERAUDE supposes that the equipment (pumping station, borehole, valve) works in the same way as before the communication failure. It supposes that the PLC will respect the constraints of the electrical contracts. If the communication failure concerns a reservoir, this reservoir is considered unavailable by EMERAUDE.

Any fault in a pump unit might affect the current schedule. If the faulty pump is essential for the execution of the control, EMERAUDE finds a new schedule for the new state of the water network.

The reservoirs levels are carefully followed to avoid violation of the minimum and maximum limits which assigned to each reservoir or tank. EMERAUDE takes a corrective action when such a violation occurs.

In such system, the reservoir level is very important. If a fault in the level measure occurs, EMERAUDE thinks that the reservoir is unavailable and works with the other reservoirs on the network.

When EMERAUDE sends a control to a pump, it verifies the result. If EMERAUDE can’t control the pump, it fixes the pump scheduling until the problem is corrected.

4.2.6. *Communication Module*

The communication module makes the connection of the “Water Demand Forecast module” and the “Optimisation module” with the process.

At the moment, this module can communicate with the TOPKAPI SCADA system, the SDG system (a data server) and with other systems which can discuss in MODBUS protocol (PLC for example). EMERAUDE can be adapted to other type of SCADA system or data servers.

5. An Example of Crisis Management

5.1. NETWORK DESCRIPTION

Saphir's objective is to provide survey engineers and dispatchers with the necessary resources so they can formulate an optimal **daily** strategy for managing a network.

Saphir takes into account structural data which do not change over time and which characterise a water network, and temporary and event-based data which describe a particular network situation.

Saphir provides the following output data:

Management strategy: The volumes to produce, the flow rates to transfer and pump, the levels of reserves for a day and **on an hourly basis**.

Missing water: The quantity of water to supply to a demand site in a crisis situation, in order to keep the supply reservoir at 0 level and meet demand. Water shortages constitute criteria for assessing the seriousness of a crisis situation or a situation subject to reduced output.

The operating costs: Saphir provides the treatment and pumping costs for the strategy calculated.

In addition, when the user makes a request, Saphir can:

Display the results curves for each element in the network

Display and print out detailed reports regarding the results and the costs

5.1.1. *Network Element*

The network model is constructed by using the following icons corresponding to a well-defined network element.

Treatment plant

Borehole

Demand zone

Reservoir

Connection point

Water source

Pumping station

External network

Tower

Transfer

"Treatment" is the term used to refer to plants, sources and boreholes. "Storages" refers to towers and reservoirs.

5.1.2. Network Description

Our network model is similar to a real one. However, the electricity or treatment costs and some other characteristics are changed for our simulations purposes.

The water network that will be considered in our simulations is composed of three main treatment plants and three boreholes. The most important treatment plant is Station 3 whose daily maximum capacity is 225,000 m^3.

Production name	Electricity tariffs	Electricity contracts	Treatment cost (/m^3)	Daily capacity (m^3/day)
Station 1	Vert-Base	LU	12.7	48,000
Station 2	Vert-Base	LU	10.4	96,000
Station 3	**Vert-Base**	**TLU**	**9.97**	**225,000**
Borehole O	Vert-Base	TLU	0.5	2,400
Borehole C	Vert-Base	CU	0.9	22,008
Borehole B	Vert-Base	TLU	0.5	1,608

The storage elements (tower and reservoirs) are composed of seven reservoirs and five towers.

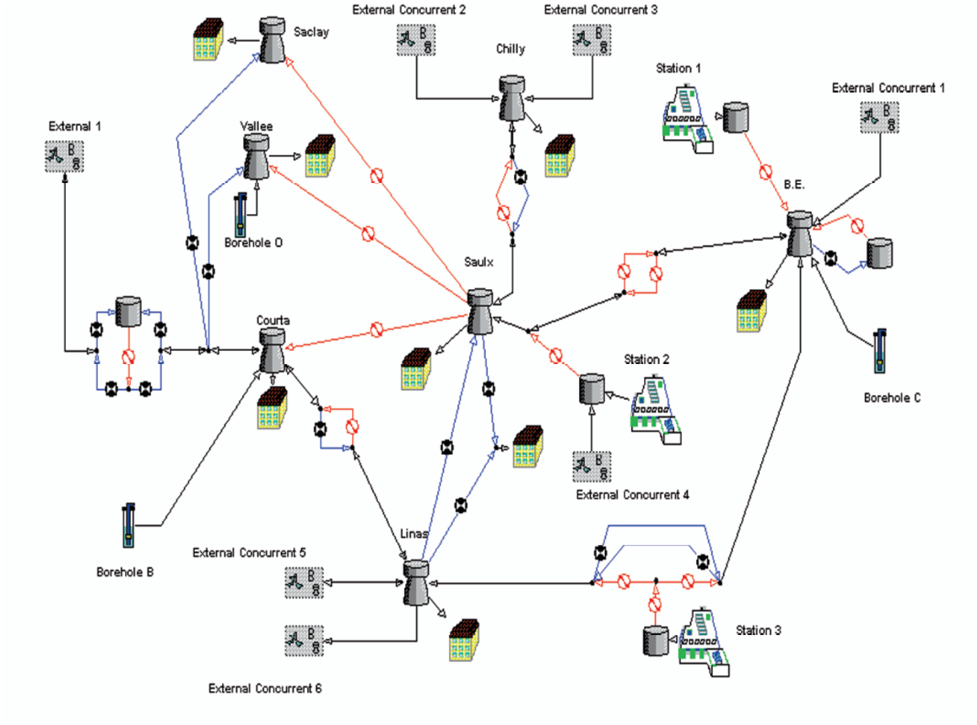
Reservoirs and towers	Security level (m)	Max (m)	Useful Volume (m^3)
Courta	4	8	**2,000**
Saulx	1	7.8	**19,550**
Linas	1.5	8.2	**15,075**
B.E.	1.5	5.65	**22,144**
Vallee	2	6.5	**5,693**
Saclay	2	4.8	**1,806**
Chilly	3	7.8	**2,016**
Croix du Bois	3	7	**5,600**
Tower 3	2	4.5	**10,000**
Tower 2	1.18	2.7	**3,861**
Tower 1	1	3	**4,000**
Extension BE	1	6.6	**7,095**

Owing to the useful volume, we can optimise the electrical costs. The treatment plants and the pumping stations will work in priority during the low electrical cost periods. Of course, the surplus production capacity depends essentially on the storage capacities of the towers and reservoirs.

The electrical costs in our simulations are calculated in function of the tariffs used by EDF (Electricité de France). According to those electrical tariffs, the prices from 22:00 to 6:00 are less than during the rest of the day for each period. It means that the production during this period of the day is optimal in financial terms

All our simulations are made upon a 24 h period. In order to make possible the comparisons between our simulations, we suppose that at the end of a simulation; the storage elements of the network must have the same capacity as at the start of this simulation.

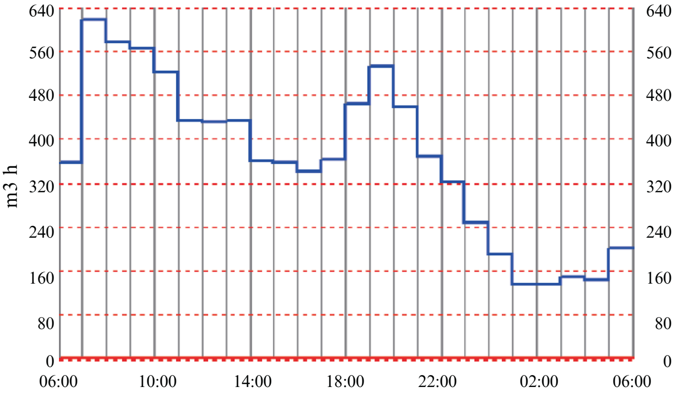
The model and the network elements are represented in the following scheme:



Since the network looks like a graph, we will call pumping stations, valves, transfers and connections "*arcs*", and the other entities "*nodes*".

5.1.3. *Demand profile*

In these simulations, the demand profile considered for each demand zone is the following one:



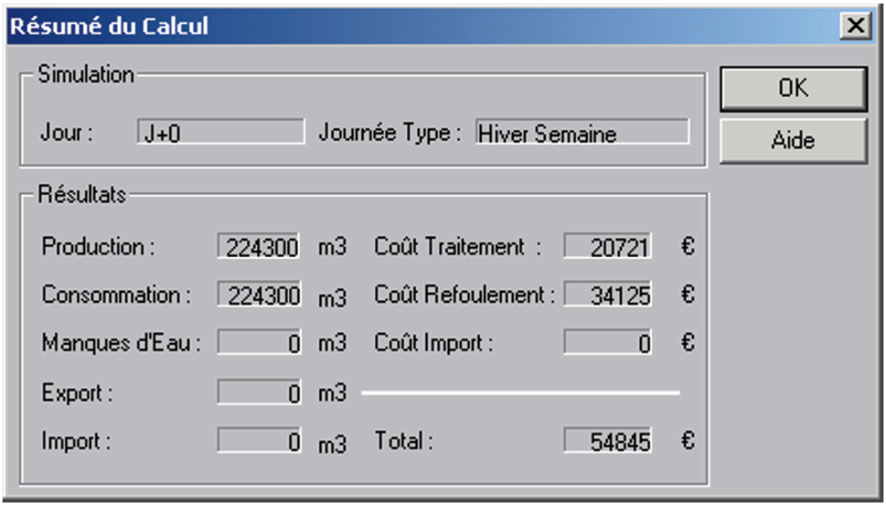
However the user can retrieve demand data from files or can change them manually.

5.2. SIMULATIONS

Our simulations are based on a 24 h period (daily period). On a **daily profile simulation,** the system looks for a management profile for the situation defined. The objective is to fulfil demand, with a minimal economic cost, without loss of volume (initial levels on day D + 1 = initial levels on day D). We use this type of calculation to find a cyclic strategy for managing the network.

5.2.1. *Normal Simulation*

The summary results of this simulation (treatment and electricity costs, demand and production as well as water insufficiencies) are given in the following image:



Simulation

Jour : J+0 Journée Type : Hiver Semaine

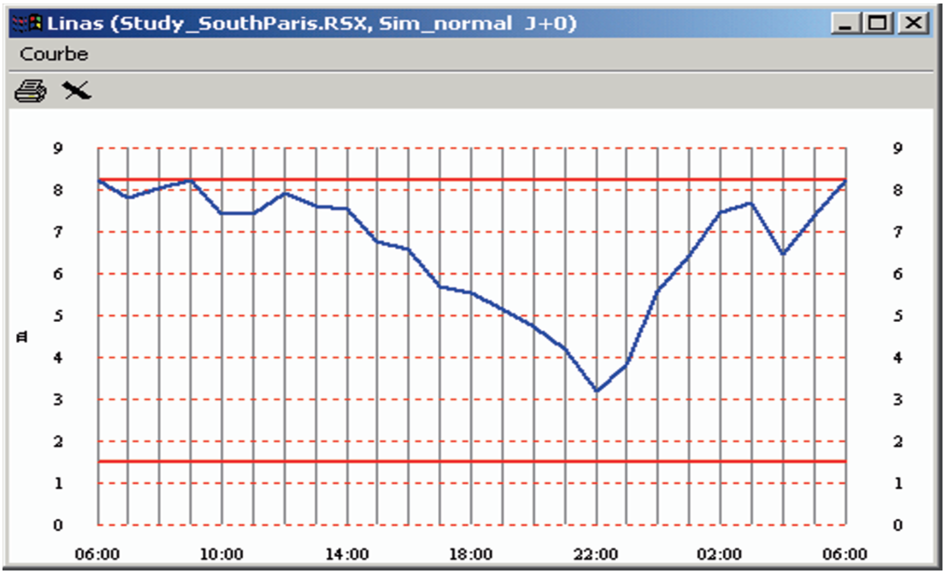
Résultats

Production :	224300 m3	Coût Traitement :	20721 €
Consommation :	224300 m3	Coût Refoulement :	34125 €
Manques d'Eau :	0 m3	Coût Import :	0 €
Export :	0 m3		
Import :	0 m3	Total :	54845 €

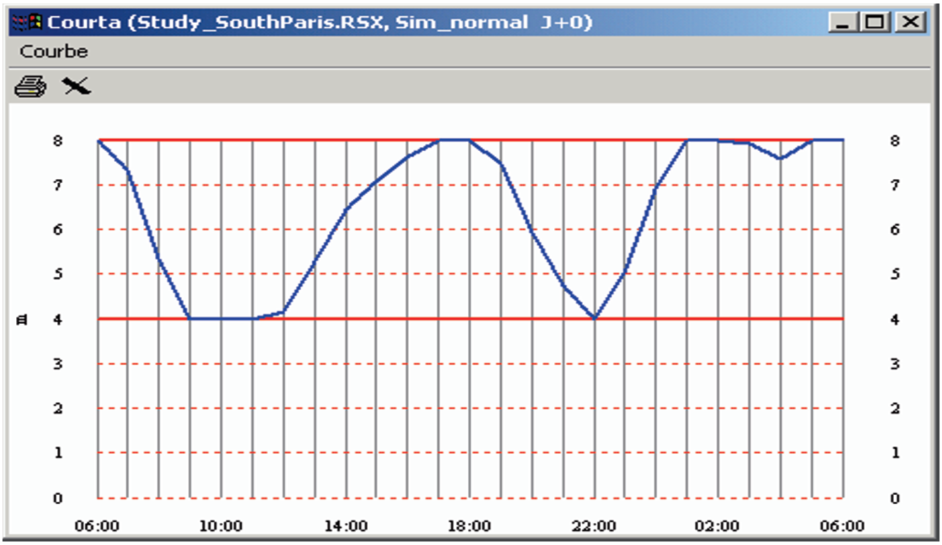
Summary results of the simulation

We remark that there are no water insufficiencies (missing water) in our simulation.

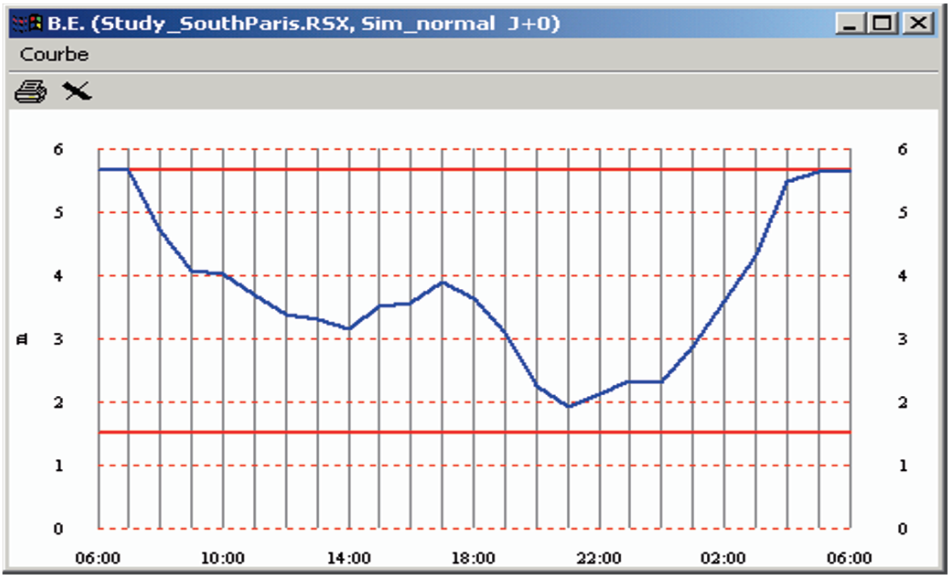
Moreover, all the storages behaviour (see images below) show that they are filled up during the less electricity costs hours. The minimum level is reached always at 22:00.



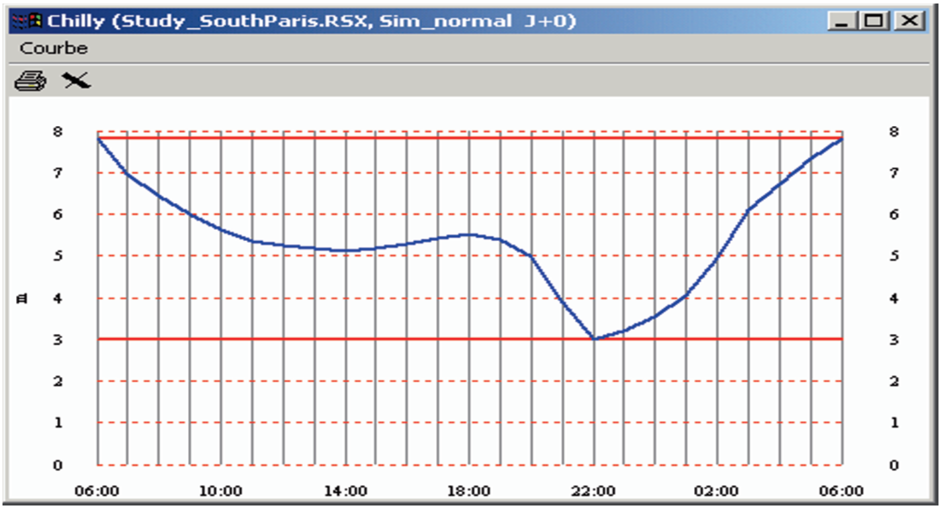
Linas Tower level during the 24-hours simulation



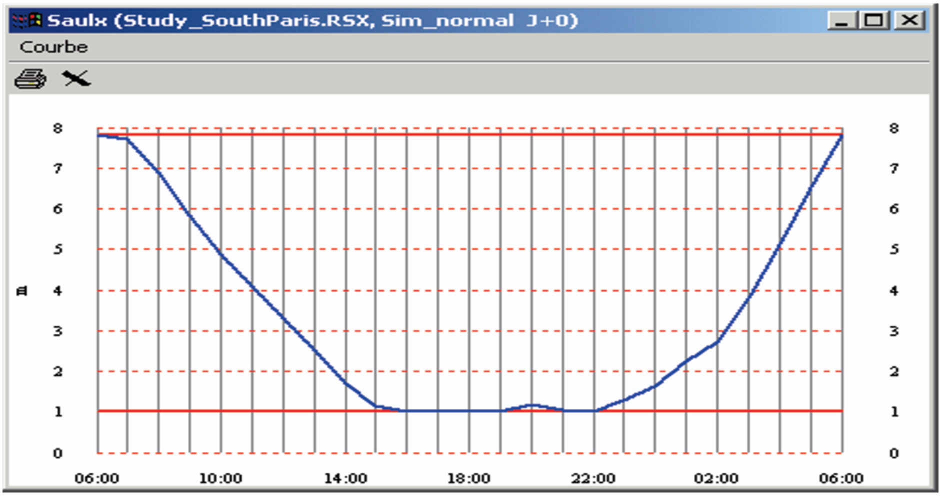
Courta Tower level during the 24-h simulation



B.E. Tower level during the 24-h simulation

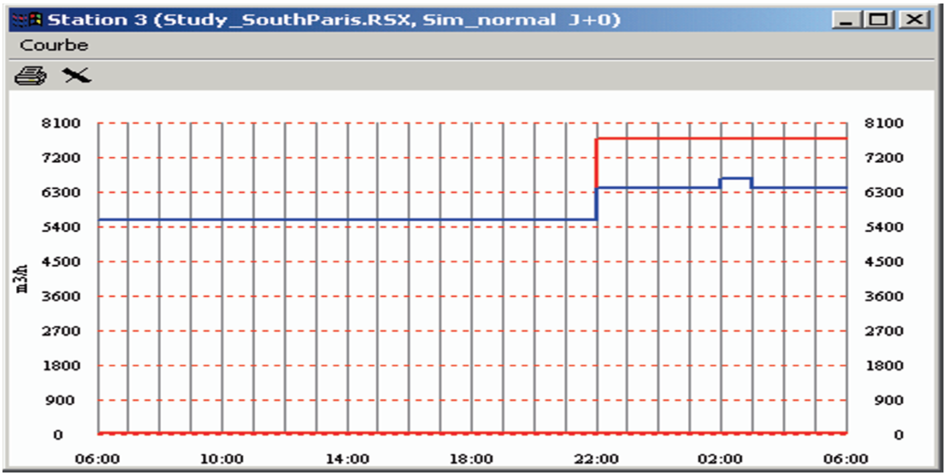


Chilly Tower level during the 24-h simulation

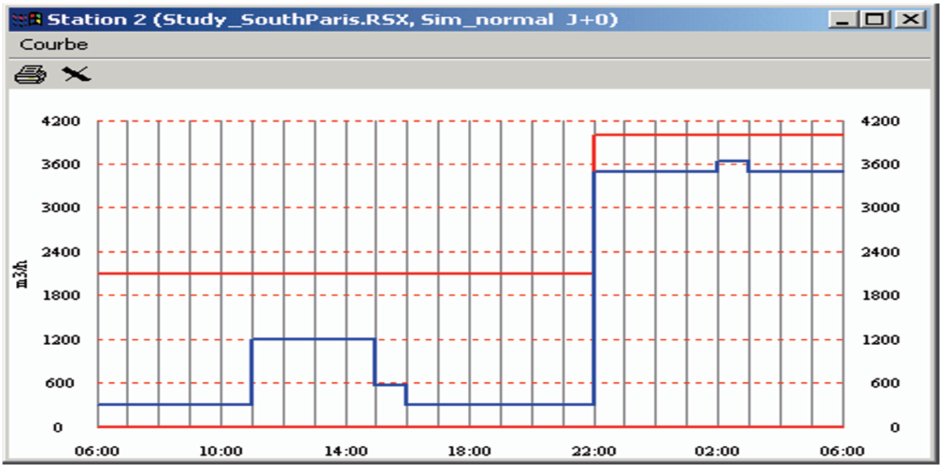


Saulx Tower level during the 24-h simulation

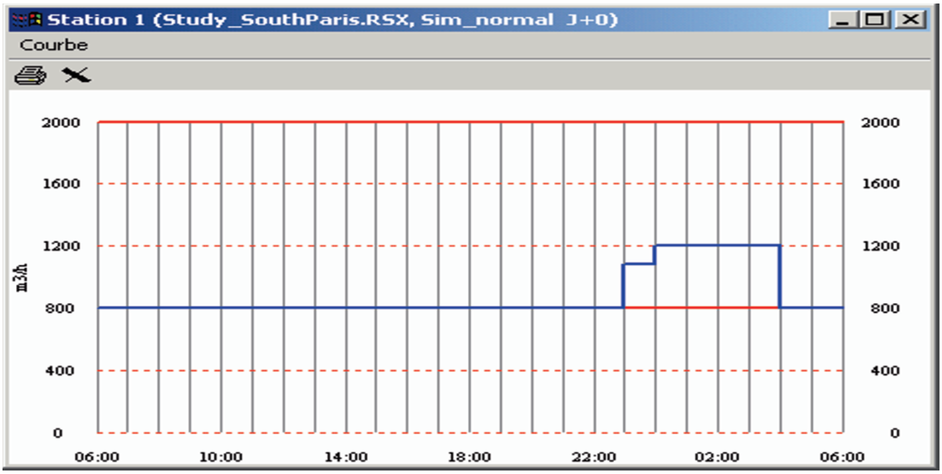
On the other hand, all the treatment plants (see graphics of the treatment plants) show that the capacity per hour during the less electricity cost hours (22:00 to 6:00) is greater than for the rest of the day.



Station 3 production (m^3/h) during the 24-h simulation



Station 2 production (m^3/h) during the 24-h simulation



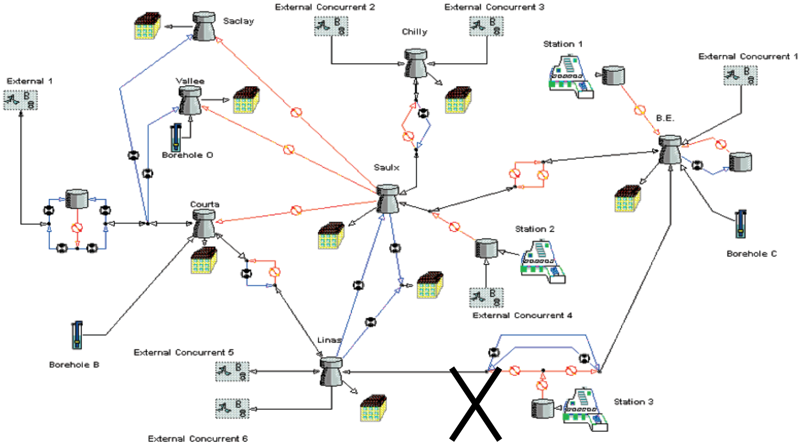
Station 1 production (m^3/h) during the 24-h simulation

5.2.2. *Out of Order Simulation*

The following are a few examples of out of order cases that can be studied:

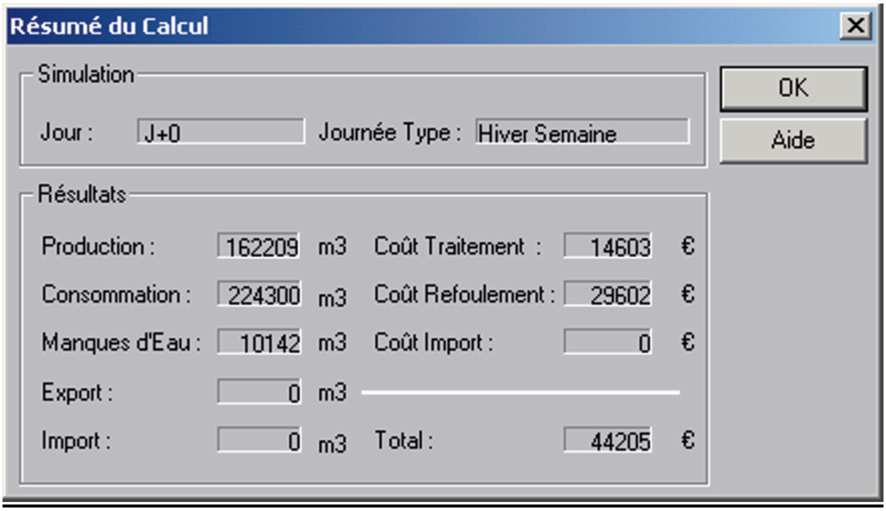
- Shut-down of a plant from H+0 to H+5.
- Washing one of the compartments in a reservoir for a day: the reservoir's effective volume divided by 2 in the description of the associated event.
- The limitation of pumping flow rates due to a pump breakdown: instead of flow rates of 0, 1,000, 2,000 and 3,000 m^3/h, you can set a maximum flow rate of 2,000 m^3/h for the duration of the event.

In our case, we have considered the most important water treatment in the network. We have supposed that the pumping on the left side of Station 3 is broken down. Thus there is no more possibilities to send water on the left side of this treatment plant.



The pumping station on the left side of the Station 3 is broken down.

The summary results of this simulation is given in the following image:



Résumé du Calcul

Simulation

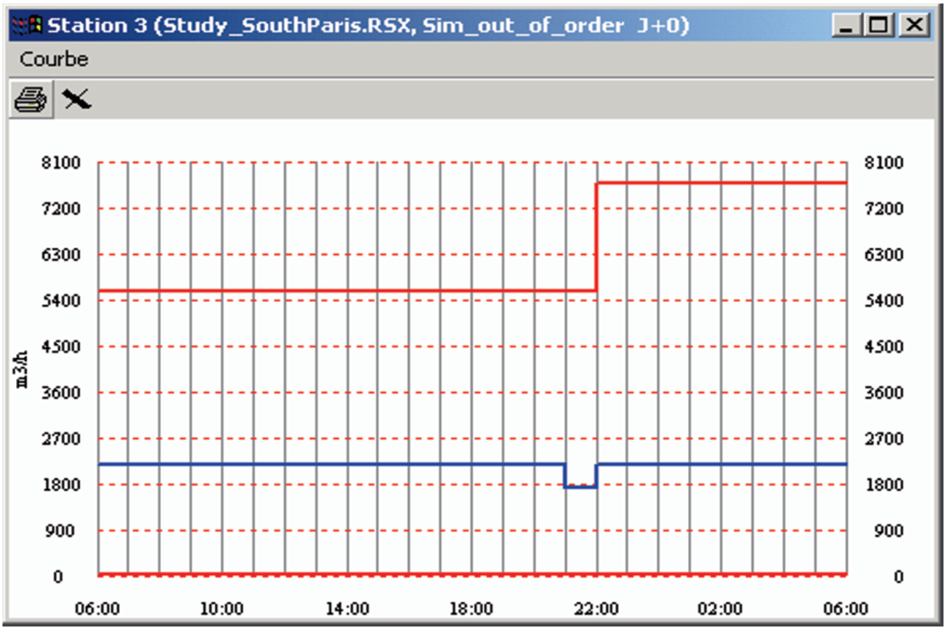
Jour : J+0 Journée Type : Hiver Semaine

Résultats

Production :	162209	m3	Coût Traitement :	14603	€
Consommation :	224300	m3	Coût Refoulement :	29602	€
Manques d'Eau :	10142	m3	Coût Import :	0	€
Export :	0	m3			
Import :	0	m3	Total :	44205	€

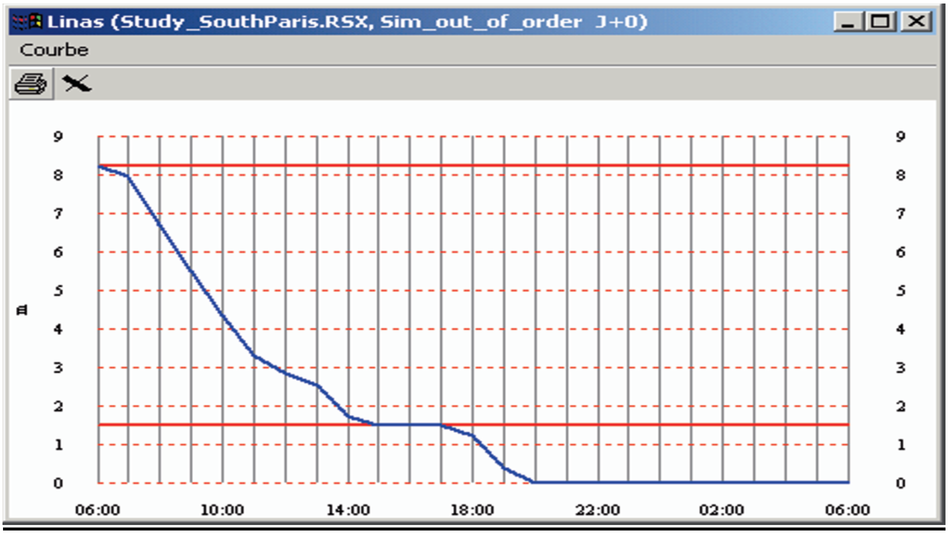
Summary results of the simulation

We remark that there are water insufficiencies (missing water = 10,142 m^3) in our simulation.

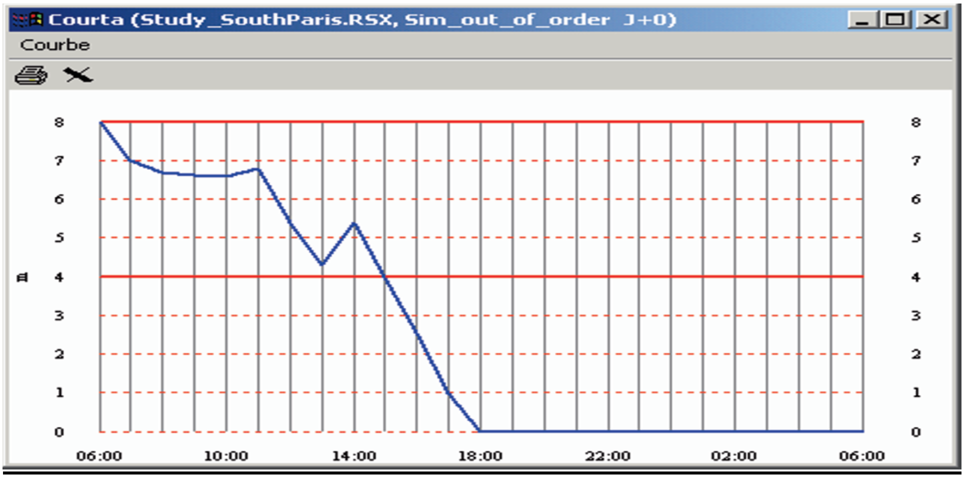


The station 3 is running on less than half of his capacity.

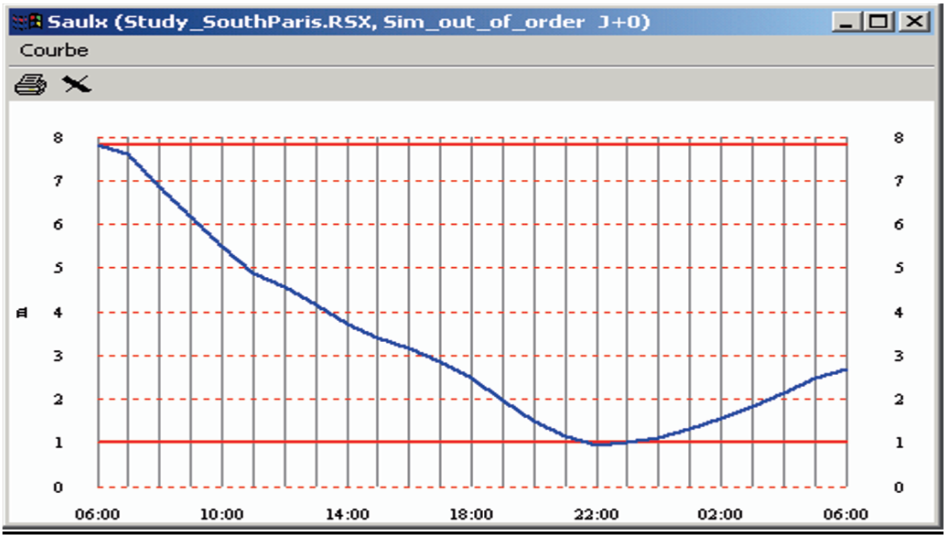
On the other hand, the most dependant towers from left side pumping station of Station 3 can no more satisfy the demand. These tower's levels stay at 0 for many hours.



Linas Tower level staying at 0 after 20:00



Courta Tower level staying at 0 after 18:00



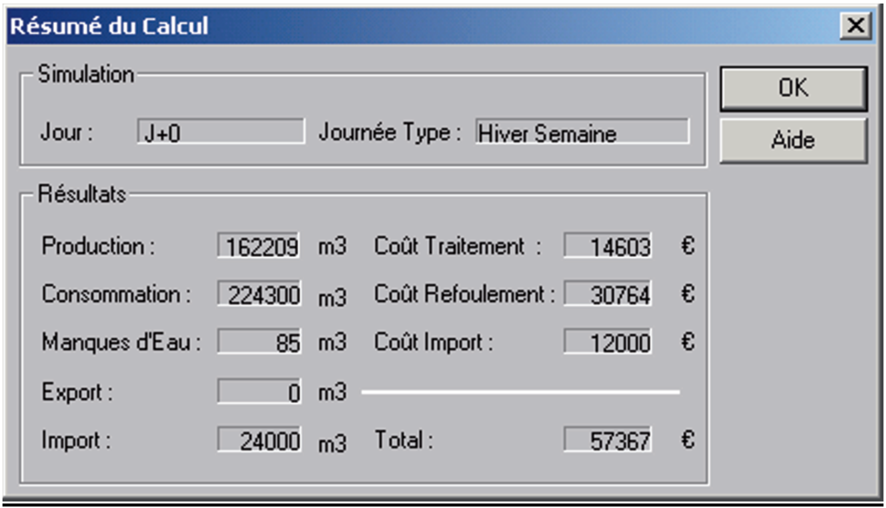
Saulx Tower level can't reach the same level as at the start of the day

It's impossible to manage this kind of situation without an external solution. Our network is connected to seven external networks managed by external companies whose prices are different.

Getting help from an External Network – Solution 1

We use for this simulation only the External 1 which daily capacity is 24,000 m^3.

The summary results of this simulation is given in the following image:



Résumé du Calcul

Simulation

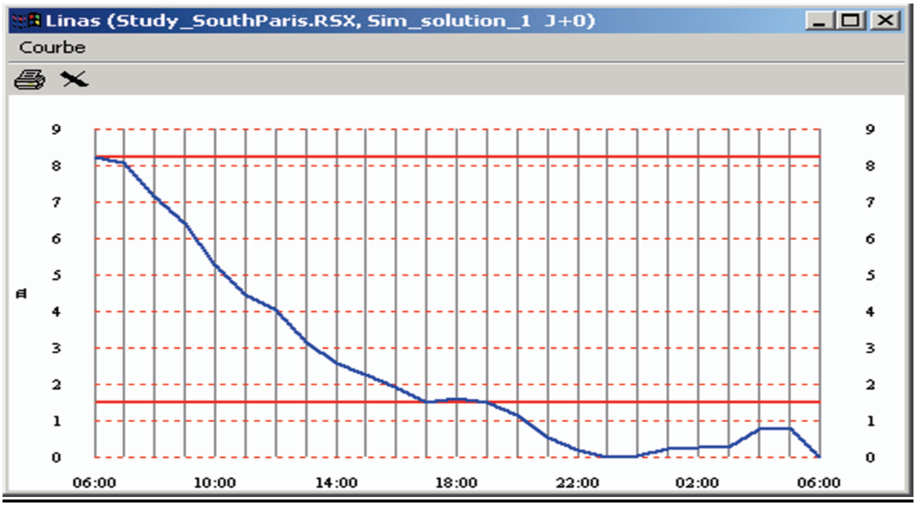
Jour : J+0
Journée Type : Hiver Semaine

Résultats

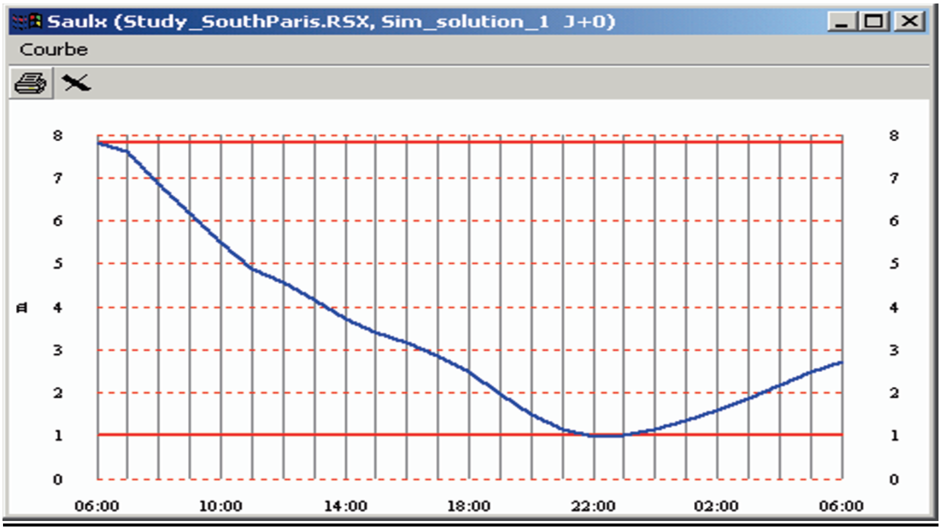
Production : 162209 m3
Consommation : 224300 m3
Manques d'Eau : 85 m3
Export : 0 m3
Import : 24000 m3
Coût Traitement : 14603 €
Coût Refoulement : 30764 €
Coût Import : 12000 €
Total : 57367 €

Owing to the water quantity imported (24,000 m^3), the quantity of the missing water has reduced neatly.

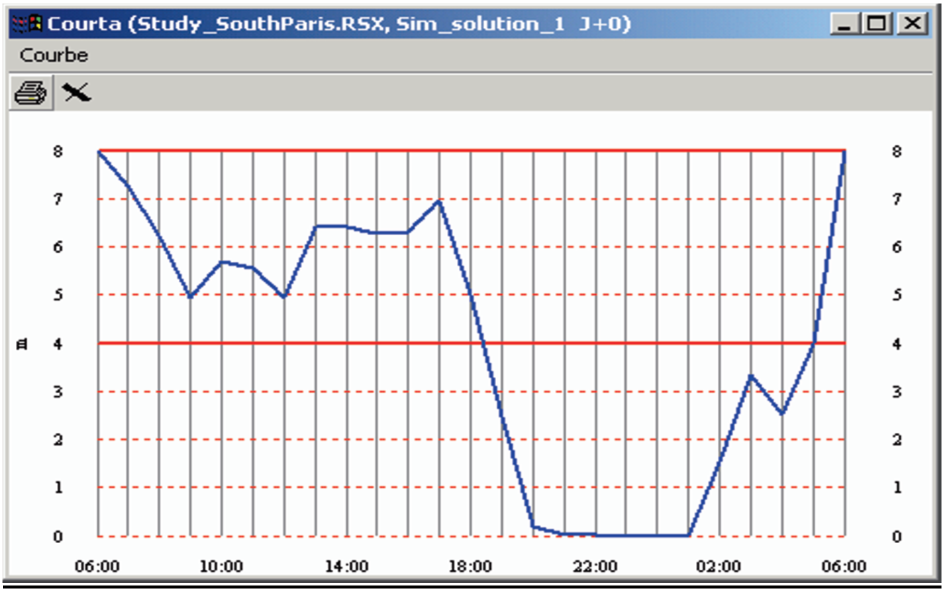
However, the Linas Tower can't get any more the start level. At the end of the day it level goes dangerously at 0.



Linas Tower level reaching at 0 at the end of day simulation



Saulx Tower level can't reach the start level at the end of day simulation

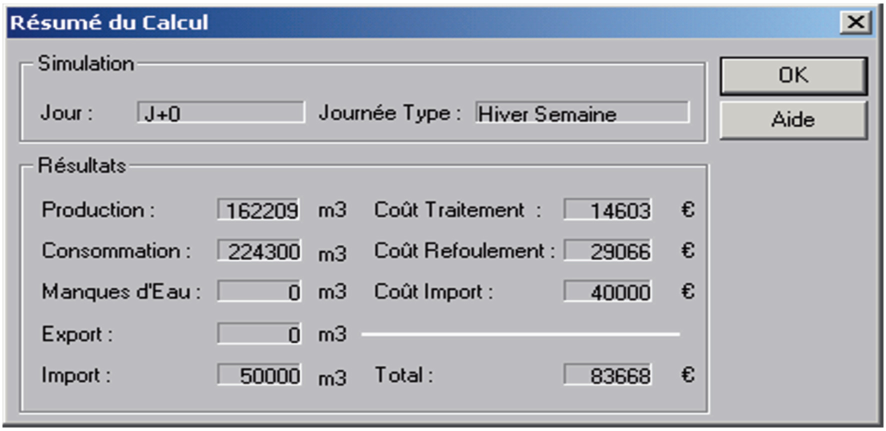


Courta Tower behaviour shows that it can't satisfy the demand from 22:00 to 02:00

Getting help from an External Network – Solution 2

We use for this simulation only the External Concurrent 5 which daily capacity is 50,000 m^3.

Owing to the water quantity imported (50,000 m^3), there is no more missing water in the network. However, the production and the imported water don't reach the demand. It means that at the end of the simulation we can't reach the same levels as the start levels.



Simulation

Jour : J+0 Journée Type : Hiver Semaine

Résultats

Production : 162209 m3 Coût Traitement : 14603 €

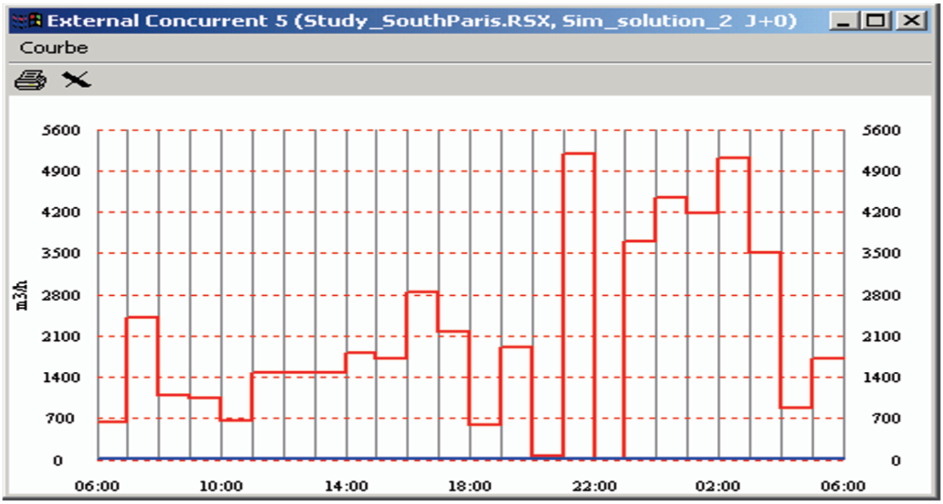
Consommation : 224300 m3 Coût Refoulement : 29066 €

Manques d'Eau : 0 m3 Coût Import : 40000 €

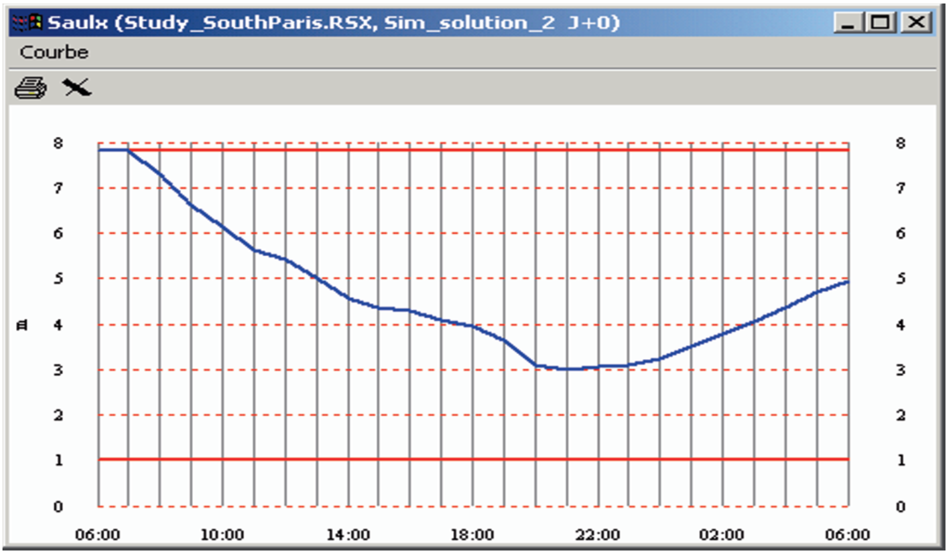
Export : 0 m3

Import : 50000 m3 Total : 83668 €

The summary results of Solution 2



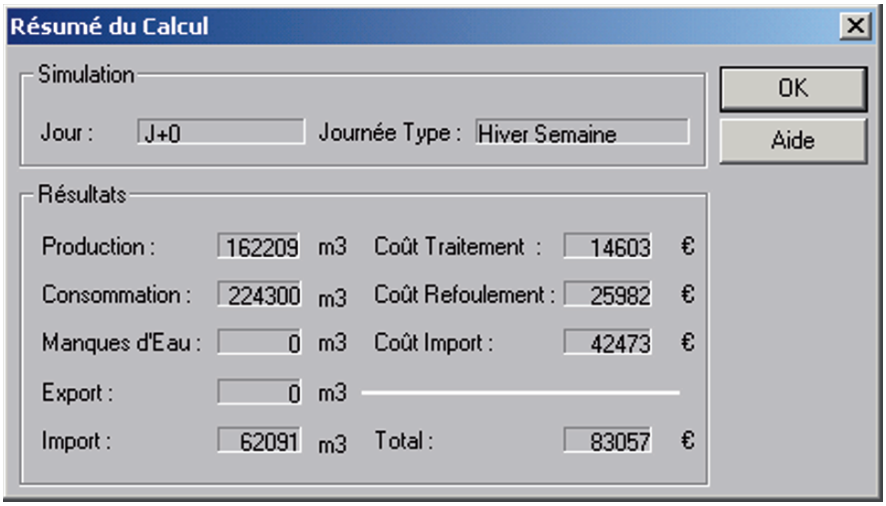
Water imported over a 24-h period



Saulx Tower level can't reach the start level at the end of day simulation

Getting help from an External Network – Solution 3

We use for this simulation External Concurrent 5 which daily capacity is 50,000 m^3 and External 1 which daily capacity is 24,000 m^3.



Résumé du Calcul

Simulation

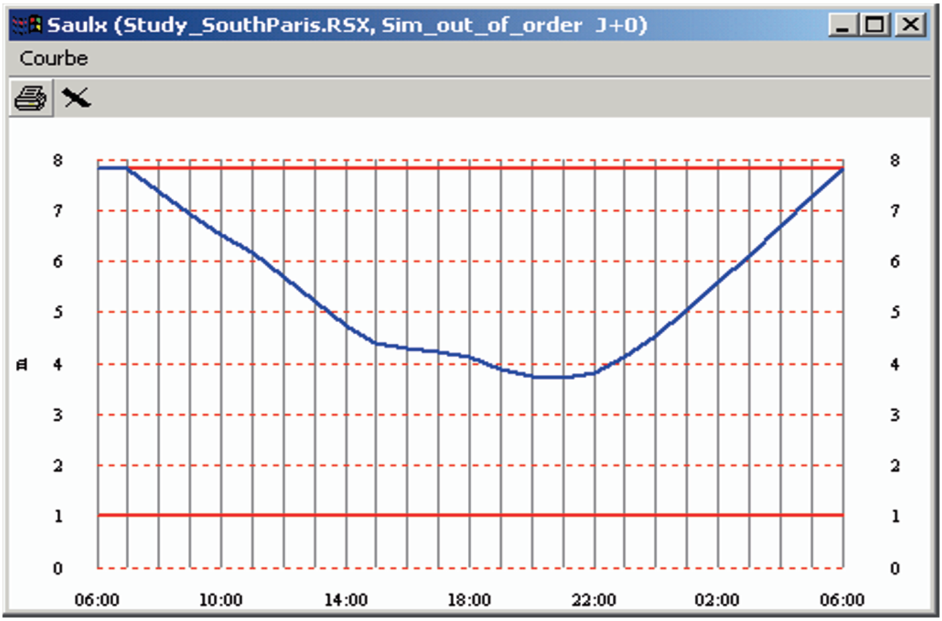
Jour : J+0 Journée Type : Hiver Semaine

Résultats

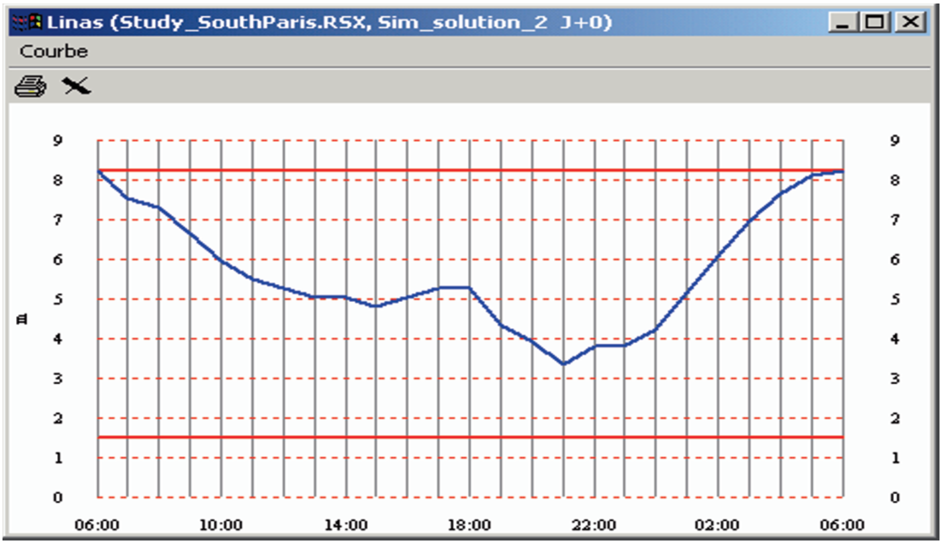
Production :	162209	m3	Coût Traitement :	14603	€
Consommation :	224300	m3	Coût Refoulement :	25982	€
Manques d'Eau :	0	m3	Coût Import :	42473	€
Export :	0	m3			
Import :	62091	m3	Total :	83057	€

The summary results of Solution 3

There is no more missing water and the quantity of water produced and imported equal the demand of the network. At the end of a day simulation, all the storages come at their starting levels.



Saulx Tower level reach the start level at the end of day simulation



Linas Tower level reach the start level at the end of day simulation

We have bought all the quantity possible from External 1 whose price for cubic meters is lower than the price of External Concurrent 5

Name	Start	Duration (h)	Quantity (m^3)
External 1	06:00	24	24,000
External Concurrent 5	06:00	24	38,091

6. Conclusion

SAPHIR is a Windows based software program designed to solve the scheduling problem for water supply and distribution. Based on a user friendly graphical interface, it provides a invaluable help to network managers. Simplifications made on the optimisation problem formulation remain reasonable on operation mode and give satisfaction in all studied networks.

The SAPHIR product is already installed and used in more than 20 Lyonnaise des Eaux water distribution networks in France (City of Dijon, Paris Sud, Paris West, City of Bordeaux,...), Great Britain (Essex & Suffolk Water, Northumbrian Water) and USA (United Water New York).

EMERAUDE can be considered as a real time application of SAPHIR principle. It gives excellent results from several points of view. First, the stabilization of raw water flow rates has been improved. This objective has been reached thanks to the EMERAUDE's predictive capabilities and it's adapted algorithm compared to what a classical PLC can do. The second point is electrical cost optimisation. This is done by maximizing water transfer at night and by using the best available pumping combination.

Today, the EMERAUDE system is fully operational at six water networks in France: Morsang sur Seine (installed in 1993, production 200,000 m^3), Viry sur Seine (1994, 120,000 m^3), Bischwiller (1996, 35,000 m^3), Creil (1997, 30,000 m^3), Bordeaux (1998, 60,000 m^3) and Dunkerque (1999, 60,000 m^3).

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