# Optimisation of hydroelectric power stations operations with WOLF package

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**ABSTRACT:**
*For years, original free-surface flow solvers have been developed and continuously improved by the Laboratory of Applied Hydrodynamics and Hydraulic Constructions (HACH) at the University of Liège. The resulting fully integrated WOLF computation package allows engineers to accurately study a very wide range of various free surface flows, from hydrological runoff (WOLF HYDRO) and river propagation (WOLF 1D) to extreme erosive flows on realistic mobile topography (WOLF 2D), such as gradual dam breaching processes.*
*All the finite volume models, process oriented, use efficient and original numerical methods to solve free surface flows equations. Each code handles general multiblock meshes, dealing with natural topography, dry and wet cells and mobile bed simultaneously, for any unsteady situation with mixed regimes and moving hydraulic jumps. The interactive and unique user-interface, with high performance pre- and post-processing, allows monitoring 3-D large-scale runs graphically while they proceed, as well as generating 3D videos. In addition, powerful optimisation capabilities based on the Genetic Algorithms technique (WOLF AG) are implemented within WOLF, interconnecting all the package components. An efficient tool is thus available to calibrate physical parameters in any of the models and to manage any problem of optimisation with the different solvers.*
*In this paper, the numerical optimisation process of the system of hydroelectric power stations installed on a 60 km long section of the rivers Amblève and Warche in Belgium is presented in detail. The river network is modelled in quasi-2D using real natural topographic data on almost 1,100 finite volumes. In a first step, the hydrological balance is closed using the solver WOLF HYDRO. Roughness coefficients are calibrated from water level and discharge field measurements. Secondly, the hydroelectric production is maximised by an automatic calibration of the parameters of the hydrograph released in the network at the upstream dam.*
*This approach leads to a substantial gain in hydroelectric production, brings significant financial benefits and deals with all management and security criteria of the river network.*

## INTRODUCTION:

The potential of hydroelectric production in Belgium is relatively small because of the quite flat relief and of the lack of important chutes along the main rivers. Except the Coo power station of accumulation by pumping (1,164 MW), the installed hydroelectric capacity of the country did not exceed 250 MW in 2003 in comparison with a total installed power of about 15,600 MW (BFE-FPE, 2003).
Between Bütgenbach dam and Heid-de-Goreux, on 47,8 km of the rivers Warche and Amblève, 6 power stations exploit a 407.4 meters chute, with a downstream equipment discharge of 26 m³/s. Called the “Eastern Hydropower plants System”, it represents the most important one on the river hydroelectric complex of Belgium. This complex is managed by the private society Electrabel and its total production capacity is 19,8 MW.
Two successive large dams, the 28 m high Bütgenbach one and the 57 m high Robertville one, were built upstream of the rivers in order to create water reservoirs and to increase the natural chute. They directly feed the first power station of Bévercée (9,2 MW) and are thus used to maximise its production in regards with electricity demand and the kWh selling curve. When managing the hydrograph released from the dams, the other downstream power stations are however not directly taken into account. The total production of the hydroelectric power stations cascade is thus not optimised on the basis of objective hydraulic considerations.
After a general description of the package WOLF and of the three solvers used in this study in particular, the numerical optimisation of the hydropower plants system based on objective considerations is presented in detail.

## WOLF SOFTWARE PACKAGE:

### Overview:

The WOLF package is an original and efficient device for the computation of free surface flows developed by the HACH team (http://www.ulg.ac.be/hach) during the last years. Its reliability has been shown through numerous applications, theoretical as well as experimental at the Laboratory of Hydraulic Constructions of the University of Liège. [Erpicum, Archambeau, 2004, Archambeau, Dewals, 2004]
It is made up of several flow solvers, process oriented, which are integrated in a unique, powerful and user-friendly interface to realize the stages pre- and post-processing with 2D and 3D animated visualizations. An optimisation software, WOLFAG, completes the numerical computation package. Based on the innovating method of genetic algorithms, it is interconnected with all other package components. It is thus available to calibrate any physical parameter in the aforementioned models and to manage any problem of optimisation with the different solvers. The finite volume models use efficient and original numerical methods to solve continuous or discontinuous free-

surface flows. They handle multiblock structured grids with both first and second order accurate explicit or implicit algorithms in time and space.
Following the way of water on the earth surface, WOLFHydro first computes the hydrological runoff and ground flows on a catchment, providing thus the inflow discharge to the rivers. The input requirements for WOLF Hydro are rain data and topographic data through a digital elevation model (DEM).
Secondly, WOLF1D models the rivers networks in quasi-two dimensions. Both components of flows in compound channels are handled separately, with an explicit computation of lateral exchanges during the transient stages.
Finally, WOLF2D allows, in quasi 3D, local impact or design studies as well as dam breaching or flooding simulations. Comprehensive risk maps are plotted as a result. The potential vertical curvature of the bed is taken into account thanks to a specific model derived in curvilinear coordinates in the vertical plane. Non-unifrom velocity profiles are computed automatically thanks to additional transport equations, such as the moments of momentum.
The two last models can take into account sediment, pollutant and air transport effects. [André, Dewals, 2003, Dewals, Archambeau, 2004]

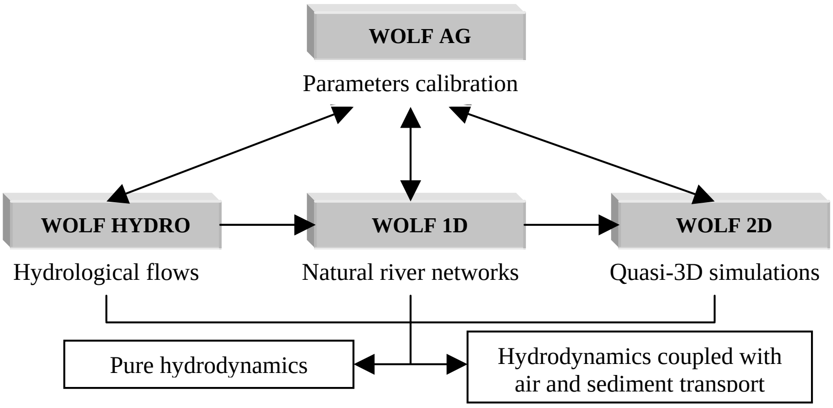


*Figure 1: General organization of WOLF computation units*

Continuous experimental – numerical interactions are carried out at the Laboratory of Hydraulic Constructions of the University of Liège to improve scale models studies as well as to validate the numerical solvers. [Pirotton, Lejeune, 2003, Dewals, Erpicum, 2004]

## WOLFHydro: process oriented runoff calculation

The present version of the hydrological software, WOLFHYDRO, solves the conservative equations of the 2D diffusion wave model with a finite volume method for three specific vertically distributed layers (figure 2). Different roughness laws (Manning, Darcy-Weissbach, Bathurst…) are implemented to take into account the macroscopic roughness of the hydrological propagation with various flow regimes [Archambeau, Erpicum, 2001].

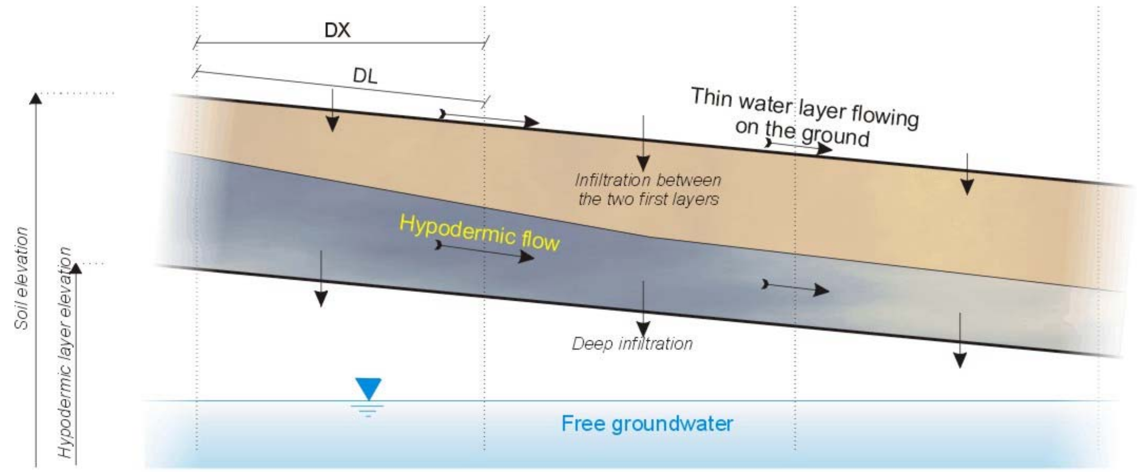


*Figure 2: Three flow layers computed in WOLFHYDRO*

Originating from the well-known shallow water equations (SWE) describing the flows, the diffusion wave approach is obtained by ignoring the inertia terms compared with the gravitational ones, friction and pressure heads. The SWE model can then be replaced by the following system of parabolic differential equations:

$$\left( S_{fx} + \frac{\partial H}{\partial x} \right) = 0 , \quad [1]$$

$$\left( S_{fy} + \frac{\partial H}{\partial y} \right) = 0 , \quad [2]$$

where $H(x,y,t)$ is the water surface elevation above an horizontal datum, $x$, $y$ are horizontal Cartesian coordinates and $S_{fx}(x,y,t)$, $S_{fy}(x,y,t)$ are friction slopes in $x$ and $y$ directions.

In addition and applying, for example, the Manning-Strickler law to the description of the friction slopes that appear in the above equations, the relation between the velocity components and the water depth can be obtained as

$$S_{fx} = \frac{n_x^2}{h^{\frac{4}{3}}} |w| u = \frac{n_x^2}{h^{\frac{4}{3}}} u \sqrt{\left(u^2 + v^2\right)} , \quad [3]$$

$$S_{fy} = \frac{n_y^2}{h^{\frac{4}{3}}} |w| v = \frac{n_y^2}{h^{\frac{4}{3}}} v \sqrt{\left(u^2 + v^2\right)} , \quad [4]$$

where $h(x,y,t)$ is the local water depth, $u(x,y,t)$, $v(x,y,t)$ are depth averaged flow velocities in $x$ and $y$ directions, $w = \sqrt{u^2 + v^2}$ is the velocity magnitude, $n_x$, $n_y$ are the Manning roughness coefficients in the directions $x$ and $y$, respectively, and therefore

$$|w|^2 = u^2 + v^2 = h^{\frac{4}{3}} \sqrt{\frac{S_{fx}^2}{n_x^4} + \frac{S_{fy}^2}{n_y^4}} \quad [5]$$

Lastly, using the above relation in the expressions [3] and [4] for $S_{fx}$ and $S_{fy}$ determines the following expressions for the components of the velocity vector:

$$u = -\frac{\partial H}{\partial x} \frac{h^{\frac{2}{3}}}{n_x^2} \frac{1}{\left[ \left( \frac{\partial H}{\partial x} \right)^2 \frac{1}{n_x^4} + \left( \frac{\partial H}{\partial y} \right)^2 \frac{1}{n_y^4} \right]^{\frac{1}{4}}} , \quad [6]$$

$$v = -\frac{\partial H}{\partial y} \frac{h^{\frac{2}{3}}}{n_y^2} \frac{1}{\left[ \left( \frac{\partial H}{\partial x} \right)^2 \frac{1}{n_x^4} + \left( \frac{\partial H}{\partial y} \right)^2 \frac{1}{n_y^4} \right]^{\frac{1}{4}}} , \quad [7]$$

As other main features, the model has three bunk layers to simulate respectively the thin runoff, the hypodermic propagation and the transfer to the groundwater. It handles the rainfall propagation, spatially and temporally variable according to the cloudy fronts location on the DEM. A complete 1D model propagates the lateral floods components in the drainage path. The unsteady infiltration law permits the reforming of the soil capacity after the rain has stopped, and thus the calculation of long periods is possible without interrupting the software.

## WOLF1D: modeling river networks

Historically, the floods of the year 1998 in Belgium and the recent ones all over Europe proved again that rivers, as a part of nature, have to be mastered not by force but by understanding. In this scope, WOLF1D, a quasi-bidimensional model, has first been developed in order to better manage floods in complete river networks. This solver has been validated using other numerical and experimental models as well as field measurements of the transient behaviour of natural river flows [Pirotton, 1997]. It has then been extensively used as a management tool for analysing extreme natural events. Now, since more efficient and accurate quasi-3D solvers, such as WOLF2D, are available for simulating flood case studies even on large river sections, the one dimensional model is preferentially used for large scale modelling of river networks, dedicated to applications such as flood propagation, pollutant transport as well as the evaluation of the global water quality and of environmental effects.

As common methods based on conveyance considerations lead to substantial errors, WOLF1D takes explicitly into account the flows in compound channels, in both situations of large floodplains with totally developed streams (case 2 on figure 3), or lateral storage areas with hydraulic dead zones, where water movements have the same order of magnitude in both directions (case 1 on figure 3).

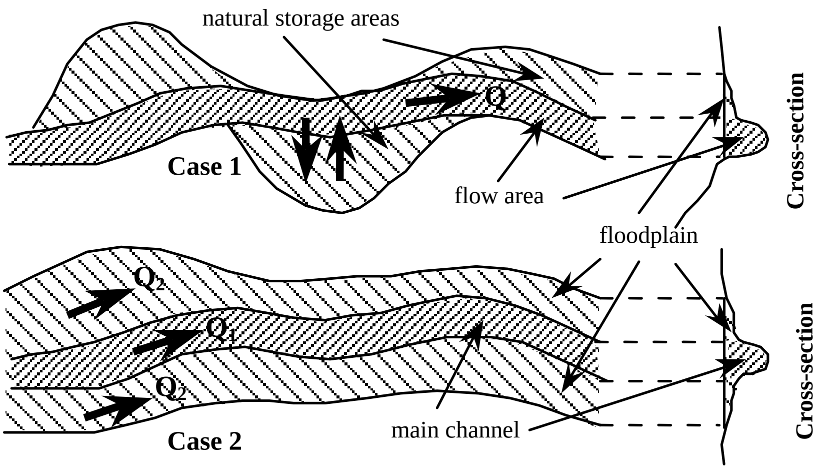


*Figure 3: Interactions between the main channel and the floodplain*

The possible transient situations are shown above, with the subsequent lateral exchanges. Mutual fluid friction effect are taken into account and evaluated by a Prantl mixing approach.

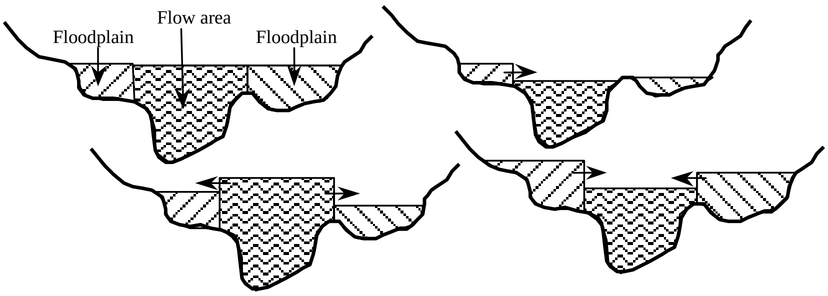


*Figure 4: Transient situations and exchanges between the main channel and the floodplains*

The coexistence of several flow rates with shocks and bores in ramified nets of variable cross section arms requires to deal with suitable shock capturing methods to solve the conservative form of the 1D Saint-Venant equations. The complete set of equations solved in WOLF1D for each flow bed is expressed as follows:

$$\frac{\partial}{\partial t}\begin{bmatrix}\omega \\ q\end{bmatrix}+\frac{\partial}{\partial x}\begin{bmatrix} q \\ \rho_{\omega}\dfrac{q^2}{\omega}+g\cos\theta\, p_{\omega}\end{bmatrix}+\begin{bmatrix} -q_L \\ -g\omega\sin\theta+g\omega J+g\cos\theta h l_b\dfrac{\partial(-h_b)}{\partial x}-g\cos\theta\, p_x\end{bmatrix}=\begin{bmatrix}0\\0\end{bmatrix} \quad [8]$$

where ω is the cross section, q the discharge, h the water height, $q_L$ the lateral exchanges, J a global term for bottom roughness and shear fluid effect, θ the channel bottom slope and l the channel width. The pressure terms are defined by:

$$p_{\omega}(h)=\int_0^h (h-\xi)\, l(x,\xi)\, d\xi$$

$$p_x(h)=\int_0^h (h-\xi)\frac{\partial l(x,\xi)}{\partial x}d\xi \quad [9]$$

$$l=l_g+l_d$$

The spatial discretisation of the equations is performed by a widely used finite volume method. Flux treatment is based on an original flux-vector splitting technique developed for WOLF. Fluxes are split according to the sign of the flow path, requiring a suitable downstream or upstream reconstruction for both parts of the convective term according to a stability analysis. Efficiency, simplicity and low computational cost are the main advantages of this scheme. Variable reconstruction can be selected to gain first or second order accuracy on regular grids. However, it is well known that such second order finite volume schemes, although very accurate in smooth regions, cause unphysical oscillations near the discontinuities. The flux reconstructions are therefore limited to prevent such spurious effects. Besides, an explicit Runge-Kutta scheme or an implicit algorithm (based on the GMRES) is applied to solve the ordinary differential equation operator, and an original treatment of the confluences based on Lagrange multipliers allows the modelisation in a single way of large rivers networks.

## WOLFAG: an efficient tool for parameters optimization

WOLF AG, has been developed to provide a robust parameters fitting tool for all the different components of WOLF. It is an optimization software based on the Genetic Algorithms method.

Genetic Algorithms are exploration algorithms imitating the natural selection and genetic mechanisms [Goldberg, 1989]. At each step, they improve a set of N coded representations of the value of the parameters to be optimized, called a population of N *chromosomes* or *chains*. Several genetic operators such as selection, crossover and mutation govern the evolution. These operators act in such a way that the best individuals of the population are preferentially used to build the new ones. Thus, a kind of natural selection occurs.

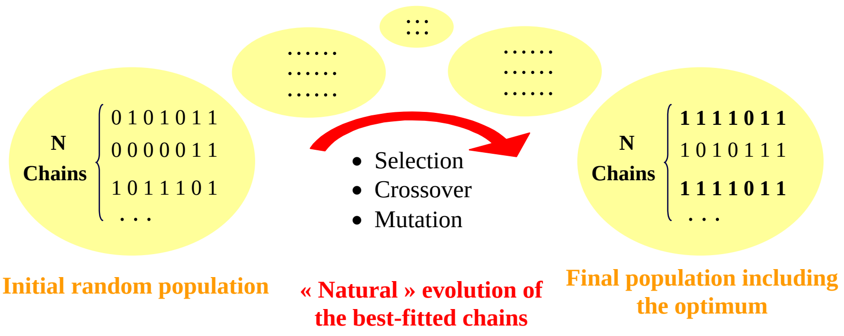


*Figure 5: WOLFAG principle diagram*

The principle of evolution is quite simple. The process starts with a random initial population and the performance of all the different chains is evaluate thanks to a fitness function $f_{obj}$. Then, a new population is created chain by chain, using the following sequence. Two chains are selected in the initial population, with a probability $p_j$ directly dependent on their adaptation to the problem:

$$p_{sélection,i} = \frac{f_{obj,i}}{\sum_{j=1}^{N} f_{obj,j}} \qquad [10]$$

The coding of these two chains is combined by exchanging parts of their elements (crossover). The crossing place is chosen randomly. There can be one (figure 6 - case A) or several (figure 6 - case B) crossing places, depending on the type of crossover and of the number of parameters. A third possibility (figure 6 - case C) is to exchange all the elements of both the chains with a probability of 50 percents for each. It is the uniform crossover.
During the exchange of two elements, their value can mutate (for example, a 1 becomes 0 and conversely), with a very small probability. It is the mutation.

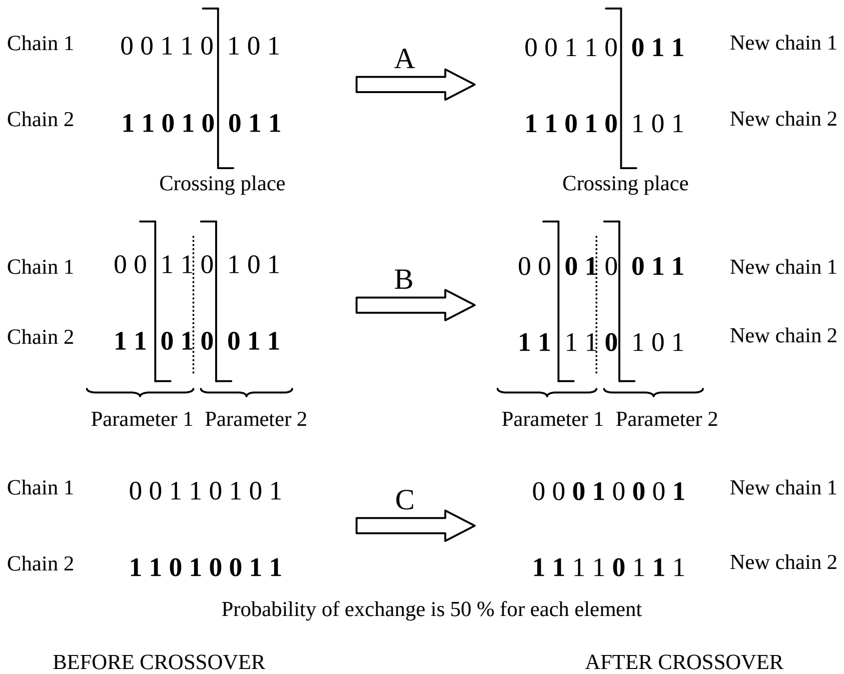


*Figure 6: Different kinds of crossover: simple (A), in one point per parameter (B) and uniform (C)*

This sequence is repeated N/2 times, until a complete new population is created. The whole creation process of a new population is called a generation. It is repeated until the optimum is reached.
It is obvious that Genetic Algorithms are situated between classical optimisation methods, applied locally in the search space of solutions, and purely random or systematic optimisation methods, that explore all possible solutions. Genetic algorithms constitute a kind of intelligent and pseudo-random exploration of the search space of

solutions. Thus, they can be used to study discontinuous and disjointed functions and always converge towards the absolute optimum.
In the case of WOLF, the coded chains represent the value of the physical parameters of the different solvers. For each fitness function evaluation, the adequate solver is called by WOLFAG to compute the solution (hydrograph, water line…), which is compared to the reference values of the problem. The fitness function is for example a least-square function between measured and computed values of water levels or discharges.
For complex problems, when some parameters are constant for a lot of different set of comparison data while the others depend on the particular case treated, several fitness functions can be used to better optimise the different parameters. For instance, a roughness coefficient is calibrate according to more than one measured water line but a discharge value has to be fit for each different sets of water heights. In such cases, WOLFAG builds a global fitness function (with all measured data) to calibrate the general parameters, and local ones are evaluated to fit the local parameters.

## OPTIMISATION OF THE WARCHE – AMBLÈVE HYDROPOWER SYSTEM:

### Numerical model:

As explained in the introduction, the "Eastern Hydropower Plants System" in Belgium if made up of six hydroelectric power plants following each other on the Warche and Amblève rivers (figure 7). In order to realize a global optimisation of the hydroelectric production of the system, the whole network, with the main rivers and their most important tributaries, has first been modelled with WOLF1D. The simulation represents almost 60 kilometres of river using 1,098 real cross sections data.

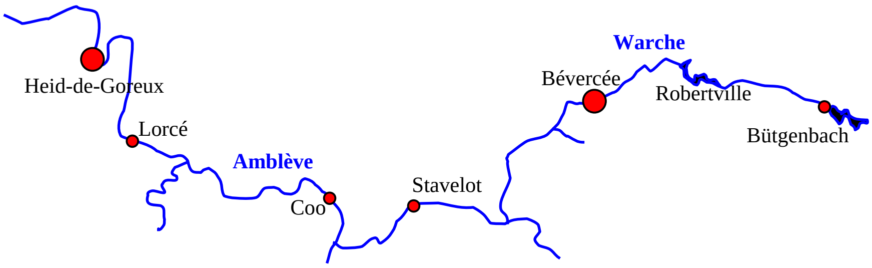


*Figure 7: Drawing of the modeled river network*

Cross sections data came from topographic measurements realised by the Natural Resources and Environment Administration of the Walloon Region (DGRNE) during the early 70's and updated for some reaches in 1995. The distance between cross sections varied between 2, for bridge locations, to 149 meters. Since the time step for explicit simulations is directly correlated to this mesh size, and since many runs of the model are needed to perform the optimisation process, topographic data have been post treated to increase the lower limit of the mesh size. Moreover, the calculation accuracy is improved by a more uniform distribution of the distances between cross sections. That's why eventually a distance varying from 39 to 149 meters with an average value of 62 meters separated the 952 cross sections used. The resulting loss of accuracy in water height evaluation near river singularities such as bridges for example was not prejudicial to the study as the most important parameter of the flow in this case is the discharge, which is correctly represented with this so called "large scale model" of the rivers network.

### Hydrological balance:

The dams of Bütgenbach and Robertville feed the network upstream. The upstream points of the three tributaries explicitly modelled, the Lienne, the Salm and the Warchenne, are located at gauging stations. The network downstream limit is similarly located at the Lorcé gauging station. Rivers discharges are thus known upstream and downstream of the model. For steady situations, the sum of the upstream discharges is nevertheless not equal to the downstream one because of the lateral inflows all along the network from rain and ground water. That's why the 96,620 ha watershed of the Amblève has been modelled using WOLF HYDRO in order to close the global hydrologic balance by taking into account lateral inflow contributions (Figure 8).

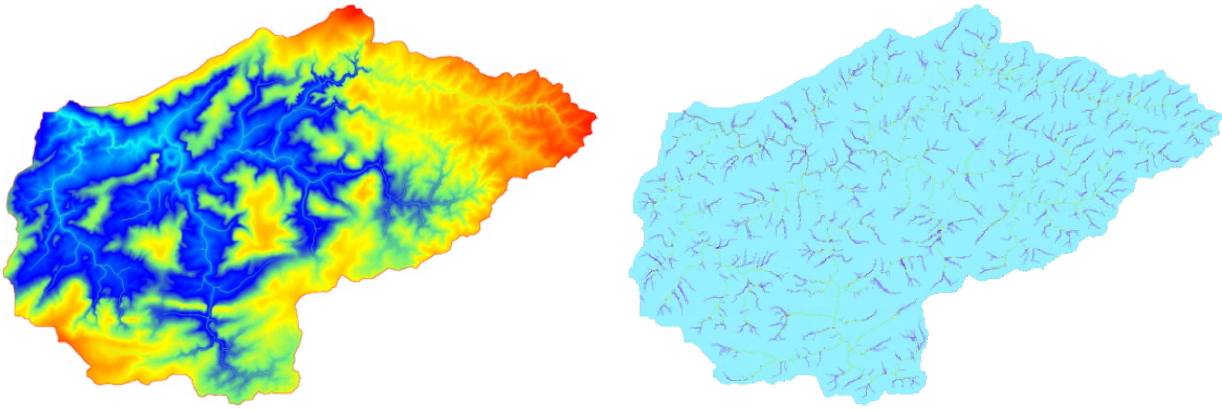

*Figure 8: Amblève catchment DEM (left) and preferential runoff paths (right) from WOLFHydro*

From the preferential runoff paths to the rivers computed by WOLFHydro, the catchment area attached to all the rivers discretisation points has been evaluated. The difference between steady state inflow and outflow discharges has then been linearly distributed along the rivers accordingly to the catchment area they drained.

**Physical parameters optimisation:**

At this point of the numerical model development, the only unknown parameter is the roughness coefficient. It has been fitted by WOLFAG using water levels and discharge data from eight limnimetric stations along the network.

In a first time, the fitness function was taken as the mean square difference between computed and measured water lines for three different and constant discharges on the rivers Amblève and Warche. Then the solution has been improved by using unsteady measured and computed water heights from real significant waves propagation in the network (figure 9).

A value of the Manning roughness coefficient of 25 for the two main rivers and of 31 for the tributaries has finally been found.

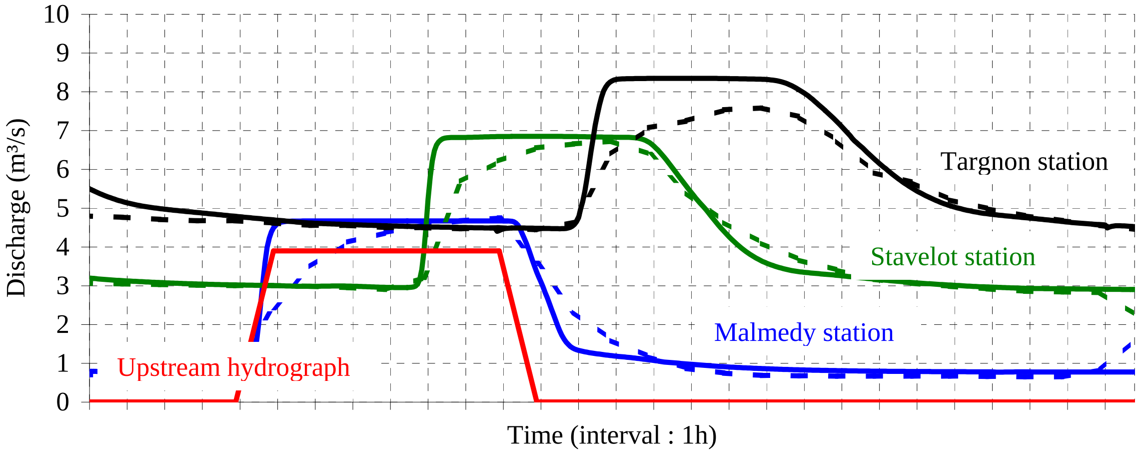


*Figure 9: Measured and computed hydrographs with fitted roughness coefficient*

**Constraints and parameters for the system optimisation:**

As the network is fed upstream by a reservoir, the first imposition comes from the available water quantity to produce electricity. Indeed, Robertville and Bütgenbach have to play a part in flood regulation during winter and have recreational goals during summer. Water levels in the two reservoirs have thus to remain confined between strictly defined values along the whole year. From this, the volume of water, which can be used to produce electricity, is imposed depending on the meteorological conditions of the day or of the reservoir management policy for the next months. This represents the first constraint to deal with during optimisation.

A second constraint is the discharges in the river network, with a minimum value for low-water level and a maximum one to avoid flooding.

On the basis of the kWh selling curve, optimisation calculations have been done on a period of 24 hours, with the objective to maximise the benefit produced by the whole system, by fitting the 6 parameters of the hydrograph released downstream of Robertville dam (figure 10), with respect of the constraint explained here above. Only a maximization of the production is thus not sufficient, as the electricity has to be produced when it is interesting to use it, in other words when its price is high during the day.

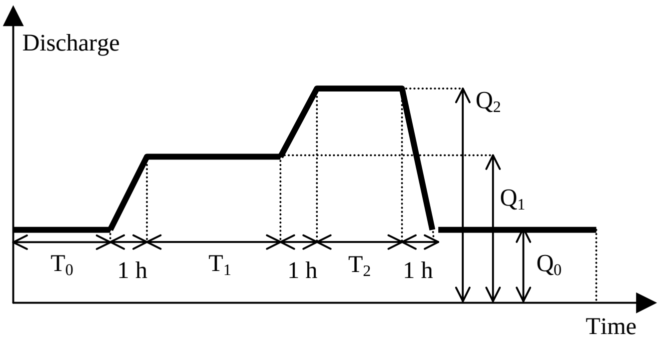


*Figure 10: Parameters of the injected hydrogram*

The calculations have been realized in different successive phases: the propagation of an upstream hydrograph was computed in the numerical model, then the evolution of the discharge along time to each power plant was transformed into electric production by way of the turbines characteristic curve fitted on real measured data. Afterwards the electric production was converted into income using the kWh remuneration curve. The total benefit generated by the different tools on a day represented the fitness function.
Only the main stations of Bévercée and Heid-de-Goreux have been taken into account to evaluate the hydroelectric production during the numerical simulations, as accurate working data were not available for the other production tools. Nevertheless, these two power plants represent 87.4 percents of the total installed production capacity of the system.

**Results:**
Two simulations have been carried on. One in summer, when the volume of water available per day is generally limited, and the other in winter, when this volume is more important.
In order to compare the solutions with real case ones, the optimisation process considered the same available volume of water per day than in well known real situations.
In the first case, a 2.3% increase in the production has been reached with a 6.1% increase of the benefits. In the second case, the increase was 2.1% in production and 1.1% in benefit.

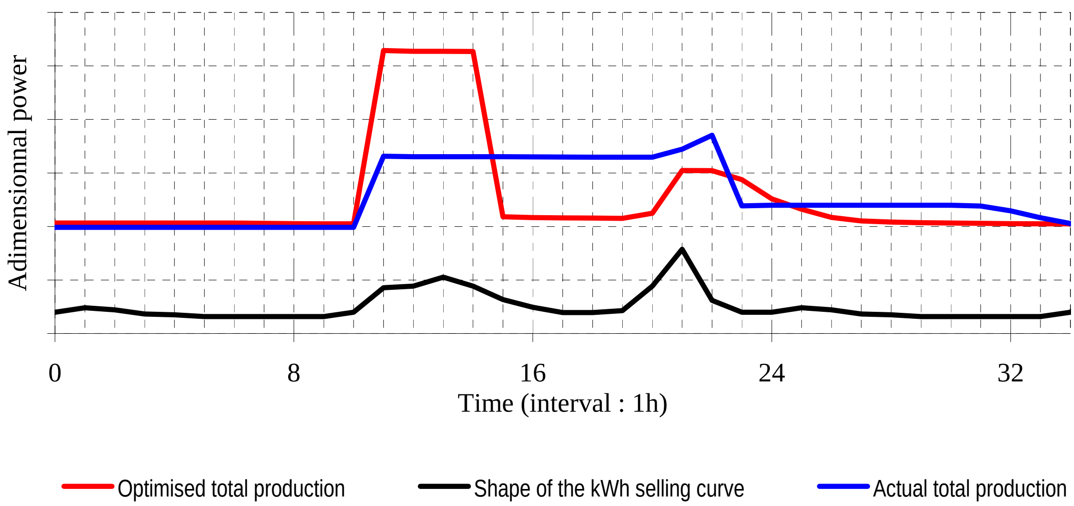


*Figure 11: Comparison of the production along time during summer case*

These increases in production and benefit come from an adequate shape of the hydrograph to better use the production tools in regards with their working characteristics curve, while producing the most during peaks of the kWh curve (figure 11).
In particular for winter case, where the real solution seemed quite good in comparison with the shape of the kWh selling curve as well as with the most efficient discharge of the power plants, WOLFAG found a better solution using a hydrograph shape which hadn't been imagined by manager experience and intuition.

**CONCLUSION:**
The availability in the unified WOLF package of reliable physically based free surface flow solvers along with an efficient and robust optimization tool allows now engineers to study whole real complex hydraulic rivers networks as well as to optimize their management.

The sample presented in this paper shows that, thanks to a good physical understanding and numerical modelling of the hydraulic processes along with an objective calibration of the physical parameters, a significant benefit can be generated in the hydroelectric production of a set of six on the flow power plants with respect of all security and production criteria.
It is thus shown that a set of efficient numerical tools can propose to decision makers rules to better use and valorise water resources, which is of a great importance in the scope of a rational and efficient management of our natural resources.

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