Optimising a cascade of hydroelectric power stations with the WOLF package

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Abstract

Original free-surface flow solvers have been developed by the HACH during the last years. The resulting fully integrated WOLF package allows engineers to study a very wide range of free surface flows situations. Successful and accurate computations are performed for phenomena as various as hydrological run-offs and dam breaking in quasi 3 dimensions including solid transport effects, as well as rivers networks modelling with explicit exchanges between river paths.

All the models, physically based, use efficient and original numerical methods to solve continuous or discontinuous free-surface flow equations. They handle structured or unstructured grids with both first and second order accurate explicit or implicit algorithms in time and space. WOLF also includes powerful user-friendly pre- and post-processing with 2D and 3D animated visualizations as well as a parameters optimization software interconnected with all the package components and based on the innovating method of genetic algorithms.

In this paper, the production of the hydroelectric power plants installed on a 60 km long section of the rivers Amblève and Warche in Belgium is presented in details to illustrate the numerical calculation and optimization process. The river network is modeled using real natural topographic data.

Hydrological balance is closed and roughness coefficients are calibrated from water level and discharge field measurements. Hydroelectric production is optimized by an automatic calibration of the parameters of the hydrogram injected in the network from the Robertville dam.

This approach leads to a substantial gain in both hydroelectric production and financial benefits and deals with all management and security criteria.

1. Introduction

The WOLF package is an original and efficient device for the computation of free surface flows developed by the HACH (http://www.ulg.ac.be/hach) during the last years. Its reliability as been shown through number of applications, theoretical as well as experimental at the Laboratory of Hydraulic Constructions of the University of Liège (Mouzelard & al. [1], Archambeau & al. [2]).

It is composed of different flow solvers, physically based, which are integrated in an unique, powerful and user-friendly interface to realize the stages of pre- and post-processing with 2D and 3D animated visualizations.

An optimization software, WOLFAG (Erpicum [3]), completes the numerical computation package. Based on the innovating method of genetic algorithms, it is interconnected with all the package components, and is thus available to calibrate physical parameters in any of the aforementioned models and to manage any problem of optimization with the different solvers.

The finite volume models use efficient and original numerical methods to solve continuous or discontinuous free-surface flow equations (Mouzelard [4], Pirotton [5]). They handle structured or unstructured grids with both first and second order accurate explicit or implicit algorithms in time and space.

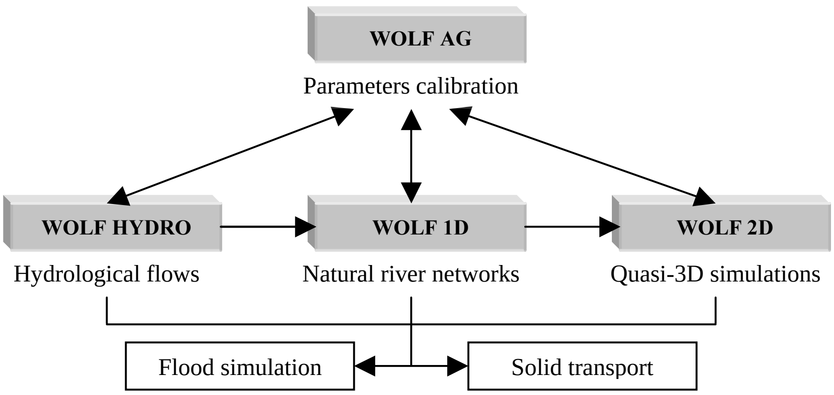


Figure 1 : General organization of WOLF computation units.

WOLFHydro computes, from rain data and digital elevation model, the hydrological runoff and ground flows on a watershed to the river. WOLF1D models the rivers networks in quasi 2 dimensions. Both components of flow 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 with risk maps calculation. All these models can take into account sediment transport effects (Dewals & al. [6], Archambeau & al. [7]).

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 (Mouzelard & al. [8]).

2. WOLF1D: the modeling of rivers networks

Historically, the floods of the year 1998 in Belgium and the recent ones in Europe proved again that rivers, as a part of nature, have to be mastered not by force but by understanding. WOLF1D, a quasi-bidimensional scheme, has been developed in order to better manage floods in complete river networks. This solver has been validated using others numerical and experimental models as well as transient behavior of natural river flows, before an extensive use as management tool for extreme natural events (Pirotton [9]).

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

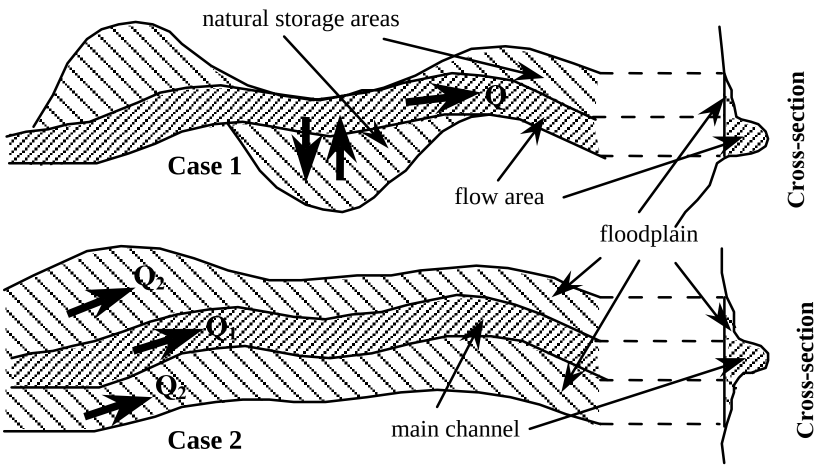


Figure 2 : Interactions between the main channel and the floodplain

The possible transient situations are shown above, with lateral exchanges.

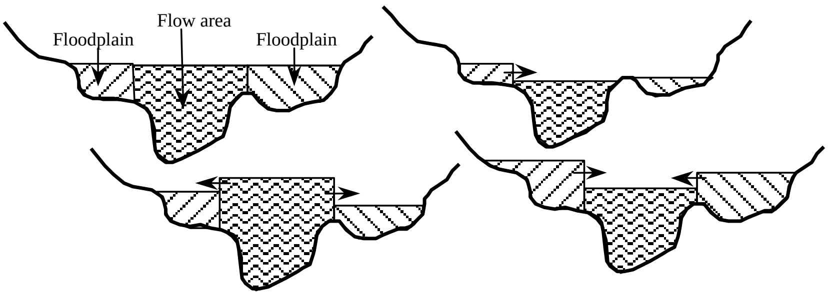


Figure 3 : Transient situations and exchanges between the main channel and the floodplains

Mutual fluid friction effect is taken into account and evaluated by a Prantl mixing approach (Pirotton [9]).

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

$$\frac{\partial}{\partial t}\begin{bmatrix}\omega_i \\ q_i\end{bmatrix}+\frac{\partial}{\partial x}\begin{bmatrix}q_i \\ (qu)_i + gp_{\omega}^{i}\end{bmatrix}+\begin{bmatrix}-q_L \\ -g\omega_i \sin\theta + F_i + p_x^i + 2\left(\nu_t \omega_i \frac{\partial u_i}{\partial x}\right)\end{bmatrix}=\begin{bmatrix}0 \\ 0\end{bmatrix} \quad (1)$$

$$\equiv \frac{\partial \mathrm{X}_i}{\partial \mathrm{t}}+\frac{\partial B(X_i)}{\partial x}+D'(X_i)=0$$

where the variables for each channel i are defined as follows :

- ω_i = section of both channel components
- q_i = discharge of both channel components
- u_i = section-averaged velocity
- q_L = lateral exchanges
- F = global term for bottom roughness and shear fluid effect
- θ = channel bottom slope

$$p_{\omega}(h)=\int_0^h (h-\xi)l(x,\xi)d\xi$$
$$p_x(h)=\int_0^h (h-\xi)\frac{\partial l(x,\xi)}{\partial x}d\xi \quad (2)$$
$$l = l_g + l_d$$

- ν_t = total kinematic viscosity, sum of the fluid viscosity and turbulence effect, described with a Prantl model
- h = water height
- l = channel width

The spatial discretisation of the shallow-water equations is performed by a widely used finite volume method. The partial differential equations are integrated on control volumes covering the whole computational domain. This ensures the mass and momentum properties to be conserved, especially across discontinuities such as hydraulic jumps.

Flux treatment is based on an original flux-vector splitting technique developed for WOLF. Fluxes are splitted according to the sign of the flow path, requiring a suitable downstream or upstream reconstruction for both part according to the stability analysis. Efficiency, simplicity and low computational cost are the main advantages of this scheme.

On the other side, the well-known approximate Riemann solver of Roe brings its robustness to the code, and was introduced as reference in the scope of numerical comparisons. Both methods showed their ability to simulate sharp transitions without excessive smearing on several meshes or excessive growing of dissipative processes.

Variable reconstruction can be selected to gain a first or second order accuracy on regular grids. However, it is well known that such second order finite volume scheme, although very accurate in smooth regions, causes unphysical oscillations near the discontinuities. The flux reconstructions are therefore limited to prevent such undesired effects. The limiter bounds the reconstructed variables between the minimum and maximum of neighboring cells value. In spite of its effectiveness, this limiter suffers from parasite activation in near-constant regions. The limiter modification introduced by Venkatakrishnan (Venkatakrishnan [10]) was adopted to avoid this drawback.

Besides, an explicit Runge-Kutta or implicit algorithm is applied to solve the ordinary differential equation operator.

3. WOLFAG: an efficient tool for parameters optimization

In order to have at one's disposal a robust parameters fitting tool available for all the different WOLF solvers, an optimization software based on the genetic algorithms method, WOLFAG, has been recently developed.

Genetic algorithms are exploration algorithms based on the natural selection and genetic mechanisms (Goldberg [11]). At each step, they improve a set of N coded representations of the value of the parameters to optimize, called a population of N chromosomes or chains, using some genetic operators such as selection, crossover and mutation. These operators are such that the best individuals are preferentially used to built a new population. Thus, a sort of natural selection is occurring.

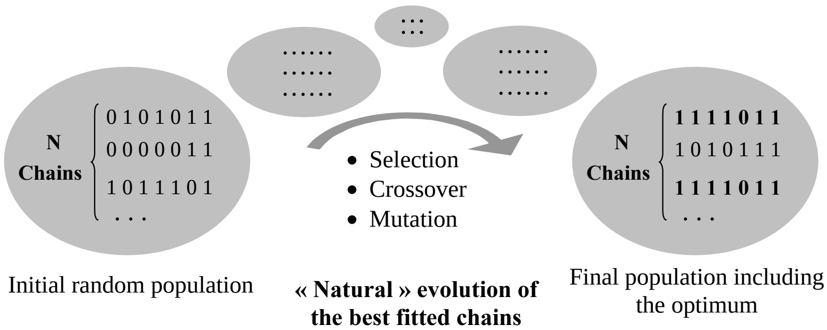
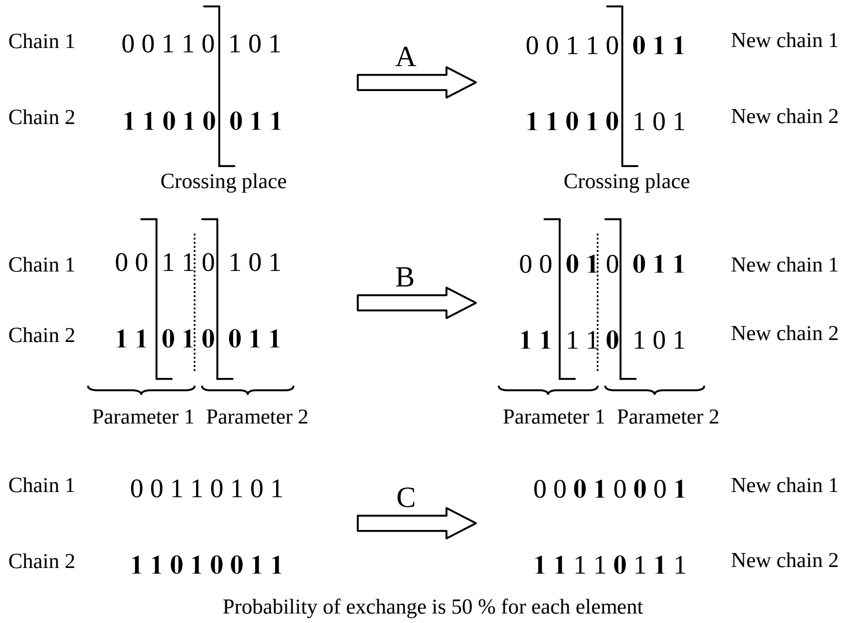


Figure 4 : WOLFAG principle diagram

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 dependents on their adaptation to the problem:

$$p_{sélection,i} = \frac{f_{obj,i}}{\sum_{j=1}^{N} f_{obj,j}} \quad (3)$$

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 or several crossing places, depending of the type of crossover. During the exchange of 2 elements, their value can mutate (for example, a 1 becomes 0 and conversely), with a very small probability. It is the mutation.



BEFORE CROSSOVER AFTER CROSSOVER

Figure 5 : 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 of the 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 sort 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 on 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 (hydrogram, 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 built a global fitness function (with all the measured data) to calibrate the general parameters, and local ones are evaluated to fit the local parameters.

4. Numerical modeling of the Warche – Amblève cascade of hydroelectric power stations

In Belgium, between the Bütgenbach dam and Heid-de-Goreux, six hydroelectric power plants follow one another on the Warche and Amblève rivers, with a total head of 407.4 meters. They constituted the so called System of the Eastern Hydraulic Power Plants. The installed power is 19.8 MW, that is almost 23% of the on the flow hydroelectric production of the country (2002).

In order to realize a global optimisation of the hydroelectric production of the system, the whole network has been modelled with WOLF1D, that is almost 60 kilometres of river with more than 1098 real sections data (Dumoulin [12]).

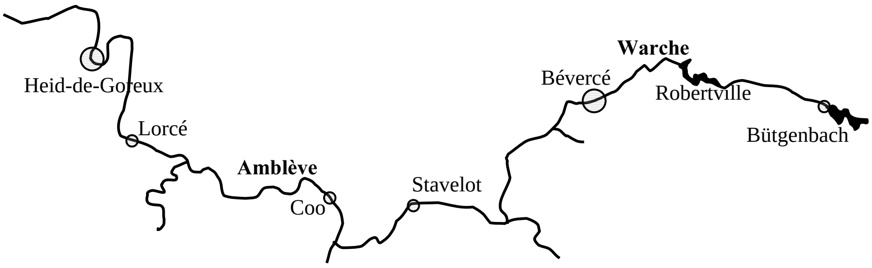


Figure 6 : Drawing of the Amblève and Warche river network

The network is fed upstream by the dams of Bütgenbach and Robertville. There are three tributaries to the main rivers: the Lienne, the Salm and the Warchenne. The discharges in these rivers have been calculated from limnimetric stations data. The 96620 ha watershed of the Amblève has been modelled using WOLFHydro in order to close the global hydrologic balance by taking into account rain contributions.

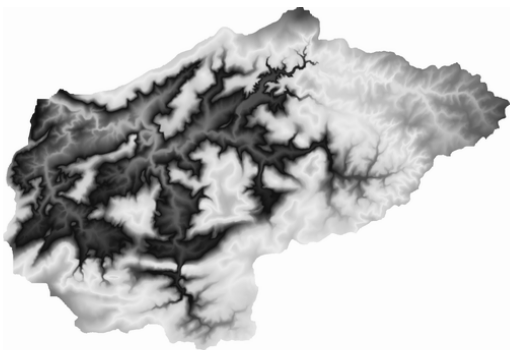


Figure 7 : Topography of the watershed (from WOLFHydro)

5. Optimization of physical parameters and production

In a first time, using water levels and discharge data from eight limnimetric stations on the different rivers, a roughness coefficient for the main rivers of the network has been fitted.

The fitness function was the mean square difference between computed and measured water lines for three different and constant discharges on the Amblève and the Warche. A mean value of 23 has been found for the Manning-Strickler roughness coefficient K_M.

This value has been validated by comparison of measured and computed waves propagation in the network. A value for K_M of 25 has finally been chosen.

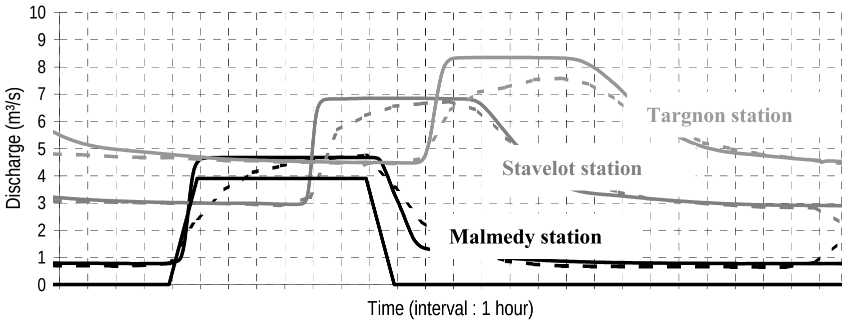


Figure 8 : Measured and computed hydrograms with K_M = 25

A roughness coefficient K_M of 31 has been found for the two main rivers tributaries by the way of steady state water lines comparison.

In a second time, the production of the hydroelectric power plants on a 24 hours period has been maximized by optimizing the hydrogram injected in the network downstream of the Robertville dam. This optimization has been realized taking into account the criteria of security in the network (maximum and minimum water levels and discharges) as well as some production criteria (water volumes available and minimum - maximum reservoir water levels).

The parameter to fit was the shape of the hydrogram injected by the way of the six coefficients T_0, T_1, T_2 (time) and Q_0, Q_1, Q_2 (discharge) of the following figure.

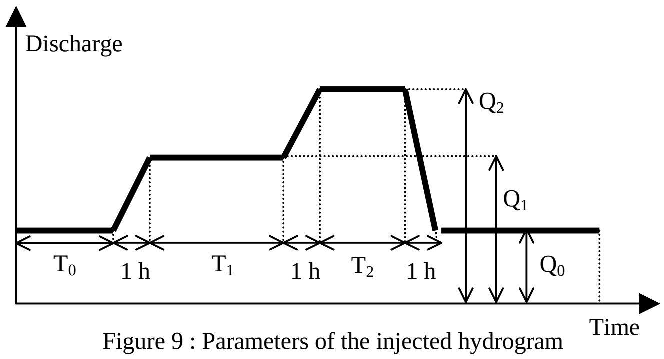


Figure 9 : Parameters of the injected hydrogram

The fitness function was the total benefit obtained from the power plants production on a 24 hours period and taking into account the variation of the selling price of the kWh over the day. Indeed, only a maximization of the production is not sufficient, as the electricity has to be produced when is it interesting to use it, it is when its price is high during the day.

Two simulations have been carried on. One in winter, when the volume of water available per day is important, and the other in summer, when this volume is generally more limited. In order to compare the solutions with real case ones, the optimization process had to considered the same volumes 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. This is due to the good accord of the discharge peak propagation time in the network between the two main power plants with the discrepancy between the two most important peaks of remuneration of the kWh (Figure 10).

In the second case, the increase was 2.1% in production and 1.1% in benefit.

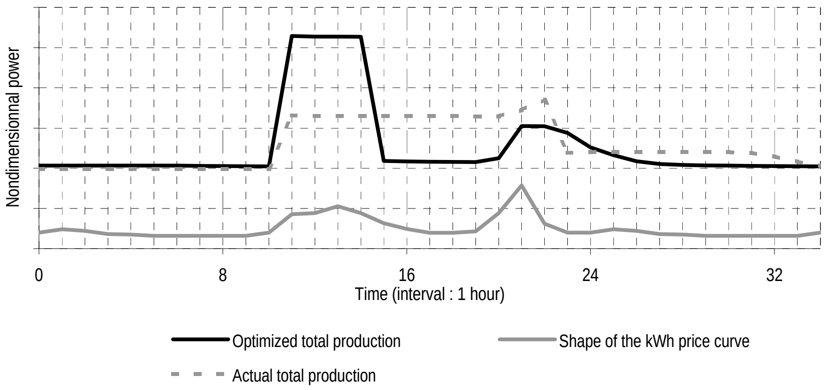


Figure 10 : Evolution of the total production of the power plants

6. Conclusions

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 on their 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 modeling of the hydraulic processes along with an objective calibration of the physical parameters, a significant profit 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 valorize water resources, what is of great importance in the scope of a rational and efficient management of our natural resources.

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