LARGE SCALE 2D NUMERICAL MODELING OF RESERVOIRS SEDIMENTATION AND FLUSHING OPERATIONS

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Abstract: The quasi-3D flow solver WOLF has been developed at the University of Liege for almost a decade. It has been used to carry out the simulation of silting processes in large reservoirs and to predict the efficiency of flushing operations. Besides briefly depicting the mathematical and numerical model, the present paper demonstrates its applicability on the case of a large hydropower project in India. The silting process of the reservoir has been simulated by means of the quasi-3D flow model with a quasi-steady approach. For simulating flushing events, both the topography changes and their interactions with the flow have been carefully handled in a strongly coupled approach. This narrow coupling has required the development of a suitable upwind numerical scheme. Results are presented with 2D- and 3D-views, completed by cross-sections and curves of the variation of key variables. The numerous observations based on those results lead to a global assessment of the silting mechanism and of the flushing efficiency.

Keywords: Numerical model, finite volume, silting, flushing, bank failure, upwind scheme, sediment

1. INTRODUCTION

Practitioners in hydro-engineering are highly interested in powerful tools for the prediction of a large scope of hydraulic behaviours involving complex solid transport processes. Experimental modelling has been considered for decades as the single tool for the design of hydraulic structures. Today numerical models are steadily more available and supply results with an always increasing level of confidence. They are considered as a credible alternative to classical scale models for a large set of applications. In this way, the quasi-3D flow solver WOLF is currently developed and used at the University of Liege for simulating silting processes in large reservoirs and for predicting the efficiency of flushing operations. Other typical applications of WOLF include various aspects of inundation mapping, river basins sustainable management and hydraulic structures design.

Besides a brief description of the depth-averaged model for pure hydrodynamics, the present paper presents the model for solid transport. An application of the model is described in detail in the framework of a hydropower project in India.

2. FREE-SURFACE FLOW SOFTWARE WOLF 2D

The free-surface flow solver WOLF 2D, developed by the Division of Applied Hydrodynamics and Hydraulic Engineering of the University of Liege, has been used to carry out all the numerical computations of silting and flushing processes for the application discussed below. WOLF 2D software solves the 2D shallow-water equations (SWE) on multi-block rectangular grids (Archambeau et al. 2003; Archambeau et al. 2004), dealing with natural topography and mobile bed. A mass balance for bed load sediments is coupled to the hydrodynamic model (Dewals et al. 2002).

2.1 Hydrodynamic mathematical model

In the shallow-water approach the only assumption states that velocities normal to a main flow direction are smaller than those in the main flow direction (Pirotton 1994). As a consequence the pressure field is found to be almost hydrostatic everywhere.

The divergence form of the SWE include the mass balance:

$$\frac{\partial h}{\partial t}+\frac{\partial q_i}{\partial x_i}=0 \tag{1}$$

and the momentum balance:

$$\underbrace{\left[\frac{\partial q_i}{\partial t}+\frac{\partial}{\partial x_i}\left(\frac{q_i q_j}{h}\right)\right]}_{\text{inertia terms}}+gh\left(S_{fi}+\frac{\partial H}{\partial x_i}\right)=0; \quad j=1,2\,, \tag{2}$$

where Einstein's convention of summation over repeated subscripts has been used. H represents the free surface elevation, h is the water height, q_i designates the specific discharge in direction i and S_{fi} is the friction slope. The SWE model simulates any steady or unsteady situation. A modified-SWE model is available in WOLF to take into consideration the vertical bed curvature thanks to an original approach based on curvilinear coordinates in the vertical plan.

The total friction includes three components: bottom, wall and internal friction. The first one is modelled thanks to an empirical law, such as the Manning formula. The friction along vertical boundaries, such as bank walls, is introduced thanks to a physically-based model developed by the authors. The internal friction is properly reproduced by a turbulence closure based either on the Prandtl mixing length concept or on the k-ε transport model.

2.2 Solid transport modelling

A depth-averaged mass balance for the transported solid phase is added to the model.

2.2.1 Mass balance for the sediments

The time evolution of the bed level is balanced by the advective fluxes of solid materials. Hence the continuity equation for the sediments is stated by the well-known Exner equation:

$$(1-p)\frac{\partial z_{\mathrm{b}}}{\partial t}+\frac{\partial q_{\mathrm{b}x}}{\partial x}+\frac{\partial q_{\mathrm{b}y}}{\partial y}=0 \tag{3}$$

where z_{b} stands for the bed level, p is the porosity and $q_{\mathrm{b}x}$, $q_{\mathrm{b}y}$ represent the unit solid discharges in both horizontal directions. Solid load discharges are evaluated by using algebraic relations for both bed and total load. Several of them are available within WOLF.

2.2.2 Gravity-induced solid transport

The sediment discharges result not only from the action of flow-related forces but also from gravity or from a combination of both origins. In the scope of the herein-presented study, this class of phenomena is modelled by an appealing approach in terms of computation time as well as realism of the results (Fäh 1997). As soon as the bank becomes locally unstable, solid particles are assumed to move from one element to its neighbour so that the local slope tends to be reduced to the slope of natural repose γ_{nat}. The stability analysis is based on a threshold value of the local slope, called "critical slope" γ_{cr}. Although simple, this model reproduces the sudden bank collapses, which occur in the case of flushing operations.

2.2.3 Sediment characteristics

As realistic values as possible have been retained for the sediment characteristics in this work. In particular the relative density of the sediments is taken equal to 2.5 and the bed porosity, used in the sediment mass balance only, is estimated at 30 %.

2.3 Numerical implementation of the conceptual model

A finite volume technique is used to solve the equations formulated in a conservative form. An original upwind scheme has been developed for both the hydrodynamic part and the fully coupled model (Dewals 2001). The stability of this second order upwind scheme has been demonstrated through a theoretical study of the mathematical system as well as a von Neumann stability analysis. The source terms representing topography gradients are handled properly.

The numerical implementation of the model is made more sophisticated by several specific features, such as the realistic modelling of transitions between submerged and emerged areas, the interactions between these transitions and the mobile topography, as well as the ability of the solid transport model to distinguish both erodible and non-erodible topographies.

In addition an automatic mesh refinement tool is available in the model to enhance the convergence rate towards accurate steady-state solutions (Archambeau et al. 2003).

The validation of WOLF has been performed continuously by comparisons with analytical solutions as well as field and laboratory measurements.

3. APPLICATION TO A LARGE HYDROELECTRIC PROJECT IN INDIA

3.1 Framework of the study

The hydropower project involves the construction of a large embankment dam, with a crest 500 meters long. The site topography was provided by EDF (Fig. 1). The dam, the approach channel and the spillway specific topographies have been added thanks to the WOLF user interface. Fig. 2 shows 3D views of the downstream part of the reservoir.

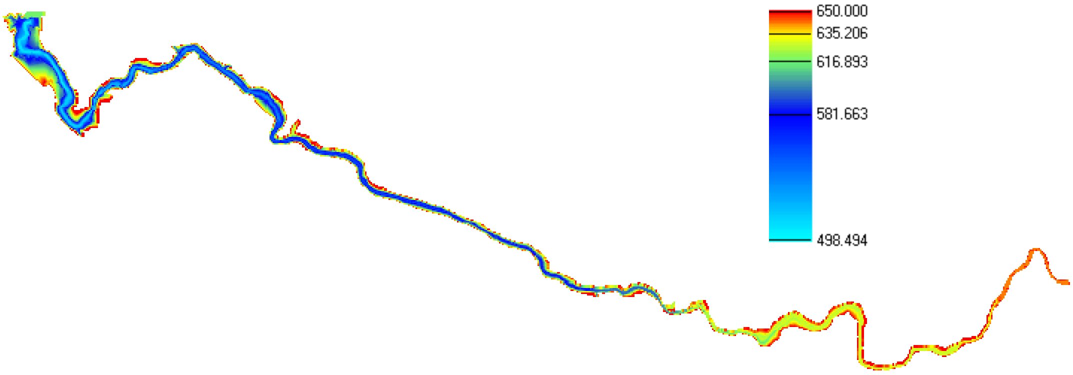


Fig. 1 Digital Elevation Model (m) of the whole reservoir (over 50 km long).

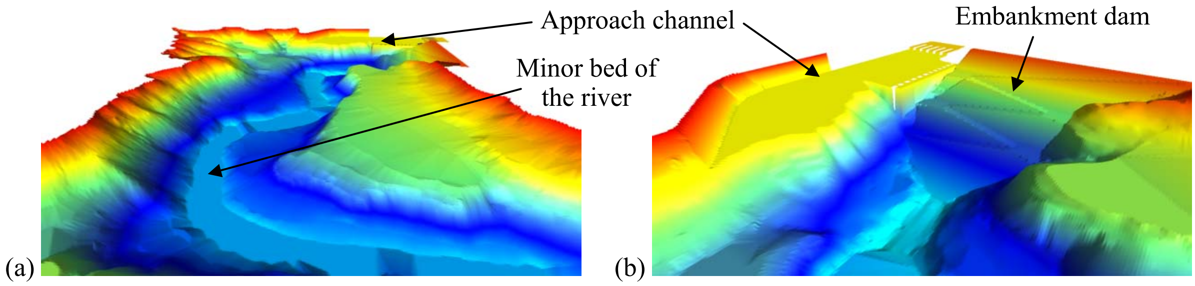


Fig. 2 (a) 3D view of the downstream part of the reservoir. (b) Detail of the dam and spillway topography.

3.2 Simulation of the silting process in the reservoir

The main goals of the first part of the numerical study are the evaluation of the duration of the reservoir complete silting, and the description of the evolution of the sediment front.

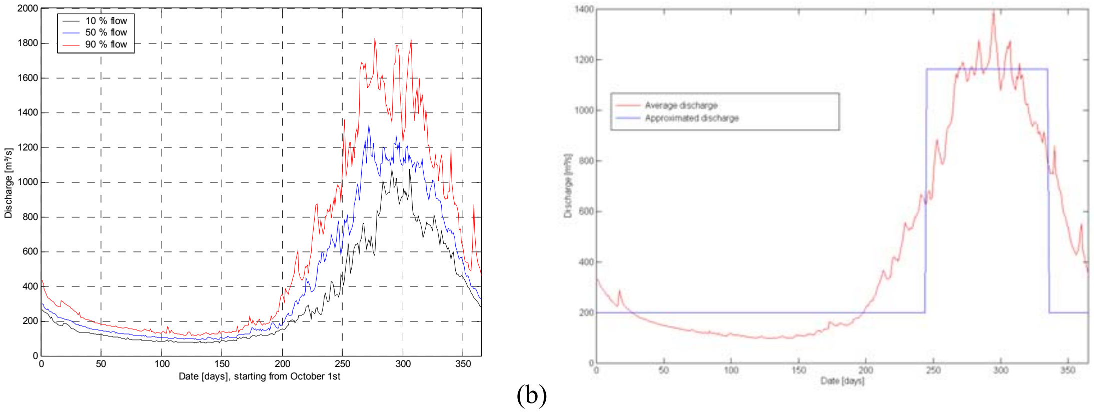
3.2.1 General strategy

The long-term and large-scale study of silting in a reservoir requires so huge computational resources that it is not possible to perform the simulation with a fully unsteady and coupled numerical model. In the present case, a lighter approach, well sustained on the physical point of view, is applied to drastically reduce the CPU time while reserving reliable results. The strategy adopted consists in describing the water flow by a series of 2D equilibrium states, while the bathymetric evolutions remain estimated by a transient computation.

3.2.2 Discharge and boundary conditions

The simulation takes into account the seasonal discharges deduced from the measures obtained at a gauging station located 6 km upstream of the dam. This hydrograph is characterized by high seasonal variations depicted on Fig 3(a). During the main part of the year the upstream discharge in the reservoir is about 200 m³/s, while this latter can be multiplied tenfold during the monsoon. This hydrograph has thus been divided into two parts: the first corresponding to a non-monsoon discharge and the second to a monsoon one. Furthermore both levels will be simply characterized by as seasonal mean value as shown on Fig. 3(b).

At the spillway, a water depth boundary condition is applied in order to respect the mean operation level of the free surface at the elevation 642 m.



(a) (b)

Fig. 3 (a) Yearly distribution of the daily discharges at the gauging station (1986 to 1999 period)
(b) Averaged inflow discharges (red) and approximated value retained for quasi-steady simulations (blue).

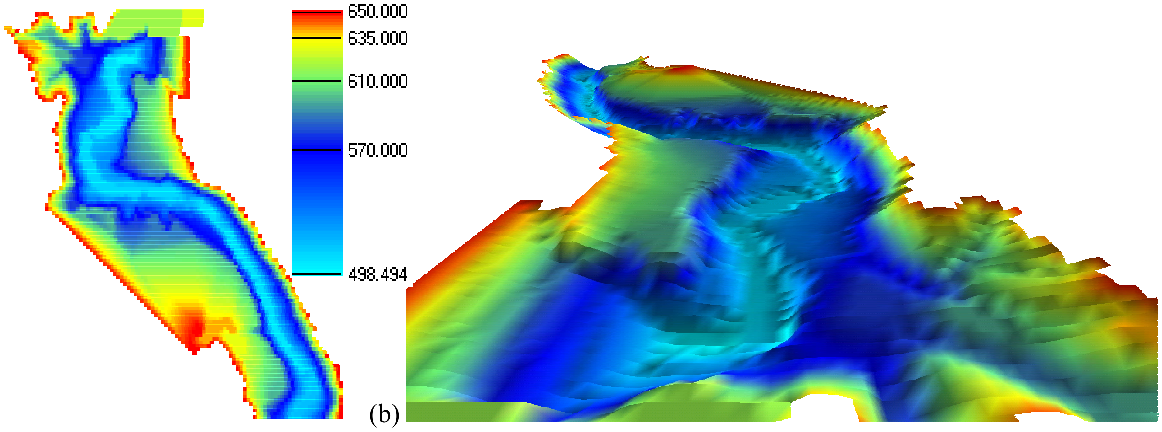
3.2.3 Results

The transient evolution of the bathymetry shows that the propagation of the sediments is widely influenced by the bi-dimensional geometry of the reservoir (Fig. 4 to 6). This confirms the relevance and the usefulness of using a fully 2D computation model. It can also be seen that the sediments front keeps a stiff shape. The plan views on the following figures show clearly this effect. The total filling duration is discussed in the subsequent parapgraph.

3.2.4 Conclusion

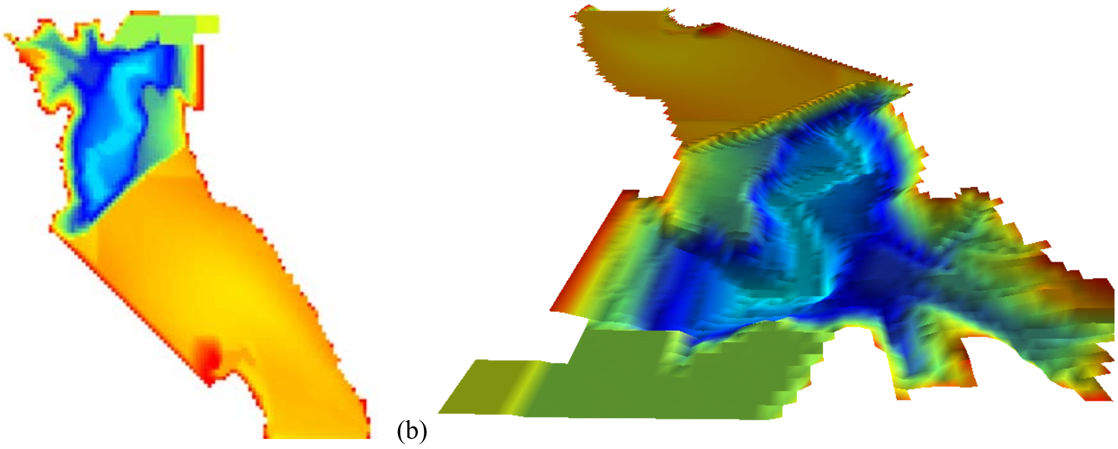
An equilibrium state has been determined for the global topography in the reservoir. This state is obtained for a flood mean discharge of 1762 m³/s and solids inflows in accordance with observations performed in the Bhakra reservoir on the same river (Singh 1999). From this result the total volume of silted material can be easily deduced and then the filling duration estimated thanks to the hypothesis formulated for the inflow sediment concentrations. The total silting time is evaluated to about 1660 days of flood, which represent approximately 18 years.

When reading these final results, the different sources of uncertainties affecting the computation accuracy (lack of accurate data for inflows, grain sizes, transport mechanisms) have obviously to be kept in mind. Nevertheless, let’s recall that fully 2D simulations, mainly unsteady, constitute the state-of-the-art approach accessible up to now for modellers in terms of an acceptable balance between computation time and faithfulness to the physical processes for engineering purpose.



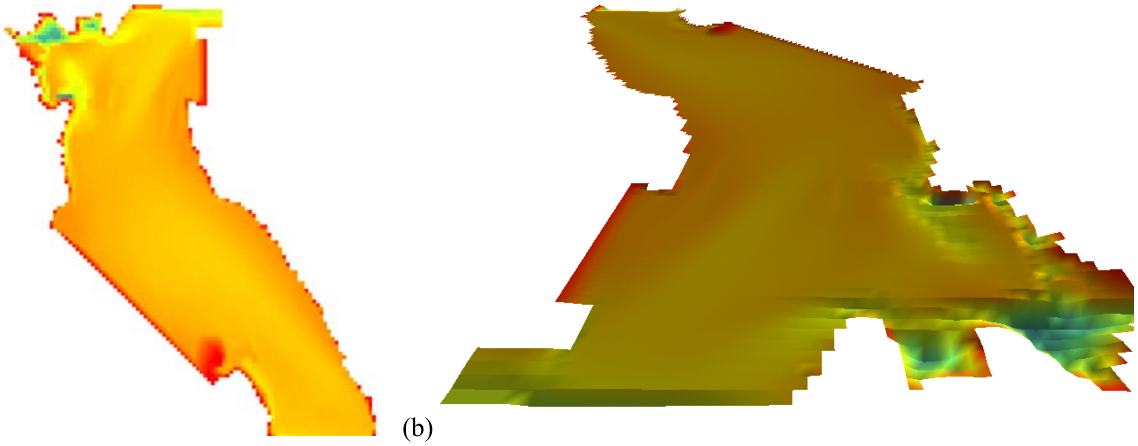
(a) (b)

Fig. 4 Initial topography (m) of the reservoir downstream area: (a) 2D plane view and (b) 3D view.



(a) (b)

Fig. 5 Topography of the reservoir downstream area after 300 days of flood.



(a) (b)

Fig. 6 Topography of the reservoir downstream area after 568 days of flood.

3.3 Analysis of flushing operations

The main goal of the second part of this numerical study consists in predicting the effect of a given flushing scenario in terms of changes in bathymetry in the reservoir.

3.3.1 General strategy

On the contrary of the gradual silting process induced by sediments reaching the reservoir during several decades, a flushing operation is performed in a much shorter period of time. As a consequence the physical characteristic times of morphology changes are likely to take values of the same order of magnitude as those prevailing for the hydrodynamic phenomena. The computation must thus guarantee a tight coupling between the hydrodynamical part of the model and the sediment transport simulation. A proper computation strategy has thus been applied, ensuring a perfect coupling between the flow and the corresponding solid transport.

3.3.2 Boundary and initial conditions

At the upstream boundary of the reservoir a suitable hydrograph suggested by EDF, including the effect of the more upstream section of the reservoir, has been applied. The specific hydrograph flowing into the simulated part of the reservoir during a typical flushing operation is characterized by a decreasing phase, starting from a typical flood discharge (2000 m³/s) and finishing at the constant discharge of 1200 m³/s. These boundary conditions, in two successive intervals, are directly considered for the numerical simulation and are extracted from the hydrograph presented on Fig. 7(a).

The downstream boundary condition at the outflow has been directly deduced from the limnigraph of Fig. 7(b), which represents the time variation of the free surface elevation in the vicinity of the flood spillway as the gates are progressively lifted. The free surface elevation is assumed to remain uniform along the width. The sub-critical regime of the flow at the outflow boundary has been confirmed after the computation in order to warrant that the problem is not ill posed.

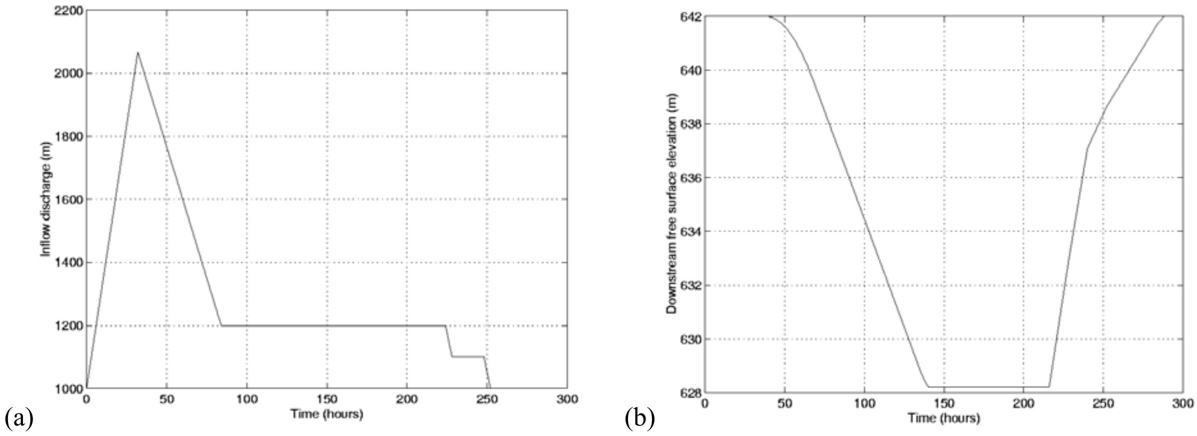


Fig. 7 (a) Typical hydrograph reaching the downstream area of the reservoir at a suitable time for executing a flushing and (b) limnigraph downstream of the reservoir, according to the flushing program.

A hydrograph similar to Fig. 7(a) but giving the solid discharge has to be supplied to the model. This one is simply deduced by applying the solid transport capacity law to the hydrodynamic conditions calculated in the most upstream area of the computation domain.

The initial bathymetric configuration to be considered for simulating the flushing program corresponds to the reservoir nearly fully silted with alluvia. The corresponding topography is illustrated on Fig. 6 and is perfectly similar to the final topographic conditions reached after the numerical simulation of the gradual silting process in the reservoir.

3.3.3 Results

Fig. 8 and Fig. 9 show the transient evolution of the bottom level in the reservoir. The rate of increase in the regenerated storage volume reaches its maximum value between the fourth and the fifth days of flushing. The instantaneous flushing efficiency is thus optimal during this period of time.

The total recovered storage capacity at this time is estimated to a value higher than five million cubic meters. The sediments on the approach channel are however not completely washed out because the main flow “rushes” towards the flood spillway. The intense erosive effect induced by the flow acceleration is concentrated in a new channel created in the neighbourhood of the dam wall. Fig. 10 shows more precisely the results by means of sections in the topography, clearly highlighting the space extension of the flushing effect in a direction transversal to the dam. These cross-sections are precisely located on Fig. 8(a).

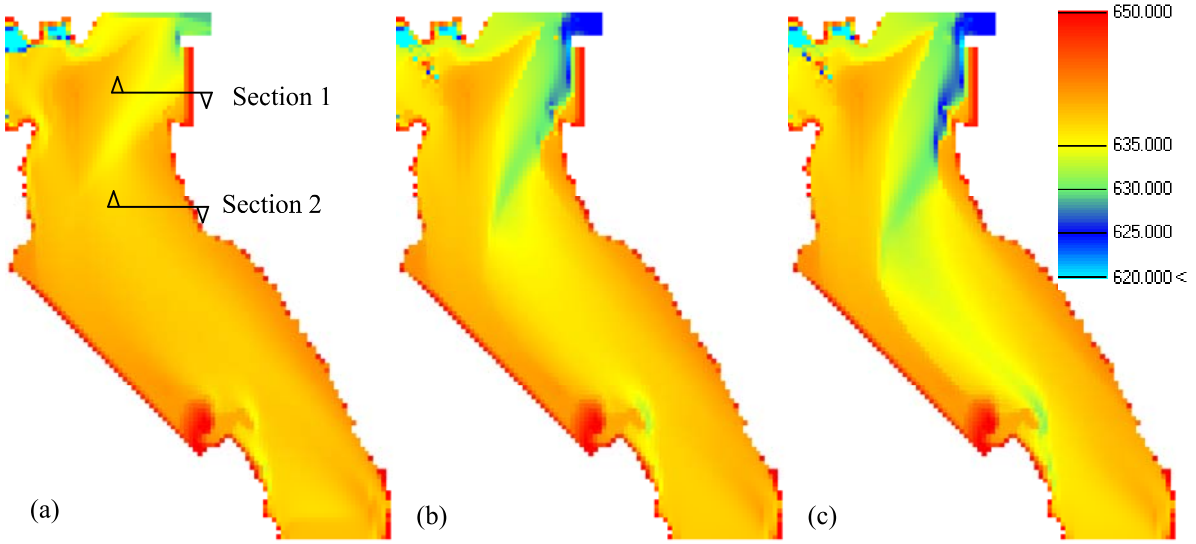


Fig. 8 Topography (m) of the bottom of the reservoir after (a) 3 days (b) 6 days and (c) 9 days of flushing.

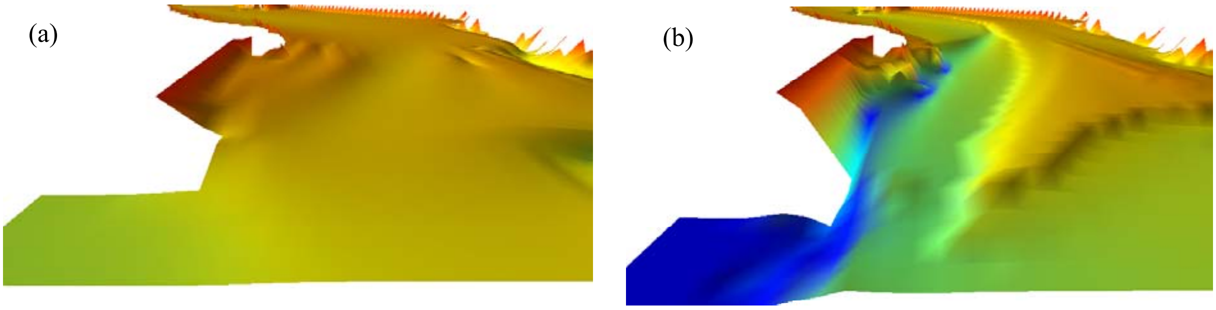


Fig. 9 (a) 3D view of the topography at the beginning of the flushing and (b) 3D view, from downstream, of the bottom elevation in the part of the reservoir close to the dam (m) after eight days of flushing.

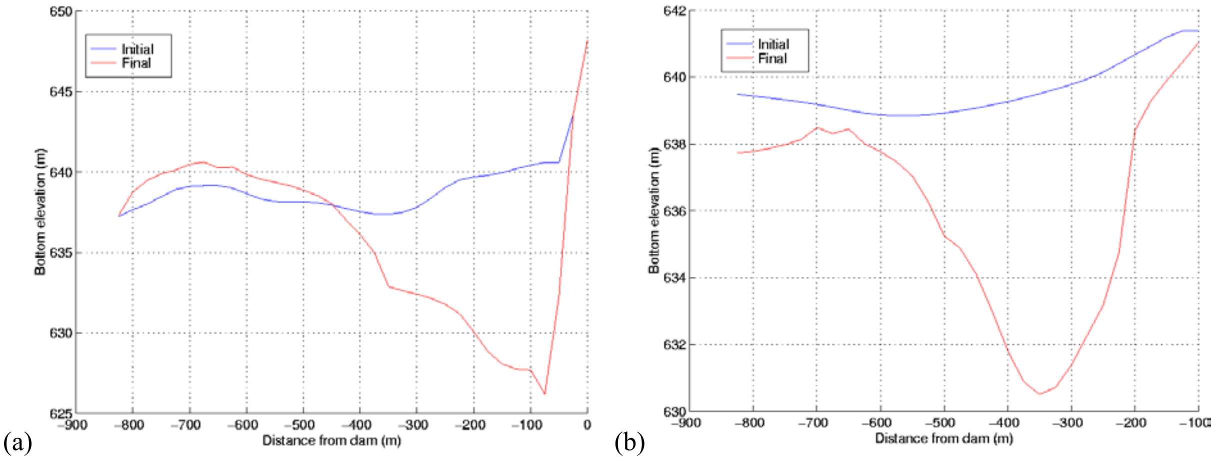


Fig. 10 Cross-sections in the bottom topography, along a direction normal to the dam wall, at the beginning and at the end of the flushing: (a) cross-section 1; (b) cross-section 2 (see Fig. 8(a) for locating the cross-sections).

3.3.4 Conclusion

Highly erosive effects are observed locally but seem unable to extend to a very broad part of the reservoir width and, more particularly, are insufficient to clean completely the approach channel. A well-defined channel appears next to the flood spillway and extends along the dam wall. Not surprisingly, this channel generated by the flushing effect remains relatively narrow in comparison with the total width of the reservoir. According to the modelled flushing scenario, the total recovered storage volume is as high as about 5 millions cubic meters.

In conclusion, the numerous and various reported observations based on the results of the 2D simulation lead finally to a global assessment of the flushing effectiveness. The large set of results can be advantageously exploited in the framework of an economical appraisal of the flushing impact and its general efficiency, by balancing the advantage brought by the recovered storage capacity with the opportunity cost of the volume of lost water (Bouchard 2001). They also recall the question of an economically effective use of a desilting structure.

4. CONCLUSION

The quasi-3D flow model WOLF has been described. Based on a conservative mathematical formulation and numerical scheme, WOLF enables the simulation of any steady or unsteady free surface natural flow, possibly involving regime changes such as moving hydraulic jumps. A computation unit for modelling sediment transport is integrated within the hydrodynamic model of WOLF. This modelling tool has been used to analyse the silting processes and to assess the efficiency of flushing operations in the Indian reservoir.

All conclusions presented above are deduced from simulations taking benefit from a maximum of available data. They are based on the most sophisticated developments available for engineering purpose, both on the theoretical and the numerical levels, keeping in mind the heavy CPU time required. Breakthroughs in computer science being currently so fast, the simulations have just demonstrated their original character when they already open the door to others, still more advanced in terms of space extension and studied physical mechanisms.

Obviously the presented results demonstrate the ability of WOLF to treat complex flow phenomena interconnected with sediment entrainment transport and siltation. Further research is currently undertaken for investigating more carefully grain sorting effects and interactions between the transport rate and the turbulence characteristics.

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