Erosion and sedimentation in a hydropower project: assessing impacts and opportunities

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Abstract

The paper presents first the modelling system WOLF developed by the group HECE at the University of Liege. Next, we give an insight into three recent contributions in the field of hydropower and sediment management. These include *(i)* sophisticated morphodynamic analyses enabling the modelling of a broad spectrum of sedimentation and erosion processes affecting hydropower reservoirs, such as the simulation of flushing operations in shallow reservoirs; *(ii)* the stochastic modelling of future sedimentation in a large reservoir under a semi-arid climate; and *(ii)* hydrodynamic analyses of complex turbulent flow in engineered shallow reservoirs (e.g., settling basins).

1 Introduction

Hydraulic structures play a decisive role in our societies, by contributing to critical services such as water supply, shipping, flood control, low water replenishment, trapping of (contaminated) sediments, as well as renewable energy production and storage. However, the effective operation of hydraulic structures, particularly hydropower schemes, is strongly influenced by the pressures induced by global change on the water cycle, such as more intense hydrological extremes. Besides, their operation becomes increasingly hampered by short- and long-term morphodynamic processes, such as local scour or reservoir sedimentation, and research gaps remain in the development of sedimentation and erosion mitigation techniques which satisfactorily meet our technical, economic and environmental needs (Annandale, 2011).

In this paper, we focus on three aspects, in which our group made recent contributions. First, we developed sophisticated morphodynamic analyses, providing accurate descriptions of sediment dynamics in a wide range of settings of relevance for civil and environmental engineering. Among others, this includes the modelling of flushing operations in shallow reservoirs, as well as other rapid geomorphic flow. Second, we set up a stochastic framework to address the quantification of uncertainties in the estimation of future sedimentation rates for reservoirs under a semi-arid climate. Third, we advanced our basic understanding and our predictive capacity for morphodynamic processes in engineered shallow reservoirs (e.g., settling basins). This involves the analysis of complex turbulent shear flow and the occurrence of bi-stable flow fields.

In the following sections, we first present the modelling system developed in the framework of the whole research program of the group (section 2). Next, we give an insight into the three main contributions mentioned above, mainly based on case studies (sections 3, 4 and 5).

2 Integrated modelling system WOLF

The integrated modelling system WOLF enables the simulation of the whole range of flow and transport processes of relevance for research and real-world applications in civil and environmental engineering. Including a hydrological model as well as 1D, 2D-horizontal, 2D-vertical and 3D hydraulic models, WOLF constitutes a unique tool for rainfall-runoff modelling, flood risk analysis, design of hydraulic structures, sediment transport analysis and morphodynamic modelling, as well as modelling of air entrainment and contaminant transport by surface flow.

The complex turbulent flow involved in these processes are modelled by means of standard and advanced formulations of the Reynolds-Averaged Navier-Stokes equations, as well as depth- and cross-sectional averaged forms of these equations. A unified mathematical description of free surface and pressurized flow is used (Kerger et al., 2011). Sediment transport models reproduce bedload and suspended load transport, together with the resulting erosion and deposition processes (Rulot et al., 2012). In depth-averaged simulations, a two-length scale k-ε turbulence model is used to account explicitly for the anisotropic turbulent mixing induced both by the lateral shear and by the bottom-generated turbulence (Erpicum et al., 2009).

A consistent numerical approach is applied to discretize the different models throughout the whole spectrum of considered scales, from the pipe level up to the reach and catchment levels. It consists in a finite volume approach based mostly on structured multiblock grids. An original flux vector splitting guarantees the stability, accuracy and efficiency of the computations, even under highly transient flow and transport conditions (Erpicum et al., 2010). In 2D-vertical and 3D simulations, suitable techniques, such as the level set approach, are used to track moving interfaces. To accommodate the broad spectrum of time scales involved in sediment transport modelling, the modelling system enables different levels of coupling between the flow submodel and the submodels for sediment transport and morphodynamic updates. The model also includes a customized iterative procedure to account for locally non-alluvial beds (armoured layer, bedrock, concrete) free of mass-conservation error, which was validated based on experimental data (Rulot et al., 2012).

For twenty years, the model has been entirely self-developed by the research group HECE. The computational core is now coded in object-oriented Intel Fortran 2008 and the model offers a user interface enabling GIS-type operations for processing of input and output data. The modelling system also includes an optimization tool based on genetic algorithms, which enables automatic model calibration or the optimal geometric design of hydraulic structures. WOLF offers parallel computing capabilities, suitable both for a single multi-processor computer (OpenMP) and for computer clusters (MPI, CoArray).

Widely recognized nationally and internationally, WOLF is routinely exploited for research, education and consultancy. It was verified against many experimental datasets and other reference test cases (Camnasio et al., 2014; Camnasio et al., 2013; B. J. Dewals et al., 2008; Erpicum et al., 2009; Roger et al., 2009). It has been used in over 30 international peer-reviewed journal publications and within several national and European research projects, particularly in projects focusing on the hydrological impacts of climate change. WOLF was selected by the regional authorities in Belgium to perform all detailed 2D flow simulations to support official inundation mapping, including in the framework of the European Floods Directive (Beckers et al., 2013; Detrembleur et al., 2015; Ernst et al., 2010). It was also used to assess the safety of nuclear reactors situated along Belgian rivers and has been recognized as one of the very few models suitable to conduct fully coupled computations of highly erosive flows such as induced by dam breaching or dam break in natural erodible valleys (B. Dewals et al., 2011). It has also been used in different engineering companies (e.g., in Switzerland) as well as in other European Universities (e.g., Politecnico di Milano).

The development of WOLF is conducted in parallel with experimental modelling at the Engineering Hydraulics Laboratory of ULg, which has made pioneering contributions in hybrid numerical-experimental approaches for the analysis of flow in civil and environmental engineering. The equipment of the 1,100 m² laboratory enables hydraulic tests involving flow rates up to 400 l/s and pressures up to 12bars. Four glass (tilting) flumes are available, with lengths up to 20 m. Cutting-edge measurement devices, such as electromagnetic, acoustic and imaging techniques, enable accurate quantification of spatially distributed 3D flow characteristics and morphodynamic evolutions.

We believe that this combination of numerical and experimental modelling, in a so-called hybrid (or composite) modelling approach, is highly rewarding. It supports not only the development and validation of the numerical models; but it also provides a better access to basic understanding of flow and sediment transport processes.

3 Detailed morphodynamic analyses: application to a hydropower project in the French Alps

Depth-averaged flow and morphodynamic modelling was performed with WOLF to assess sediment management issues in the largest on-going hydropower project in France. The project is located in the South-East of France on a reach of river Romanche, which is a tributary of river Drac (itself a tributary of river Isère). The considered river reach is a 10 km long, with an overall chute of about 270 m. The mean flow rate is 45 m³/s.

Six existing hydropower plants are located along this river reach, together with five existing dams at the different water intakes. They will all be removed, and replaced by just a single dam and water intake in the upper part of the reach. A 9 km long gallery of almost 5 m in diameter is being excavated to divert the water to a single underground hydropower plant located downstream. The upstream dam will create a new shallow reservoir upstream, extending over about 2.5 km.

3.1 Analysis of issues related to sediment transport and river connectivity

A number of analyses were required, several of them having direct links with sediment transport and river connectivity. This includes:

- the design of the dam and water intake, with fish passage issues
- sedimentation in the new reservoir
- and sustainable management of these sediments

In addition, as highlighted in the title of this paper, the project causes not only impacts related to erosion and sedimentation; but it also offers opportunities, such as river restoration in the bypassed reach where all existing dams and hydropower plants will be removed, thus enhancing connectivity of the river.

The aspects to be analysed may be classified:

- either based on their characteristic scales: from structure up to reservoir and reach levels;
- or based on the degree of complexity of the involved processes: from mainly shallow flow to significant sediment transport and morphodynamics, and up to complex 3D aerated flow.

For each part of the analyses, the most relevant approach was selected in-between numerical modelling, physical modelling or a combination of both. As a result, most aspects were handled through numerical modelling, with connections in-between them and with the physical modelling.

3.2 Design of the dam and water intake

To support the validation of the dam and water intake design, a combination of numerical and physical modelling was undertaken.

The flow in the far field of the structure was simulated by a depth-averaged flow model with a two-length-scale k-ε turbulence model. The simulation covered part of the upstream reach as well as the entry into the channelized part of the reservoir. The two length scales involved in the k-ε model reflect the influence both of the turbulence generated by the bed shear stress, mainly in the river-like flow upstream, and of the horizontal turbulent mixing in the reservoir.

For validating the design of the dam and water intake, the results of these numerical simulations were used for defining the extent of a dedicated physical model of the near-field of the structure, and to provide this physical model with adequate inflow boundary conditions. This helped to save time and money by optimizing the extent of the physical model and it also enabled the use of a larger scale factor, thus minimizing both the scale effects and the measurement errors.

The physical model was operated to check the design of the structure under normal operation as well as with a partly submerged wall at the inlet of the water intake. This wall was designed to create a superficial flow towards the downstream reach, preventing thus small fishes from entering the water intake and the gallery.

3.3 Reservoir sedimentation and sediment management

The sedimentation issues in the reservoir involve processes characterized by very different temporal scales:

- from a few hours for sediment transport through the reservoir,
- hours or days, for sediment management operations, such as flushing operations,
- and months or years for accumulation of sediments in the reservoir.

To accommodate these very different time scales, the modelling system WOLF enables different levels of coupling between the flow submodel, the sediment transport submodel and the model for morphodynamic updates. This lead to the following analysis steps:

- the reservoir cut-off diameter was assessed with a Lagrangian approach, without feedback from sediment transport on the flow, since there is no significant morphological change at this time scale;
- the pattern of deposits in the reservoir was determined based on a sequential resolution or the application of the morphological acceleration technique, which are valid due to the relatively slow morphological response during reservoir sedimentation;
- finally, a synchronous resolution of the flow and morphodynamic submodels was applied to simulate hydraulic flushing operations, which involve fast interactions between flow and morphodynamics, as well as changes in flow regime.

3.4 River restoration opportunities

Opportunities for river restoration were analysed in the reach where existing dams will be removed. Removal of the dams will restore fish passage and improve the overall longitudinal connectivity of the river. However, dam removal may also lead to the destabilization of the upstream reach, where flow is accelerated as a result of the dam removal, particularly during floods.

In order to minimize the stability concerns, numerical simulations have been used to compare different options, such as: complete dam removal *versus* complete dam removal with a widening of the main riverbed to compensate for the expected increased flow velocity. Bed stability parameters could be deduced from the numerical simulations, which were conducted for flood discharges of different return periods and for the different scenarios of dam removal.

A simple threshold channel analysis was performed. This approach is valid due to the strong deficit in sediment supply in this particular river reach, mainly as a result of the presence of large reservoirs further upstream and due to the morphology of the upstream valley.

For some of the five dams to be decommissioned, the simulation results revealed that simply removing the dam was relatively safe, as the extent where bed protection is needed remains fairly limited. In contrast, at other dams, a large scale destabilization of the bed profile could result from a simple dam removal. Therefore, the model was used to design improved solutions, while preserving the objective of enabling fish migration.

4 Reservoir sedimentation in a semi-arid watershed

In this second case study, the focus is set not on the details of the pattern of sediment deposits within the reservoir, but more broadly on the overall sediment yield to the reservoir. The reservoir of interest is located in the North of Algeria. It has a catchment of about 900 km². The initial reservoir capacity was almost 300 M m³ and, since it was commissioned in 1986, it has faced a high siltation rate of about 2 M m³ every year. So, the main goal of this research was to estimate how this siltation will progress in the future (Adam et al., 2014).

First, we computed the past inflows, which were not available. We used measured time series of the pool level and of reservoir outflows for irrigation and water supply. These services are highly seasonal. We also used the time evolution of evaporation depth, which follows a pretty regular seasonal pattern. These two components contribute together to 98 % of total reservoir outflows; the rest being water releases through the bottom outlets and various leakages.

The computed inflows to the reservoir show a very high variability, with a mean discharge close to 1.5 m³/s, but peak discharges exceeding 200 m³/s. Nonetheless, these inflows follow also a seasonal pattern, with distinctive wet and dry periods. A complete statistical characterization of these inflows was performed. All the details are provided by Adam et al., (2014).

This statistical characterization enabled stochastic modelling of future sedimentation in the reservoir. The stochastic features of the modelling lead to a quantification of uncertainties resulting from hydrological variability. These are information of very high relevance for decision-making related to sustainable sediment management at the reservoir site. This model is readily available and is rather straightforward to transfer to other sites.

5 Flow and sedimentation in engineered shallow reservoirs

A third aspect of our research on flow and sedimentation issues in hydropower projects consists in a series of contributions to advance the understanding of fascinating turbulent flow and sedimentation patterns in engineered shallow reservoirs (Dufresne et al., 2012; Dufresne et al., 2010b). These are very common structures both as part of hydropower schemes (e.g., settling basins, compensation basins …), and also in a wider context fluvial and urban hydraulics (e.g., as a part of sewage networks …). They also constitute a useful idealization of more complex configurations, providing thus a better insight into individual flow and sediment transport processes.

Despite a simple geometric setup, such as a rectangular horizontal shape, the obtained flow patterns are characterized by complex large-scale turbulent structures, the occurrence of bi-stable flow fields and two-way couplings between flow and sediments (Camnasio et al., 2013; B. J. Dewals et al., 2008). The flow field in these rectangular shallow reservoirs may correspond either to a straight jet, or to a reattached jet, or even to a meandering flow. These different flow patterns have a critical influence on the trapping efficiency of the tank.

To investigate this complex flow behaviour, we first combined numerical simulations with analytical stability analysis (B. J. Dewals et al., 2008). The analysis revealed hysteresis effects, which were later confirmed by means of a tailored experimental setup at ULg (Dufresne et al., 2010a) and based on numerical simulations (Dufresne et al., 2011). This analysis also (Dufresne et al., 2010a):

- clarified the influence of hydraulic parameters (such as inflow Froude number) on the flow patterns,
- characterized the variability of the resulting flow field
- and delivered a first prediction formula to forecast the occurrence either of a straight jet or of a reattached jet.

This formula has since been confirmed by all experimental results published so far (Camnasio et al., 2011). Practical guidelines were also derived to enhance the efficiency of sediment traps (Dufresne etal., 2012; Dufresne et al., 2010b).

Based on numerical analyses, we contributed to the analysis of the influence of asymmetric locations of the inlet and outlet channels on the velocity fields and sedimentation patterns in these reservoirs (Camnasio et al., 2013). Consistently with our previous findings, the existence of bi-stable flow fields was highlighted and significant feedback effects of sediment deposition on the flow field were revealed and explained.

Recently, we investigated meandering flow occurring in shallow reservoirs. By means of large-scale particle image velocimetry (LSPIV) and proper orthogonal decomposition (POD), this research provides the first ever experimental quantification of the frequency and spatial modes of the meandering jet in such reservoirs (Peltier et al., 2014a; 2014b). The research also delivered an extended typology of the flow fields in engineered shallow reservoirs, enabling the prediction of the flow pattern from the reservoir geometry and the inflow and outflow conditions (Peltier et al., 2014a). Finally, a mind-blowing agreement with numerical computations was obtained for the dominating modes. Compared to a symmetric flow pattern, the meandering flow leads to a dramatic increase in the trapping efficiency and in the lateral dispersion of sediment deposits, as revealed by our morphodynamic simulations.

These findings are of high engineering relevance, for instance for planning maintenance operations or for developing operation rules of these shallow reservoirs, as well as at the design stage of these structures.

6 Conclusion

In this paper, we presented several analyses of complex flow and sedimentation processes in real-world engineering applications. The analyses all built upon interactive exchanges between different components of the modelling system WOLF, as well as between numerical and experimental modelling. This approach proved to be particularly beneficial and efficient to perform the wide range of flow and sediment transport analyses necessary to contribute to comprehensive hydropower projects, particularly as regards reservoir sedimentation issues at different scales, ranging from the structure level up to the catchment level.

7 References

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