Design and modeling of reservoir operation strategies for sediment management

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1. Introduction

Appropriate operation strategies that allow for sediment flushing and sluicing (sediment routing) can reduce rapid storage losses of (hydropower and water-supply) reservoirs. In this study we have shown, using field observations and computational models, that the efficiency of these operations increases when utilizing dynamics of flow and sediment movement. For instance, operating at a minimum level during the sediment-laden high flows at the start of the flood season, and a rapid short draw-down flushing event later-on, allows much of the incoming sediments to pass the reservoir. Hence, operations can be more effective when using the dynamics of the high river flows, arrival of suspension peaks, and timing of emptying and filling of the reservoir.

This study shows how state-of-the-art modelling techniques can reproduce the morphodynamic processes in the reservoir, and how they can be combined in a systematic way as essential tools to design more effective strategies. Since the large-scale morphodynamics (delta formation, channel development, etc.) determines the loss and gain of reservoir storage, the modelling techniques should reproduce and combine detailed physical processes such that it simulates the large-scale response properly. This study also shows how such an approach can compensate for lack of data, if the outcomes are integrated to useful management parameters, such as trap-efficiency and annual volume loss.

![Figure 1: Sluices of Upper Atbara Dam Complex under construction, February 2014.](Image)

The research is carried out in connection to the completion of a new hydropower/water-supply dam complex at the confluence of the Atbara and Setit Rivers (forming the most Northern main tributary of the Nile) in Sudan. The operation of the new dam will be based on decades of experience with sediment management in the existing Kashm El-Girba Dam (KED) and reservoir just downstream of this new dam (47 m high KED, reservoir 1300 Mm³, started operation in 1964). The new reservoir has a storage capacity of 3688·10⁶ m³ (2508·10⁶ m³ active storage) and a hydropower station with installed power of 320 MW. The dam complex actually consist of two dams because it is located just before the confluence of Setis and Atbara River. Spilling capacity is 11,800 m³/s (Burdana dam: 6 bottom outlets and 2 surface sluices), and 7,300 m³/s (Rumela dam: 4 bottom outlets and 1 surface sluice) respectively.

2. Reservoir sluicing and flushing in this study

Sediment sluicing (or draw-down routing) is the operation during which reservoir levels are lowered during a high inflow, such that sufficient velocity is maintained to keep sediments in suspension (Kondolf et al., 2014). Flushing is the operation where water levels completely drawn down to generate increased velocities to erode existing deposits (Morris and Fan, 1998). While sluicing still allows power generation, flushing means complete shutdown.

Flushing can remove deltaic deposits (that directly affect the active storage) only with full drawdown of water levels, as the erosion away from the dam is driven by backwater effects. Nevertheless, most of the erosion remains limited to a flushing channel. If water-levels remain low for some time, the channel gradually grows by bank-erosion processes, but most of the ‘flood plain deposits’ remain fixed. An extreme example of such channel formation in reservoir deposits, is the river channel that formed after removal of the Elwha dam in USA, and beautifully visible in Figure 2.

![Figure 2: Erosion channel developing in Elwha Reservoir after removal of the hydropower dam (photo Elain Thompson, Associated Press).](Image)

Also (actively) sluicing of sediments is an operation that relies on backwater effects (increased velocities by reduced depths over the full reservoir length), and therefore requires some drawdown of water levels as well. To design these flushing and sluicing operations,
knowledge is required on the inflow of sediment, the settling and erosion processes, availability of water (to be able to fill again), and environmental impacts to the downstream.

Note that in this study we did not consider other types of sediment management for reservoirs.

2. Kashm El-Girba Dam and Upper Atbara Dam Complex

Operation of the new Upper Atbara Dam Complex (UADC) will follow a similar operation rule as KED, including sluicing (sediment routing) and draw-down flushing during the flood season, see Figure 3. The timing of sluicing, flushing and filling, and the associated levels have been subject of study. During rapid storage loss of KED during the first 10 years of operation (40 Mm³/year), these flushing and sluicing operations were designed already in the 1970’s.

Records show sediment-concentration peaks of 100 kg/m³ (100,000 ppm) at the dam outlet, see Figure 2. The highest concentration peak occurs during the first day, after the discharge peak. In the second day, the concentrations drop and reach the values of inflow concentrations.

2. Modeling approach for operation strategies

To design operation strategies it is useful to consider the overall sediment balance of the system, coupling all the relevant individual components. The components or toolbox should be selected on basis of a good understanding of the processes. Figure 4 presents the processes that are relevant for the sediment balance and management of KED and UADC.

A distributed open-source hydrological model (WFLOW, OpenStreams), a sediment module (GIS based), and river-basin model (RIBASIM) have been coupled to generate discharge series and sediment loads (involving time-dependent and seasonal variations). These account for all possible changes in the catchment (such as upstream dams, deforestation, climate change, etc.). Interestingly, an important part of the upstream catchment is located in Ethiopia. There are no data exchanged between the countries. Moreover, the Ethiopians are constructing a hydropower cascade in the upstream Setit River (Tekeze dams). The lack of data, and the impacts of the new dams, are all tackled by using the catchment/basin model with global data sources.

Subsequently, a 2D (quasi-3D) morphodynamic model, using Delft3D, calculates the detailed reservoir processes. The Delft3D model simulates the distribution of sediments of mixed gravel, sand and mud fractions: both for the reservoir and river channels directly up- and downstream. Figure 5 shows a detail of the curvi-linear computational grid, with refinement at the thalweg of the rivers.

The river is characterised by high loads of fine sediments (10 to 40 kg/m²) during floods (peak flows for each branch are in the order of 4 to 6 thousand m³/s, 1/10-year floods, July to September). The annual load of the Atbara River is in the order of 60 million tons, of which about 12 million tons is still deposited in KED annually (despite the operations). About 80% of the load is coming from the Setit River, but this may change because of impacts of new dams in the upstream Setit or Tekeze River in Ethiopia.

Figure 2: Recorded sediment concentrations at Kashm El-Girba dam during 2012 flushing event.

During flushing of KED, water levels are reduced by about 24 m, for a period of 2 days, with discharges peaking over 6000 m³/s at the first day.

Figure 4: Analysis of the most relevant processes that determine the sediment behaviour in the reservoir.
The model uses a morphological factor to reduce computation time (bed-level change at each flow time-step is multiplied with this factor, and end time of simulation will be the original flow-time divided by this factor). To make sure that all discharge variations in a year are accounted for in the right morphological time, the flow hydrograph has to be compressed (same annual hydrograph passing in a time equal to 1 year divided by the factor). However, this creates a mismatch between rates of filling and emptying, and the inflow volume (that is compressed). During filling, water level is lagging behind, as inflow volume is much smaller. This was solved partially by adding or extracting a temporary extraction from the water surface (similar to rain or evaporation). However, in Delft3D this extra diffusive inflow is only added to the mass balance, hence large volumes lead to deceleration of flow in the lake (they absorb the momentum of the reservoir flow). This will cause sediment to settle faster.

Simulation scenarios included variations in discharge hydrograph (wet year versus dry year), variations in inflow concentration, minimum operation level, flushing operation (with or without), and time of filling (at end of flood season). Figures 6 and 7 show computed bed-level change (relative to present topography) for a simulation with and without sediment sluicing. With sluicing deposition is more diffused and more located in the dead-storage reach (and less severe). With sluicing also the main channel remains more or less clear, with most sediments settles on the banks.

For the observed morphological impacts, fine sediments (i.e. silt and clay) are dominant. Bed-exchange is simulated using the approach of Partheniades-Krone (Partheniades, 1965). This defines entrainment flux at the bed 

\[ E = M \left( \frac{\tau_b}{\tau_{cr, e}} - 1 \right) \text{ if } \tau_b > \tau_{cr, e}, \]  

\[ E = 0 \]  

else \( \tau_b \leq \tau_{cr, e} \), and deposition flux 

\[ D = w_s c_b (1 - \frac{\tau_b}{\tau_{cr, d}}) \text{ if } \tau_b > \tau_{cr, d}, \]  

\[ D = 0 \]  

diffusion parameter, \( \tau_{cr} \) = critical shear stress.

As duration of erosion events (sluicing/flushing) is limited, the rate of change of sediment removal highly depends on the critical shear stresses of silt and mud fractions (the dominant fines), and erosion parameter \( M \). Hence, it is important to obtain these settings from time-dependent topographic measurements during erosion events. In the present study, data for these parameters were lacking. Therefore we tested the sensitivity of the model. The following table shows the possible range. In Case 1 the absolute sedimentation and erosion fluxes ate the bed are bigger than Case 2, but the net flux is almost the same. Consequently the resulting morphological changes at the
end of each year are similar for both cases. However, the speeds at which the changes occur are much different. This range is selected on basis of observed changes during sluicing and flushing in KED Reservoir.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>0.0001</td>
<td>0.001</td>
</tr>
<tr>
<td>$w_c$---erosion</td>
<td>0.1 mm/s</td>
<td>0.08 mm/s</td>
</tr>
<tr>
<td>$r_c$---sedimentation</td>
<td>1000 Pa</td>
<td>20 Pa</td>
</tr>
</tbody>
</table>

Table 1: Range of sediment parameters for silt and clay

Although, this suggests a failure of the approach, it is not as bad as it looks. The detailed models are able to reproduce the physics still quite well, considering that there is significant lack of data. Furthermore, the decisions on operation rules are primarily based on overall storage loss and loss of power production (e.g., energy production as calculated with RIBASIM). The storage loss (or gain) is expressed by the trap efficiency (%) on an annual basis, which is defined as the ratio of [annual sedimentation volume]/[annual volume of incoming sediment]. A high value (100%) means that all sediment is trapped. For KED the sediment management has resulted in a trap efficiency of about 20%.

Using the results of the Delft3D simulations for different scenarios, a graph can be drawn as shown in Figure 8.

Figure 8: Trap efficiency (annual) in % calculated from simulations for all scenarios

In this graph, the trap efficiency is plotted as two bars per scenario, which reflects the bandwidth of outcomes. This bandwidth follows from the sensitivity analyses (e.g., the sediment parameters of Case 1 and Case 2 in Table 1). Generally this graph shows lowest trap efficiency for wet years with sluicing and full drawdown flushing, and start of filling as late as possible (i.e., Sept. 9). Large differences can be found between the wet and dry years, as well as between high and low sediment inflows. This proves the importance to consider the need of system modelling, in which reliable predictions of inflow of water and sediment are equally important as a good prediction of the processes within the reservoir.

Also the effect of flushing is significant for UADC, and most effective if all sluices are used. The highest velocities and erosion rates occur in the simulations when the water-level is dropping as fast as allowed, and a surface wave is propagating upstream. In this period also some of the overbank deposits will erode. After most of the water is drained, the velocities drop rapidly again, and the remaining flow is running mostly through the original (narrow) river channel. No further erosion of the bank deposits occurs. Similar to the observed concentration at KED, the highest computed concentrations occur during the first phase of the flushing event, when water levels are dropping rapidly.

Additionally, we judged the effectiveness of mitigation measures with annual volume loss (%), which reflects the loss of lifetime of the reservoir. These losses are in the order of 1% (with management) to 2.5% (without management) per year. For Burdana branch (Setit river) these numbers are doubled, assuming that sediment concentrations remain higher in this reach despite the construction of the Tekeze dams in Ethiopia.

3. Conclusions

This study provides a reference for other studies that aim at design of mitigation measures for reservoir-sedimentation issues. State-of-the-art approaches for catchment hydrology and erosion, linked to data sources, and for morphodynamics of the lakes and rivers, are integrated to a system approach.

Because detailed 2D/3D models can reproduce the physical conditions with much detail, they provide important insight in effect of mitigation measures even if data are poor. Nevertheless, for decisions on operation, the outcomes are lumped and integrated to provide overall indicators for trap efficiency and annual storage loss (and impacts of mitigation measures on these indicators).

A good approach for hydrology and sediment yield (catchment models) is equally important for assessment of reservoir sedimentation and mitigation, as a good approach for the reservoir itself.

The system approach allows the study of joint operation, including timely sediment flushing and sluicing operations, if a dam cascade is considered.

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References