Reservoir sedimentation: different type of flushing - friendly flushing example of genissiat dam flushing

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Reservoir Sedimentation
Different Type of Flushing - Friendly Flushing
Example of Genissiat Dam Flushing

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ABSTRACT

CNR (Compagnie Nationale du Rhone) France, has built and operates 18 multipurpose developments (one dam: Genissiat Dam and 17 Run of the River) along the Rhone River, France. IRSTEA (Institut national de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture) is a famous French Research Centre (previous name was CEMAGREF) and is specialised in water resources. Both companies have been working in close collaboration for years in hydrology and sediment management.

Reservoir flushing is becoming a very important and complicated worldwide issue. On the one hand, water resources demand increases with growing world population, while the capacity of reservoirs decreases because of sedimentation. So flushing is necessary to maintain the reservoirs at the best operating capacity. In some countries, reservoir flushing is regulated and mandatory i.e. European Directives requiring sufficient sediment transport downstream of the dams.

On the other hand, reservoir flushing must be organized in order to respect the environmental constraints downstream of the dams, regarding the concentrations of fine sediments. '*Environmental friendly flushing*', to send only solid concentration that environment can withstand, is required today, while '*hard flushing'* to send as much sediment as possible, resulting in probable damages to environment, is not sustainable and must be avoided.

Friendly Flushing of Genissiat dam, organised by CNR every 3 years for the past 40 years on the Upper Rhone River, is taken as example.

Physical phenomena regarding sediment transport during flushing are emphasized, both in the reservoir and downstream of the dam. A particular focus is made on the 1D mobile bed model RubarBE, developed by IRSTEA, which has significant interest for the understanding of flushing dynamics.

Key Words: dam sedimentation flushing mathematical modelling

1. SEDIMENTATION IN RESERVOIRS

Bed load deposits at the entrance of the reservoir which is not always at its maximum level, while suspension deposits in the whole reservoir. Generally few materials can cross the dam except the wash load, too fine to deposit, see Fig. 1.

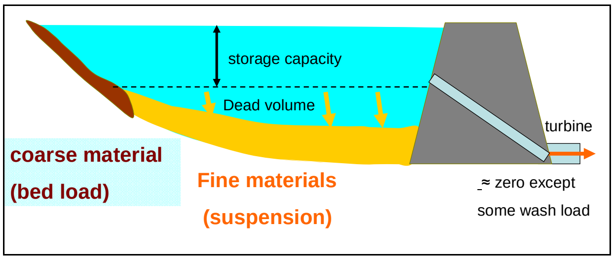

Figure 1. Reservoirs long profile - Deposition location

Coarse materials produce bed aggradation upstream in the river and can increase inundations during floods.

Sedimentation leads to loss of capacity of the reservoir, to the detriment of water supply for agriculture - potable water, production of energy at peak hours and flood mitigation.

2. DOWNSTREAM OF DAM CONSEQUENCES

2.1 Small Reservoirs

Small reservoirs (some million m^3) trap solid materials but not the floods. The dam can be called: *Sorting Dam* [9]. Shortage of sediment (coarse materials) leads to bed incision (*hungry water effect, M. Kondolf concept*). Bed incision can stop if enough coarse materials are present in the bed and if not already '*eaten'* by dredgers.

Bed incision is a very sly phenomenon because it begins slowly and cannot be stopped afterwards. On many French alpine rivers, bed incision has reached up to 14m since the 1950's [2].

Consequences of bed incision are numerous: problems of water table levels and wells, water supply, scouring of dyke toe and piles of bridges, shortage of local inundations sending aggravated floods downstream and finally shore erosion.

2.2 Large Reservoirs

Very large reservoirs (some billions m^3) trap solid materials but also mitigate the floods or completely store them. The dam can be called: *Black Hole Dam* [9].
Downstream of the dam the '*conveyor belt*' transporting solid materials is almost stopped. So the river is not able to convey solid transportation coming from the downstream tributaries and bed aggradation happens.
This phenomenon is the contrary of *Hungry Water* and can be called *Replete Water* [9].
For instance in Vietnam, downstream of the Hoa Binh dam with $5Bm^3$ capacity, there is important bed aggradation of the Red River downstream Thao and Lo tributaries, see Fig. 2.

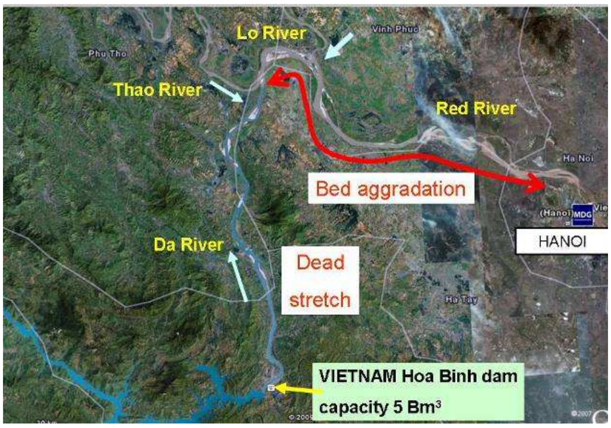

Figure 2. Bed aggradation downstream Hoa Binh dam

3. DIFFERENT KIND OF FLUSHING

3.1 Pressure Flushing

First idea to flush the reservoir is to open sometimes the bottom gate. The level of the reservoir remains the same in order not to loose water or/and energy.

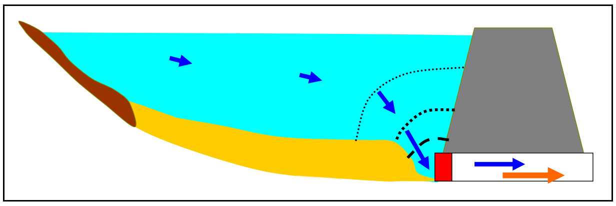

Figure 3. Pressure flushing principle

For safety reason the bottom gate must be always ready to work, so to keep free of sediment the area close to the gate is necessary. Nevertheless Pressure Flushing it is not consistent for flushing the whole reservoir because velocities are too low, except very close to the bottom gate, see Fig.3.

3.2 Drawdown Flushing

Reservoir level is lowered using the bottom gate in order to increase velocities. Sediments move. Maximum of sediments is sent downstream of the dam, without regards to environment, see Fig. 4.

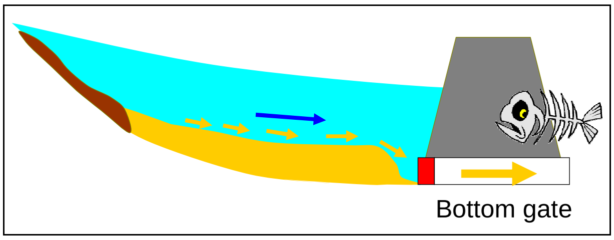

Figure 4. Reservoir long profile with drawdown flushing

Hard Flushing is efficient but too high and uncontrolled concentrations are sent downstream. Damages on environment can be huge. Aquatic life is damaged, fishes are directly killed and spawning areas are clogged. This solution is not sustainable and must be avoided.
Compared to *Friendly Flushing* explained afterwards, this type of flushing without regards to concentration sent downstream can really be called *Hard Flushing.*

3.3 No Flushing

To do nothing is often the choice made by operators. There are no visible consequences during decades. But materials slowly deposit in the reservoir until equilibrium is at last reached when the reservoir is almost full, see Fig. 5.

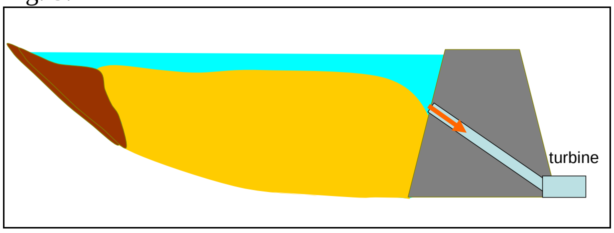

Figure 5. Reservoir long profile with No Flushing

Then there is almost no more storage capacity for agriculture. Fairly profitable peak energy is no longer possible. Run of the River production indeed remains possible. But fine sediments now cross the reservoir, the pipes and the turbines, damaging turbine blades by wearing. Blades must be repaired very often with associated costs, plus energy losses. In case of large floods, uncontrolled flushing will happen with unacceptable concentrations sent downstream. The Bottom gate will be silted up by dozen of meters of sediment, and ineffective for ever (lot of examples worldwide). Decommissioning the dam will be the worst with such an amount of sediments mixed with wood log.
No flushing is not sustainable as well.

3.4 Bypass for Sediments

An alternative is to bypass sediment through a lateral tunnel from the mouth of the reservoir to downstream of the dam. This solution has been carried out at Miwa dam in Japan, see Fig. 6. Before Miwa dam reservoir had huge rate of sedimentation and reduced time life.
This system has the big advantage to transport also coarse materials downstream of the dam. The bypass tunnel is used during floods permitting dilution of fine materials.
This bypass is costly (construction of the tunnel, losses of energy) but quite efficient according to Fig. 6 figures. It is in fact a great investment for the future.

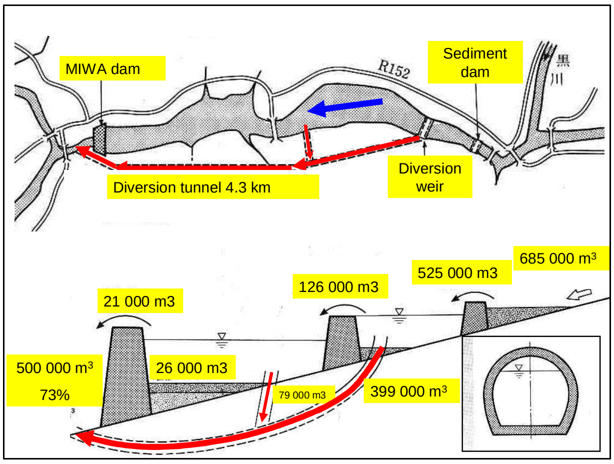

Figure 6. Miwa dam, figures about sediment transit *(Miwa dam documents)*

3.5 Environmental Friendly Flushing

Definition is: *to send downstream only the concentration of sediment that the environment can withstand.* [6]

The reservoir level is lowered until obtaining a gradient of concentration for fine materials. The great concentration of the bottom gate is diluted by the half depth gate in order to regulate the appropriate concentration downstream of the dam, see Fig. 7.

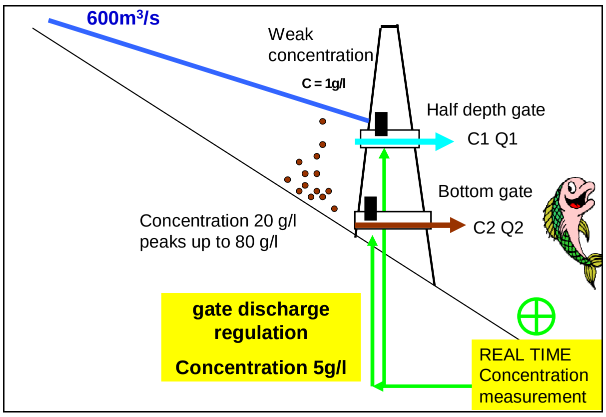

Figure 7. Genissiat reservoir and dam long profile

At Genissiat dam on the Rhone River France managed by CNR, several environmental friendly flushing have been organised for the past 40 years every 3 years. Goal is 5g/l regulated concentration, which has been proved not damaging bio diversity downstream (lot of bio parameters measured, electrical fishing before and after the flushing…).
Admitted concentrations are:

- 5g/l average
- 10g /l 6 h maximum
- 15g /l 30 minutes maximum

Concentrations of sediment are measured in real time by Gamma Ray devices and other complementary methods: Picnometre (water density measurement with temperature correction), Pan Cake method (filtering, quick drying and weighting).
See Fig. 8 Genissiat dam during friendly flushing

Figure 8. Genissiat dam during flushing – bottom gate on the right bank, photo CNR

Fine material concentration being maintained at low level, *friendly flushing* efficiency seems much less than the *hard flushing* way. Friendly Flushing seems expensive because of energy losses, power station being closed during one week, plus staff costs for the operation and monitoring (around 80 people for Genissiat flushing). Nevertheless, 600,000 tons have been flushed during 2003 flushing. Cost efficiency remains interesting because the cost of extracted sediments, is very weak (≈1€/ton), much less than classical method using dredgers. *"Flushing is dredging for free"* (almost).

3.6 Friendly Flushing and Floods

Generally floods are a good opportunity to organise flushing of reservoirs, permitting dilution of fine materials.
In the case of Genissiat, flushing is organized at fixed dates. Month of May is generally chosen because of low water temperature and important discharge given by snow melt in the Alps. Flushing is organized in close cooperation with Switzerland (Seujet, Verbois and Chancy-Pougny Swiss upstream dams are involved). Flushing the whole chain benefits from a great discharge provided by the Geneva Lake for a week (600m^3/s).

4. COARSE MATERIAL ISSUES

4.1 Bed Load Shuttle

Coarse materials unfortunately cannot cross the dam with different type of flushing explained here before. Mechanical means are generally necessary.
For dams equipped with lock, opportunity is given to transport coarse material by barges from upstream of the reservoir to downstream of the dam. This solution has been proposed by CNR experts for Xayaburi dam project on the Mekong River Lao, see Fig 9.

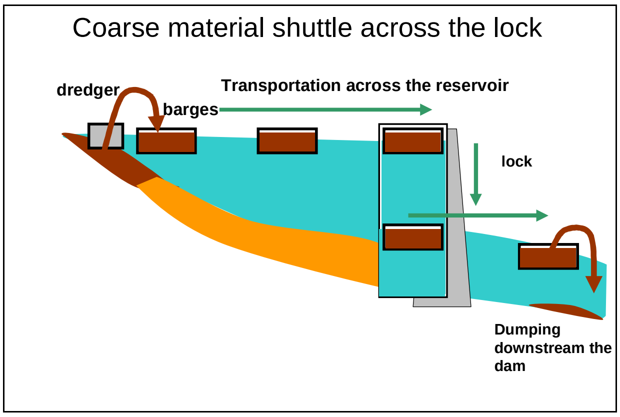

Figure 9. bed load shuttle principle

4.2 Downstream Bed Nourishment

If transit of coarse material is not possible, disequilibrium of the bed downstream of the dam can be stopped feeding the bed with coarse materials, see Fig. 10.

Figure 10. Nourishment of the Rhine River by barges of gravel, photo L. Schmitt

5. FLUSHING RESERVOIR ISSUES

Before modelling solid transportation in the reservoir and downstream of the dam during flushing and determining the way of flushing, issues must be clearly specified for each cases.
Bed load issues upstream and downstream of the dam must be specified and sustainable long term solutions proposed. Fine material issues must be also specified because can have impacts far downstream.
The main issue is at least to prolong the time life of the reservoir. To worry about this issue must start when designing the gates and not after decades of operation when too late. Flushing organisation seems costly and not consistent tendency to fight could be 'wait and see'.
Therefore a long term vision is necessary, exceeding concession duration (generally 30 - 40 years).
The best way is to design a *transparent dam* [9] or at least to get a very good rate of transparency regarding solid materials. *Transparency concept for dams* can be extended to navigation; fish migration…[9].
At the end of the concession period, the concessionary company must return to the state the dam and structures in good conditions. In order to boost flushing organisation, suggestion is to impose in the concession contract the maximum final sedimentation rate of the reservoir, with surcharge or bonus, whether or not sedimentation rate objectives have been achieved.
In case of a chain of dam on the same river, consistency of the chain is needed for organising friendly flushing. If only one link of the chain is not able to pass the solid materials, the chain is disrupted.
Organizing flushing is also not easy between possible different operators with their own constraints. So the concession contract should impose to flush the reservoir in cooperation with other contractors if any.

6. PHYSICAL PHENOMENA DURING FLUSHING

Before choosing a mathematical model to simulate flushing operation, among numerous existing ones, it is necessary to specify physical phenomena happening in the reservoir during flushing, which ones are necessary to be modelled and which ones need other means to be modelled.

6.1 Solid Transportation Starting Up

Coarse Material - Bed Load
τ shear stress N/m^2, τ critical shear stress, bed load starts when $\tau > \tau c$

Fine Material - Suspension
W fall velocity, U* turbulent velocity, suspension starts when U*>W/2.

6.2 Consolidation of Fine Materials

In the downstream part of the Genissiat reservoir as in numerous reservoir worldwide, fine materials settle slowly, its concentration c (g/l) increases along years then corresponding critical shear stress increases a lot τ_c=f (c^4 to c^5) according to C. Migniot works. Fine materials can be finally much more stable than coarser ones. Because of that, <u>flushing must be frequently organised</u>. In the reservoir there are stripes of different materials. Core boreholes are necessary to determine τ_c of each stripe. Mathematical models must be able to manage scouring of these different stripes.

6.3 Suspension with Gradient of Concentration

For friendly flushing, gradient of concentration is required in the lowered reservoir. Mathematical model with turbulence simulation seems necessary. Nevertheless Hunter Rouse diagram can be sufficient. Fine material concentration at the half depth gate level must be weak but there is no need to get a precise value, which would be illusory taking into account landslide phenomenon explained hereafter. For Genissiat flushing, Hunter Rouse approach is very relevant, see Fig. 11.

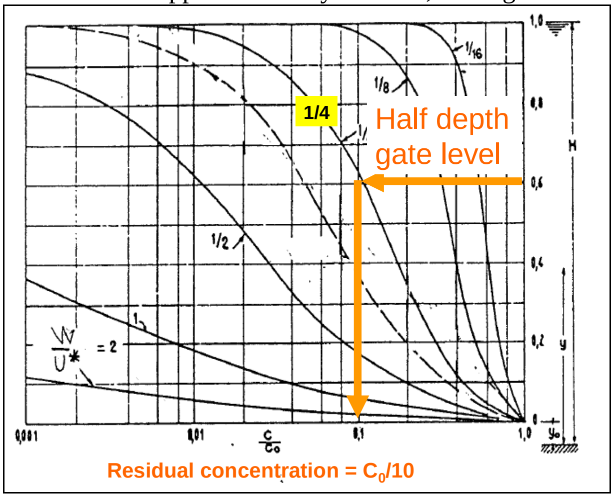

Figure 11. example of Hunter Rouse diagram use

Assessment is W/U* = ¼. Putting the half depth gate at 60% of the reservoir height, its concentration is 10% of the bottom gate concentration. The half depth gate is then able to dilute the great concentration of the bottom gate.

6.4 Landslides in Reservoir

During Genissiat dam flushing, peaks of concentration up to 80g/l have been observed, see Fig. 12. They correspond to mud landslides into the reservoir, slopes being destabilized by the reservoir drawdown.

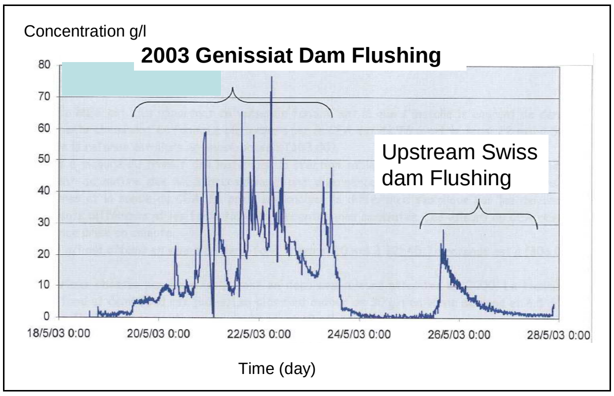

Figure 12. bottom gate concentration (g/l) during Genissiat dam flushing

Mathematical models must take into account this landslide phenomenon. That is the case of RubarBE software developed by Irstea [5] El Kadi Thesis.

6.5 Bottom Gate Blockage Risk

Close to the Genissiat bottom gate, there is a wall of sediments, see Fig.13. This phenomenon results on pressure flushing operation.
Flow is typically 3 dimensional around the bottom gate. So a 3D mathematical mobile bed model seems necessary. Unfortunately, flows are not Newtonian anymore because of great concentrations and corresponding hydraulic equations in models not valid as well. At the present time CNR intends to use scale model in its laboratory or mathematical biphasic model.

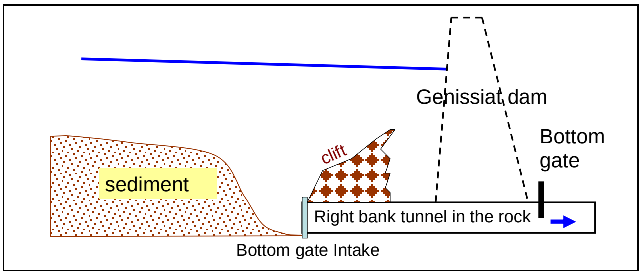

Figure 13. Sedimentation in front of Genissiat dam bottom gate

7. GENISSIAT FLUSHING MODELLING

7.1 Possible Modelling of Flushing

Possible modelling depends first on the reservoir topography. Genissiat reservoir on the Rhone River France is very narrow with almost vertical limestone cliffs, see Fig 14. 1D mobile bed model is obviously relevant to simulate flushing and it has been chosen.

Figure 14. Genissiat narrow reservoir Rhone River G.Earth

When reservoir level is lowered, a narrow bed develops in the sediments. Even simulating only 1 dimension, RubarBE software is able to represent this shape evolution, thanks to an original repartition of shear stress along the cross section: merged perpendicular method, developed by Irstea [4] P. Balayn Thesis.

7.2 Genissiat Flushing Modelling

For CNR it was important to establish a close cooperation with a Research Centre having skills in mobile bed modelling. Irstea Lyon France has worked with CNR for a long time and it was obvious to pursue this collaboration in the aim of reservoir flushing mathematical modelling.
Irstea has developed and improved for years RubarBE 1D software [3] A. Paquier thesis 1995. RubarBE characteristics fit the requirements of Genissiat flushing modelling explained chapter 6.
Mathematical modelling will be used to improve present Genissiat flushing and also to simulate flushing in new conditions, such as flushing during floods.
In 2010, modelling of Genissiat reservoir flushing has been performed [7] with already interesting result as follows.
Zones of sedimentation have been measured after 2003 flushing and are the references to calibrate the model.
Different formulae have been tested such as Engelung Hansen.
The semi empirical Bagnold formula [1] 1966 for sand transportation fits rather well with observations, see Fig. 15.

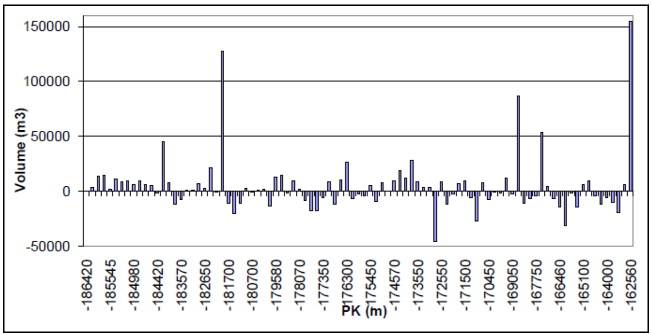

Figure 15 calculated zones along the Genissiat reservoir after the 2003, Erosion (<0) and deposition (>0)

Results are encouraging, but further developments of the model and additional data are obviously needed, as follows:

7.3 Thesis on Going

This first step will continue with a thesis beginning in 2012 with objectives to improve simulations, benefiting from new data from June 2012 flushing. Aims of the thesis are:

- Specify the characteristics and the dynamics of arriving materials in the Genissiat reservoir
- Determine part between bed load and suspension in the total solid transportation
- Determine the process leading to high concentrations at the bottom gate
- Improve downstream impacts mitigation
- Determine what long term flushing management could be
- Identify main process of material input, Swiss material input, landslide in the reservoir, toe scouring, and critical slope due to channel incision…

7.4 Additional Data Collection during 2012 flushing

Lot of measurements has been already performed during past Genissiat flushing every 3 years (concentrations at the bottom gate, half depth gate and downstream with gamma ray devices and additional methods, topography, hydraulic and hydro bio parameters…).
In order to calibrate properly the model, opportunity of June 2012 Genissiat flushing is taken to perform additional measurements. Focus will be on:

- grain size measurements
- iso-kinetic device intake in order not to introduce bias in grain size measurement
- bed load measurement with Helley Smith device.

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