An innovative approach to restore reservoir capacity

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Introduction

Almost every reservoir is affected by sedimentation. The World Commission on Dams estimated that each year almost 1 % of worldwide storage capacity is lost due to this effect. Even the actual new build of reservoirs does not level out over-all storage decrease. Dredging and disposing reservoir sediment is extremely expensive. On the other hand the sediment which is missing downstream of reservoirs leads to erosion damages, substrate deficits and ground water problems.

When removing the sediments or even reducing the sediment volume in the reservoir of hydropower plants or other hydro facilities plant operators are faced with exorbitant costs; we talk several million Euro range even for small reservoirs. Moreover, the various sediment removal procedures applied so far – flushing through the main valve, manual or sludge dredging – all have various additional negative secondary effects ranging from compromising the operation (up to plant shut down for several months), loss of huge quantities of water to negative morphological or ecological impacts.

This paper presents an innovative technical approach which makes reservoirs penetrable for sediment avoiding above mentioned secondary effects. Incoming as well as already settled sediment is continuously transferred through the reservoir and fed over long time spans in morphologically and ecologically compatible concentrations downstream by applying newly developed equipment. Reservoir management is not affected and the approach is performed during daily reservoir operation. It is applicable to almost any range of plants, small to large and run-of-river to pump storage. This approach does not only restores the overall sedimentation process to a near to natural state but also fulfils the requirements of the Water Framework Directive 2000/60 of the European Community as well as the US Sediment Acts. Moreover, as the equipment is fully automated, it is also economically very competitive, even without considering the costs of the secondary effects.
As will be shown in Chapter 3 of this paper, this technology has been successfully implemented an applied to a reservoir in Germany.

1. Background on Reservoir Siltation

1.1 Sedimentation & Erosion in undisturbed river regimes

Like water and organisms also solid components are essential ingredients of every river. This solid fraction mostly is of natural origin and finds its way via erosion processes into the water body. Starting at the rivers source solid components usually begin their career as eroded massive rock. Transport processes changes rock size first to gravel size bedload and furthermore to fine-grained sediment. This sediment settles at the river floor. Depending on the local current this sediment does also come loose again by erosion effects. In middle and lower parts of natural rivers sedimentation and erosion usually balance each other (Figure 1).

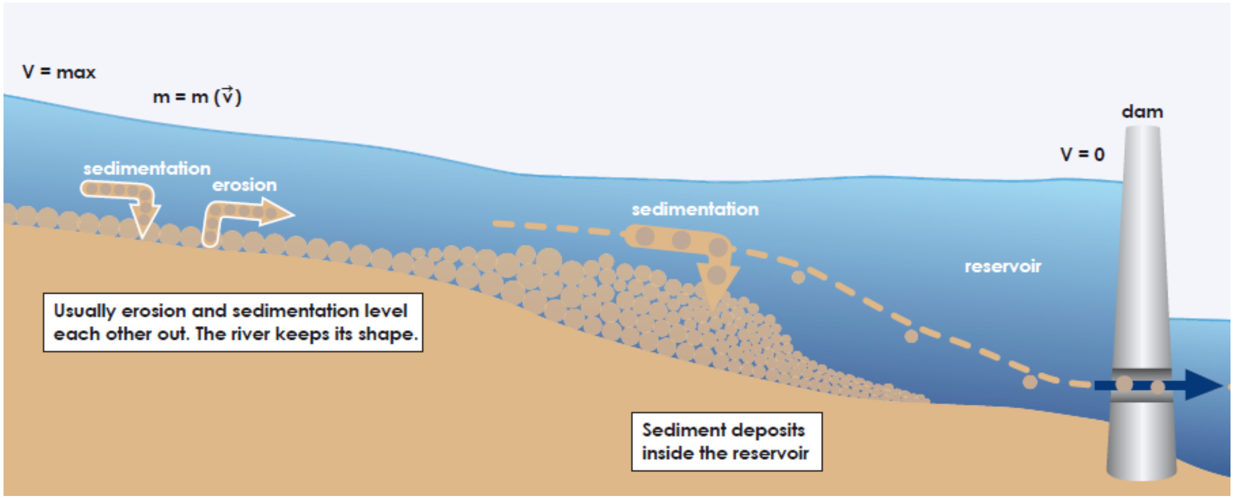

Figure 1. Sedimentation/Erosion equilibrium in natural rivers and influenced by reservoirs

1.2 The influence of man-made barrages

A natural river changes it morphology fundamentally when installing a dam or other barrage across a river section. Permeability is still given for water and mostly for aquatic life by discharge elements and if applicable fish ladders. The extended cross-section upstream of a barrage leads to low current velocities and therefore to profoundly more sedimentation while erosion is minimized. Therefore a barrage often is a massive barrier for sediment transport. Many reservoirs are affected by massive sedimentation and consequently a loss of storage volume (Figure 2). The same is true for pump storage reservoirs in a similar way.

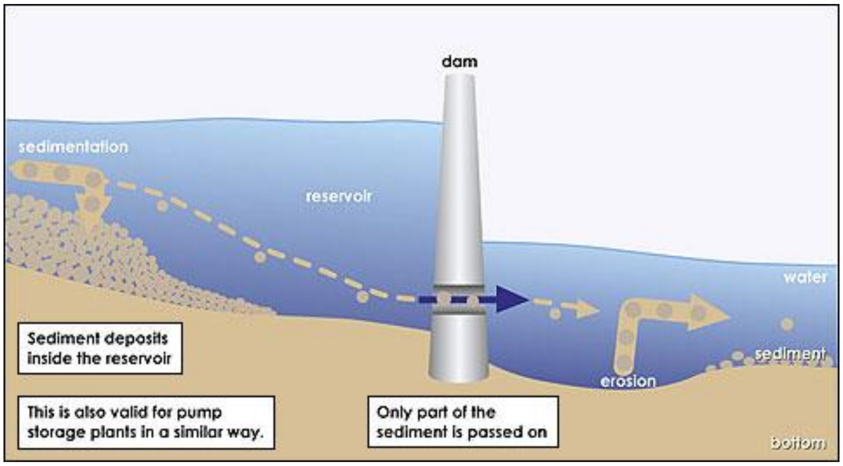

Figure 2. Reservoirs change the sediment balance profoundly

Extracting large sediment quantities from the river upstream of the dam also leads to massive changes downstream. For Example, by trapping sediment in its tributary reservoirs, the German river Rhine alone - which certainly does not represent a major sediment carrier concerning worldwide average - is facing an annual sediment deficit of 2.5 million tons. To heal only major riverbed erosion damages an annual mass of more than 600.000 million tons of soil is dropped into the Rhine at its middle and lower reaches, causing significant expense.

1.3 Impact on Operation

Operational restrictions for reservoir users caused by sedimentation do not come overnight. They increase gradually over long time periods, usually years. Therefore many operators get used to live with these restrictions and consider them as normal, though they are not. Even worse, they grow over time if no counteraction is taken. Foreseen dead storage capacity to store a bulk of sediment below the actively operated reservoir range often does not fully apply because sediment does not tend to settle plain but accumulates within the foreseen active storage volume.

2. Conventional Solution Approaches

In many cases of sediment issues action is taken not until problems are in far progressed stage. Previously conducted solutions attempts are briefly outlined below.

2.1 Opening the base outlet

Sedimentation processes usually start at the up-stream entrance into the reservoir which typically is the most distant point from the dam axis. As sedimentation increases the settled sediments eventually reach the dam. To prevent the dams discharge elements from plugging the operator is now forced to flush the base outlets periodically (e.g. every six months). If neglected, the equipment will become inoperable within short term because the sediment will cover the gear. The tremendous runoff generated by opening the outlets erodes the sediment right upstream of the intake. The eroded sediment is transported downstream in short time and at a high rate (Figure 3).

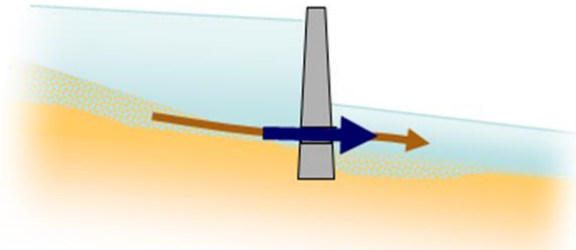

Figure 3: Opening the base outlet

Performing this method is quite simple and requires no further physical facilities. However, with this technique a tremendous quantity of water for power generation or water supply is lost. Furthermore, significant amounts of sediment are moved into the downstream river section in a very short time period. This can lead to negative morphological and ecological effects. Anyway, the method is applicable only when sedimentation already reached the dam line. Opening the base outlet then only leads to a dissipation of sediments in close vicinity of the outlets. The overall operative range of the reservoir is not restored.

2.2 Manual dredging

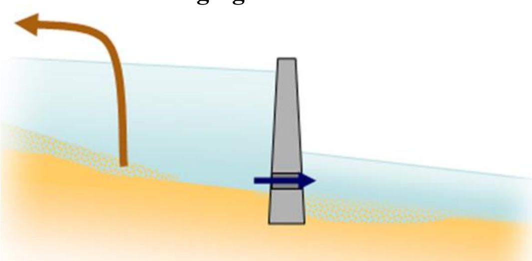

Figure 4: Manual Dredging

Another procedure is manual removal of sediments. Here the sediment is excavated by suction dredgers, hydraulic excavators or - after lowering the reservoirs water level and initial draining - wheel loaders (Figure 4). After the often expensive removal and transport the sediment has to be stored on separate drainage fields for years or decades in order to reduce the water content. Thereafter it may be used as covering material for simple ground work applications. The relatively high percentage of organic ingredients (usually 2 … 30 %) prevents a use as a ground construction material even after dredging. In many cases, landfill is required.

The procedure allows for a thorough cleaning of reservoirs, but at exorbitant costs. Expenses consist of sediment dredging activities, plant/reservoir shutdown of several months as well as transport and dump expenditures which are in a million dollar range even at small reservoirs.

2.3 Sludge dredging and disposal downstream

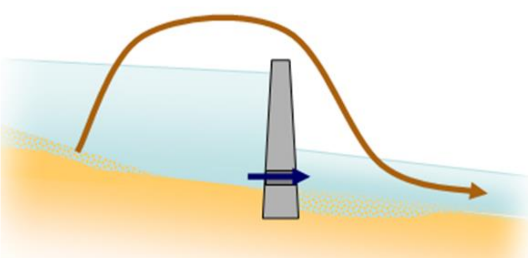

Figure 5: Sludge Dredging and Disposal Downstream

This method involves several suction dredging campaigns where sediment is dug, transferred over the barrage and dumped downstream (Figure 5). For good reason this is not allowed in many countries. The loss of great amounts of flushing water for power production or irrigation may be even acceptable. The short-time transfer of large sediment quantities into the downstream river section however causes a massive intrusion into the river morphology and ecology.

2.4 Ecological, Economical and Legal Aspects

Ecology & Morphology

When opening the base outlet the downstream riverbed is often blocked for months. In any case the morphology is changed significantly. With manual removal, the sediment is extracted permanently from the water body. This leads to increased erosion in the lower reaches and therefore also affects the river, albeit with opposite effect. Dredging and disposal downstream usually is not compatible with river morphology due to the large amounts that need to be transferred in a short period of time. Thus, the above described existing methods are problematic in a morphological point of view.

In addition to the above described effects on river morphology the emptying of the reservoir required for a manual dredging leads to a destruction of the current reservoir's fish population. With sludge dredging and direct disposal downstream the underwater benthos structure is widely destroyed within a few days. Opening the base outlet or even failing to do any maintenance on the reservoir and risking siltation ends in a profoundly long-term change of the developed ecosystems. Some coastal river deltas already face salt water infiltration into ground water reservoirs by missing fresh sediment coverage.

Economic evaluation

The opening of the base outlet initially appears as a cheap solution. However, in cases in which opening the base outlet seems to be a suitable solution, the degree of sedimentation is already far advanced with often severe operational restrictions on reservoir management. The basic problem, i.e. the loss of a mayor part of the storage volume, and also the operational restrictions are not solved by this method as are resulting financial implications. Both will continue because sediment is eroded in the up-stream area near the outlet only; the bulk of the sediment will remain within the reservoir. In addition it has to be taken into account that flushing large quantities of sediment downstream in a short period of time generally causes severe negative impacts on river morphology and the whole aquatic habitat which might lead to compensation liabilities.

The latter aspect also is valid for suction dredging with direct disposal into the downstream river section. For this reason, this variant in most cases is not licensable or generally unlawful.

Excavation of sediment from the reservoir usually is exorbitant expensive due to high direct construction costs, enormous disposal expenditures and long plant/reservoir downtime. For this reason, operators choose this option usually only when threatened by plant/reservoir loss.

Legal constraints

The above presented methods usually require permission by local or regional authorities before starting any physical activity. For permission the authorizing body will take into account appropriate guidelines as European Water Framework Directive or U.S. Sediment Acts. Usually the facility owner has to expect more or less extensive obligations for project execution even if permission is granted.
When digging the sediment and extracting it from the water body the contractor or plant operator usually becomes owner of the removed material. If critical ingredients are detected, the extracted sediments have to be dumped as contaminated material at enormous expense. This also applies in the case that the critical components found are of endogenous and thus natural origin (e.g. certain heavy metals).

3. The Innovative Approach

As an intelligent alternative to the previous discussed conventional methods a new "ConSed-Process" has been developed and already successfully applied in cooperation with Aachen University of Technology, Germany. This approach does not only avoid the negative impacts discussed in chapter 2.4 but does also restore the overall sedimentation process in a river to a near to natural state by making reservoirs permeable for sediment. Thus the approach brings the balance of sedimentation and erosion in a river system back to a natural or close to natural sustainable state fulfilling the requirements of the Water Framework Directive 2000/60 of the European Community as well as the US Sediment Acts. Moreover, as the equipment is fully automated, it is also economically very competitive, even without considering the costs of the secondary effects as discussed in chapter 2.4.

3.1 Technique: Continuous Sediment Transfer

In contrast to the conventional approaches the ConSed-Solution is based on a device allowing continuous and controlled transfer of sediment within the reservoir in a relatively small scale but permanent mode. Key element is an automatically working vessel with a suction dredging system installed that can be diesel or preferably electric driven. To allow for an exact positioning the vessel is directed by tractor cables. Sediments are loosened by a suction head, pumped towards the reservoir's outlet and dumped in front of the outflow elements. The vessel gradually strikes the reservoir floor until the complete surplus sediment is removed (see figure 6).

The newly dumped sediments are eroded by the hydraulic discharge and therefore carried out of the reservoir, passing turbines or outlet valves. Both types of outflow elements are able to handle water flow with some degree of sediment load. The sediment transfer rate can be adapted to the outflow rate and parameters to guarantee a compatible process speed. For an environmentally sound project implementation the time span should be set to months or years, depending on local conditions. A commercially competitive project performance is still assured by a high degree of automation.

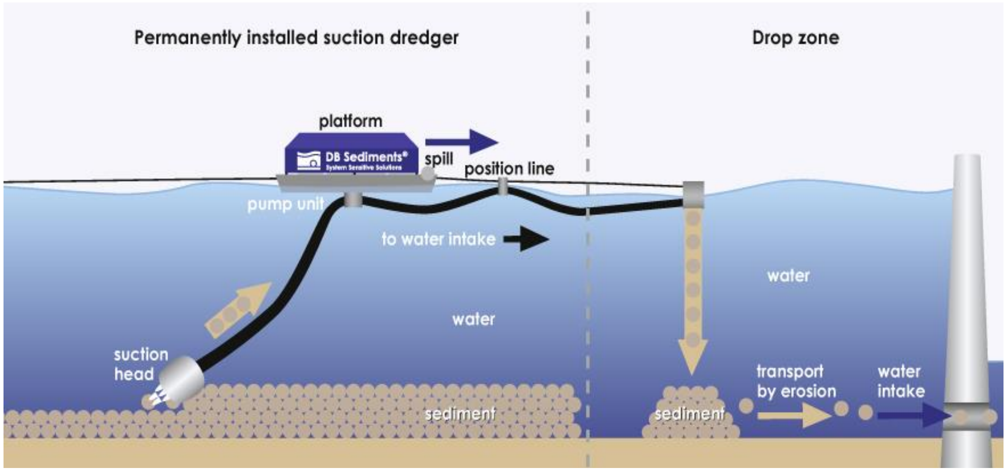

Figure 6: Continuous Sediment Transfer

Step 1: Sediments are dredged by a suction head, pumped across the reservoir and dumped in front of the power stations/hydro facilities water intake.

Step 2: The dumped sediments in their smoothed condition are eroded by the reservoirs outflow.

The process is also applicable in pump storage reservoirs. When starting up a new pump storage plant, the newly created upper basin does not contain any sediment. After several years of operation the owner will frequently find a substantial degree of sedimentation, often limiting the plants operational parameters and commercial benefit. By using the process described here the initial state can be restored in an environmental friendly and commercially effective way.

As mentioned above the sediment leaves the reservoir via the usual outflow organs consisting of turbines, spillways, weirs etc. Wear on the discharge elements (e.g. turbine blades) remains within normal range unless sediment content is increased to a considerably high degree. Anyway, process benefit should easily outrange slightly higher rehab costs or useful turbine blade coating.

3.2 Ecological, Economical and Legal Impacts

Ecology & Morphology

When attaching a dam to a natural waterway the river morphology changes considerably. By applying the described method the natural morphology is widely restored. During the time span required for the reservoirs surplus sediment removal the concentration of solid components in the outflow will be slightly higher than long time average. Even this is a natural condition as sediment processes are not continuous but vary in time and concentration. Furthermore, reservoir flushing and discharging high amounts of sediment in a short period of time as done by opening the base outlet or with sludge dredging will be avoided as the accompanying negative impacts on river morphology and the aquatic ecosystem.

Before starting the permanent sediment transfer the relevant ecological aspects have to be determined for the reservoir and the downstream river. The process has a positive impact on changes in storage volume. Periodically striking the reservoir floor with the suction dredging tools however affects the benthos structure. This is similar to natural erosion. As the suction dredging never affects the overall floor at once and the process is stretched on a wide time span the reservoirs ecosystem should compensate the interference even better than natural erosion events.

At the beginning of a sediment transfer the downstream river will experience a higher than average but not unnatural sediment concentration. When transitional effects fade out the river will be set back to a natural sediment equilibrium. This is the aspired ecological state where natural conditions are restored and regulatory frameworks are fulfilled.

Economic advantages

Since sediment is simply transferred back to the natural flow using an intelligent mechanism, no disposal or dump costs occur. Even the necessary technical facilities are relatively small and cost effective. The process benefit is achieved by continuous small and sustainable changes on a large timescale instead of large interventions in a short period. The cost of the necessary components is a fraction of the cost of conventional methods. Plant shutdown is limited to a few hours for equipment installation instead of months for excavation works. The former storage volume and operating range is restored within some months or few years and kept permanently.

For these reasons, in many applications the method is economically very attractive, even if no immediate action in terms of solving sediment problems is obligatory. Additional benefit can be gained if the above described improvement of the ecological status is financially honoured as in Germanys Renewable Energies Act (EEG).

For reservoirs that are almost inoperable due to sedimentation the operator should first think of restoring the existing facility by sediment transfer instead of placing an additional new reservoir, the latter including major construction work and flooding of additional land.

Legal aspects

In many countries the method requires no riparian permission of local authorities because it represents a way of maintaining the hydraulic system, the active sediment transfer takes place only inside the reservoir, a natural condition is restored and the appropriate sediment acts/water directives are fulfilled. Due to these benefits the process has actively been supported by authorities so far.

In fact, the effects provided by the described process are asked for in many ecological programs. The ‘European Water Framework Directive’ identified sediment deficit as a major problem and in its Annex 5 actively promotes sediment permeability for rivers in their entire length including reservoirs. In any way the operator should consult the relevant administrative bodies in advance. The same procedure is significant for patent legislation (PCT 2008).

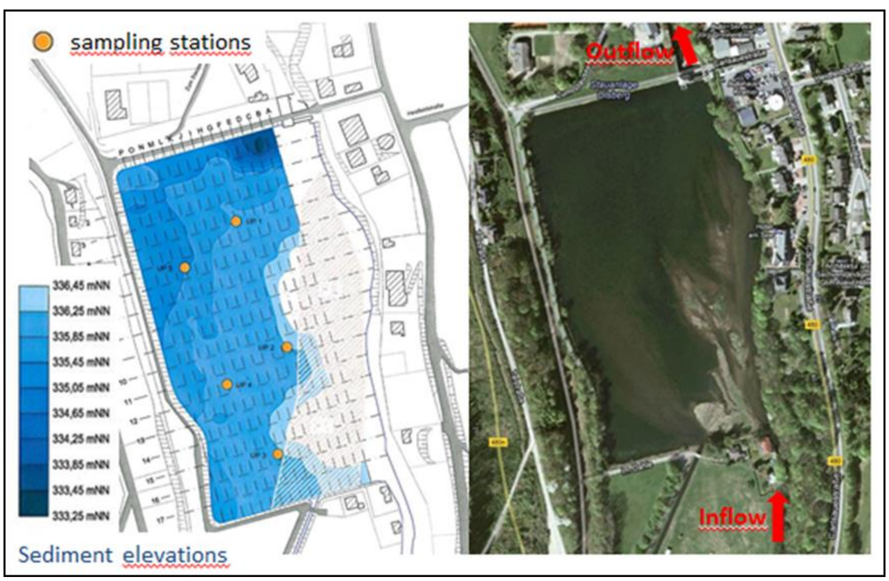

Figure 7: Birds view and sediment situation of “Olsberger Stausee”

3.3 Application

The above described technology is currently applied in the reservoir “Olsberger Stausee” in Germany. The reservoir is feed by the river Ruhr and acts as upstream reservoir for a hydropower station. In large part reservoir capacity is lost due to siltation compromising plant operation and power generation. Figure 7 gives an overview and Table 1 summarizes the main characteristics of the reservoir and the sediment

Main Characteristics of Reservoir & Sediment	
Reservoir Volume:	~175.000 m³
Reservoir Geometry [m]:	250 m x 350 m x 2 m (l x w x d)
Average Inflow MQ:	2,5 m³/s
Sediment Volume:	~90.000 m³
Average Depth of Sediment Layer	~1 m
Sediment Characteristics:	S and g
Particle Size Distribution	0,002 mm – 10 mm

Table 1: Reservoir & Sediment characteristics

As can be seen from Table 1 approximately 50 % of the reservoir capacity has already been lost due to siltation and the average depth of 2 m has been reduced by 1 m. The Sediment can be characterized as dark-brown sandy silt with high organic content and soft to liquid consistency with particle size varying from 0,005 mm – 0,3 mm (clay – sand).

Start of operation was December 10th, 2011. Figure 8 shows the fully automatically operation vessel as well as the transfer line on the water table leading to the drop zone. Parallel to the transport line the power supply cable is installed.

Figure 8: Operational overview on “Olsberger Stausee“

Main Characteristics of vessel Type 101:	
Size:	4,50 m x 2,30 m (length x width)
Weight:	2.000 – 2.800 kg (depending on equipment)
Power Supply:	electrical, 400 V, 25 A
Pump Unit:	up to 80 m³/h
Sediment Transfer Rate:	∅ 200.000 kg/month
Operation:	permanent, fully automatic

Figure 9: Transfer Vessel Type 101 on reservoir „Olsberger Stausee“

The electrically driven vessel operates fully automated. A video camera has been mounted to the vessel allowing visual inspection and control without being on site. The unit is remote controlled by an internet connection allowing operational monitoring as well as checking and regulating all main functions of the vessel, e.g. Frequency of main pump and flushing pump, vessel speed and direction, sediment transfer and other process parameters. It shall be mentioned that current sediment transfer is not limited by installed equipment but by desired sediment concentration. The equipment is able to handle sediment particle sizes of up to 40 mm, however in this application the transferred particle size is limited to 5 mm.

During operation the system proved to work stable and reliable. No breakdowns have been noted, except for a minor required valve repair and a planned shut down during winter when the reservoir was ice covered. The system has proven to be able to continuously dredge, transfer and drop sediments in front of the reservoir outlet in a controlled manner, adapted to the operational rules of the (hydropower) scheme or to any ecological/morphological restrictions of the aquatic ecosystem, e.g. sediment concentration in the turbine flow or in the downstream river reach, turbidity, max. particle size, etc. A benefit of the application is a major increase in downstream biological river quality which significantly improved in only 4 weeks!

3.4 Operational Restrictions

The process can be applied on almost any reservoir size. Of course equipment needs to be adjusted for different dimensions. For small applications fully automated vessels are available which completely fit into a 20'-container. Large applications require sectional built vessels with manned operation. Actual equipment is able to deal with water depths up to 20 m though no real constriction consists that would restrict operational range. On other equipment tests with up to 160 m water depth have already been performed with successful results.

For most hydro stations sediment abrasion is not a topic concerning machinery. Nevertheless hydro operators faced with heavily sediment loaded waters may fear additional wear on plant installations, especially on turbine equipment. Factors to sediment abrasion and erosion are multiple, ranging from involved materials to particle size and shape (Neopane 2010). Little is known about critical sediment loads yet while at the same time modern coatings like Tungsten carbide gives reliable surface protection if applied properly.

From a practical perspective additional wear is not a topic unless sediment ration exceeds 1,000 mg/l, Francis heads range more than 200 m or Pelton turbines are involved. Even then in most cases cost savings on reservoir operation will more than level out additional wear on turbine equipment.

4. Conclusion

A new, environmentally friendly and cost effective approach to remove sediments from reservoirs has been developed and successfully applied in a reservoir at the river Ruhr in Germany. This new approach does not only allow for a continuous and permanent removal of sediments thus ensuring full operation ability but at the same time fulfills the requirements of the Water Framework Directive 2000/60 of the European Community as well as the US Sediment Acts by ensuring sediment permeability of the reservoirs and bringing back the balance of sedimentation and erosion in a river system to a natural or close to natural state.

In addition this new approach avoids various negative secondary effects which are generally part of the conventional approaches, e.g. damage to the downstream morphology and/or aquatic ecosystem (opening base outlet; sludge dredging), longtime plant shut down (manual dredging) or huge loss of process water (all 3 conventional approaches). Moreover, the process is very cost effective – a rare and ideal combination of economic and ecological benefit – and scalable to almost any dimension.

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