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"A Climate Resilient Mekong: Maintaining the Flows that Nourish Life"
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RESERVOIR SEDIMENT FLUSHING AND FISH RESOURCES

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1 INTRODUCTION

The estimated sediment discharge of the Mekong River is 160 million tons per year which is 12% larger than that of the Amazon River (Wolanski and Nguyen Huu Nhan 2005, Sarkkula et al. 2010-). The Mekong Basin is also experiencing rapid development, with in particular plans for the construction of 72 new hydropower dams by 2030 (ICEM 2010). However when river flows enter a dam reservoir they decrease in velocity, which results in a deposition of the transported sediment (Palmieri et al. 2003). Thus a 75% reduction of the sediment load at the mouth of the Mekong is expected by 2030 if all planned dams are built (25% of reduction due to mainstream dams alone; ICEM 2010). As sediments accumulate in reservoirs the volume available for water storage decreases, which shortens the reservoir's lifetime and reduces its capacity for energy generation (Brandt and Swenning, 1999).

Engineers have developed a variety of methods for managing dam sedimentation. One method to manage sediment once it has settled in the reservoir is *reservoir flushing*. Essentially, outlets in the dam are opened in order to create a flow with enough velocity to resuspend sediment and flush it downstream (Palmieri et al. 2003). Typically these outlets are located at the bottom of the dam; the flow of water generated during these events is known as a flushing flow. Flushing flows are laden with sediment and possibly contaminants, and impact downstream biota and the riverine life is several ways.

The current report reviews the impact of sediment flushing at dam sites on downstream fish resources, and the best ways to flush sediment for fish protection or conservation. This specific environmental objective requires a certain understanding of the biological issues involved, which is detailed in the first section of this report ("*Impact of sediment flushing on fish*"). Then the concentrations acceptable to fish are reviewed ("*What are sediment concentrations acceptable to fish?").* Since the biological review highlighted temperature change and contamination issues associated to flushing, these complementary issues are also detailed ("*Flushing and temperature changes*" and "*Flushing and sediment contamination*"). Based on these different aspects, we review the best ways to flush sediments at dam sites for a minimal impact on fish. Last, the knowledge gaps identified during this review are detailed as well as the subsequent research needs, with a particular focus on those most critical ones for the Mekong region.

1. IMPACT OF SEDIMENT FLUSHING ON FISH

Sediment flushing results in three main categories of impacts on fish:
- physical impacts (fish gill clogging, but also changes in riverine habitats and changes in downstream river temperature);
- chemical impacts (decreased dissolved oxygen levels, chemical contamination), and
- biological impacts (changes in migration or spawning triggers, reduced ability to feed, reduced food abundance, impact on egg development and increased vulnerability to diseases).

These factors will be reviewed in detail in a companion report, and we focus here on the major impacts that result directly from flushing at dams.

1.1 Physical impacts

1.1.1 Fish gill clogging

One of the first publications noting the negative impact of sediments on downstream fish is that of Kanthak (1924) and refers to the flushing of the Alicante Dam in Spain during the 17th century (cited in Brandt 1999). In 1961 Herbert and Merkens noticed fish gill alterations due to clay particles and two decades later Morgan and Rasin (1983) reported higher mortality among white perch larvae submitted to high levels of suspended solids. Studies of fish mortality associated with fish gill clogging are generally well documented and are reviewed in Brandt (1999), Garric *et al.* (1990) or Tazaki *et al.* (2003), and we detail in a section below the state of knowledge about particle sizes, exposure time and mortality rates.

Actually sediment flushing can impair fish gill function in two ways, depending on particle size:
- particles between 75-250 µm in size, corresponding to very fine sand and fine sand on the Wentworth class, can cause mechanical abrasion to fish gills (Staub 2000, Tazaki et al. 2003).

- particles smaller than 75 µm, including silt, clay and colloids, can pass through the gill membranes and create a film that covers the interlamellar spaces of the gill tissue; this impairs the gill function by i) blocking oxygen diffusion and ii) stimulating mucus production which in turn results in reduced oxygen transfer (Tazaki et al. 2003).

In the case of the Mekong, the particle size whose frequency dominates in sediment load is that of fine silts and clays the overall (Irvine et al. 2007, Sarkkula *et al.* 2009), which, from a fish resource perspective, would correspond to the second type of impairment of the gill function (i.e. clogging rather than abrasion).

1.1.2 Changes in riverine habitats

Flushing tends to modify downstream habitats by first eroding the channel-bed and bank deposits and later by depositing material from the reservoir, which covers the river bed and banks with a layer of fine-grain sediments. The infilling of deep pools and small spaces between stones will lead to habitat loss for the species that use these spaces (Ackers and Thompson, 1987, Buermann et al. 1995). Thus Hess and Newcomb (1982) detail the case of the Niobrara River in Nebraska (USA), in which flushing at dam site resulted in deposits of up to 1 meter of sediments as far as 1 kilometer downstream of the site. In the Reventazon River in Costa Rica, Brandt and Swenning (1999) observed that following a flushing event, 295,000 tonnes of sediment were deposited on a 30 km stretch of river downstream of the reservoir (i.e. 10 tons per linear meter of river). The consequence of such deposits is a mass killing of the fish –in particular larvae and juveniles- and change in the species diversity, composition and biomass of the whole river system (Buermann et al. 1995).
As for the fish community, a number of pelagic fish species tend to move downstream towards alternative habitats and feeding zones, but territorial species or species with limited swimming capabilities are wiped out, and the recolonization of the modified habitat takes at best several months (e.g. Gray and Ward 1982, Crosa *et al.* 2010)

Figure 1: River bed before (left) and after (right) flushing of the Cachi Dam in Costa Rica, 7 kilometers downstream of the dam. Source: Brandt and Swenning 1999.

1.1.3 Increased temperature

Since most reservoirs are characterized by a thermal stratification, flushing bottom water through sluice gates located at the basis of the dam usually results in sudden changes in the river water temperature downstream of the dam. Warm water is usually released from the top of the dam, whereas cooler downstream temperatures may result when cool water is released from the bottom of a reservoir. In fact several field studies have reported downstream water temperature increases during flushing events, most likely due to the warming of the still water in the reservoir:

- downstream temperatures increased by 3-4 °C during a flushing event in the Niobrara River in the US (Gutzmer et al. 1996) or in the Geum River in Korea (Chung et al., 2008);
- downstream temperature decreased due to cold-water releases from Colorado river dams, resulting in a decline in native fish abundance (Holden and Stalnaker, 1975).

In temperate countries the water released can be alternatively cooler or warmer than the river temperature depending on the season (Figure 2)

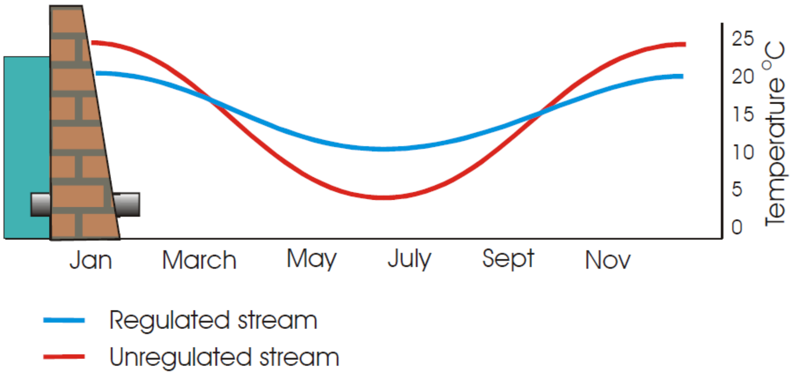

Figure 2: Seasonal variability of the water flushed downstream of a dam in temperate countries. Source: EPA Victoria 2004.

In tropical climates the reservoir is less unlikely to be stratified, or bottom layers would be colder, resulting in similar to lower temperatures downstream, but this point remains to be explored in the case of Mekong dam reservoirs.
Water temperature changes due to water releases have been detected over 100 km downstream of reservoirs (Walker 1979, Lelmkuhl 1979). Petts (1984) considers, in his extensive review of impounded rivers, that thermal changes caused by water storage have the most significant effect on in-stream biota. In all cases the area affected and the magnitude and extent of the temperature change depends on a variety of variables such as air temperature, discharge volume, groundwater and tributary additions and substrate type (Walburg 1981 and Figure 3).

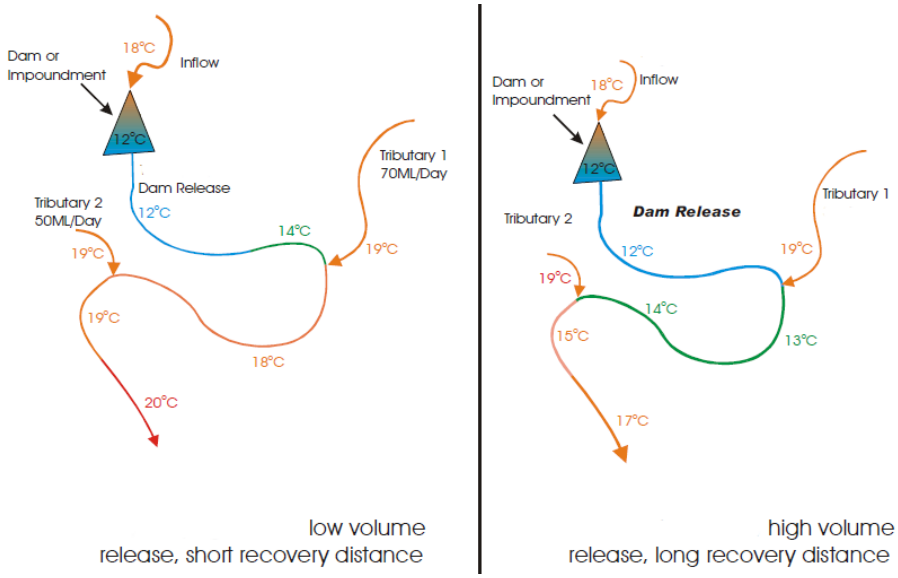

Figure 3: Extent of downstream temperature change following a flush, depending on several factors. Source: EPA Victoria 2004.

1.2 Chemical impacts

Flushing events are generally characterized by concomitant increases in suspended solids, a drop in oxygen and a rise in the concentration of ammonia, whose toxicity is dependent upon the oxygen concentration (Thurston et al. 1981, Garric *et al.* 1990). We review below these chemical impacts.

1.2.1 Decreased dissolved oxygen levels

As detailed by Francis-Floyd (2011), "oxygen depletion refers to low levels of DO and may result in fish mortality. A concentration of 5 mg/L DO is recommended for optimum fish health. Sensitivity to low levels

of dissolved oxygen is species specific, however, most species of fish are distressed when DO falls to 2-4 mg/L. Mortality usually occurs at concentrations less than 2 mg/L. The number of fish that die during an oxygen depletion event is determined by how low the DO gets and how long it stays down. Usually larger fish are affected by low DO before smaller fish are."
The measured average dissolved oxygen concentration in the running water of the Mekong mainstream is in the range from 5.5-8.5 mg/l (1985-2005 data; MRC 2009).

Numerous field studies, reviewed in Brandt (1999), show a drastic decrease in dissolved oxygen levels downstream of dams in relation to flushing events. This is mainly due to the fact that bottom waters in reservoirs are cold, exposed to oxygen-demanding organic sediments, and are subsequently characterized by low to very low dissolved oxygen levels. In addition, sediments such as silt exert their own oxygen demand and the high levels of sediment introduced during flushing flows (suspended and settled) contribute to anoxic conditions downstream of reservoirs during flushing. Thus in the Olifants River in South Africa, dissolved oxygen levels dropped to 0.1 mg/l during flushing flows and remained low for several hours before recovering. Fish mortalities were though to be caused by a combination of high silt loads and the associated very low DO levels (Buermann et al. 1995).

1.2.2 Chemical contamination

Hydrogen sulfide and ammonia are typical products of the anaerobic processes occurring in reservoir hypolimnic waters and are toxic to fish. Hydrogen sulfide concentrations above 0.002 mg/l may result in fish kills and in a reduction in diversity of benthos and algae (Walburg *et al.* 1981). Ammonia toxicity is affected by temperature and water pH, but concentrations between 0,6 and 2.0 mg/l are lethal to fish after short-term exposure (Boyd 1979). Reservoirs provide a suitable environment for bacteria that break down inorganic mercury, naturally present in eroded soils and transform it into methyl-mercury, a toxin (mercury contamination, McCartney et al. 2001). Schentagne *et al.* (2000) noted elevated methyl-mercury levels in fish downstream of the La Grande Hydroelectric Complex, Quebec and found that 33% of the methy-mercury found downstream was transported by suspended particulates such as organic debris. The methyl-mercury transported by sediment during flushing events can bioaccumulate within the aquatic ecosystem, and methyl-mercury is already present in elevated levels in the Cambodian section of the Mekong (Murphy *et al.* 2008, Dove 2009).

Hypolimnic discharges may also contain high concentrations of reduced iron, manganese or other heavy metals can accumulate in reservoir sediments (Keskin 2011) but we found no research studying the effects of flushing events on concentrations of these metals in downstream fish.

1.3 Biological impacts

1.3.1 Changes in the environmental triggers

In the Mekong, 87% of the species whose migration status is known (i.e. 135 species) are migrant species; environmental factors trigger the migration of at least 18% of the latter species (i.e. 30 species out of 165; Baran 2006). Of these 30 species dominant in catches, nine responds to change in turbidity or water colour. This makes these species possibly sensitive to large scale flushing, through a perturbation of their migration trigger. These species are:
Pangasius polyuranodon, Pangasianodon gigas and *Pangasius bocourti* (3 catfishes, including a critically endangered species), *Cyclocheilichthys enoplos* and *Paralaubuca typus* (two cyprinids very dominant in catches), *Bangana behri, Labeo chrysophekadion, Mekongina erythrospila* and *Tenualosa thibaudeaui.*

Among macroinvertebrates, extreme fluctuations in releases select for species that are able to colonize and complete larval development between major disturbances (Henricson and Muller 1979).

1.3.2 Reduced nutrition and growth

Flushing events can adversely impact fish growth (McLeay *et al.* 1987, Sigler et al. 1984, Newcombe and MacDonald 1991, Horppila et al. 2004):

- fish exposed to elevated sediment concentrations tend to swim more in order to find areas in which to avoid the suspended sediment concentrations. This and other metabolic demands decrease the energy available for growth;

- decreased food intake among visual predators (both decreased light intensity and light scattering, the latter having more pronounced effects);
- decreased food supply (in particular phytoplankton and photosynthetic algae)
- decreased food conversion efficiency.

McLeay et al (1987) note from Arctic Grayling juveniles exposed to to three different concentrations of placer mine sediment for 42 days, that the growth reduction ranges between 6% for 100 g/l and 33% for 1000 g/l.
The duration of exposure mediates the effect of suspended sediment concentrations on growth rates. As both concentration and duration of exposure increase, the severity of the reduction in growth increases as well.

Our review has not found any studies measuring the effect of flushing events on downstream food abundance. However flushing events which alter the composition or density of riverine invertebrates can also affect the fish that feed upon them. Thus Hess and Newcomb (1982) found that macrobiota density declined drastically following a flushing event on the Niobrara River, Nebraska. According to Gray and Ward's study (1982), the macroinvertebrate community composition on the North Platte River (Wyoming, USA), changed over more than 20 km after a reservoir flushing event, with for instance a 90% loss among chironomids; recovery took several weeks.
However Tsubaki et al. (2010) also underline the positive consequences of periodical flushing in highly regulated rivers, a disturbance that mimics natural variability and can help restoring conditions closer to normal and the corresponding food items that sustain local fish populations.

1.3.3 Impact on egg development

A high sediment rate can cause abrasion and mortalities among drifting fish eggs; it can also result in burying of eggs stuck to plants or rocks. Gravel fish spawning areas can be covered by fine silts making them unsuitable for anchoring fish eggs and prevent those eggs from receiving oxygen.

1.4 Scale of impacts

The various consequences of sediment flushing on fish and the aquatic life have been formally classified by Newcombe and Jensen (1996) into a scale of 14 degrees:

0: No behavioral effects

Behavioral effects

1: Alarm reaction
2: Abandonment of cover
3: Avoidance response

Sublethal effects

4: Short-term reduction in feeding rates; short-term reduction in feeding success
5: Minor physiological stress: increase in rate of coughing; increased respiration rate
6: Moderate physiological stress
7: Moderate habitat degradation; impaired homing
8: Indications of major physiological stress: long-term reduction in feeding rate; long-term reduction in feeding success; poor condition

Lethal and paralethal effects (paralethal = habitat damage, reduced growth, reduced fish density and reduction in population size)

9: Reduced growth rate: delayed hatching: reduced fish density
10: 0-20% mortality; increased predation; moderate to severe habitat degradation
11: >20-40% mortality
12: >40-60% mortality
13: >60-80% mortality
14: >80-I00% mortality

This scale will be used for the definition of required levels of flushing.

2 WHAT ARE SEDIMENT CONCENTRATIONS ACCEPTABLE TO FISH?

The overall impact of a flushing flow on fish is primarily determined by the suspended sediment concentration of the flow as well as the duration of the flushing event. Broadly, i) the higher the flushed sediment concentration, the larger the impact on fish, and ii) the longer the duration of a certain sediment flush, the more serious the impact on fish.

2.1 Sediment concentrations and duration of the stress

There is a large number of papers on the impact of sediment concentrations on fish in different riverine environment featuring different species (in particular salmonids). In presence of contradictory results, Newcomb and MacDonald undertook in 1991 a review of the topic. These authors reached the conclusion that it is the combination of sediment concentrations and exposure time that determines the impact, and they developed a stress index that takes both concentration and duration into account:

Stress index = $\log_e$ [Concentration in mg/l x Duration in hours])

The stress index was somehow related to the scale of impacts defined in section 1.4., but was not formally or quantitatively correlated to impacts on fish.

This approach was developed further by Newcomb and Jensen (1996) in a meta-analysis of 80 studies that resulted in six empirical equations that relate biological response to duration of exposure and suspended sediment concentration for different fish groups (salmonids and non-salmonids, juveniles and adults, freshwater and estuarine environment). We detail below for non salmonid fishes in freshwater the empirical relations Newcomb and Jensen reviewed in the literature, and the impact they calculated based on their model.

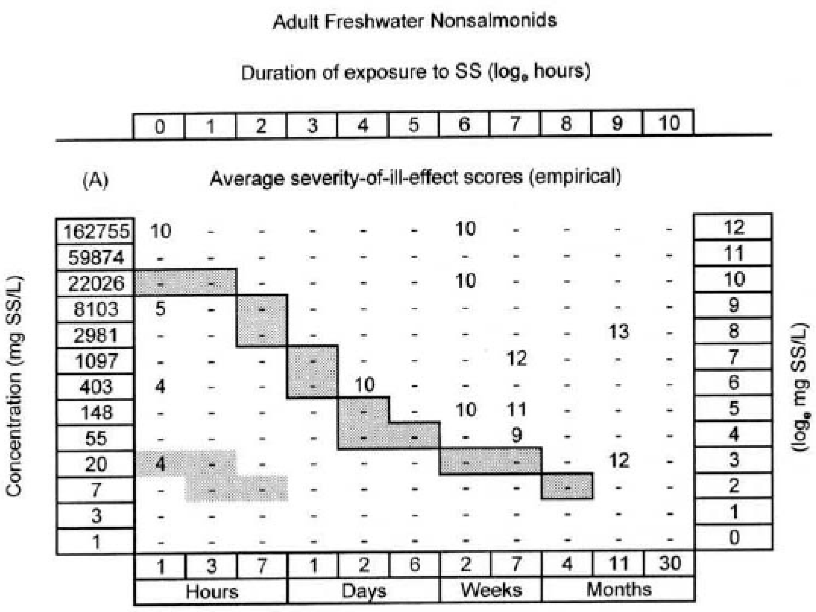

Figure 4: Observed response of non-salmonid adult freshwater fish to concentration of suspended sediment and exposure. X axis: duration; Y axis: concentration in mg/l; impact: 4: reduction in feeding rates; 5: impaired homing; 9: reduction in growth rates; 10: 0 to 20% mortality; 11: > 20 to 40% mortality; 12: >40 to 60% mortality, severe habitat degradation; 13: > 60 to 80% mortality. Dashes mean "no data." Shaded bands denote inferred (by manual interpolation) thresholds of lethal effects. Source: Newcomb and Jensen 1996.

Adult Freshwater Nonsalmonids

Duration of exposure to SS ($\log_e$ hours)

(B) Average severity-of-ill-effect scores (calculated)

Concentration (mg SS/L)	0	1	2	3	4	5	6	7	8	9	10	($\log_e$ mg SS/L)
162755	7	8	9	10	10	11	12	12	13	14	-	12
59874	7	8	9	9	10	11	11	12	13	14	14	11
22026	7	8	8	9	10	10	11	12	13	13	14	10
8103	7	7	8	9	9	10	11	12	12	13	14	9
2981	6	7	8	8	9	10	11	11	12	13	13	8
1097	6	7	7	8	9	10	10	11	12	12	13	7
403	6	6	7	8	9	9	10	11	11	12	13	6
148	5	6	7	8	8	9	10	10	11	12	13	5
55	5	6	7	7	8	9	9	10	11	12	12	4
20	5	6	6	7	8	8	9	10	11	11	12	3
7	5	5	6	7	7	8	9	10	10	11	12	2
3	4	5	6	7	7	8	9	9	10	11	11	1
1	4	5	6	6	7	8	8	9	10	10	11	0
	1	3	7	1	2	6	2	7	4	11	30	
	Hours			Days			Weeks		Months			

Figure 5: Modelled response of non-salmonid adult freshwater fish to concentration of suspended sediment and exposure. X axis: duration; Y axis: concentration in mg/l; impact: 4: reduction in feeding rates; 5: impaired homing; 6: poor condition of organism; 7: moderate habitat degradation; 8: physiological stress and histological changes; 9: reduction in growth rates; 10: 0 to 20% mortality; 11: > 20 to 40% mortality; 12: >40 to 60% mortality, severe habitat degradation; 13: > 60 to 80% mortality; 14: >80 to 100% mortality. Shaded areas represent extrapolations beyond empirical data. Diagonal terraced line denotes thresholds of sublethal effects. Source: Newcombe and Jensen 1996.

The matrix in Figure 4 is illustrated in Figure 6, which summarizes best available knowledge about the likely impact of concentration and exposure on adult fish similar to those found in the Mekong. The model is:

$$\mathbf{z = 4.0815 + 0.7126\ (\log_e x) + 0.2829\ (\log_e y)}$$

with z = impact on fish (see scale below), x in hours and y in mg/l

z values: 1: alarm reaction; 2: abandonment of cover; 3: avoidance response; 4: short-term reduction in feeding rates and feeding success; 5: minor physiological stress; 6: moderate physiological stress; 7: moderate habitat degradation and impaired homing;; 8: major physiological stress;; 9: reduced growth rate or delayed hatching ; 10: 0-20% mortality;; 11: >20-40% mortality; 12: >40-60% mortality; 13: >60-80% mortality; 14: >80-i00% mortality;

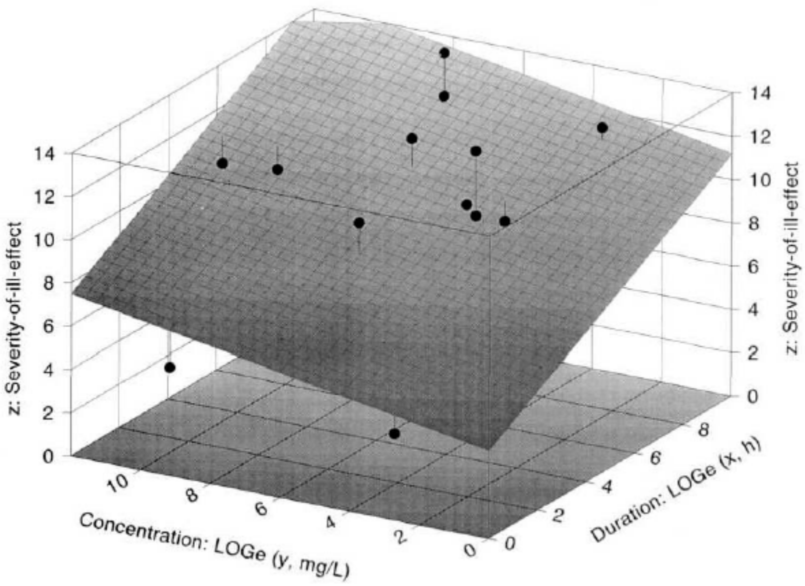

Figure 6: Dose-response surface describing the impact for non-salmonids adult freshwater fish, as a function of suspended sediment concentration and duration of exposure. Source: Newcombe and Jensen 1996

During routine flushing operations, downstream sediment concentrations above 40,000 mg/l are often measured and experience at sites in Costa Rica, Iran, Switzerland, France and China shows that peak suspended sediment concentrations exceeding 200,000 mg/l can be expected (Garcia 2008).

Despite the remarkably synthetic nature of Newcombe and Jensen's results, a couple of reservations must be flagged:

- experience from the Tennessee suggests that these results apply to cold rivers and their fish communities, but that aquatic communities of warm-water streams can withstand higher levels of sediment-related stress (Diehl 2010)
- temperature, fish size and particle size are additional variables influencing the impact of sediment flushing on fish (Bergstedt and Bergersen 1997).

2.2 Downstream extent of the stress

In studies investigating the downstream effects of reservoir flushing events sampling sites are typically set up within several kilometers downstream of the dam and few studies have been designed to explicitly test the downstream extent of the stress.

Brandt and Swenning (1999) maintained a sampling site 30 kilometers downstream of the Cachi dam in Costa Rica. Sediment concentrations at this site remained above 75,000 ppm for over 6 hours during a flushing event. A riverbank deposit analysis of the same flushing event found that 45 km downstream of the dam 1.3 tonnes of sediment were deposited per linear meter along the riverbanks, evidence that the flushing flow reached at least this far downstream.

In Wyoming (USA), Gray and Ward (1982) studied average suspended solids concentrations during a 20-days long flushing event, and noted:

- week 1: 100 mg/l both 4 km and 23 km downstream.
- week 2: 422 mg/l 4 km downstream and 339 mg/l 23 km downstream
- week 3. 302 mg/l 4 km downstream and 259 mg/l 23 km downstream

In the same state and in relation to a brief flushing event, Bergstedt and Bergersen (1997) noted:

- 8 mg/l for normal low flow conditions and 500 mg/l during rain and runoff conditions throughout the study area
- 4000 mg/l directly below the dam and 2000 mg/l 29 km downstream after 18 hour.

In conclusion flushing flows can elevate suspended sediment concentrations tens of kilometers downstream of the dam site. The effects of sediment flushing decrease in proportion to distance downstream and inflow from tributaries (Nisbet 1961). The river stretch actually impacted will depend on concentrations released, but also on particle size composition, on channel hydraulics, on discharge (i.e. on the season considered) and on the species dominant in the impact zone during that season (Gray and Ward, 1982).

3 SEDIMENT FLUSHING OPTIONS

Four methods exist to remove sediments accumulated in reservoirs: excavation, dredging, hydrosuction dredging and flushing. We briefly review below the various flushing options, since flushing is the only economic approach to restore the storage capacity of the reservoir with severe deposition (Liu *et al.* 2004).

Flushing is implemented to remobilize sediment that has already deposited. Flushing a reservoir involves opening a dam’s bottom outlet(s) in order to create a flow with enough velocity to re-suspend sediment that has settled in the reservoir (Atkinson, 1996). There are two main flushing methods: partial draw-down flushing (also called flushing under pressure) or full draw-down flushing (also called free flow flushing or empty flushing; Palmieri et al. 2003).

Partial draw-down flushing: this occurs when the bottom outlets are opened but the water level in the reservoir is not allowed to drop significantly. In this case, a flushing flow is created but only succeeds in removing sediment in a localized area around the bottom outlet (Brandt 1999). Sediment located in other parts of the reservoir basin will also resuspend and relocate closer to the bottom of the dam but will not be flushed out; thus partial draw down flushing clears only a limited area of the reservoir (Palmieri et al. 2003).

Full draw-down flushing: when the reservoir water storage is allowed to be completely drawn down, inflowing water acts as an erosive agent and resuspends sediment and flushes it through the bottom outlet. This inflow creates a channel through the sediment in the reservoir and as the channel broadens and swings, more and more sediment will be flushed (Brandt, 1999). Draw down flushing succeeds in removing much more sediment than partial draw-down flushing. Channelization during draw-down flushing is a slow process and the flushing event can last up to several weeks. Full draw-down flushing is usually done during the flood season to ensure that the reservoir is quickly filled back up after the flushing event). From an environmental viewpoint, empty flushing tends to release the pollutants from the sediment and increase sharply the concentration of pollutants in water, impairing the downstream ecology (Wang and Hu 2009). This technique is not widely practiced because it is usually only effective in narrow reservoirs, it consumes large volumes of water and emptying the reservoir is risky in terms of power generation (Atkinson, 1996).

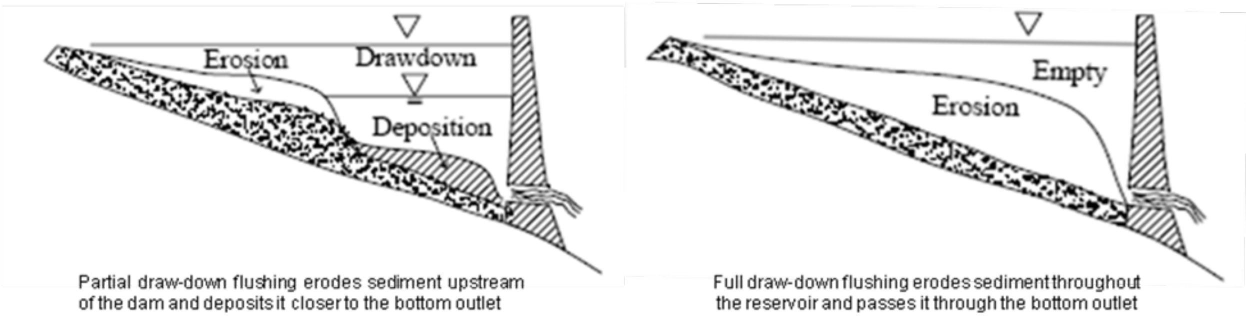

Figure 7: Main options for sediment flushing: partial draw down flushing (left) and full draw down flushing (right). Source: Wang and Hu 2009.

Figure 8: A flushing flow being released from a bottom outlet in Jiroft, Iran. Source: Schleiss 2008

Sediment sluicing is an alternative sediment management technique designed to prevent reservoir sedimentation. Dam sluices are opened and used to pass sediment laden flows through the dam as they enter from upstream (Palmieri et al. 2003). Thus sediment is not deposited but passes through the dam with the water that is transporting it, and does not drop out of suspension. This sediment management technique is useful if dam managers are expecting a sediment laden flow to arrive from upstream.
Since the peak of sediment frequently precedes the discharge peak, it is best to open the gates to pass the sediment peak and then close them before the arrival of the peak discharge (Shen, 1999, pp 752).
According to Pitt and Thompson (1984), for reservoirs with water storage to inflow ratios smaller than 0.5, sediment sluicing should be preferred, and Bouvard (1992) recommends sluicing if the natural flow is greater than the flow diverted.

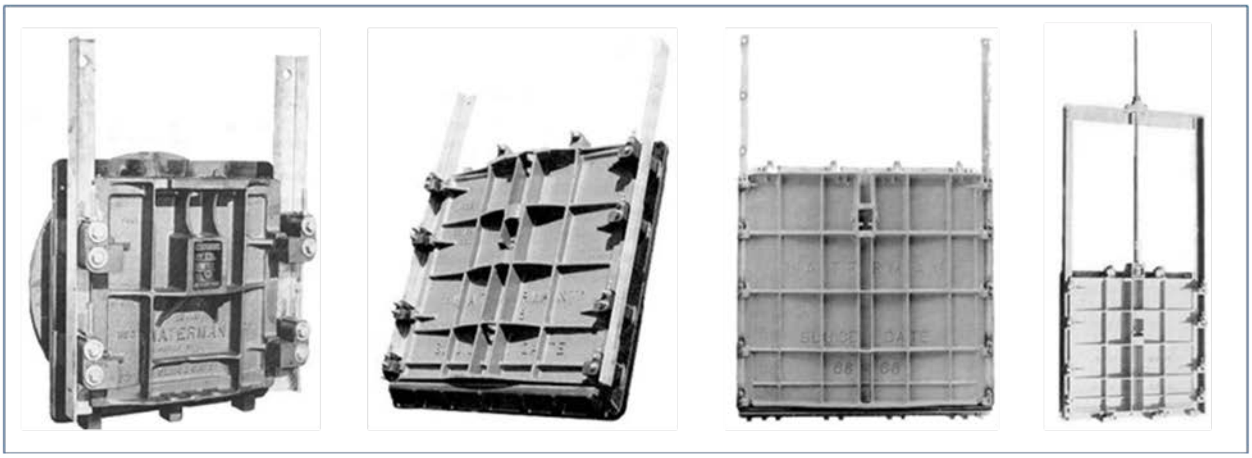

Figure 9: Different models of sluice gates

4 FLUSHING FOR MINIMAL IMPACT ON FISH

The strong and negative impact of hard flushing (i.e. with high and uncontrolled concentration) on the downstream biota has long been acknowledged. This led to the development of “environmentally friendly flushing” techniques, detailed in particular by Fruchard (2008): “*Environmentally Friendly Flushing aims to send only the concentrations of sediment that the environment can withstand*”

Environmentally Friendly Flushing

At dam site, this method is a modification of the partial draw-down flushing technique. In addition to a bottom outlet, a mid-depth outlet is required. During flushing water is released from both the mid depth outlet and the bottom outlet simultaneously. The hypolimnic water from the bottom outlet, which is high in suspended sediment mixes with the water from the mid depth outlet, which is low in suspended sediment. Thus, the flushing flow created during the event will have much lower concentrations of suspended sediment than would otherwise be the case (Fruchard, 2008).

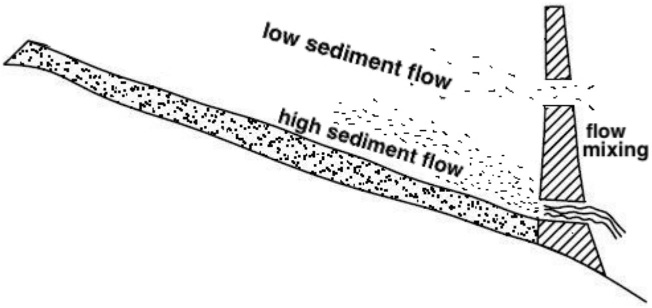

Figure 10: Combination of bottom and mid-depth flushing to reduce the concentration of sediments released downstream.

Actually this techniques also improves downstream oxygen concentration and minimizes temperature changes and pollution: water released from near the bottom of a stratified reservoir is usually cold, oxygen-depleted, and high in hydrogen sulphide and other pollutants, whereas water released from mid-depth is more oxygenated, warmer and less concentrated in heavy metals and pollutants (McCartney et al. 2001)

On the Upper Rhone River, which crosses both Switzerland and France, the Genissiat dam has been "environmentally friendly flushed" every three years since 1970:

- Downstream concentration limits have been 5 g/l in average (10 g/l during 6 hours maximum, 15 g/l during 30 minutes max);
- real time monitoring has been implemented (oxygen, water temperature, bacteriology, toxicology and clogging of spawning areas),

the release of sediments being controlled so that pre-defined critical thresholds are not reached.

The benefits of this approach are multiple: more than thirty years of experience show that the biological and morphological equilibrium of the river is respected and the downstream environment is not impacted; flushing remains efficient and the storage capacity of the reservoir is maintained over decades; the method, although expensive, is much more cost-effective than dredging. The downside of this method is its heaviness, since it requires a lot of monitoring over 150 km of river and the involvement of several dozens of technicians during one week to monitor in real time and adjust sediment releases. The environmentally friendly flushing technique is reflected in the MRC guidance for mainstream dams (2009, guidance point 128): "*The dam design should include not only bottom gates to pass/flush the sediment, but also releases from mid-level gates (or spillways) and to allow dilution of the highly concentrated bottom waters that are released*".

On a less sophisticated mode, Scheuerlein (1995) recommended that flushed sediment concentrations should not exceed the upper limit measured during high floods or, if possible, during historical natural-flood events, the flushing discharge being reduced as soon as this threshold is reached.

Coordinated flushing

The Mekong River Commission has stressed the importance of dam coordination along the Mekong River (MRC, 2009). If an upstream dam is flushing sediment, coordination to ensure that the flushing flow passes through downstream dams is recommended. More generally, coordinated flushing is useful in case of a flood, so that all dams benefit from the natural flow for reservoir cleaning, as exemplified in France (Genissiat reservoir flushing coordinated with Verbois and Chancy-Pougny dam operation in Switzerland since 1978; Habara *et al.*, 2001) and in Japan (Kantoush et al. 2011).

Flushing in relation to fish ecology

Flushing should be avoided during certain seasons so that the natural ecology of the river is not suddenly perturbed; in that regard and from a fish protection perspective, flushing at the beginning of or during the monsoon season, when water is naturally loaded with sediments, should be preferred to flushing during the dry season[1]. In Soudan for instance, Salih (1994) showed that the optimal time for flushing was when many fish migrated upriver during the flood season. According to Kereselidze et al. (1986), flushing should be performed immediately before fish spawn and after they rear the fry. However Gray and Ward (1982) underline that faunal composition and life cycles vary from stream to stream, calling for pre-release studies to determine major periods of recruitment and growth before deciding about flushing dates for a given dam.
In the Mekong, at the end of the dry season, more than 100 migratory species migrate upstream of tributaries to lay eggs in a riverine environment characterized by clear water and its associated seasonal flora and benthofauna.

The frequency of flushes is also a factor to be considered; according to Sundborg and Jansson (1992), flushing less than once a year or every second year may increase the negative downstream effects of flushing. For cohesive clay deposits in particular, flushing should be done regularly, before deposits

[1] However the MRC (2009) notes that "*For convenience and safety, flushing is often implemented during base flow periods, because if problems occur with low-level outlets (such as debris jams), they can more easily be fixed, and because there is less risk to personnel working during the non-flood months. However, base flow flushing may have the greatest environmental effects because the sediment release is out-of-phase with the seasons when higher sediment concentrations occur naturally, such that organisms are not adapted to such concentrations and deposits in the channel downstream may remain for months until mobilized by the next high flow.*"

consolidate (Shen and Lai 1996). To alleviate the environmental damage associated with flushing events, reservoirs can send scouring flows to resuspend sediment that has settled downstream. Nelson et al. (1987) reports that dams along the Trinity River in Northern California routinely use scouring flows to flush silt that has settled on gravel spawning beds.

Importantly, when a flushing event is considered access to tributaries and shelters should be considered: "*fish definitely use such tributaries and small side streams to escape from the silt. Flushing should therefore be coordinated with flow in these tributaries*" (Buermann et al. 1995). In the case of the Mekong, this may imply a control of fishing gears and a momentary interruption of fishing in tributaries – to be compensated- during the flushing event.

5 CONCLUSIONS

Fruchart (2008) in a series of presentation to the Mekong River Commission, listed several points and questions regarding sediment management should be addressed during dam feasibility studies; we detail below those relevant to the protection of fisheries resources:

- despite a higher initial cost of operation, sediment management through Environmentally Friendly Flushing does have economic benefits and reduce environmental impacts. This approach, as demonstrated by thirty years of operation along the Rhone River, is not a matter of subjective environmental preferences but is economically beneficial to the country;
- infrastructure for sediment sluicing and flushing needs to be incorporated into the dam design from the start;
- Downstream water quality and aquatic habitats should be considered when planning sediment flushing; in particular what will be the effects of irregular opening of sediment sluices on downstream water quality and fish spawning areas?
- the effectiveness of sediment sluices and flushing activities should be evaluated thoroughly and demonstrated during feasibility studies. Sediment sluice gates being most probably insufficient, periodic sediment flushing may be required and should be incorporated into the operation plan. In absence of such maintenance during the concession period, the cost will be borne by the country, left wilt a reservoir largely filled with sediments and poorly effective operational for a hydropower generation viewpoint;
- Limits on downstream sediment concentrations should be set and agreed upon prior to dam operation. Baseline surveys and monitoring data should be made available to the Governments and the MRC
In the case of a cascade of dams, Environmentally Friendly Flushing requires the coordination of dam operation, which calls for the establishment of a dam operation coordinating body.

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