## Contributing Paper

# Flushing of Sediments from Reservoirs

Dr W. Rodney White
HR Wallingford, UK

**Prepared for Thematic Review IV.5:**
Operation, Monitoring and Decommissioning of Dams

*For further information see http://www.dams.org/*

# Disclaimer

**This is a working paper of the World Commission on Dams -** the report herein was prepared for the Commission as part of its information gathering activity. The views, conclusions, and recommendations are not intended to represent the views of the Commission. The Commission's views, conclusions, and recommendations will be set forth in the Commission's own report.

World Commission on Dams
5th Floor, Hycastle House
58 Loop Street
PO Box 16002
Vlaeberg, Cape Town
8018, SOUTH AFRICA
Telephone: +27 21 426 4000
Fax: +27 21 426 0036
Email: info@dams.org
http://www.dams.org

## Introduction

There are around 40 000 large reservoirs worldwide used for water supply, power generation, flood control, etc. Between a half and one percent of the total storage volume is lost annually as a result of sedimentation and 300 to 400 new dams need to be constructed annually just to maintain current total storage. However, increasing populations and increasing consumption per capita mean that the demand for storage is rising inexorably despite the increasing use of alternative sources and the more efficient use of water. The introduction of flushing facilities in some old dams, where appropriate, and in the design of new dams could help to minimise this need for additional storage.

The benefits attributable to dams and reservoirs, most of which have been built since 1950, are considerable and stored water in reservoirs has improved the quality of life worldwide. These benefits can be classified under three main headings:-

***Irrigation:*** About 20% of cultivated land worldwide is irrigated, some 300 million hectares. This irrigated land produces about 33% of the worldwide food supply. Irrigation accounts for about 75% of the world water consumption, far outweighing the domestic and industrial consumption of water.

***Hydropower:*** About 20% of the worldwide generation of electricity is attributable to hydroelectric schemes. This equates to about 7% of worldwide energy usage.

***Flood control and storage:*** Many dams have been built with flood control and storage as the main motivator eg the Hoover dam, the Tennessee Valley dams and some of the more recent dams in China.

In many areas of the world the life span of reservoirs is determined by the rate of sedimentation which gradually reduces storage capacity and eventually destroys the ability to provide water and power. Many major reservoirs are approaching this stage in their life.

One way of preserving reservoir storage is to flush sediments through purpose built outlet works within the dam. This technique can be applied to existing dams (with adaptation of the engineering works) and to new dams. However the technique is only effective under certain favourable conditions and is not universally applicable. The alternative is to build more dams to replace the depleting storage of the existing stock. However, there are fewer and fewer good dam sites available and new dams can have serious environmental and social consequences.

A recent study carried out by HR Wallingford (White, Attewill, Ackers and Wingfield, 1999) has evaluated where and when the flushing of sediment may be an appropriate method of sustaining reservoir storage. The study included the following aspects:

- an assessment of the scale of the problem of reservoir sedimentation.
- an estimation of the volume of storage that is likely to be required to meet continuing demand.
- a review of the current state of knowledge of mechanism of sediment flushing from reservoirs.
- a review of the worldwide experience of sediment flushing from reservoirs.
- identification, in general terms, of the areas of the world where flushing is likely to be most useful.

This contribution for the World Commission on Dams summarises the lessons learned in the HR study without giving the supporting evidence. Readers are referred to the HR report for full coverage of the work.

There is a distinction between sediment flushing and sediment sluicing. Sediment flushing is concerned with the removal of sediments which have settled in the reservoir at a previous time whereas sediment sluicing is concerned with passing sediments straight through the reservoir during times of flood. The distinction is sometimes difficult to make but, generally, sediment flushing is used to remove sediments up to and including sands and gravels whereas sediment sluicing removes only the finer fractions. It is the sands and gravels which determine the ultimate sustainable volume of any reservoir and hence the following sections predominantly relate to ***sediment flushing***.

## Review of sedimentation in reservoirs

***World storage:*** The best estimate of world storage in reservoirs (excluding natural lakes used as storage for power and irrigation) is approx. 7 000 km³.

***Distribution of storage:*** The worldwide distribution of existing storage and storage under construction as determined from the ICOLD Register (1998) is shown below:

| Region | Number of dams | Gross Storage ($km^3$) | Fraction of world total | Average size of reservoir ($M.m^3$) |
|---|---|---|---|---|
| N. America | 7 205 | 1 845 | 29% | 256 |
| S. America | 1 498 | 1 039 | 16% | 694 |
| N. Europe | 2 277 | 938 | 15% | 412 |
| S. Europe | 3 220 | 145 | 2% | 45 |
| Sub Saharan Africa | 966 | 575 | 9% | 595 |
| North Africa | 280 | 188 | 3% | 652 |
| China | 1 851 | 649 | 10% | 351 |
| S. Asia | 4 131 | 319 | 5% | 77 |
| C. Asia | 44 | 148 | 2% | 3 364 |
| South East Asia | 277 | 117 | 2% | 424 |
| Pacific Rim | 2 778 | 277 | 4% | 100 |
| Mid. East | 895 | 224 | 3% | 250 |
| *WORLD TOTAL* | **25 422** | **6 464** | **100%** | **254** |

The Americas together with northern Europe and mainland China account for 70% of the existing world stock of reservoir storage.

***Demand for more storage:*** The world population in 1999 is estimated to be 6 000 million, growing at an annual rate of 1.5%. This rate of growth is forecast to decline in the coming decades giving an estimated population in 2050 of 10 000 million.

Water demand is expected to continue to grow at a faster rate than that predicted by population growth alone. Much of this demand will be satisfied by increased surface and groundwater abstraction, water re-use and no direct linkage between overall demand and water storage can be assumed.

From the rates of growth for population, water consumption, estimated irrigation and hydropower requirements, the demand for new storage is estimated as:

| Region | Demand for new storage (km³) | | |
|---|---|---|---|
| | 2000 - 2010 | 2010 - 2020 | 2020 - 2030 |
| Europe | 50 | 50 | 55 |
| South & Central America | 465 | 495 | 425 |
| Africa | 165 | 205 | 250 |
| Asia & Oceania | 315 | 280 | 215 |
| **Total** | **995** | **1030** | **945** |

***Loss of storage:*** The rate of loss of storage for a given reservoir is dependent on the sediment yield from the catchment which, in turn, is dependent upon the rate of erosion and the transport, by water, of the sediment within the catchment. In regions where the catchments have remained stable, e.g. Northern Europe and North America, the rate of loss of storage is sensibly constant. In regions where deforestation has occurred the rate of catchment erosion and consequently the rate of loss of storage increases.

The highest rates, in percentage terms, of loss of storage are found in the smallest reservoirs and the lowest rates in the largest. Of the 1 105 reservoirs documented, 730 have a storage volume of less than 1 233 $M.m^3$ and an average rate of loss of storage in excess of 1% per annum. At the other extreme, 23 of the reservoirs have a storage volume in excess of 1 233 $M.m^3$ and an average rate of loss of storage of 0.16% per annum. The worldwide average for the loss of storage due to sedimentation is between 0.5% and 1.0% per annum - a very significant amount.

## Factors which influence viability and efficiency of sediment flushing

For effective flushing the following factors need to be considered and satisfied:

***Hydraulic conditions required for efficient flushing:*** Riverine conditions must be created in the reservoir for a significant length of time. The reservoir level must be held low throughout the flushing period, possibly with minor fluctuations in level to activate sediment movement. To achieve this:

- The hydraulic capacity of the bypass must be sufficient to maintain the reservoir at a constant level during the flushing period.
- Flushing discharges of at least twice the mean annual flow are required.
- Flushing volumes of at least 10% of the mean annual runoff should be anticipated.

***Quantity of water available for flushing:*** There must be enough water available to transport the required volume of sediment. This has the following implications:

- Reservoirs where the annual runoff is large compared with the volume of the reservoir are best suited for sediment flushing.

- A regular annual cycle of flows and a defined flood season provide optimum conditions for sediment flushing. This favours sites in monsoon areas and sites where flood flows are generated by annual snowmelt in the spring and summer months.
- A balance must be achievable between the significant quantities of water required for sediment flushing and water required to satisfy demands at other times of the year - for irrigation and hydropower, for example.

***Mobility of reservoir sediments:*** Sediment sizes are an important factor in determining whether the quantity of water available for flushing will be adequate to remove the desired quantity of sediment from the reservoir.

- Deposited coarse sediments are more difficult to remove than fine sediments. These sediments progress from the upstream end of the reservoir and the toe of the fore-set slope reaches the dam well into the life of the reservoir. The sustainable volume achievable by sediment flushing depends on the nature of the deposited sediments and other factors.
- The sediment sizes in transport in rivers entering a reservoir can be of paramount importance in determining the success of flushing. From the point of view of achieving a sediment balance, a large factor is desirable between the sediment sizes being transported as suspended bed material load in the rivers entering the reservoir and the sizes found in the river bed material. Such conditions are typical for gravel rivers with a widely varying bed material composition. In large rivers this situation is found where the longitudinal bed gradient is between, say, 0.002 and 0.001. In smaller rivers the equivalent range may be 0.005 to 0.002.
- From the point of view of sediment size alone, delta deposits of fine sand and coarse silt are the most likely to produce success in flushing a reservoir. Coarser material may inhibit a sediment balance and finer material will deposit in the body of the reservoir outside any incised channel and so will not be available for reworking during flushing.

***Site specific factors:*** The most suitable conditions for flushing are to be found in reservoirs which approximate in shape to the incised channel which develops during flushing. Long, relatively narrow reservoirs are better suited to flushing than short, wide, shallow reservoirs.

## Worldwide experience of sediment flushing

The HR study looked at 50 reservoirs which are being, or have been flushed. In some cases the flushing was successful, in others there was little or no success. The main findings from this worldwide review, some of which confirm directly the semi-independent analysis of those hydraulic factors which favour sediment flushing, are:

- ***The hydrology and sedimentology of the catchment:*** The hydrology and sedimentology of the catchment need to be fully understood in the planning of flushing facilities for new or existing reservoirs and to provide the background for analyses of past sedimentation and flushing performance.
- ***The storage capacity of the reservoir:*** Successful hydraulic flushing is more likely to be practicable in reservoirs which are hydrologically small, with a storage capacity less than 30% of the mean annual inflow. The smaller the reservoir, the greater the chance of it being successfully flushed and the larger the likely residual storage capacity.

- ***The sediment deposition potential:*** Flushing is vital for the preservation of long-term storage in reservoirs where the sediment deposition potential is greater than 1% to 2% of the original capacity.
- ***The shape of the reservoir basin:*** Worldwide experience confirms that the shape of the reservoir basin can have a large impact on the practicability of effective flushing and the residual storage capacity. Narrow steep-sided reservoirs in valleys with a steep longitudinal slope are the easiest to flush. Wide valleys where the impoundment covers former floodplains can be less effectively flushed, because the deposits tend to consolidate and are remote from the flushing channel.
- ***The deployment of full or partial drawdown:*** Full drawdown and empty flushing have been found to be much more effective than partial drawdown.
- ***The low-level outlet facilities provided:*** Worldwide experience confirms that, for effective flushing, the low-level outlets must be both low enough and of sufficient capacity to allow significant drawdown of water levels to be controlled during the time of year when flushing is undertaken. Proportionately larger outlets are required for flood-season sediment sluicing during the flood season than for sediment flushing at the outset of the flood season.
- ***The scope for enhancements to flushing:*** Fluctuations in water level and discharge during flushing are beneficial to the promotion of bank slumping, increasing the rate of sediment movement. Also, the deployment of lateral and longitudinal diversion channels has been successful in promoting flushing in reservoirs which are hydrologically large or contain significant proportions of deposition in areas remote from the main flushing channel.
- ***Operational limitations:*** Operational considerations, such as water and power demands, can inhibit the ability to flush successfully.
- ***Downstream impacts:*** Downstream impacts can act as a constraint in the planning and operation of sediment flushing. In some cases flushing may be ruled out, whereas sediment sluicing, which approximately preserves the seasonal distribution of sediment load, may be a practicable alternative during the early life of a reservoir.

## Geographical areas suited to flushing

***Erosion rate:*** The erosion rate depends on a complex interaction of the following factors:

- ***Climate:*** Precipitation and runoff, temperature, wind speed and direction
- ***Geotechnics:*** Geology, volcanic and tectonic activity, soils
- ***Topography:*** Slope, catchment orientation, drainage basin area, drainage density
- ***Vegetation***
- ***Land use and human impact***

Estimates of global average rates of denudation have ranged from 0.06 mm/year to 0.16 mm/year (Morris and Fan, 1998). This is equivalent to estimates of between 15 x $10^9$ t/km$^2$/year and 20 x $10^9$ t/km$^2$/year (Walling and Webb, 1996). Areas with sediment yield over 1 000 t/km$^2$/year are 8.8% of the total land area and account for 69% of the total sediment load. Regions with less than 50 t/km$^2$/year account for about half of the land area and 2.1% of the sediment yield.

***Sediment yield:*** Sedimentation occurs in reservoirs when the eroded sediment is transported down the river system into the reservoir. The efficiency of the transport process is expressed by the sediment delivery ratio, which is the proportion of sediment eroded from the land that is discharged into rivers (Morgan and Davidson, 1986).

The sediment delivery ratio is generally higher for sediment derived from channel-type erosion which delivers sediment to the main channels of the transport system more quickly and directly than in the case of sheet erosion.

The poor correlation between sediment yield and erosion rates makes it difficult to estimate the sediment load entering a reservoir on the basis of the erosion rate within the catchment (Morris and Fan, 1998). Most studies that have attempted to relate the delivery ratio to catchment characteristics have found that the delivery ratio decreases as the catchment area increases (Walling and Webb 1983).

***Climatic zones:*** An understanding of the precipitation regimes throughout the world may allow the definition of climatic zones based on temperature and precipitation regimes. This may permit the definition of areas of high and low erosion rates. It is difficult to classify distinct climatic zones as they tend to merge into one another rather than have sharp boundaries but a number of general models have been produced.

There have been many climatic classifications produced but one of the most common is based on the original Koppen classification (Pidwirny, 1999) with eight climatic regions based on four temperature zones and one moisture zone and the seasonal domination of air masses.

The eight Koppen climatic regions are as follows:

- Tropical Wet
- Tropical Wet and Dry
- Tropical Desert
- Mid-Latitude Wet
- Mid-Latitude Winter Dry
- Mid-Latitude Summer Dry (Mediterranean Climate)
- Polar Wet and Dry
- Polar Desert

***Hydrological characteristics required for successful flushing:*** Experience has shown that low reservoir water levels provide the most effective conditions for sediment flushing. To allow water levels to be lowered requires confidence that rainfall can be relied upon to refill the reservoir. It follows that well defined wet and dry seasons will be favourable for a sediment flushing regime. Such a climate is defined by Koppen as tropical wet and dry.

***Areas of the world which are best suited to reservoir flushing:*** It is not possible to define precisely which specific areas of the world will provide conditions for successful flushing. In reality there is a spectrum of conditions ranging from those sites where conditions are ideal to those sites which are quite unsuited to sediment flushing.

From the Koppen classification of climatic zones the requirements for successful flushing are most likely to be met in the ***Tropical Wet and Dry Region***. Conditions in another region may also be suitable for sediment flushing, namely the ***Tropical Wet Region***.

Locations with these types of climates include:

- Parts of central America extending into Brazil in South America.
- A region of central Africa from the Ivory Coast in the west to Sudan in the east would be suitable.
- Parts of central Asia including Pakistan, India, Nepal, China, Cambodia, Vietnam and Thailand.

## Costs and benefits of flushing facilities

With the current procedures for assessing costs and benefits to justify the financing of new projects it is often impossible to build sediment flushing facilities when the dam is first commissioned. This is because sediment flushing (as opposed to sluicing) only becomes effective when the deposited sediment reaches the proximity of the dam and in most cases this will be many years after commissioning. The costs are up-front and the benefits are twenty to thirty years down the line - not a situation that impresses pure accountants! We need to find a way of putting a much higher value on sustainability in our justification procedures for the construction of dams.

The rejuvenation of existing reservoirs by the introduction of flushing facilities, particularly those which have lost between 40% and 60% of their original storage, is attractive in that costs are likely to be between 10% and 30% of the cost of new dams of a similar capacity.

## Design implications for flushing facilities for new and existing reservoirs

Flushing facilities require extensive investigative work to establish their viability and this will be required on a site by site basis. There are numerous stages for such investigations which include the following:

***Site investigations:*** Flushing facilities have to be able to withstand high velocity flows with high concentrations of sediment. Such flows are highly abrasive and expensive steel lining will normally be required to avoid undue damage to the structures. Hence it is important that the site allows for the construction of relatively compact flushing facilities, either orifices within the dam itself or relatively short tunnels or channels. Energy dissipation works will normally be required at the downstream side and it is an advantage if these facilities can be shared with other outlets such as high head spillways or irrigation outlets. It is advantageous if the flushing facilities discharge to the downstream channel well away from any power station outlets as any local deposition of sediments will increase tailwater levels and reduced power output.

The reservoir itself requires a detailed survey to establish its topography. This is required to check whether the reservoir basin is a suitable shape for sediment flushing and also to provide input data for detailed modelling of the sedimentation process within the reservoir.

***Hydrological investigations:*** It has been stated above that there are certain requirements for successful sediment flushing which are related to the amount of water available and its reliability year on year and season by season. Hence inflows to the reservoir need to be established with confidence. This involves the acquisition of historical records of river flows going back at least 30 years and preferably longer. Records of river flows can often be extended further back in time by considering local rainfall records, which often go back a 100 years or more, and undertaking catchment modelling to convert rainfall into run-off.

The ideal situation for sediment flushing is an annual inflow of water of at least 3 times the volume of the reservoir (original volume in the case of existing reservoirs) and an annual hydrograph which shows distinct wet and dry seasons.

***Sediment investigations:*** The amount and nature of the sediment entering or likely to enter the reservoir needs to be established. This requires measurements over many years to establish the results with the confidence which is required. There are various approaches to this task. Most commonly sediment transport is measured at a gauging station not too far upstream of the reservoir and a relationship between flow rate and sediment transport rate is established. The long hydrological record is then used to compute the total amount of sediment passing the gauging station by integrating over the period of the record. There are some dangers in doing this because there is no unique relationship between flow rate and sediment transport rate for fine cohesive sediments, the quantities of sediment being determined by the amount being washed off the catchment not the capability of the river to transport them. Bed load is difficult to measure and is often estimated as 10% of the total sediment load. An alternative approach is to calculate the bed load using established predictive techniques.

In the case of existing reservoirs, information about the amount of sediments entering the reservoir can be augmented by surveys of the amount and nature of the material settling within the reservoir. Care is required, however, to allow for the amount of material, mainly fine, which passes through the reservoir without deposition.

Bed material sampling should be undertaken in the reservoir and in the rivers which feed the reservoir. A sound knowledge of the nature of these sediments, including their size and specific gravity, is an essential requirement to provide inputs for numerical models which simulate sediment movement, (see later).

***Hydraulic modelling:*** Sophisticated numerical (computer) modelling of the way sediment is likely to behave within the reservoir and the amount and nature of the sediment which will be passed to the downstream reach is the cornerstone of any detailed evaluation of flushing facilities. One dimensional models with quasi two-dimensional simulation of the incised channel which develops during sediment flushing are the most appropriate tools. These models are computationally efficient and are capable of making long term simulations, decades rather than hours or days. They have reached reliability levels which permit them to be used "cold" on new reservoirs which are only at the investigative stage. When used on existing reservoirs they have the added benefit of measured sedimentation data for verification purposes.

Computer simulations of reservoirs ideally use representative, long term sequences of water and sediment inflows to the reservoir. The models are capable of looking at the effectiveness of various aspects which affect reservoir sustainability over periods of up to 50 or 60 years, including:

- Measures to reduce the amount of sediments entering reservoirs such as catchment conservation or upstream storage
- Measures to manage sediments within reservoirs such as variations in the operating rule curves for the reservoir. Rules which permit emptying of the reservoir annually promote movement of sediment towards the dam, rules which maintain high water levels ensure storage of sediments at

the upstream end of the reservoir and help to extend reservoir life albeit with the penalty of reduced water yield.

- Measures to evacuate sediment from the reservoir including dredging and sediment flushing.

***Engineering and Costs:*** The design of the civil works involved in all the options for helping to sustain reservoir capacity need to be estimated so that the best solution can be found.

***System Simulation Modelling:*** System Simulation Modelling is required to evaluate the conflicting demands of hydropower production, irrigation and other requirements, and must be able to assess the impacts of the various reservoir operating strategies. The simulation model must be able to replicate the outputs of water and power under a range of operating strategies so that an optimal economic and technical solution may be identified. In addition, it must be possible to take account of the effects of other reservoirs upstream and downstream of the one under consideration.

***Economic and Financial Analysis:*** The main aim of economic and financial analyses is to assist in the identification and selection of the most favourable sediment management option. For each option the most important factor, from the economic viewpoint, is to define the 'with' and 'without' project cases. These will illustrate the net economic impact of the availability of water resources over time, including any seasonal variations. Evaluation of the impact of alternative investment phasing is also important.

The greatest challenge in the evaluation of projects which promote sustainability of reservoirs is to assign realistic values to the benefits of extending reservoir life. This is beyond the scope of this paper. Work, however, is progressing in this direction (Palmieri, 1998).

## References

ICOLD (1998) *World Register of Large Dams.* CD ROM

Morgan R P C and Davidson D A (1986) *Soil erosion and conservation*, Longman Group UK

Morris L M and Fan J (1998). *Reservoir Sedimentation Handbook: design and management of dams, reservoirs and watershed for sustainable use.* McGraw Hill, New York. ISBN 0-07-043302-X.

Walling D E and Webb B W (1983) *Patterns of Sediment Yield.* In K.J Gregory [ed] Background to Palaeo-Hydrology, John Wiley, New York, pp 69-100

Palmieri A, Shah F and Dinar A (1998) *Reservoir sedimentation and the sustainable management of dams.* World Congress of Environmental and Resouce Economists, Venice, June 23-27.

Pidwirny M (1999) *Climatic regions of the world: Climatology - The geographic study of the atmosphere*, Introduction to physical geography II. Department of Geography, Okanagan University College, http://www.arts/ouc.bc.ca/geog/G121/ln.html p 1-9

White W R, Attewill L, Ackers J, Wingfield R (1999) *Guidelines for the flushing of sediment from reservoirs.* HR Wallingford. Report SR 563. November.