
Worldwide Experience of Sediment Flushing Through Reservoirs

MUHAMMAD ASIF CHAUDHRY*, AND HABIB-UR-REHMAN**

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ABSTRACT

Globally there are about 25,500 storage reservoirs with total storage volume of about 6,464 Bcm. The maximum number of reservoirs are in North America, i.e. 7205 with the total storage volume of about 1,844 Bcm, whereas minimum number of reservoirs are in Central Asia, i.e. 44, with the total storage volume of about 148 Bcm. Over the globe, average annual reservoir storage loss due to sedimentation varies from 0.1-2.3%, however, average annual world storage loss is about 1.0%. In order to combat the storage loss, the techniques used globally are: watershed management, dredging of deposited sediments, sediment routing/sluicing, sediment bypassing, density current venting and sediment flushing through reservoir, separately and also in combination. Each approach has its own limitations, depending on the site conditions. Sediment flushing technique is used by two ways i.e. Drawdown flushing and Emptying and Flushing. In Emptying and Flushing, the reservoir is emptied before the flood season, resulting in the creation of river-like flow conditions in the reservoir. The flow velocities in the reservoir are increased to such an extent that deposited sediments are remobilized and transported through the low level outlets provided slightly above the original riverbed level with sufficient flow capacity. Flushing is not a new technique and has been experienced for the last 6 decades on several reservoirs of the world. The results of the study reveal that there are about 50 reservoirs which are flushed, out of which flushing data is available for about 22 reservoirs only. However 6 reservoirs have been found with successful application of flushing operation and all other are flushed with low flushing efficiency. Flushing has been successfully implemented at Baira-India, Gebidem-Switzerland, Gmund-Austria, Hengshan-China, Palagnedra-switzerland, Santo-Domingo-Venezuela Reservoirs, while the unsuccessfully flushed reservoirs are: Chinese reservoirs, Gaunting, Heisonglin, sanmenxia, Shuicaozi, Naodehai, Nanqin, Guernsey-USA, Ichari-India, ouchi-Kurgan and Zemo-Afchar of former USSR, sufid-Rud-Iran, Warsak-Pakistan, Jansenpei-Taiwan, Khashm El Gibra-Sudan, Mangahao-Newzealand, and Cachi of Costa Rica.

Key Words: Storage Reservoir, Flushing Techniques, Storage Volume.

1. INTRODUCTION

Globally there are about 25,500 storage reservoirs with the total storage volume of about 6,464 Bcm [1-2]. The maximum number of reservoirs are in North America, i.e. 7,205, with the storage volume of

about 1,845 Bcm., whereas the minimum numbers of reservoirs are in Central Asia, i.e. 44, with the storage volume of 148 Bcm. The numbers of storage reservoirs with storage volumes (in Bcm) in other regions are as:

*Ph.D. Scholar, and **Professor,
Department of Civil Engineering, University of Engineering and Technology, Lahore.

South Asia 4131(1039), South Europe 3220(938), Pacific Rim 2278(277), North Europe 2277(938), China 1851(649), South America 1498(1039), Africa 967(575), Middle East 895(224),

World annual reservoir storage loss due to sedimentation varies from 0.1-2.3%, with average annual world storage loss of about 1.0% [3]. The maximum storage loss is in China, i.e. 2.3%, whereas the minimum storage loss is in UK, i.e. 0.1%. The storage loss expressed in percentage in other regions is: Turkey 1.5, India 0.46, South Africa 0.34, South East Asia 0.30, USA 0.22, and Japan 0.15. As a result of reservoir sedimentation rate, about 300-400 new dams need to be constructed annually just to maintain current total storage. This Storage loss is mainly due to different vegetation cover, topographic and geological conditions of the watershed areas [3].

The 20th Century was concerned with the development of reservoir storage, more emphasis will be required in the 21st century on the conservation of storage. Sediment management will become crucial. The goal will be to convert today's inventory of non-sustainable reservoirs into sustainable assets for future generations [4].

Several methods by which the life enhancement of storage Reservoir can be made are: Watershed Management, dredging (conventional dredging, hydrosuction and dry excavation), flushing of sediments from Reservoir, sediment routing/sluicing, sediment bypassing and Density current venting, used independently or in combination [5].

Flushing sediments through a Reservoir has been practiced successfully and found to be inexpensive in many cases. However, the great amount of water consumed in the flushing operation might affect it [6]. Every Reservoir of the world cannot be flushed successfully due to the number of parameters affecting it like flatter bed slope, wider section, higher height of the dam and availability of

water for flushing. Flushing also causes sediments to be released from the Reservoir at a much higher concentration than occurs in the natural fluvial system which may create unacceptable environmental impacts downstream, however, these impacts are less severe as compared to absence of flushing at all. Two approaches to flushing exist; complete drawdown flushing, partial drawdown flushing. In complete drawdown flushing the Reservoir is emptied before the flood season, resulting in the creation of river-like flow conditions in the Reservoir. Low level outlets for flushing operation are provided close to the original riverbed level and sufficient hydraulic capacity to achieve full drawdown [2]. Some irrigation Reservoirs in China are emptied for flushing during the first part of the flood season, passing early season floods through the impoundment without significant detention. The Reservoir is refilled during the latter part of flood season [7]. Flushing is most effective in preserving Reservoir storage when outlets are placed near the original streambed level and Reservoir is completely emptied. However constraints may limit either the allowable drawdown or the invert elevation of flushing outlet, requiring the flushing be undertaken with only partial drawdown. Flushing with partial drawdown may be used to clear more live storage space and locate the sediments in a more favorable position for future complete drawdown flushing [8].

Flushing is not a new technique and has been attempted for the last 6 decades on several reservoirs of the world. The study reveals that there are about 50 reservoirs which are flushed, out of which flushing data is available for about 22 reservoirs. The maximum numbers of reservoirs are flushed in China which are 21. The number of flushed reservoirs in different countries are as: Switzerland 5, Former USSR 4, India 3, USA 3, Puerto Rico 2, Algeria 1, Austria 1, Costa Rica 1, Guatemala 1, Iran, Japan 1, New Zealand 1, Pakistan 1, Sudan 1, Taiwan 1, Tunisia 1, Venezuela 1.

Worldwide flushing has been successfully implemented at Baira-India, Gebidem-Switzerland, Gmund-Austria, Hengshan-China, Palagnedra-switzerland, Santo-Domingo-Venezuela Reservoirs, while the unsuccessfully flushed reservoirs are: Chinese reservoirs, Gaunting, Heisonglin, sanmenxia, Shuicaozi, Naodehai, Nanqin, Guernsey-USA, Ichari-India, ouchi-Kurgan and Zemo-Afchar of former USSR, sufid-Rud-Iran, Warsak-Pakistan, Jansenpei-Taiwan, Khashm-el-Gibra-Sudan, Mangahao-Newzealand, and Cachi of Costa Rica [2,9]. Flushing experiences of successfully and unsuccessfully flushed reservoir are given Tables 1-2, respectively.

2. WORLDWIDE EXPERIENCES IN FLUSHED RESERVOIRS

In this study worldwide flushing experiences of different reservoirs are discussed. Worldwide flushing has been successfully implemented at Baira-India, Gebidem-Switzerland, Gmund-Austria, Hengshan-China, Palagnedra-switzerland, Santo-Domingo-Venezuela Reservoirs, while the unsuccessfully flushed reservoirs are: Chinese reservoirs, Gaunting,

Heisonglin, sanmenxia, Shuicaozi, Naodehai, Nanqin, Guernsey-USA, Ichari-India, ouchi-Kurgan and Zemo-Afchar of former USSR, sufid-Rud-Iran, Warsak-Pakistan, Jansenpei-Taiwan, Khashm-el-Gibra-Sudan, Mangahao-Newzealand, and Cachi of Costa Rica [2,9]. The reservoirs; Guernsey, Ichari, Shuicaozi and Warsak seems to be unsuccessfully flushed due to absence of any flushing outlet and flushing is being done through the spillway at higher elevation. Different modes of sediment removal from the total available 50 flushed reservoirs are: flushing alone, flushing alongwith Routing, flushing alongwith density current venting, flushing aided both by Routing and , density current venting, and density current venting alongwith flushing. Among the 50 flushed reservoirs 42 reservoirs are desilted by flushing mode, whereas 3 reservoirs by flushing alongwith routing, 2 reservoirs by flushing alongwith density current venting, 2 reservoirs by flushing alongwith routing and density current venting, 1 reservoir basically by density current venting aided by flushing. These reservoirs are discussed as:

TABLE 1. SUCCESSFULLY FLUSHED RESERVOIRS

No.	Reservoir	Country	Capacity (Mm ³)	Flushing Experience
1.	Baira	India	2.4	Used diversion tunnel, clearing 0.38 Mm ³ in 40 hours, interruption to generation, annual flushing thereafter.
2.	Gebidem	Switzerland	9.0	Reservoir emptied for 2-4 days per year and about 3 Mm ³ water was used, virtually no sediment accumulation, because of gorge-type and annual flushing.
3.	Gumend	Austria	0.93	Flushing undertaken intermittently between 1946-1960 and annual flushing thereafter.
4.	Hengshan	China	13.3	3.19 Mm ³ deposition between 1966-1973. Emptied and flushed for 37 days in 1974, removing 0.8 Mm ³ of deposits; 52 days flushing in 1979 removed 1.03 Mm ³ deposits.
5.	Palagnedra	Switzerland	5.5	1978 flood caused 1.08 Mm ³ deposition, flushing between November 1978 to March 1979 removed 2.4 Mm ³ deposits, virtually full capacity of reservoir can be maintained in the long term.
6.	Santo Domingo	Venezuela	3	Only one flushing operation in May 1978, after 4 years of operation and flushed 50-60% of deposition in 3 days. Concluded that flushing should be annual.

2.1 Baira Reservoir, India

Baira Reservoir used for hydropower generation was constructed in 1981 on combined flow of three tributaries

of river Ravi. The basin length of reservoir is 4.1km, with initial storage capacity of 2.4 Mm³ [10].The average annual inflow is about 0.3 MTons. A mean rate of annual rate of

TABLE 2. UNSUCCESSFULLY FLUSHED RESERVOIRS

No.	Reservoir	Country	Capacity (Mm ³)	Flushing Experience
1.	Guanting	China	2270	Only one flushing operation in 1954, removing 10% of annual flow, partly venting by density current.
2.	Guernsey	USA	91	Attempted in four years 1959-1962, but not considered effective, as recovered less than 0.2% of the original capacity of reservoir.
3.	Heisonglin	China	8.6	From 1962, density current venting and flood season sluicing reduced trap efficiency to about 15%; lateral erosion technique successfully implemented from 1980, recovering some lost storage; long term capacity expected to be 30-35% of original.
4.	Ichari	India	11.6	No bottom outlet built for flushing and reservoir flushed annually by fully opening spillway gates.
5.	Ouchi-Kurgan	Former USSR	56.4	Sluiced for 3-4 months annually since 1963.
6.	Sanmenxia	China	9640	Rehabilitation from 1966 included construction of larger low level outlets; flushed for 4 months annually; six development stages are described in literature.
7.	Sufid-Rud	Iran	1760	Flushing (about 4 months/year) commenced in 1980; after 7 years 26% of lost storage had been recovered; from 1992 flood plain erosion enhanced using diversion channels; expected that long term capacity could be upto 90% of original reservoir capacity.
8.	Shuicaozi	China	9.6	Implemented experimentally from 1965; but limited by high elevation of spillway and short duration annually to about one third of inflow.
9.	Naodehai	China	168	Bottom outlets ungated prior to 1970, so flushing appears to have been natural.
10.	Nanqin	China	10.2	Density current venting commenced in 1977, discharging about 2.43 MTons of suspended sediment load between 1977-1984. Experimental flushing from 1984 with good results, concluded that flushing should be undertaken for 4 days every 3-4 years.
11.	Zemo-Afchar	Former USSR	Not found in literature	Implemented from 1939, with full drawdown and appeared to keep situation stable upto 1955, removing about 1 Mm ³ per year
12.	Warsak	Pakistan	170	No bottom outlet provided. Five flushing operation over spillway crest performed between 1976-1979, with total duration 20 days and scoured 4.2 Mm ³ of deposited sediments.
13.	Jensanpei	Taiwan	7	Flushing commenced 1955 for 2.5 months annually, virtually arresting subsequent sedimentation, but not restoring capacity, minor raising of impounding level in 1942 and 1958
14.	Khashm-El-Gibra	Sudan	950	Flushing operations in 1971 and 1973 each removed 85 MTons.
15.	Mangahao	Newzealand	Not found in literature	Flushed in 1969 through low level diversion tunnel and 73% of accumulated sediment removed in one month; subsequently annual emptying and flushing performed during 3 week closure of power use.
16.	Cachi	Costa Rica	54	Commenced 1973 and 14 flushing operations performed in 18 years and reduced trapping efficiency from 82-27%.

siltation had been estimated as 0.092 Mm³ but in the first 18 months of operation, silt volume of 0.45 Mm³ had been accumulated.

The first flushing operation was undertaken in August 1983. The duration of flushing was about 40 hours with the flushing discharge of 44 m³/s. The recommendation made for further flushing were that it should be carried once a year, for a period of 24 hours and that it would be more effective in April or May when the discharge from Baira is about 100 m³/s. The achieved value of LTCR is 0.85 with the estimated long term capacity of 85% of the original storage capacity and hence sediments flushing proved to be successful for Baira Reservoir [2].

2.2 Gebidem Reservoir, Switzerland

Gebidem Reservoir used for hydropower generation was constructed in across Massa River, a tributary of the Rhone. The basin length of reservoir is 1.4 km, with initial storage capacity of 9 Mm³. The average annual sediments inflow is about 0.5 MTons.

The dam was originally designed with two flushing tunnels each contained two gates located directly below the power intakes and close to the original streambed level. The Reservoir is being flushed annually since 1982 between May and July with duration of flushing varying from 40-101 hours. During flushing Reservoir level is lowered to a minimum operating level, then drawdown flushing is initiated over a period of 2 hours by opening both gates progressively, raising discharge from 10-60 m³/s. it takes between 3 and 6 hours for free flow condition to be achieved at the outlet, typically at discharges of between 10 and 20 m³/s. Due to the gorge shape geometry of the impoundment flushing has resulted in the entire Reservoir basin being kept virtually sediments free. Estimated value of LTCR is 0.99 with the estimated long term capacity of 100% of the original storage capacity and hence sediments flushing proved to be successful for Gebidem Reservoir [2].

2.3 Gmund Reservoir, Austria

Gmund Reservoir used for hydropower generation was constructed in 1945 across Massa River, a tributary of the Rhone. The basin length of reservoir is 0.94 km, with initial storage capacity of 0.93 Mm³.

After commissioning Durlassboden reservoir upstream, the average annual sediments inflow reduced from 0.2-0.07 MTons since 1967. From then until 1981, as a result of annual sediments flushing and the construction of Durlassboden reservoir upstream, the total sediments volume was generally less with a typical value of about 0.15 Mm³.

The bottom outlet passes around the right abutment of the dam in curved tunnel with an inlet elevation 28m below the crest. A second outlet was added in the middle of the dam in 1963 with an inlet elevation of 27m below the crest.

During the first period of flushing from 1949-1960, flushing was not executed every year, but was carried out depending on the amount of sediments accumulated. However from 1960, flushing was carried out every year. In the most instances flushing was carried out for a week, with flushing discharge of 6 m³/s. The efficacy of flushing improved after the addition of second outlet. From 1967 with the beginning of operation of Durlassboden Reservoir, Reservoir period required for flushing reduced to one day. Construction of Durlassboden Reservoir upstream of Gmund Reservoir has been key factor, reducing the incoming sediments load. Estimated value of LTCR is 0.98 with the estimated long term capacity of about 86% of the original storage capacity and hence sediments flushing proved to be successful for Gmund Reservoir [2].

2.4 Hengshan Reservoir, China

Hengshan Reservoir used for irrigation and flood control was constructed across Massa River, a tributary of the Rhone. The basin length of reservoir is 1.0 km, with initial storage capacity of 13.3 Mm³. Average annual sediments inflow is about 1.18 MTons.

The dam has a small outlet 2.6m above the base of the dam with discharge capacity of 17 m³/s at full impounding level. There is also another outlet for flood discharge, 14.5m above the river bed, capable of passing a maximum discharge of 1260 m³/s. From 1966-1973, the first eight years of Reservoir operation 3.19 Mm³ of sediments had deposited in the Reservoir with height of deposits behind the dam reaching 27m.

Flushing was carried out in July 1974, Reservoir emptied and flushed for 37 days. During this, 0.8 Mm³ of sediments removed from the Reservoir. The Reservoir was then impounded for five years to June 1979, before flushing for the second time for a period of 52 days during the flood season. The second flushing period removed 1.03 Mm³ of sediments, reducing the volume of sediments in the Reservoir to 2.62 Mm³. Emptying and flushing were carried subsequently undertaken in 1982 and 1986. Estimated value of LTCR is 0.77 with the estimated long term capacity of about 75% of the original storage capacity and hence sediments flushing proved to be successful for Hengshan Reservoir [2].

2.5 Palagnedra Reservoir, Switzerland

Palagnedra Reservoir used for hydropower generation was impounded in 1952 across Melezza River. The basin length of reservoir is 2.6 km, with initial storage capacity of 5.5 Mm³. The average annual sediments inflow is about 0.08 MTons.

There were no particular problems with sedimentation in the first seven years of operation [11]. By the end of 1968, volume of the deposits had reached 1.47 Mm³. In August 1978, due to large flood with peak discharge 1000 m³/s, caused 1.8 Mm³ of deposition in the Reservoir. A 1.76 km long diversion tunnel, with discharge capacity of 225 m³/s was constructed in 1974 from the upstream of the basin to downstream of the dam, with the main purpose of sediments laden flows to be bypassed. Two number outlets, one upper with the elevation of 12m from the river bed, while the other lower outlet is commissioned at the river bed level.

Flushing of sediments, following 1978 flood was accomplished in two different phases and required a period of 4.5 months, commencing in mid November 1978 and finished by the end of March 1979. First phase was accomplished by flushing through the upper outlet with flushing discharge of 0.3 m³/s for a period of 1.5 months and evacuated about 0.3 Mm³ of the material. Then in the second phase, flushing through lower outlet was accomplished with flushing discharge of 1.25 m³/s, for duration of 3 months, from January 1979 to March 1979. During this 3 months phase it was estimated that approximately 2.1 Mm³ of the material was flushed from the Reservoir. Estimated value of LTCR is 1.0 with the estimated long term capacity of about 100% of the original storage capacity and hence sediments flushing proved to be successful for Palagnedra Reservoir [2].

2.6 Santo Domingo Reservoir, Venezuela

Santo Domingo Reservoir used for hydropower generation was impounded in 1974 at the confluence of the Santo Domingo and Aracay rivers. The basin length of Reservoir is 1.0 km, with initial storage capacity of 3.0 Mm³. The average annual sediments inflow is about 0.2 MTons.

The dam is provided with three bottom outlets for flushing sediments from Reservoir, two in deeper Santo Domingo River valley with flushing discharge of 5 m³/s and one in the Aracay River valley with flushing discharge of 3 m³/s. During the first 4 years of operation, from 1974-1978, there was not any problem of sediments deposition. The first flushing of Reservoir took place in May 1978, after four years of operation, it was estimated that bottom outlets flushed between 50-60% of the deposited sediments with flushing discharges 5 m³/s for Santo Domingo side and 3 m³/s for Aracay for a duration of 3 days of free flow flushing. The entire flushing operation was sufficient to remove the majority of the sediments which had been in the Reservoir basin over the four years of operation., restoring the storage value to 2.85 Mm³. Estimated value of LTCR is 1.0 with the estimated long term capacity of about 97% of the original storage capacity and hence sediments flushing proved to be successful for Santo Domingo Reservoir [2].

2.7 Guanting Reservoir, China

Guanting Reservoir used for flood protection, river regulation and hydropower was impounded in 1953 across Yonding River. The basin length of Reservoir is 30 km, with initial storage capacity of 2270 Mm³. The average annual sediment inflow is about 73 MTons.

The dam has a gated spillway with the discharge capacity of 2950 m³/s. There is an 8m diameter bottom outlet tunnel, with maximum discharge capacity of 560 m³/s. In October 1954 when a discharge of 80 m³/s was passed for five days at a ponded depth of 8m and removed about 10% of annual sediment flow. One incident of blockage occurred in 1962 resulting in minimal outflow for first few minutes after a sluice gate was opened, but eventually the area was flushed clear of sediment. Since then it is reported that sediment level is monitored and the gates each opened for about 20 minutes whenever the level more than 0.5m above the lower gates with a minimum interval of one month. These operations removed only local load accumulation and no attempt was made to flush a significant portion of the sediment inflow. Partial blockage of gate occurred in 1974, which was sluiced away after the gate was raised above 1m. By 1986, general sediments level had reached 17m above the invert of the lower gates within 250m distance of bottom outlet and occasional blockage was reported. Since 1986 no information about sedimentation and flushing experiences is available. The estimated LTCR is only 0.2 and hence sediments flushing proved to be unsuccessful for Gaunting Reservoir [2].

2.8 Guernsey Reservoir, USA

Guernsey Reservoir on North Pallete River is primarily used for irrigation, was completed in 1927. The Reservoir length is 23.5 km with original storage capacity of 91 Mm³. the average annual sedimeknt inflow is about 1.7 MTons [12]. Until 1957 the reservoir was subject to a high sedimentation rate, losing 39% of its original storage capacity over a period of about 30 years. After 1957 there was significant reduction of sediment inflow due to the construction of dams like Glendo dam upstream.

Partial drawdown (by 12-13m) was carried out at Guernsey reservoir annually between 1959 and 1962 and flushing carried out through overflow spillway [8]. Flushing discharge used was 125 m³/s for duration of 5 days. From the inflow and outflow data during 1957- 1962, it was estimated that only 0.144 Mm³ of accumulated sediment was removed from the reservoir basin. It was concluded that, with future annual drawdowns only 0.2% of the original storage capacity could eventually be recovered with the estimated LTCR value of 0.26 and hence the reservoir proved to be unsuccessful towards flushing [2].

2.9 Heisonglin Reservoir, China

Heisonglin Reservoir used for irrigation and flood control, was impounded in 1959 across Yeyu River, a tributary of the Yellow River. The basin length of Reservoir is 2.9 km, with initial storage capacity of 8.6 Mm³. The average annual sediment inflow is about 0.71 MTons.

For the first 3 years of operation, upto June 1962, the Reservoir was purely as an impounding Reservoir, with no flushing, resulting in serious siltation of 1.62 Mm³. The Reservoir is equipped with a single 2mx1.5m bottom outlet at an elevation of 7m above the river basin. Starting in 1962, mode of operation was changed to involve emptying the Reservoir, during flood season. Turbidity currents were also released. These measures managed to reduce trap efficiency of Reservoir to 15%, but the Reservoir was still losing capacity. Estimated value LTCR is 0.3 and hence the reservoir is not flushed successfully [2].

2.10 Ichari Reservoir, India

Ichari Reservoir used for hydropower generation was impounded in 1975 across the River Tons, a tributary of Yamuna. The basin length of Reservoir is 11 km, with initial storage capacity of 11.6 Mm³. The average annual sediment inflow is about 5.7 MTons.

Between 1976 and 1984 the estimated total annual amounts of sediments inflow had been value of 2.2 Mm³, which is about 20% of the original storage [13]. Just after one year

of operation, sediment had reached the crest of spillway, which is 16m below the full Reservoir level, reducing the storage capacity by 23%. By then and 1981, the sediment level through the Reservoir basin rose progressively, reaching a total storage loss of 60%.

The only facility for sediment flushing from the Reservoir basin is by opening the gated spillway, which is done during the rainy season, whenever the powerhouse is closed. The spillway gates are fully raised, to allow free flow through the Reservoir along the top of the deposits. Annual flushing for the period 1976-1984 is likely to result in a fairly stable residual storage capacity of the order 4 Mm³ has been achieved. with the estimated value of LTCR 0.36. The Reservoir is not flushed successfully achieving the estimated long term capacity of about 35% of the original capacity of the Reservoir [14].

2.11 Ouchi-Kurgan Reservoir, Former USSR

Ouchi-kurgan Reservoir used for irrigation and power production was impounded in October 1961. The basin length of Reservoir is 17 km, with initial storage capacity of 56.4 Mm³. The average annual sediment inflow is about 13 MTons [15].

The volume of deposited sediment reached about 30 Mm³ by 1968 and reasonably stable at 50-55% of the original storage capacity upto 1970 after which no further data is available (WR White, 2000). The dam has eight outlets, having discharge capacity of about 350 m³/s at maximum impounding level.

Since 1963, drawdown flushing of the Reservoir has been operated, which was achieved by lowering the water level by 4-5m during May to August of flood season. The estimated LTCR value is 0.1 and hence the Reservoir proved to be unsuccessful for flushing [14].

2.12 Sanmenxia Reservoir, China

Sanmenxia Reservoir was impounded in 1960 across middle reach of Yellow River. The basin length of Reservoir

is 120 km, with initial storage capacity of 9640 Mm³. The average annual sediment inflow is about 1600 MTons.

Immediately after impounding began, severe sediment problems became evident. Sedimentation and flushing history can be described in six phases:

In the first phase (1960-1962) impounding of Reservoir began in September 1960, serious sediments deposition occurred, sediment accumulation raised bed level by 4.5m near the upstream end of the Reservoir and backwater effects 250 km upstream of the dam. In second phase (1962-1966), Reservoir operation was changed from April 1962 to maintain a lower water level throughout the year, using the 12 outlets at an elevation of 300m. However the outlets capacities was proved to be insufficient and resulting in the trapping of a further 3400 MTons over the four flood seasons. In third phase (1966-1970), sluicing capacity for the Reservoir enhanced by the excavation of two, 11m diameter bypass tunnels, with an invert level of 290m. Four of the eight power intakes were converted to sediment sluices and pool level was lowered during flood season, but did not lower the bed elevation at the upstream end of the Reservoir basin. In fourth phase (1970-1973), eight of the original river diversion outlets filled with concrete, were reopened. The Reservoir operation was changed to flood detention and sediment sluicing, with all outlets constantly opened. The bed elevation at the upstream end of the basin fell by nearly 2m. In the fifth phase (1973-1978), an overall sediment balance had been achieved. At the start of flood season, in July 1973, all the outlets were opened and the high capacity bottom outlets allow a low pool level maintained. The high discharges carrying the sediment load also prevent excessive deposition in the Yellow river downstream of the dam. During sixth stage (1978 onward), two additional bottom outlets were opened in 1990 and the net storage capacity has fluctuated between about 3000 and 33000 Mm³. Estimated value of LTCR is 0.39 with the estimated long term capacity of about 31% of the original storage capacity and hence sediments flushing proved to be unsuccessful for Sanmenxia Reservoir [14].

2.13 Sufid-Rud Reservoir, Iran

Sufid-Rud Reservoir used both for irrigation and power generation, was built in 1962, across Sufid-Rud River, a tributary to Caspian Sea. The basin length of Reservoir is 25 km, with initial storage capacity of 1760 Mm³. The average annual sediment inflow is about 50 MTons.

The reservoir was built with 3 bottom outlets on the right hand side with total discharge capacity of 430 m³/s at an elevation 191.3m and two bottom outlets on the left hand side with a total discharge capacity of 550 m³/s at an elevation of 193.8. These outlets are close to the original river bed level.

Sedimentation was a serious problem in the first 17 years of operation and caused an average storage loss of about 36.5 Mm³ per annum, equivalent to an annual rate of 2.1%. Because of rapid and continuing reduction in storage capacity, flushing was commenced since 1980. Flushing program was designed to occur from October to February, virtually emptying the Reservoir down to an elevation of 197m, then allowing the Reservoir to fill in time for the start of the irrigation season. From 1980-1990 drawdown flushing the total sediments removed were of about 514 MTons with the duration of flushing varying from 10-138 days in different years. The value of LTCR estimated is 0.13 and the estimated long term capacity is less than 26% of the original storage capacity of the Reservoir, so the Reservoir is flushed unsuccessfully [14].

2.14 Shuicaozi Reservoir, China

Shuicaozi Reservoir used for hydropower generation was built in 1958 across Yill River. The basin length of Reservoir is 6 km, with initial storage capacity of 9.6 Mm³. The average annual sediment inflow is about 0.63 MTons.

No bottom outlet for sediment flushing is available. Sediment flushing was severe, amounting to 85% of the original storage capacity of Reservoir by 1981. The remaining 1.4 Mm³ was insufficient for flow regulation

which required 3.6 Mm³. Between 1965 and 1981, six flushing operations were conducted on drawing down the water level in Schiucaozi Reservoir to erode sediments deposits. Flushing was being done through spillway which has a crest elevation of about 17m higher than the original river bed.

The duration of flushing is about one day during which about 0.2 Mm³ of sediment can be removed by 1-3% of annual flow. This is only about one third of the average sediment inflow. The Reservoir proved to be unsuccessful towards flushing. The estimated value of LTCR is 0.39 and the Reservoir proved to be unsuccessfully flushed [14].

2.15 Naodehai Reservoir, China

Naodehai Reservoir is a flood detention Reservoir across the Liuhe River, with original storage capacity of 168 Mm³ with average annual sediment inflow of 16 MTons. It was initially built with ungated outlets near the original river bed. Control gates were installed (apparently in 1970) to preserve clear water for using for irrigation in non-flood season [15].

Liuhe River is heavily silt laden with an annual average sediment concentration of 77 g/l, so the detention of floods resulted in the deposition of sediment deposits within the Reservoir basin. High volumes of sediment deposition are reported during floods in 1949 and 1963. In the flood 1963 quantity of sediment deposited within 12 days (20th-31st July, 1963) is reported to be about 72 MTons (4.5 times the annual sediment inflow).

Flushing which occurs in a Reservoir of this sort is essentially uncontrolled. Although there is some scope of control since the installation of gates on the outlets, no information is available to judge if their use has had any effect on sedimentation of this case. UNESCO [15] shows the reported variation in available storage capacity in Naodehai Reservoir reducing from 168 Mm³ in 1942 to a minimum of 97 Mm³ in 1950.

2.16 Nanqin Reservoir, China

Nanqin Reservoir, used for flood and irrigation, was built in 1974. The length of Reservoir is 2.4km. The original capacity of Reservoir is 10.2 Mm³ and the mean annual suspended sediment inflow is 0.53 MTons [16].

The Reservoir history can be divided into three phases: between 1974 and 1976 it is solely served as flood detention Reservoir, between 1976 and 1983, Reservoir is impounded to middle level of 110m and released for irrigation purposes, since 1984, with an improved regime of sediment management. By the end of 1983, 53% of the storage capacity (5.4Mm³) of Reservoir was reported to be occupied by deposited sediment and it was estimated that life span of the Reservoir would end by the year 2000(Chen, et. al. [16]). The maximum depth of deposition near the dam was of the order of 12m.

A 3m diameter tunnel, 3m above the original bed level was built into the dam, for the purpose of sediment flushing with flushing discharge of 14 m³/s when the pool level reaches the soffit, rising to 110 m³/s at maximum impounding level. Due to the steep bed slope of Nanqin Reservoir, density currents can easily reach the dam. Sediment sluicing by density current venting began in 1977. Between 1977 and 1984, 2.43 MTons of suspended sediments entering the Reservoir was successfully discharged by this method. Although the removal achieved by density current venting was considered good, it was realized that more effective methods would be needed to deal with bed load deposition and persevere storage in the long term. At the end of 1984 flood season an experimental flushing operation by emptying the Reservoir was carried out. Flushing was carried out for a period of 4 days with the flushing discharge of 14 m³/s in which all the sediments deposited in the current year was flushed out, alongwith 0.72 Mm³ that had deposited in the earlier years. From the experience gained in the 1984 flushing test, it was concluded that drawdown flushing should be undertaken at the end of flushing season once every 3-4 years. It was estimated that if these modes of sediment managements within the Reservoir applied, a long term capacity of 74% of the original capacity can be sustained

and hence the Reservoir made to be successfully flushed [2]. No details were given of the success of subsequent flushing operations.

2.17 Zemo-Afchar, Former USSR

This hydropower Reservoir emptied in 1927 located just d/s of the confluence of two rivers. No data are available about the original capacity of the Reservoir; although basin length is given as 8 km along one tributary and 1.8 km along the other [15].

During the first two years of operation, the storage capacity reduced by 44% and during the following 8 years a further 32% of the capacity was lost. Only 4% more was lost during the next 18 years (1937-1954). No details of the flushing facilities are given but they are sufficient to pass over double the mean annual flow when Reservoir is emptied.

Prior to 1939, the Reservoir apparently operated with a limited annual drawdown of 2.3m, but this was not effective. Between 1939 and 1966 it is reported that 38 flushing operations (between 1 and 4 per year), were reported.

Each flushing event comprised two stages; partial drawdown as the Reservoir was being emptied followed by total drawdown. The duration of flushing varied from 8.5-65.5 hour, with a mean of 18.5 hours with flushing discharge of 450 m³/s. Flushing was carried out mainly in the month of April, May or November. The volume scoured each year ranged between about 0.5 and 2 Mm³, with an average of approximately 1 Mm³.

2.18 Warsak Reservoir, Pakistan

Warsak Reservoir used for irrigation and hydropower generation was impounded in 1960 by the construction of 76m high concrete gravity dam across the River Kabul (tributary to river Indus), at about 30 km from Peshawar in North-West Frontier Province of Pakistan. The power generation capacity of the reservoir was upto 240 MW in 1981. The project was financed by the Canadian Government under Colombo Plan.

Reservoir length is 42 km with original storage capacity of 170 Mm³ (live storage of 31.2 Mm³ at normal operating level of 387.1 m). The average annual water inflow is about 21100 Mm³ and the average sediment inflow is about 15.3 MTons. The total catchment area of the reservoir is 67340 km². A spillway of length 140.2m with nine gates is provided to discharge 15,290 Cumecs of flood water.

During the period 1960-1971, the average measured suspended concentration was 727 mg/l, giving an average sediment inflow of 15.3 MTons, suggesting the average annual sedimentation rate of 8%. The particle size distribution of measured suspended load comprised 12% sand, 60% silt and 28% clay. In addition, the Kabul river carries a bed load of gravel and cobbles, which were not included in the measured concentrations [2].

After the first year's operation, 30 Mm³ of the sediment had deposited in the reservoir increasing to 70 Mm³ after five years. By 1980, after 20 years operation, the reservoir had completely silted to the conservation pool elevation, except for a 60m wide and 6m deep channel on the right bank, where the power and irrigation intakes are located.

Five flushing operations were performed during the period of 1976-1979. The flushing was carried out by lowering the water level to the spillway crest level which is 12m below the highest impounding level. The total duration of flushing was about 20 days and during these operations the sediment removed was 4.2 Mm³ from the Reservoir amounting to about 6% of the probable sediment inflow over the same period. No bottom sluices are provided for flushing. The Reservoir had reached to a state with no residual live storage [2]. Power generation of about 100 MW is being achieved according to water inflow in river Kabul like a 'Run-of-the-River Project' [17].

2.19 Jensanpei Reservoir, Taiwan

Jensanpei Reservoir was built in 1938 for water supply to sugarcane industry. The Reservoir has an original storage capacity of 7 Mm³ and raised to 7.7 Mm³ in 1942 and 8.1 Mm³ in 1958 by raising the impounding level.

In an 18 years period from 1938-1955 storage depletion due to siltation was 4.26 Mm³, an average annual loss of 3.4% of the storage capacity. In 1955 a 1.5m diameter flushing tunnel was built through the base of dam and annual flushing commenced. Flushing is arranged by emptying Reservoir between May and July and allowing free flow through the Reservoir. Between 1955 and 1980 the sediment volume contained in Jensanpei Reservoir remained almost constant showing that the adopted flushing was highly effective, with remaining storage capacity of about 45% of the enlarged capacity of 8.1 Mm³ [2].

2.20 Khashm-El-Gibra Reservoir, Sudan

Khashm-el-Gibra Reservoir on Atbara River was completed in 1964. The Reservoir had an original storage capacity of 950 Mm³. The capacity of Reservoir was seriously depleted by an annual average sediment inflow of about 84 MTons [15]. Little information is available about flushing operations. In 1971 for 4 days of flushing (11-14 July), sediment inflow was 3.5 MTons, whereas net sediment release was 17.5 Mm³. In 1973 for 5 days of flushing (29 July to 2 August) sediment inflow was 3.3 MTons, whereas net sediment release was 12.5 Mm³ [2].

2.21 Mangahao Reservoir, New Zealand

Mangahao Reservoir on Mangahao River was constructed in 1924 on Mangahao River. By 1958 the original live storage capacity had reduced by 59%. In 1969 it was decided to attempt sediment flushing at Mangahao Reservoir through low level diversion tunnel which had not been used for the last 25 years (1925-1944). For a period of 24 hours nothing happened, then on second day silt began to extrude from the tunnel and the Reservoir emptied. During the total duration of one month of flushing 0.8 Mm³ of sediment has flushed from the Reservoir equal to the 75% of sediment that had accumulated since 1924 [2].

2.22 Cachi Reservoir, Costa Rica

Cachi Reservoir on Reventazon River was completed in 1966. The length of Reservoir is 6 km with original storage capacity of 54 Mm³. the average annual sediment inflow is 0.81 MTons.

The dam has a single bottom outlet located near the original river bed. For the first seven years the Reservoir was operated without flushing. The first flushing operation was carried out in October 1973 and due to the success of this operation it was decided to carry out flushing every year during wet season. Over the 18 years from 1973-1990 it was flushed fourteen times. The flushing was carried out in 3 stages; slow drawdown stage by lowering water level at a rate of 1m/day; rapid drawdown stage for a period of 5-10 hours: free flow stage for a period of 2-3 days allowing the river to flow freely along the original river channel: finally the refilling stage during which the Reservoir was refilled by closing the bottom outlet. The Reservoir was refilled taking a period of 16-21 days. During the 14 flushing operations, annually, from 1973-1990 the total sediment removed was about 4.41 MTons with minimum sediment removal of 0.025 MTons in May 1980 and the maximum sediment removal of 1.27 MTons in September 1988 [2].

3. RESULTLS AND DISCUSSION

The region wise distribution of storage reservoirs and storage volume are shown in Figs. 1-2, respectively. The maximum numbers of reservoirs are in North America, i.e. 7205, with the storage volume of about 1844 Bcm, whereas the minimum numbers of reservoirs are in Central Asia, i.e. 44, with the total storage volume of 148 Bcm. The numbers of storage reservoirs with storage volumes (in Bcm) in other regions are as: South Asia 4131(1039), South Europe 3220(938), Pacific Rim 2278(277), North Europe 2277(938), China 1851(649), South America 1498(1039), Africa 967(575), Middle East 895(224), North Africa 289(188), and South East Asia 277(117).

World annual reservoir storage loss due to sedimentation is shown in Fig. 3 and varies from 0.1-2.3%, with average annual world storage loss of about 1.0%. The maximum annual storage loss is in China, i.e. 2.3%, whereas the minimum storage loss is in U.K., i.e. 0.1%. The annual storage loss in other regions is: Turkey 1.5%, India 0.46%, South Africa 0.34%, South East Asia 0.30%, USA 0.22%, and Japan 0.15%.

The results of the study reveal that there are about 50 reservoirs which are flushed, out of which flushing data is available for about 22 reservoirs. The number of flushed reservoirs in different countries are shown in Fig. 4. The maximum number of reservoirs are flushed in China which

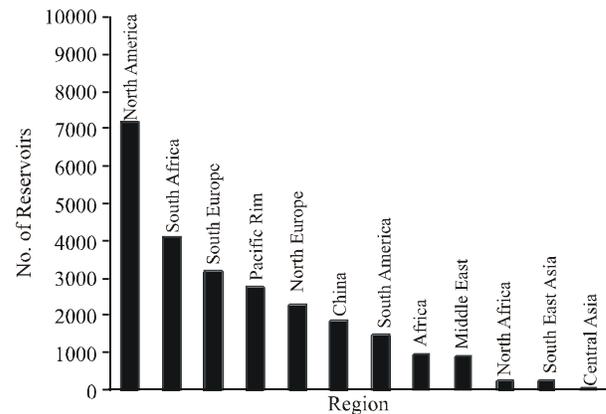


FIG. 1. WORLDWIDE DISTRIBUTION OF STORAGE RESERVOIRS

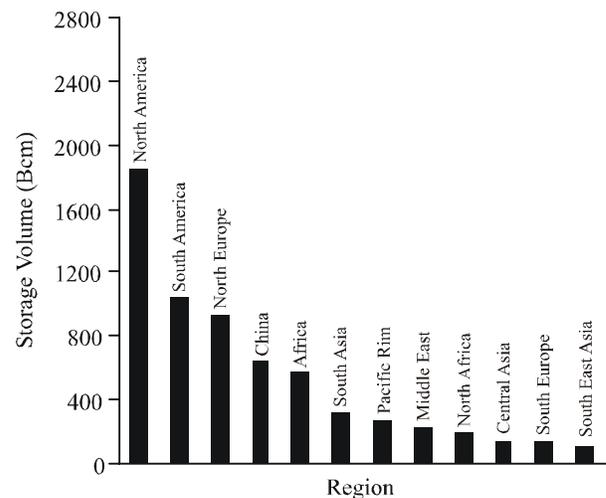


FIG. 2. WORLDWIDE DISTRIBUTION OF STORAGE VOLUME

is 21. The number of flushed reservoirs in different countries are as: Switzerland 5, Former USSR 4, India 3, USA 3, Puerto Rico 2, Algeria 1, Austria 1, Costa Rica 1, Guatemala 1, Iran 1, Japan 1, New Zealand 1, Pakistan 1, Sudan 1, Taiwan 1, Tunisia 1, and Venezuela 1.

Worldwide flushing has been successfully implemented at Baira-India, Gebidem-Switzerland, Gmund-Austria, Hengshan-China, Palagnedra-switzerland, Santo-Domingo-Venezuela Reservoirs, while the unsuccessfully flushed reservoirs are:

Chinese reservoirs, Gaunting, Heisonglin, sanmenxia, Shuicaozi, Naodehai, Nanqin, Guernsey-USA, Ichari-India, Ouchi-Kurgan and Zemo-Afchar of former USSR, sufid-Rud-Iran, Warsak-Pakistan, Jansenpei-Taiwan, Khashmel-Gibra-Sudan, Mangahao-Newzealand, and Cachi of Costa Rica.

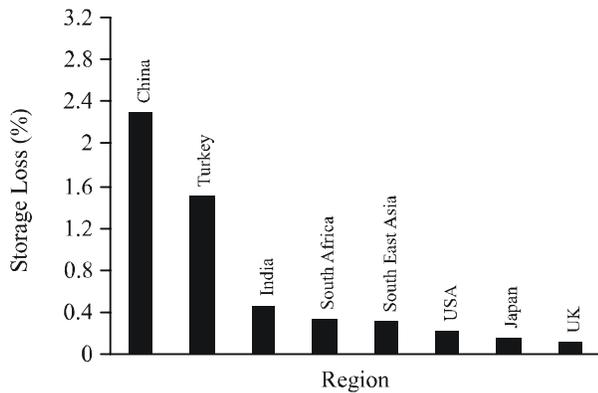


FIG. 3. WORLDWIDE RESERVOIR STORAGE LOSS

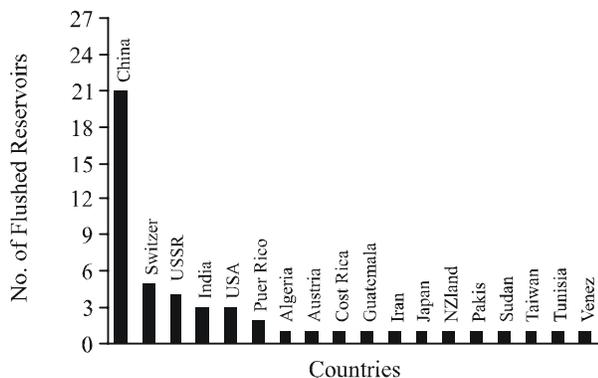


FIG. 4. GLOBAL DISTRIBUTION OF FLUSHED RESERVOIRS

Different modes of sediment removal from the total available 50 flushed reservoirs are: flushing alone, flushing alongwith Routing, flushing alongwith density current venting, flushing alongwith Routing and density current venting, density current venting alongwith flushing. Number of reservoirs with Mode of sediment removal are shown in Fig. 5. Among the 50 flushed reservoirs 42 reservoirs are desilted by flushing mode, whereas 3 reservoirs by flushing alongwith routing, 2 reservoirs by flushing alongwith density current venting, 2 reservoirs by flushing alongwith routing and density current venting, 1 reservoir basically by density current venting aided by flushing.

Where the symbols used in Fig 5 are; F is Flushing alone, FR is Flushing and Routing, FD is Flushing and Density Current Venting, FRD is Flushing, Routing and Density Current Venting and DF is Density Current Venting and Flushing.

4. CONCLUSIONS

World annual reservoir storage loss due to sedimentation varies from 0.1-2.3%, with average annual world storage loss of about 1.0%. The maximum storage loss is in China, i.e. 2.3%, whereas the minimum storage loss is in UK, i.e. 0.1%.

Worldwide, China possesses the maximum number of reservoirs being flushed. The study reveals that there are about 50 reservoirs which are being flushed with available

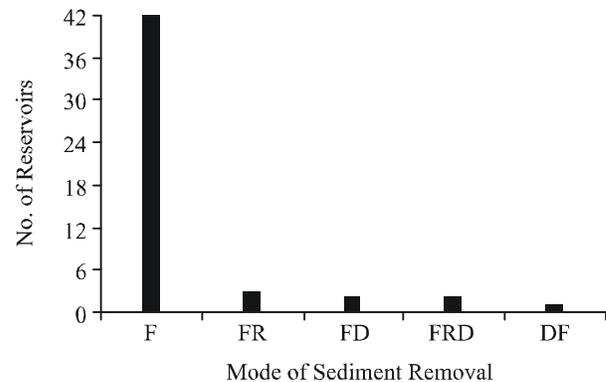


FIG. 5. FLUSHING MODES FOR FLUSHED RESERVOIRS

flushing data for only 22 reservoirs, out of which six reservoirs are successfully flushed.

Among the 50 flushed reservoirs 42 reservoirs are desilted by flushing mode, 3 reservoirs by flushing alongwith routing, 2 reservoirs by flushing alongwith density current venting, 2 reservoirs by flushing alongwith routing and density current venting, 1 reservoir by density current venting aided by flushing.

Some of the reservoirs could not be flushed successfully due to the absence of provision of proper flushing/slucing facilities.

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