ACCUMULATION OF SEDIMENT IN RESERVOIRS

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Summary

Reservoir sedimentation is a complex process that varies with watershed sediment production, rate of transportation, and mode of deposition. Sedimentation reduces reservoir storage capacity for flow regulation and with it all water supply and flood control benefits, plus hydropower, navigation, recreation, and environmental benefits that depend on release from storage. Besides storage loss, many types of sediment-related problems can also occur both upstream and downstream of dams. The combination of sediment trapping and flow regulation also has dramatic impacts on the ecology, water transparency, sediment balance, nutrient budgets, and river morphology. Even coastal process can be affected; accelerated coastal erosion can be occur because of sediment trapping in far upstream reservoirs and lack of sufficient downstream sediment supply.

The importance of sediment management has increased, as the number of dams and their ages increase, since about 45 000 large dams worldwide (higher than 15 m, ICOLD) are mostly designed and operated to continuously trap sediment, without

specific provisions for sustained long-term use. Regarding the above necessities for proper sediment management, a paradigm shift will be required from the concept of reservoir life limited by sedimentation to a concept of managing both water and sediment to sustain reservoir function, thus generating long-term benefits.

If sustainable use is aimed at, the following sediment control strategies should be studied and executed: (i) Reduce sediment inflow by erosion control and upstream sediment trapping, (ii) Route sediments by sediment sluicing, off-stream reservoirs, sediment bypass, and venting of turbid density currents, and (iii) Sediment removal by hydraulic flushing, hydraulic dredging or dry excavation.

Of the above sediment management measures, if the reservoir satisfies suitable conditions, sediment flushing is one of the most attractive methods from the point of view of costs and contribution to downstream sediment supply. At the same time, however, flushing operations entail some risk of environmental damage to downstream reaches if the sensitivity of organisms living there is not taken into account. It is important to predict how anticipated phenomena will impact on the environment and to conduct studies to develop feasible measures that will minimize the impact.

The cost and applicability of each sediment management strategy will vary from one site to another and no single control measure can be suggested because of the large number of variables involved in reservoir sedimentation problems. However, even the largest reservoirs will eventually be reduced to small reservoirs by sedimentation and, sooner or late, will require sediment management. Reservoir sedimentation is one of the most crucial issues to be solved this century for sustainable water resources management. 'Do it now and do it quick' (Bruk, 1996) is the clue to success, and this concept should be common sense for all responsible people.

1. Introduction

Most natural rivers are approximately balanced with respect to sediment inflow and outflow. Dam construction dramatically alters this balance since the increased flow depth and decreased flow velocity of a reservoir, reduces the sediment transport capacity and causes settling.

Sediments carried into a reservoir may deposit throughout its full length, thus gradually raising the bed elevation and causing aggradations. The pattern of deposition generally begins with a deltaic formation, mainly composed of coarser sediments in the reservoir headwater area. Density currents may transport finer sediment particles down to the dam.

Reservoir sedimentation is a complex process that varies with watershed sediment production, rate of transportation, and mode of deposition. Reservoir sediment depends on the river regime, flood frequencies, reservoir geometry and operation, flocculation potential, sediment consolidation, density currents, and possible land use changes over the life expectancy of the reservoir.

Sedimentation reduces reservoir storage capacity for flow regulation and with it all

water supply and flood control benefits, plus hydropower, navigation, recreation, and environmental benefits that depend on releases from storage. In addition to storage loss, many types of sediment-related problems can also occur both upstream and downstream of dams, and sediment entrainment can also interfere with the beneficial use of diverted water. Sediment can enter and obstruct intakes and greatly accelerate abrasion of hydraulic machinery, thereby decreasing its efficiency and increasing maintenance costs. Aggradations in the upstream channel may occur over long distances above the reservoir, thus increasing flood risks on these areas.
The combination of sediment trapping and flow regulation also has dramatic impacts on the ecology, water transparency, sediment balance, nutrient budget, and river morphology. The cutoff of sediment transport by the dam can cause streambed degradation, acceleration rates of bank failure, and increase scour at structures such as bridges downstream of the reservoir. Coarsened and armored streambeds will degrade or eliminate spawning beds. Even coastal process can be affected; accelerated coastal erosion can occur because of sediment trapping in far upstream reservoirs and lack of sufficient downstream sediment supply.

The importance of sediment management has increased, as the number of dams and their ages increase. Regarding the above complex phenomena, the necessities for sediment management of reservoirs can be summarized below.

(i) It prevents reservoir sedimentation from burying water intakes or outlets and causing harmful riverbed aggradations directly upstream of reservoirs, thereby guaranteeing safety of river and dam management.
(ii) It maintains the storage functions of the reservoir—to achieve sustained management of water resources for future generations.
(iii) As a key to integrated sediment management of sediment routing systems, dams must be able to discharge sediment.

Item (i) has been traditionally discussed and countermeasures considered.

Item (ii) is a relatively new problem and it has mainly been treated as a future problem. Priority has been put on ways to carry out new dam development and because sedimentation capacity for 100 years is normally guaranteed, it has not been treated as an immediate problem. But extending the service life of existing dams has become an important matter. This will be discussed in the next paragraph.

Item (iii) can, by going beyond concern limited to the reservoirs, incorporate the perspective of normal supply of sediment to the former river course, contribute to wide area sediment management extending from the sediment supply region in the mountains to the downstream river and, sometimes, to the sea coast near its mouth. Here, a sediment routing system is a concept focused on the movement of sediment over a wide range from the mountains to the coast, rather than the traditional river system focus on water flow only. This concept requires integrated implementation of feasible counter-measures in every part of the system.

In Japan, the construction of debris (sabo) dams and water storage dams in the mountains, and the collection of gravel from riverbeds for construction materials, since the end of the Second World War, have created a number of serious problems caused by a shortage of supplied sediment. These are the lowering of downstream riverbeds, increasingly monotonous river courses and the retreat of coastlines. The retreat of the coastline is a particularly serious problem, to the extent that approximately 60% of Japan's 34 000 km of coastline has been eroded, and about 40% of this erosion is caused by a reduction in the quantity of sediment supplied by rivers, as a consequence of reservoir sedimentation.

In response, intensive studies have been started to clarify the sediment balance of sediment routing systems in rivers of this kind, to appropriately manage the flowing sediment both in normal periods and during floods. To plan integrated sediment management for the sediment routing systems, it is necessary to focus on sediment management throughout the sediment routing systems instead of dealing only with the problem of the sedimentation of reservoirs. Recently, projects to excavate sediment from reservoirs and transport it downstream have been attempted. In contrast to the "normal instream flow" required to preserve river environments, we must designate the "normal sediment flow" necessary to preserve the shape of the riverbed in each river course and the coastline near its mouth, and try to supply the necessary sediment from reservoirs in order to satisfy this stipulated volume.

This chapter deals with the general concept of reservoir sedimentation and its management measures. Reservoir sedimentation is a complex phenomenon from sediment yield to transport and deposition within reservoirs. The seriousness of sedimentation and necessities for countermeasures are different in each reservoir or each river basin. Not only for tackling the traditional problems related to reservoir sedimentation, integrated reservoir sedimentation management should be considered both for sustainable management of water resources and sediment flow in the entire watershed. Reservoir sedimentation is one of the most crucial issues to be solved this century for sustainable water resources management. 'Do it now and do it quick' (Bruk, 1996) is the clue to success and this concept should be common sense for all responsible people.

2. Sustainable Sediment Management

Based on the inventory published by the International Commission on Large Dams (ICOLD) and the current rate of dam construction, as of 2000 there were about 45 000 large dams (higher than 15 m) and an estimated 800 000 smaller ones around the world, the vast majority of which were built after 1950. These improve the living conditions of many of the world's six billion people. The main functions of these modern dams are to (i) provide reliable irrigation water, (ii) generate electricity, (iii) supply water for domestic and industrial uses, and (iv) help with flood control.

Reservoir construction requires sites with particular hydrologic, geologic, topographic, and geographic characteristics, and existing reservoirs generally occupy the best available sites. The possibilities for constructing new dams are becoming increasingly limited due to physical, social and environmental constraints. On the other hand, demand for reliable water is steadily increasing throughout the world. Freshwater resources are very unevenly distributed. Even those parts of the world with large rivers may experience significant seasonal variations and unpredictable weather changes leading to occasional disastrous floods or droughts.

With their present aggregate storage capacity of about 6000 km^3, dams clearly make a significant contribution to the efficient management of finite water resources that are unevenly distributed and subject to large seasonal fluctuations. However, large dams do involve substantial set-up and operating expenses, as well as possible social and environmental costs (for example, due to problems of resettlement, negative effects on upstream and downstream ecology, downstream loss of silt and fertility, etc.). In addition, the costs of safely decommissioning a dam at the end of its useful life can be quite substantial. All of the above benefits and costs should be accounted properly when deciding to build a dam and when planning an operating strategy. It is therefore imperative to maximize the net gains from what we already have and what we are going to be able to build in the future. As a generation that has constructed most of the existing large dams, it is our responsibility to not only solve our own problems, but to also try to care for the interests of the coming generations.

Aside from dam failure through faulty design or natural hazards, which modern dam engineering has been able to reduce to socially acceptable limits, the major threat to the productivity and longevity of dams is reservoir sedimentation. An overwhelming majority of existing dams have traditionally been planned, designed, and operated to continuously trap sediment on the assumption that they have a finite "life," frequently as short as 100 years, which will eventually be terminated by sediment accumulation. Little thought has been given to reservoir replacement when today's impoundments are lost to sedimentation or to procedures to maintain reservoir services with specific provisions for sustained long-term use despite continued sediment inflow.

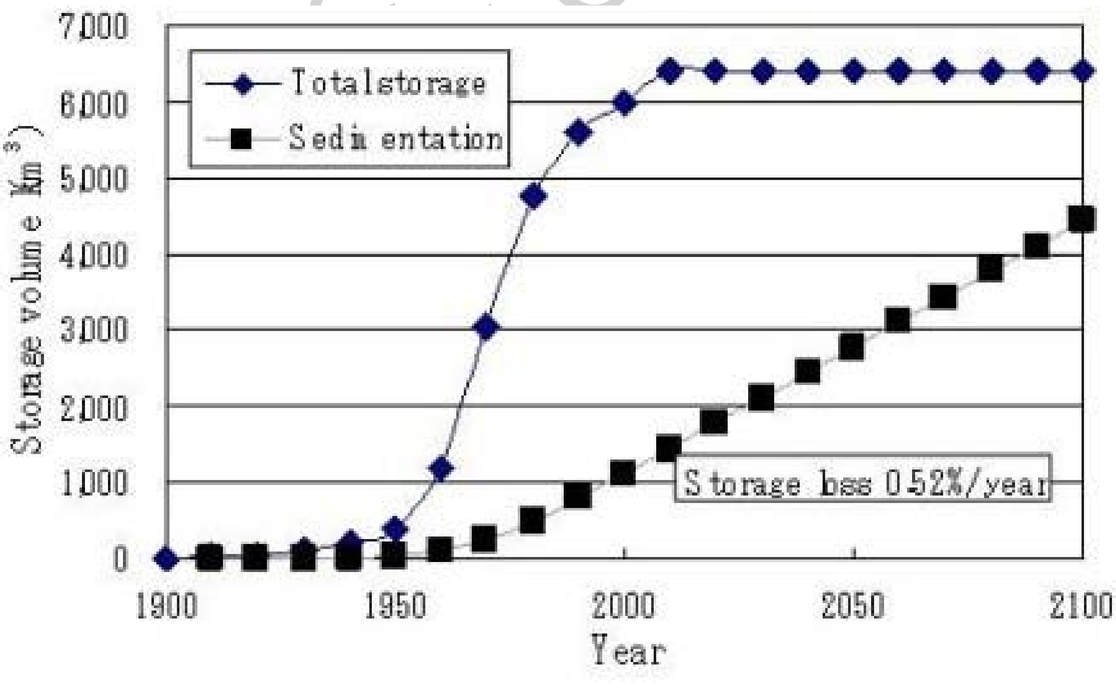

Figure 1.World storage volume and sedimentation loss

The annual sediment yield being deposited into existing reservoirs varies worldwide over a range from 20 to 5000m^3/km^2, with a world average of about 100m^3/km^2 (see section 3). Current gross storage capacity in the world is 5976 km^3, and total storage loss and annual sedimentation rate are about 567km^3 (11.8%) and 30.85km^3 (0.52%) respectively.

Region	Total Capacity (km^3)	Annual sedimentation (km^3)	Sedimentation loss (%)	Total Capacity loss (km^3)
North America	1845	3.69	7.9	112
South America	973	1.04	2.5	17
Northern Europe	822	1.88	6.8	48
Southern Europe	135	0.25	5.6	6
Sub-Saharan Africa	574	1.32	7.8	32
Northern Africa	188	0.15	2.4	3
China	526	14.93	45.8	230
Southern Asia	233	1.66	13.1	31
Central Asia	132	1.48	26.9	29
South East Asia	117	0.35	8	6
Pacific rim	232	0.75	7.6	15
Middle East	199	3.36	27.7	38
Global Total	5976	30.85	11.8	567

Table 1. Distribution of storage volume and sedimentation loss

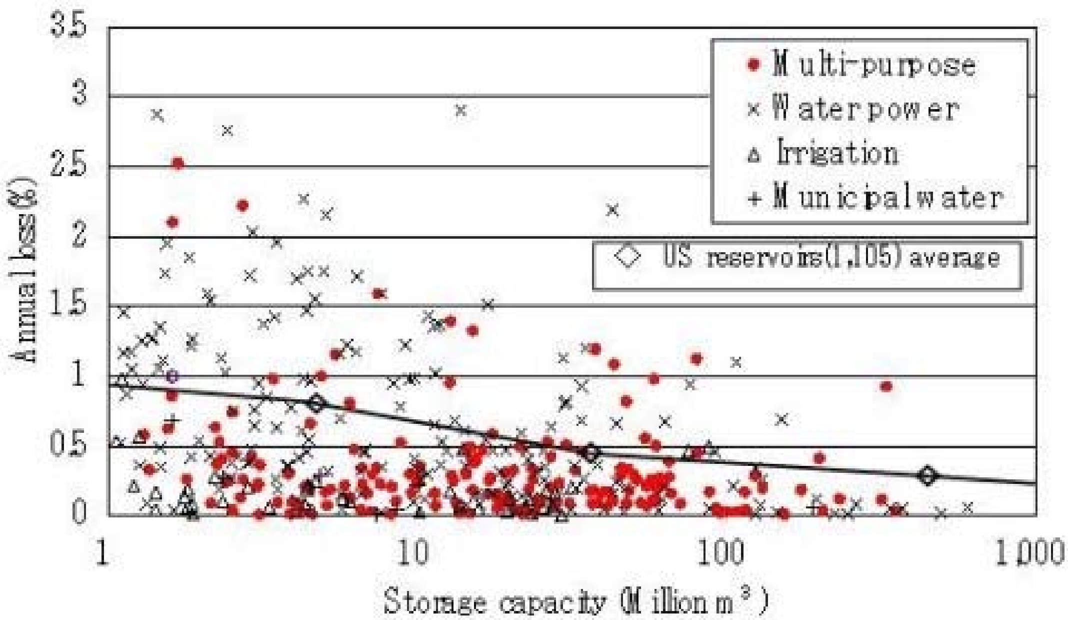

Figure 2. Reservoir storage capacity and annual loss in Japan

Based on the above record, the future scenario can be estimated. Figure 1 shows the relationship between total dam reservoir capacity changes with the loss of dam reservoir capacity by sedimentation around the world. This reveal that while the construction of new dams increases capacity, this capacity is lost at an average rate of 0.52% per year, and that if capacity that will be newly developed is not considered, total reservoir capacity will decline by more than 50% by 2100. But the severity of sedimentation varies depend on each reservoir since sedimentation rates vary greatly around the world, depending mainly on climate (Table 1) and locally on characteristics of drainage basin and reservoir size (storage volume) (Figure 2). Figure 2 can be modified using specific storage capacity (Storage capacity / Catchment area), as Figure 3. Annual losses of almost all reservoirs with specific storage capacities over 100 mm are less than 0.5%, i.e. annual average sediment yields are less than 0.5mm.

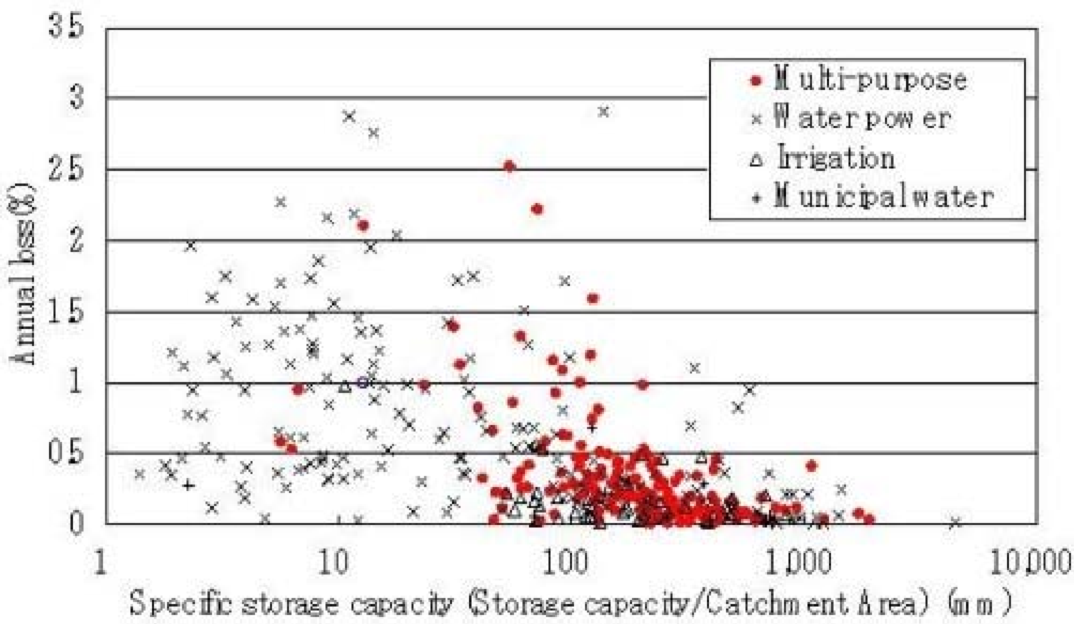

Figure 3. Specific storage capacity and annual loss in Japan

Neither current nor projected levels of population and economic activity can be sustained if today's inventory of storage reservoirs is lost to sedimentation, and, as population and economic activity grow, reliance on the services provided by dams is increasing. Sudden loss of the world's reservoir capacity would be a catastrophe of unprecedented magnitude, yet their gradual loss due to sedimentation receives little attention or corrective action.

Because of the high cost and multiple problems associated with sediment removal and disposal on a massive scale, the sedimentation of large reservoirs is to a large extent an irreversible process. If future generations are to benefit from essential services provided by reservoirs, it will be largely through the preservation and continued utilization of existing reservoir sites, not the continued exploitation of a shrinking inventory of potential new sites. The water supplies and other benefits derived from reservoirs do not constitute renewable resources unless sedimentation is controlled.

Sustainable sediment management encompasses the entire fluvial sediment system, consisting of the watershed, river, reservoir, and dam. It is not achieved without cost. As a minimum, it involves better information and improved management, but it may also include large operational and capital costs for watershed management, the construction of low-level outlets or bypass works, temporary removal of the dam from service for sediment management activities, release of increased volumes of water downstream for sediment discharge, and dredging.

It will frequently not be economically attractive to manage existing reservoirs to maintain the original active storage volume, implying that firm yield, power production, or other benefits may be reduced in the long term. At some sites the loss of benefits will be zero, but at others it will be large. Nevertheless, continued operation with reduced net benefits is preferred to project abandonment.

The fact that the world's inventory of suitable reservoir sites is limited provides an additional reason for encouraging the sustainable management of dams. So it is necessary to assess the economic feasibility of sediment management strategies that would allow the life of dams to be substantially prolonged. Even if reduced accumulation or removal of sediment is technically possible, its socio-economic viability will depend on physical, hydrological, and financial parameters, as well as environmental aspects.

There has been the tacit assumption that somebody else, members of a future generation, will find a solution when today's reservoirs become seriously affected by sediment. However, sedimentation problems are growing as today's inventory of reservoirs ages, and severe sediment problems are starting to be experienced at sites worldwide, including major projects of national importance. Sediment management in reservoirs is no longer a problem to be put off until the future—it has become a contemporary problem.

Global warming is a problem of public concern that is likely to occur in the next 100 years, but in fact the forecast temperature increase said to be of several degrees is only a very approximate estimate. But because this decline in our water resources stock caused by sedimentation is a certainty that will not improve, it must be considered to be an even more serious problem than global warming. The long-term sustainable management of water resources in this way must, just like global warming, be treated as a problem of “intergenerational equity”.

In other words, existing dams have been constructed at dam sites with relatively advantageous topography and geology, and, assuming that such good sites are in limited supply, these must not be used up and abandoned by this generation.

As regards the retirement cost of dams, if dam removals are required because of serious riverbed aggradations upstream of reservoirs or other structural problems caused by sedimentation, those removal costs might be very much higher than those of simple abandonment. Therefore, these uncertain costs should not be casually left for future generations to bear, and it is vital that now, while we are enjoying the benefits of these dams, we plan and implement measures that can be sustained as long as possible.

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Biographical Sketches

Dr. Tetsuya Sumi is an Associate Professor of civil engineering at Kyoto University, Japan. His major is hydraulics, river engineering and dam engineering. His research topics are focused on design and operation of dam hydraulic structures. Sedimentation management in reservoirs is one of the world’s most crucial intergenerational problems. He is doing a lot of research on the above topics and advising the Japanese government so as to enhance the integrated management of reservoir sedimentation. He organized the 'International workshop and symposium on reservoir sedimentation management, Toyama, Japan, 2000' and the 'Session of challenges to the Sedimentation Management for Reservoir Sustainability, the 3rd World Water Forum, Kyoto, Osaka and Shiga, Japan, 2003'. He is also conducting a research project 'Environmental assessment and mitigation of river morphology and ecosystem change downstream from large dams'. In the project, in-stream flow requirement with natural discharge variation and artificial sediment input to the downstream river are the major interests. Environmental assessment of sediment flushing from reservoir is another major interest.

Dr. Toshio Hirose is the former vice-minister of the Ministry of Construction, the former president of the Japanese Committee of the International Commission on Large Dams and the president of the Ecology and Civil Engineering Society, Japan. He is a dam engineer who originally proposed and promoted the Roller Compacted Dam (RCD) method of construction. He has established the Ecology and Civil Engineering Society, aiming at close cooperation between civil engineering and ecology. It is composed of civil engineers and biologists from all biological fields, e.g. algae, fishes, plants, birds and invertebrates. He is now becoming active actively in these fields.