Sediment Management for Sustainability of Storage Projects in Himalayas - A case study of the Kulekhani Reservoir in Nepal

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ABSTRACT

Although hydropower plays a significant role in global economy, the reservoir sedimentation is a global challenge for its sustainability. In the present situation, the worldwide average loss of storage capacity in surface water reservoirs due to sedimentation is higher than the increase of storage volume due to construction of new reservoirs.

Landslides and mass wasting are very common in the Himalayas during the monsoon season, which create tremendous amount of sediments. In the Himalayas, the high concentrations of sediments in the rivers are largely related to climatic, tectonic and geological factors. Himalayan Rivers provide some of the greatest challenges in water resources development. Any river project in the Himalayas must evolve within the context of land use practices and natural phenomena like monsoon hydrology, the complex geology and the severe sediment transport.

Watershed management alone will not keep hydropower projects sustainable in the Himalayan Region. Hence, sustainability of hydropower projects basically depends on the proper management of sediments. Whereas, the twentieth century focused on the construction of new dams, the twenty-first century will need to focus on combating sedimentation; the objective will be to convert today’s non-sustainable reservoir into sustainable infrastructures for future generations.

Key words: Hydropower, sedimentation, sediment monitoring, Sustainability of hydropower projects, sediment management options.

1 INTRODUCTION

Reservoir sedimentation is a global challenge. The current estimate of total reservoir storage worldwide is about 7 000 km$^3$ (Palmieri et al., 2003), as a comparison, this is only about $1/3$ of Lake Baikal. Using an average rate, Palmieri et al., (2003) estimated the storage loss to be approximately 45 km$^3$ per year. The cost of replacing the lost storage is about USD 13 billion per year, even without counting the environmental and social costs associated with new dams.

The growth of the dam development was intense during 1960 to 1980 as shown in Figure 1.1. The new dam development since 2000 is significantly less; however the loss of storage capacity is very high. It shows that about 1 000 km$^3$ of volume will be lost by 2020, which is about 15% of the current gross available storage.
Reports produced by United Nations Environmental Programme (UNEP) show that the total global sediment discharge is about $14 \times 10^9$ tonnes/year (UNEP, 2003). Takeuchi (2004) reported that the global suspended sediment discharges to sea range between $15$ to $20 \times 10^9$ tonnes/year, where the best estimate may be about $20 \times 10^9$ tonnes/year. He further states that more than 25% of this sediment discharge may be trapped by large reservoirs. Figure 1.2 shows the suspended sediment discharge per region, which demonstrates that Asia with Pacific Oceanic Islands contributes nearly 70% of the sediment delivery to the world’s oceans and seas. The relative suspended sediment discharge per region is presented in Table 1.1.
Table 1.1: Suspended sediment discharge, and distribution per region (UNEP, 2003).

<table>
<thead>
<tr>
<th>S. No</th>
<th>Region</th>
<th>Suspended sediment discharge (million tonnes/year)</th>
<th>Distribution of suspended sediment discharge (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Asia</td>
<td>6 349</td>
<td>47.1</td>
<td>Global suspended sediment discharge is about 15 to 20 x10^9 tonnes/year.</td>
</tr>
<tr>
<td>2</td>
<td>Oceanic Islands</td>
<td>3 000</td>
<td>22.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Central and South America</td>
<td>2 230</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>North America</td>
<td>1 020</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Africa</td>
<td>500</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Europe</td>
<td>314</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Australia</td>
<td>62</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

2 SEDIMENTATION IN THE HIMALAYAS

The Hindu Kush-Himalayan region is considered to be the Himalayas. This includes the northern small part of Afghanistan, the northern part of Pakistan, the Kashmir Region, the northern part of India, Nepal, Bhutan, Tibet and some southern parts of China, Myanmar and some parts of Bangladesh. In the Himalayas, the high concentrations of sediments in the rivers are largely related to climatic, tectonic and geological factors. Himalayan rivers provide some of the greatest challenges in water resources development. Any river project in the Himalayas must evolve within the context of land use practices and natural phenomena like monsoon hydrology, the complex geology and the severe sediment transport (Støle, 1993).

The Himalayas share a common pattern of precipitation, characterized by the occurrence of yearly monsoon or wet season. During the monsoon season of about 4 months, 60% to 80% of annual precipitation will fall. The high intensity of rainfall during the short period of time in the Himalayas causes a large number of landslides. Most parts of the Himalayas are geologically weak, unstable and hence prone to erosion. In addition the Himalayan regions have been greatly affected by soil erosion due to intensive deforestation, large-scale road construction, mining and cultivation on steep slopes (Kothyari, 1996). On many Himalayan landscapes, landslide and mass wasting are the dominant processes and their contribution to sedimentation can greatly overshadow the surface erosion contribution.

The world’s largest rivers in terms of sediment discharge are summarized in Table 1.2. This shows that rivers in the Himalayas have the highest sediment discharges in the world.

Table 1.2: Ranking of the world’s rivers by sediment discharge to sea (Morris and Fan, 1997)

<table>
<thead>
<tr>
<th>River and country</th>
<th>Average sediment discharge (million tonnes/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganges/Brahmaputra, India</td>
<td>1 670</td>
</tr>
<tr>
<td>Yellow, China</td>
<td>1 080</td>
</tr>
<tr>
<td>Amazon, Brazil</td>
<td>900</td>
</tr>
<tr>
<td>Yangtze, China</td>
<td>478</td>
</tr>
<tr>
<td>Irrawaddy, Burma</td>
<td>285</td>
</tr>
<tr>
<td>Magdalena, Colombia</td>
<td>220</td>
</tr>
<tr>
<td>Mississippi, USA</td>
<td>210</td>
</tr>
<tr>
<td>Orinoco, Venezuela</td>
<td>210</td>
</tr>
<tr>
<td>Hungho (Red), Vietnam</td>
<td>160</td>
</tr>
</tbody>
</table>
3 SUSTAINABILITY OF WATER RESERVOIRS

As reported in the IHA White Paper (IHA, 2003), Nelson Mandela states “Freedom alone is not enough without light to read at night, without time or access to water to irrigate your farm, without the ability to catch fish to feed your family. For this reason the struggle for sustainable development nearly equals the struggle for political freedom”.

Sustainable development is the development that meets the needs of the people today without compromising the ability of future generations to meet their own needs. The Food and Agricultural Organization (FAO) describes sustainable development as “A development which is environmentally non-degrading, technically appropriate, economically viable and socially acceptable” (Madan, 2005).

Sustainable development requires the integration of three components—economic development, social development and environmental protection as independent and mutually reinforcing pillars (Altinbilek, 2005). The sound government policy, and proper application of financial, technical, social and environmental management are the key factors for the success of the projects. Hydropower has a huge potential to improve economic viability, to preserve ecosystems and to enhance social justice. Skillfully planned, built and operated hydropower schemes can make significant contributions to achieving these three pillars of sustainable development.

3.1 Hydropower a Renewable Source of Energy

Hydropower has been officially declared a renewable energy source in the UN Summit on Sustainable Development in Johannesburg 2002 (IHA, 2004a). The Third World Water Forum in Kyoto in March 2003 acknowledged “the role of hydropower as one of the renewable and clean energy sources and that its potential should be realized in an environmentally sustainable and socially acceptable manner” (WWC and IHA, 2003). However, it has to be acknowledged that the recognition of hydropower as a legitimate renewable energy resource has been questioned by a number of influential interest groups.

In the lead up to International Conference for Renewable Energies 2004 in Bonn for example, there had been a concern that hydropower would not be recognized as renewal energy resources on the grounds that new hydro projects would be unlikely to meet the pre-requisite WCD guidelines (Rae, 2005).

However, the Political Declaration made at the conclusion of International Conference for Renewable Energies 2004 in Bonn gave recognition to hydropower as a renewable energy resource. Ministers and Government representatives from 154 countries gathered from June 1 to 4, 2004 in Bonn (Germany) and the political declaration signed in Bonn identifies hydropower as one of the renewable technologies “to be substantially increased with a sense of urgency” (IHA, 2004a). It is also encouraging that the United Nation’s Symposium on Hydropower and Sustainable Development held in Beijing in October 2004 drew attention to the strategic importance of hydropower for sustainable development (Rae, 2005).

3.2 Reservoir Sediment Management for Sustainability

Conversion of sedimenting reservoirs into sustainable resources requires fundamental changes in design and operation. It requires that the concept of a reservoir life limited by sedimentation is replaced by a concept of sustainable management. The suitable reservoir sedimentation management is a key factor for the sustainability of water resources. Strategies for controlling reservoir sedimentation are broadly grouped into three major categories:

- Reduce the incoming sediment to the reservoir
- Prevent sediment deposition in the reservoir
- Evacuation of deposited sediment from the reservoir

The raising of a dam could be an alternative for compensating for the loss of the reservoir, especially in arid regions; however, it does not provide a long-term solution to the sedimentation problem.
4 KULEKHANI HYDROPOWER PROJECT

The Kulekhani Hydropower system is located in the Middle Mountain Zone of Makawanpur District, Central Development Region of Nepal. The main dam and the power house are located at about 21 km and 30 km southwest of the capital Kathmandu respectively. The Kulekhani I with installed capacity of 60 MW was commissioned in May 1982. Kulekhani II Power Station with installed capacity 32 MW utilizes water from the tailrace of Kulekhani I and was commissioned in December 1996 (NIPPON KOEI, 1994). So far, this is the only project offering seasonal water storage in Nepal and the project plays a vital role in the national electric power system in the country.

The total storage capacity of Kulekhani Reservoir was 85.3 million m$^3$ of which 12.0 million m$^3$ has been allocated to dead storage and the reminder, 73.3 million m$^3$ being live storage. This project was designed for 50 years of life time; however, the expected life time is 100 years with an anticipated annual sedimentation rate of 700 m$^3$/km$^2$/year (NIPPON KOEI, 1994; Galay et al. 1995). After it was commissioned in 1982, sediment started to deposit in the reservoir. During its 22 years of operation (1982-2004) it has lost more than 21 million m$^3$ of its capacity (Sangroula, 2006).

4.1. Bathymetric Survey and Map of the Reservoir

Reservoir surveys were carried out by the author using GPS echo-sounding technology for recording and processing of bathymetric data in November of 2003 and 2004. An automated data collection system consisted of a field computer with GEODOS software, a Differential Global Positioning System (GPS), and an echo-sounder. The GARMIN GPS35 with GPS L1 antenna was mounted on the tripod at a point with known coordinates (Northing, Easting and Elevation). The rover was fixed at 2 m high wooden pole mounted on the side of the boat (see Figure 4.1).

More than 10 000 data points were traced during surveying in 2004. At an average boat speed of 2.5 km/h, data (X, Y, and Z) were collected at every 5 m along the survey track lines. A bathymetric map of the reservoir was created by using Surfer Golden Software and ESRI ArcMap programs. The bathymetric data
are gridded and modeled into a three-dimensional surface in the Surfer program. Triangulation with linear interpolation is adopted as the gridding technique.

The original capacity of the reservoir was 85.3 million m$^3$ and estimated capacity based on 2004 survey is 63.6 million m$^3$. The total loss during its 22 years operation (1982-2004) is 21.7 million m$^3$, which is more than 25% of the original capacity of the reservoir. The average annual loss rate is about 1.14% of the total original volume.

5 SEDIMENT MANAGEMENT IN THE KULEKHANI RESERVOIR

Probable management alternatives that are potentially feasible for this project are considered except dam heightening or construction of a new dam elsewhere. Hydrologically the reservoir is large. Estimated mean annual runoff to the Kulekhani Reservoir is 137 million m$^3$ (NIPPON KOEI, 1994). The original capacity of the reservoir is 85.3 million m$^3$ which shows the capacity inflow ratio of about 0.62. The current capacity is about 64 million m$^3$ and corresponding capacity inflow ratio about 0.5.

Three possible strategies to control reservoir sedimentation are mentioned earlier. Strategy to reduce sediment yield from the watershed by erosion control or upstream sediment traps alone will not sustain Kulekhani (Sangroula, 2006). This strategy is labeled watershed management.

Other possible strategy such as dredging (mechanical or hydraulic) is also not feasible for the Kulekhani Reservoir. The reason is that the reservoir is relatively deep and lifting sediment and transportation of dredged material will be quite expensive.

About 80% of the annual precipitation in Nepal falls during the monsoon season and rivers carry more than 90% of sediment load during this time of the year. To some extent it is verified from the field measurement carried out by the author. It was observed that there are few events which carry most of the sediment load for the entire monsoon season. Such hydraulic regime can be used to route inflowing sediment through or around the storage pool to minimize deposition and to remobilize and flush out deposited sediments. The author believes that hydraulic methods of sediment management options are the most feasible and favorable options for keeping reservoir sustainable in the Himalayas.

Hydraulic methods of reservoir sediment management options are sediment routing during floods (sediment bypass or sluicing), sediment flushing during floods and hydrosuction system for removal of sediment (HSRS) by using the available head as the source of energy.

5.1 Flushing Feasibility Criteria Estimation

Although there is no provision of bottom outlets in the dam of the Kulekhani Hydropower Project, crucial for sediment flushing system, attempts are made to estimate whether the flushing strategy is technically feasible or not for this project based on the available material. This is because sediment flushing is not universally applicable. If the conditions are right, flushing represents an efficient and economical way of preserving reservoir storage. If the conditions are not suitable, attempts to flush sediments from the reservoir will be disappointing (White, 2001).

It is not feasible to evacuate already deposited sediment from the reservoir under current circumstances. This is because, about 35 m of sediment is deposited around the upper part of the diversion tunnel and reopening and modifying the diversion system for flushing is considerable challenge. It is possible to sluice out incoming sediment and flush out some deposited sediment from the upstream part of the reservoir. For this purpose it is necessary to modify existing tower intake. The technical and economic aspects of reopening of the diversion tunnels are not described in this report.

Attempts are made to estimate the flushing feasibility for the Kulekhani Reservoir based on the two major criteria developed by Atkinson (1996). They are sediment balance ratio (SBR) and long-term capacity ratio (LTCR). The preliminary calculation shows that for adopted hydrological and physical parameters of the reservoir, the flushing alternative is feasible for the Kulekhani Reservoir with respect to the SBR ratio.
It is realistic to get such flushing discharge at the start of monsoon when flushing is recommended.

The second criterion is based on the sustainable capacity concept and defined by LTCR. LTCR is estimated using simplified reservoir geometry. Firstly the reservoir is assumed to approximate to a prismatic shape with trapezoidal cross sections. Therefore, a reservoir cross section at the dam site is representative of conditions within the reservoir. At this section, the ratio of cross-sectional area for the channel formed by flushing to original reservoir cross-sectional area is determined (Atkinson, 1996).

The computed LTCR value is very high. It seems that for adopted parameters the Kulekhani Reservoir is technically feasible for flushing on the basis of LTCR value also (Sangroula, 2006). It indicates that the majority of the original capacity can be maintained in the long term. In fact, this value mostly depends on the geometrical parameters of the reservoir.

Based on the SBR and LTCR values and geomorphological features, the flushing sediment management option seems to be feasible for the Kulekhani Reservoir. But, due to the following reasons the flushing is not recommended as preferred sediment management option

- As mention earlier there is no provision of bottom outlets, crucial for flushing
- The capacity inflow ration is very high
- Generally flushing is not considered as environmentally friendly sediment management option.

However, this option of sediment management is favorable for the Himalayas where flows and sediment loads in the rivers are concentrated during the monsoon. High sediment load can easily be passed thorough the bottom outlets in the dam or diverted from the reservoir by bypassing to the downstream. Therefore, this option of sediment management could be considered from the initial phase while designing storage projects in the Himalayas. The time for flushing/sluicing or bypassing is guided by the flow and sediment concentration in the streams. Therefore, high frequency of sediment monitoring system in rivers to capture such flow with high concentration is very important in this regard.

5.2 Hydrosuction Sediment Removal System (HSRS)

Hydrosuction system for removal of sediment (HSRS) is a method to evacuate deposited sediment from the reservoir by sucking a liquid/solid mixture from the bottom of the reservoir. HSRS removes sediment from reservoirs using hydraulic head represented by the difference between the water levels upstream and downstream of the dam. The potential energy thus drives water and sediment into sediment removal pipelines.

No external energy is required to transport the sediment from the intake point to the point of discharge as it is needed for traditional hydraulic dredging systems. The main advantage of this system is that sediment can be removed without lowering water level or interrupting the water supply from the reservoir. Another advantage of this system is that in some reservoirs only a fraction of the inflow is required to remove sediments. This system is expected to be feasible to transport distance up to 3 km (Palmieri et al., 2003).

Such a flow regime is of two-phase flow (of solids being carried by a liquid) and dependent on the characteristics of flow, liquid, solid and the pipe (Garde and Ranga Raju, 2000). In hydraulic transport of sediment from the reservoir, the energy gradient will always be a limiting factor. It is recommended that the sediment must not be deposited in the pipe during the transportation of sediment water mixture.

Garde and Ranga Raju (2000) reported that the term limit deposit velocity was introduced by Durand (1953). They further mentioned that the limit deposit velocity provides the line of demarcation between the heterogeneous regime and the regime with the movable bed. Jacobsen (1997) mentioned that at some mean velocity less than that required for heterogeneous flow some of the suspended particles begin to settle and the formation of bed layer starts. To avoid such formation, a certain velocity is required in the pipeline, and this is the limit deposit velocity, $V_L$. This velocity is normally also very close to the velocity at which the sediment is transported with a minimum head loss. This velocity is also has been called the economic velocity.
A number of methods for determining the limit deposit velocity have been discussed by Graf (1984), Vanoni (1977). The Durand method for estimating the limit deposit velocity is widely used and is recommended by Vanoni (1977).

For reliability of the HSRS and sustainability of the Kulekhani Reservoir it is necessary to locate the pipeline as low as possible to avoid vacuum in pipe so that no external energy is needed for removal of sediments. For the sustainability of the Kulekhani Reservoir it is important to establish a system which is able to evacuate sediment from at least 1.0-1.5 km distance from the dam. This is because, if the system is able to evacuate sediment from this area, sediment from the upper parts will be transported (through normal flushing during the onset of the monsoon) from the live storage to the “cleared volume” in dead storage where it is sluiced out.

The calculation made by the author (Sangroula, 2006) indicates that HSRS is the appropriate solution for the evacuation of sediment from the Kulekhani Reservoir. It is possible to evacuate sediment from the reservoir and establish sustainable reservoir storage capacity. HSRS is also an environmentally friendly scheme. This system improves the environmental conditions downstream, because it releases a certain amount of flow with limited volume of sediment. Minimum flow is necessary to the downstream from the environmental point of view.

A sudden release of floodwater either by bypassing or flushing with high sediment concentration may create a hazardous situation downstream, but release of limited flow and sediment improves the environmental condition downstream. In other words, the HSRS not only improves the physical sustainability of the reservoir, but it also improves the environmental sustainability of the project.

6 CONCLUSION

It is understood from the past experience that watershed management alone will not be able to keep reservoir sustainable, but a combination of reservoir sediment management and watershed management can keep storage projects sustainable.

One of the important features of the Himalayas is that during the monsoon there are a few events, which carry most of the sediment load. To some extent this is verified in the present study. The scale and duration of such events are very crucial from the reservoir sediment management point of view, because, if the system is designed to divert such sediment-laden flows, the project may be sustainable. Reservoirs have to be designed, as renewable source of energy and it is quite feasible to keep reservoirs sustainable by handling sediment carefully.

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