Erosion from the Kulekhani Watershed, Nepal during the July 1993 Rainstorm

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1. INTRODUCTION

The Kulekhani Hydropower system is located in the Makuwanpur District, Central Region of Nepal, about 30 km southwest of Kathmandu. The Kulekhani No. 1 power station has an installed capacity of 60 MW and was commissioned in May 1982. Kulekhani No. 2 power station, installed capacity 32 MW, utilizes water from the tailrace of the No. 1 power station and was commissioned in December 1986. The total installed capacity of 92 MW for the two power stations comprises about 45 percent of the system capacity of Nepal (210 MW) and is primarily utilized in the dry season because most of the other stations in Nepal are run-of-river type. The total storage capacity of Kulekhani 1 reservoir was 85.3 million m^3 of which 12.0 million m^3 has been allocated to dead storage and the remainder, 73.3 million m^3 being live storage. The original operating life of the dead storage was estimated to be over 100 years by Nippon Koei Co. Ltd. and this was based on a sediment yield estimate of 700 $m^3/km^2/yr$. A view of the reservoir and the upstream delta is shown in Figure 1. The Kulekhani Dam itself is 150 m high and is a rock-fill structure with two spillways. Further down the system, Kulekhani 2 power station is located on Khani Khola which has been undergoing significant aggradation of its river bed.

Figure 1. Kulekhani Reservoir - Coarse bed-material (cobbles, gravel and sand) are shown as a deltaic deposit at the upstream end of the reservoir. The delta is about 2 km long and floating debris is seen adjacent to the delta. The Bisingkhal Khola delta is shown at the bottom right side of photo (September 1993).

2. SEDIMENT PRODUCTION FROM THE KULEKHANI WATERSHED

2.1 General Aspects of Sediment Production in Nepal

Sediment production in Nepalese watersheds has generally been acknowledged to be the highest in the world (Carson, 1985; Laban, 1978, Tautscher, 1979) and little reliable data of actual sediment production is available. Estimates for various land uses are presented in Table 1 and indicate the wide range of values which makes prediction of sediment yields difficult. However, in planning for dams in the mountains, it is essential that sediment yield estimates be realistic.

Now that a reliable estimate of sediment yield is available from reservoir deposition, one can work backwards and attempt to estimate the source of sediments and route these volumes down the tributaries and the mainstem to the reservoir. This paper presents two approaches for estimating sediment yield and comments on needed research for improvement of estimates.

Table 1. Erosion rates, Nepal.

Description of location and site; land condition	Rate Tons/km2/yr	Reference
Siwaliks, East Nepal, Chatra; S-aspect sandstone foothills; different landuse ranging from forest to grazing	780-3680	Chatra, 1976
Siwaliks, Far West Nepal, Surkhet; S-aspect sandstone foothills;		
- degraded forest	2,000	Laban, 1978
- degraded forest, gullied land	4,000	Laban, 1978
- severely degraded heavily grazed forest, gullied land	20,000	Sakya
Mahabharat Lekh, Central Nepal, Lothar; very steep slopes on metamorphic and sedimentary rocks;	3,150-14,000	Laban, 1978
- degraded forest (+ agriculture fields)	6,300-42,000	Laban, 1978
- gullied lands		
Middle Mountains, Kathmandu Valley; northern foothills of granites and migmatites with weak consolidation;		
- mainly degraded forest and scrubland	2,700-4,500	Laban, 1978
- dominantly overgrazed scrubland	4,300	Laban, 1978
- severely gullied land	12,500-57,000	Laban, 1978
Middle Mountains, Kathmandu Valley; steep slopes, south of valley, near Godawari; 75% dense forest		Kandel, 1978
1978	800	Laban, 1978
lands with good groundcover on shales, hard limestone and quartzite		
Middle Mountains, West Nepal, Phewa Tal Watershed; S-aspect moderately steep slopes on parallel dipping phyllitic schists;		
- protected pasture	920	Mulder, 1978
- overgrazed grassland	34,100	Mulder, 1978
- overgrazed grassland	2,200	Laban, 1978
- gullied, overgrazed grassland	2,900	
Middle Mountains, West Nepal, Phewa Tal Watershed N-aspect steep slopes on phyllitic schists		
- scrubland	*	Mulder, 1978
- dense forest land	*	Mulder, 1978
Darjeeling, Indian Himalayas	5,000-7,500	Starkel,1972

*Study in progress

2.2. Rainfall Intensity and Runoff

On the 19th and 20th of July, 1993, a major rainstorm hit the south-central part of Nepal. Based on rainfall data from several stations in the Kulekhani watershed and nearby watersheds, an isohyetal map was developed by Nippon Koei Co. Ltd. (1994) and is shown in Figure 2. Peak rainfall was observed at 10:00 pm, July 19 with an intensity of 70 mm/hr. The maximum amount of rain falling in one day was 540 mm on July 19, 1993 for the Tistung Station. More details related to the rainfall distribution and frequency can be found in Nippon Koei Ltd. (1994), JICA (1993) and SMEC (1994).

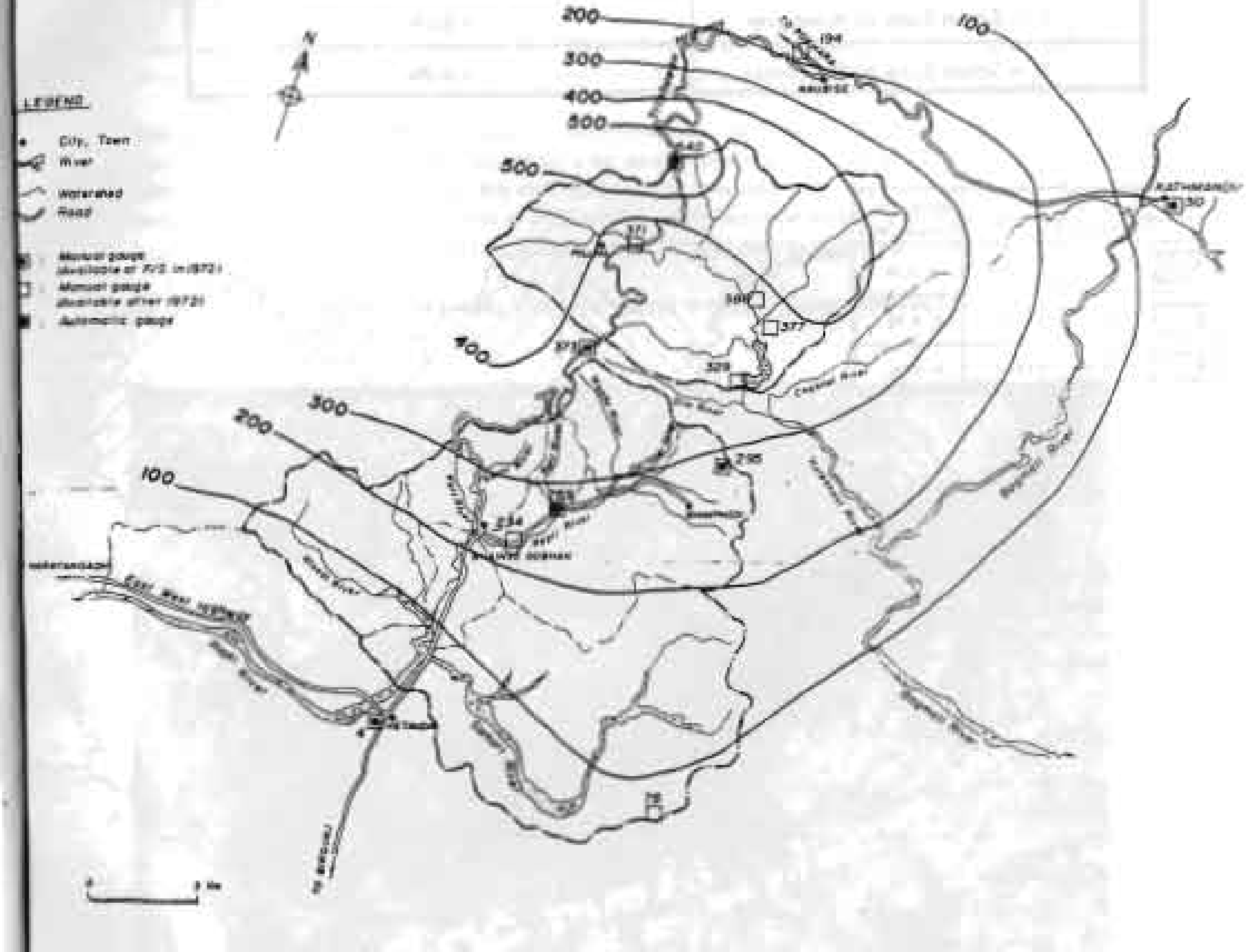

Figure 2. Nepal isohyetal map of 1-day rainfall July 19, 1993.

2.3. Sediment Sources Within Kulekhani Watershed

A geological map of the watershed, shown in Figure 3, indicates that the southern portion of the watershed is composed of Palung Granite while the northern part is predominantly schist. From reconnaissance and study of air photos taken after the flood it was evident that a large number of landslides occurred. In fact, the following table gives an estimate of the landslide surface area ratio to the catchment area for three basic geologic formations:

Zone	Area Ratio = $\frac{\text{landslide area}}{\text{catchment area}}$
G = Granite Zone	= 9.2 %
S_1 = Schist Zone on West side	= 5.9%
S_2 = Schist Zone on East side	= 4.0%

Figure 3. Location map showing density of landslides (collapses) and geology of Kulekhani Watershed.

In assessing landslides in more detail, the following characteristics were noted:

1) landslides generally occurred within the 300 mm/day rainfall isohyet indicating a "threshold" for the occurrence of extensive landsliding (Figure 4);

2) some slides deposited a large portion of their material on downstream alluvial fans and only the finer material moved further down the system as shown in Figure 5 for the Phedigaon Khola;

3) other landslides slumped directly into the main stem and the material was rapidly moved down the system;

4) some major landslides had much of their slumped material held in place by roads and gully check structures resulting in low sediment delivery to the mainstem; and

5) downstream from the first three tributaries: the Phedigaon, the Gharti and the Bhangkhora Kholas, the mainstem formed a large, wide deposition area and it appears that a large portion of the generated sediment dropped out in this reach - the sediment delivery was relatively low. From an assessment of the longitudinal slope profile, the reaches of relatively flat mainstem river slopes constitute deposition zones and sediment delivery ratios would vary along the profile and also probably with time.

Based on these characteristics, two approaches were used to compute sediment yield.

Figure 4. Watershed just south of Kulekhani Watershed. Many landslides have developed inside of the 300 mm/day rainfall isohyet (Aerial Photo - December, 1993).

Figure 5. Phedigaon Khola and Gharti Khola. The Phedigaon Khola is at the right of the photo and shows extensive alluvial fan deposits of schist while the Gharti Khola on the left shows remnants of large granite boulders (September, 1993).

2.4. Computation of Sediment Yield

Sediment yield research indicates that a significant portion of eroded sediment drops out prior to reaching the conveying main river of a watershed and "sediment delivery ratios" have been developed based on catchment area. However, most of the data used to derive this ratio was from middle and Western USA which would not be representative of the Middle Mountains of Nepal. Therefore, another relationship from Japan was used, namely the Kaki formula:

Sediment Yield, $Y = a \times E$

Where: $Y =$ sediment yield in m^3

$E =$ landslide eroded volume in m^3

$a =$ sediment discharge ratio

$$a = \frac{(\text{river slope, } S)^{0.4}}{(\text{catchment area } A, \text{ km}^2)^{0.2}} \quad \text{where } A >= 1.0 \text{ km}^2 \text{, and}$$

$$a = \frac{S^{0.4}}{A^{0.3}} \quad \text{where } A <= 1.0 \text{ km}^2$$

The above relationship was used in combination with estimates of landslide erosion volumes to arrive at a landslide sediment yield = 4.84 million m^3. The total sediment yield, which also includes river bank and bed erosion was estimated to be 5.85 million m^3 by the above method. Detailed tables for each watershed are shown in Nippon Koei Co. Ltd. (1994).

A second method based on detailed field assessment of sediment movement was also used as a check on the first technique. This second method estimated the percent sediment passing in the following manner:

Step 1	Step 2	Step 3		
% passing out of slump	X % passing out of tributary	X % passing out of mainstem	=	Sediment Delivery Factor

The above method starts with the volume of material involved in a landslide slump and estimates the percent that passes out of that slump. Using the landslide volumes measured in the field, the landslide component of sediment yield came to 5.54 million m^3. This is slightly higher than the 4.84 million m^3 computed by the first method but this second method is thought to be more applicable to Nepalese mountain conditions. More extensive research is essential to develop this "routing" of landslide volumes, but much of this research involves direct field measurements which will also result in a more thorough understanding of processes. To complete the second method an estimate of 0.10 million m^3 was made for bank erosion,) 0.55 million m^3 for bed erosion in first and second order tributaries only, and 0.25 million m^3 for sheet and rill erosion for a total sediment yield of 6.44 million m^3 entering the reservoir. The two techniques are compared to the sediment yield as determined from the reservoir surveys:

Technique	Sediment Yield	
	million m^3	million tonnes
1. Kaki formula	5.85	-
2. Sediment routing	6.44	-
3. Reservoir survey	4.00	6.40

The two techniques used to measure sediment yield are relatively close, but the yield of 4.00 million m^3 should be used since this value was obtained by direct measurement of the material deposited within the reservoir. The unit sediment yield then works out to be:

$$\frac{4,000,000}{126} = \underline{31,746}\ m^3/km^2/flood$$

From reservoir surveys, the sediment yield was computed as follows:

Sediment Yield From Kulekhani Watershed
(from reservoir surveys)

	Total over 12 years (in reservoir)	Total Yield (Upstream)	Annual Yield-Upstream	Unit Annual Yield
	(million m^3)	(million m^3)	(m^3/yr)	(m^3/yr/km^2)
1993 (pre-flood March)	2.2	1.8	150,000	1,200
	Flood Yield (in reservoir)	Flood Yield (Upstream)	Assume	(Unit Flood Yield)
1993 (post-flood Dec.)	4.8	4.0	4.0 million m^3	31,700

From the above table, it is apparent that unit sediment yields vary greatly and that major rainstorms have a devastating effect on the watershed.

Another approach to assess sediment yield is to utilize data from other rivers in the Himalaya such as shown in Figure 6. The Kulekhani data, converted to tonnes per year, ranges from 240,000 to 6.4 million tonnes per year and is plotted on Figure 6. The low value, prior to the flood, plots with the lowest values for other rivers, but the high yield for the single event plots higher than any other rivers. The main reason for this excessively high yield could be the fact that the event can be described as a debris flood which is somewhat rare. The return period of the event has been estimated to be 100 years or more (SMEC, 1994). Also, the data for other rivers probably has been averaged over a number of years resulting in a significant lowering of yield estimates due to rather dry years. If one averages the 13 years of record, the yield value becomes 658,000 tonnes/year or 5.350 tonnes/km^2/yr (3,340 m^3/km^2/yr.). This average value now plots near the highest values for other rivers. However, this technique of averaging one high value with 12 rather low values does not give a representative future yield.

3. SEDIMENT PROCESS IN THE KULEKHANI RESERVOIR

Fortunately, the Department of Soil Conservation - HMG Nepal conducted a survey of the Kulekhani reservoir just prior to the July 1993 flood and with a re-survey in December 1993, it is possible to assess the sedimentation process and the amount of deposit within the dead storage and live storage zones (Dept. of Soil Conservation, 1994). The location of the reservoir cross-sections is shown in Figure 7 and the longitudinal deposition profile is shown in Figure 8.

The March 1993 survey indicates that the entire length of the reservoir had undergone deposition with a distinct delta located 6 to 7 km above the dam. The largest volume of sediment, however, was probably in the first 1.5 km, near the dam, since the reservoir is widest through this lower reach (see Dept. Soil Conserv., March 1994 for cross-sections).

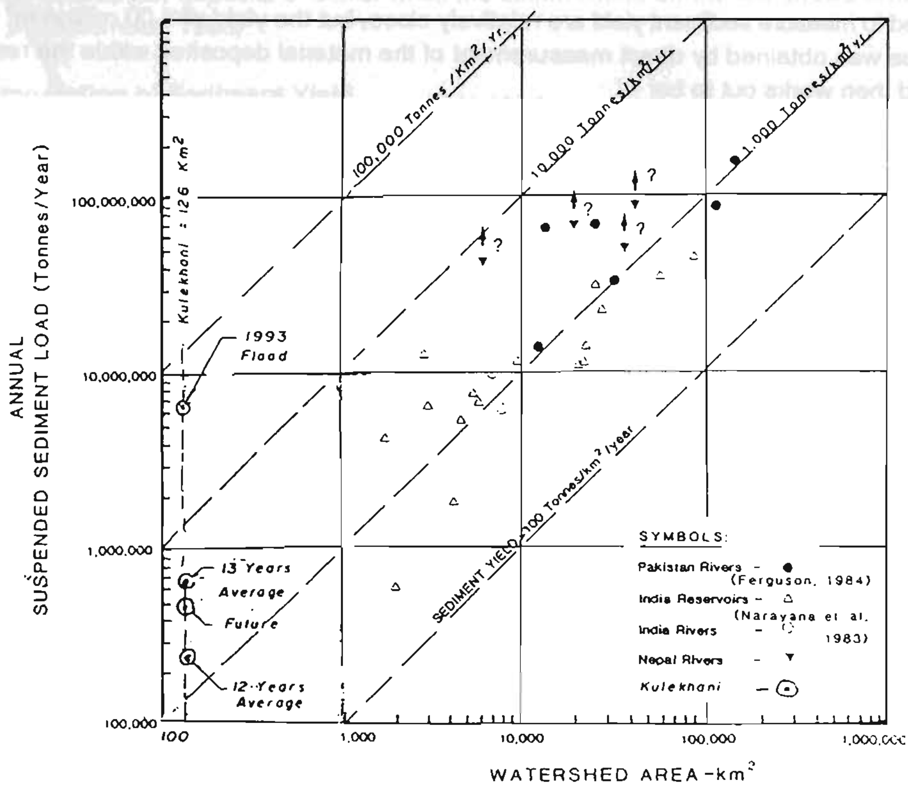

Figure 6. Comparison of Kulekhani river sediment yield to other Himalayan Rivers.

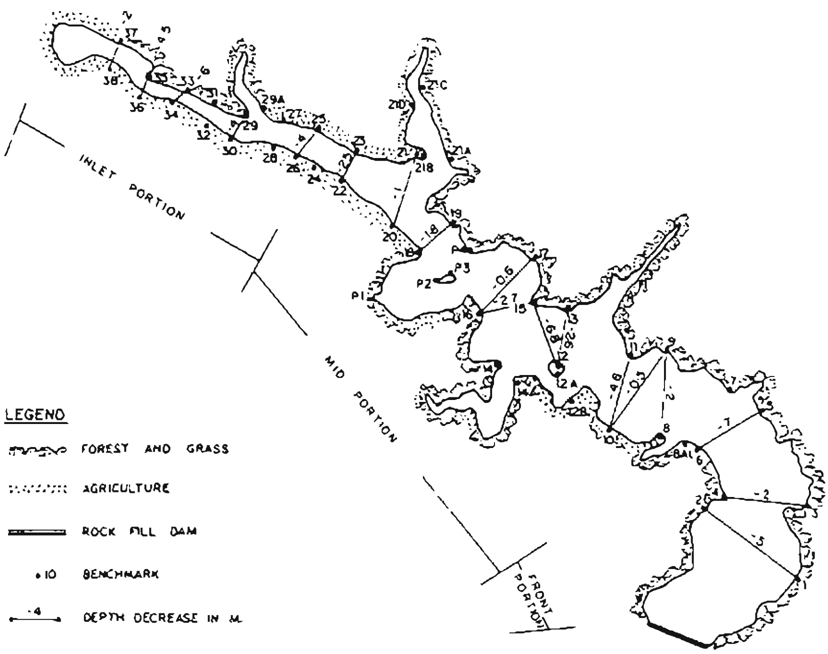

Figure 7. Kulekhani reservoir.

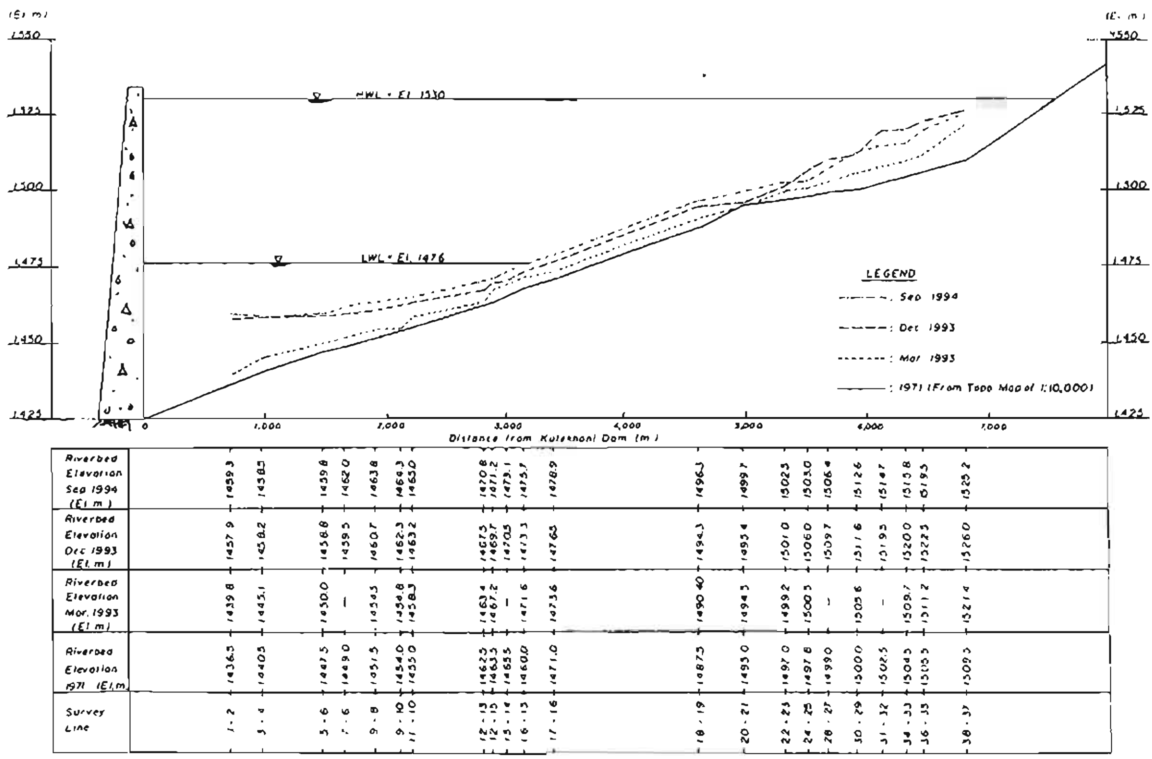

Figure 8. Trend of sediment deposition in the Kulekhani reservoir.

During the monsoon flood of 1993, the surveys indicate that most of the deposition took place in the dead zone with a bed rise of about 18 m at cross-section 1-2. Also, a distinct coarse-material delta was formed at the upstream end with its pivot point located at cross-section 31-32 (6.2 km from the dam) and the rise in average riverbed level was about 12 m as shown in the longitudinal profile (Figure 8). From computations using the end-area of the deposition and distance between representative cross-sections it was determined that about 4.8 million m^3 of sedimentation had occurred in the reservoir during the 1993 Monsoon. Further, from examination of the deposition profile it appears that the coarse material extends to about cross-section 9-10 (1.9 km upstream from dam) and that fine material has accumulated along the lower portion of the reservoir. The volume of fine material was estimated to be 2.9 million m^3 with the remaining 1.9 million m^3 made up of coarse material. The reduction of water storage within the dead zone and live zone of the reservoir were estimated to be as follows:

Storage in Kulekhani Reservoir

Year	Dead Zone Volume (million m^3)	Live Zone (million m^3)	Total Storage (million m^3)
1981	12.0	73.3	85.3
1993 (Mar.)	10.8	72.3	83.1
1993 (Dec.)	7.6	70.7	78.3

The lost storage was estimated from the reservoir storage curve and from the approximate bed profile in 1981 as obtained from the topographic map. The procedure gives approximate values of sediment volume in the reservoir until December, 1993.

Also, during the monsoon of 1993, there were two major floods with the largest being on July 20 (Q peak = 1,340 m^3/s) and the other one on August 10 (Qp=756 m^3/s) and both of these contributed to the sedimentation of reservoir. However, because the August rainfall lasted only 4 hours and because the deposition would be partly upstream from the December 1993 survey it was assumed that the 4.8 million m^3 of sedimentation could be attributed to the July 20, 1993 flood.

From surveys of the delta in June, 1994 and from field reconnaissance in September, 1994, it became apparent that head cutting had occurred and possibly 0.7 Mm^3 of delta coarse material and fine material has been added to the dead storage. The delta is composed primarily of sand overtopped by coarser gravel and cobbles as shown in Figure 9. The finer delta deposits move far into the reservoir while the gravel and cobbles stay at the upstream end as shown in Figure 10. There is concern as to when sediment will start to be drawn into the power intake which has an invert level of 1471 m.

4. RESEARCH TOPICS

After assessing the watershed and the flood event, a number of questions remain in regard to prediction of sediment yield for other watersheds.

a) Is the 300 mm/day "threshold" for extensive landslides transferable to other geologic zones?

b) What is a reasonable aerial extent for a rainstorm having a rainfall intensity of 300 mm/day?

c) Because the base of most landslides are along tributaries or mainstems of rivers, should not the sediment yield of landslides be related to stream order or stream length as opposed to catchment area?

Figure 9. Kulekhani Reservoir Delta. Headcutting of sand and gravel deposit during low stages of the reservoir. The deposits are primarily sand with gravel lenses near the top (June, 1994).

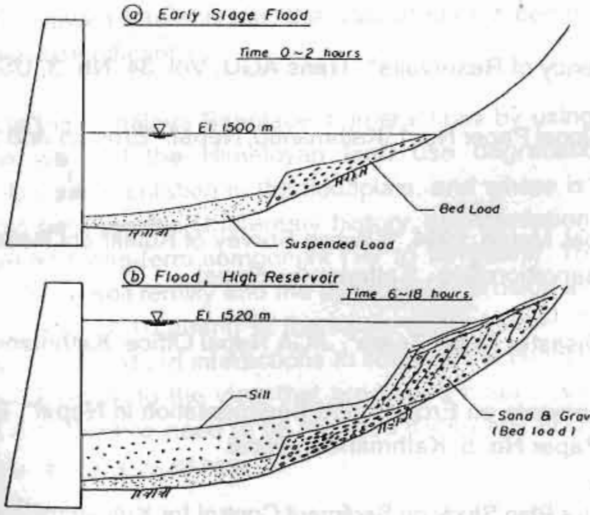

Figure 10. General concept of reservoir sedimentation.

d) How can large sediment particles be treated in terms of sediment routing when some of the particles are breaking up and wearing down in a downstream direction?

e) How does sediment yield decline with time after a massive amount of erosion is generated during a major storm?

There are certainly more questions that need to be answered in regard to managing sediment, but basically the state of knowledge is somewhat limited - how can we manage sediment processes if we don't know the magnitude nor the frequencies of sediment producing events? Meaningful data is gathered only after massive destruction or as part of a major project but this is inadequate.

5. CONCLUSIONS

The major rainstorm of July 19, 20, 1993 generated many landslides in the Kulekhani watershed which resulted in 4.8 million m^3 of sedimentation within the Kulekhani I reservoir. The majority of sediment, 83 percent, was generated from landslides which were much more frequent within the 300 mm/day rainfall isohyet. An analysis of watershed hazards and sediment routing generated a sediment yield that was somewhat higher than the actual yield as measured from reservoir deposition and this amounted to 4.0 million m^3.

The project sediment yield estimate was much lower than occurred during the 1993 flood but there are few techniques by which designers can predict sediment yields for extreme events. From this large documented event it can be conclusively stated that estimating future sediment yield on a catchment area basis, such as 700 m^3/km^2/year is inappropriate - the model is wrong - landslides occur along linear tributaries and new research is required to estimate yields from debris torrents.

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