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Sediment Transport Measurement in the Koshi River: Comparison Between Historic and Recent Measurement Results

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Abstract: This study presents the results of sediment transport measurement in the Koshi River with a comparison between historic and recent measurement techniques. Based on the historic sediment measurement data for the period 1948-1981, the yearly sediment load at Barakhshetra varied between 49 and 283 million m^3, with an average of 95 million m^3. The coarse, medium and fine fraction contribute by respectively 19, 25 and 56% to the total sediment load of the Koshi River. The average total yearly sediment load at Chatra was estimated as 130 million m^3, of which about 60 million m^3 is bed material load which contributes to the aggradation on the alluvial fan. This historic data relate to measurements with depth-averaged sampler form cableways. Recent practices collect surface sediment samples from the riverbank to estimate the sediment transport in the river, which include the JPO-SKSKI and DHM sediment samples. The average yearly sediment load at Chatara on the basis JPO-SKSKI and DHM measurement correspond to 44.5 million m^3 and 57 million m^3 respectively. Moreover, a comparison between the percentages coarse, medium and fine sediment for the historical measurements (EDI method) and JPO-SKSKI and DHM measurements (surface sampling near the bank) concluded that sampling from the bank results in a serious underestimation of the contribution of the coarse sediment to the total sediment load of the river.

Keywords: Sediment Load, Riverbank, EDI, Surface Sampling, Depth-averaged

1. Introduction

Sediment measurements are complicated and expensive. Total sediment conveyed by streams leads more than fifty percent are during flood event, which creates more challenges in measurement [1, 2]. Flood events from time to time may occur at nights that make it difficult to measure unless there is an automatic measurement system in place. The other real favourable time of measurement are tedious and laborious resulting high cost. There are a lot of sediment sampling techniques available for sampling suspended and bedload sediment in rivers and streams. More than a dozen sediment measurement techniques including bottle sampling, acoustic sampling, surface sampling, optical sampling etc. are available. It is evident that there is no one generally accepted sampling technique considered superior to others in the collection of sediment data. The accessibility of enough reliable high-quality sediment data is vital in the proper and efficient management of the river system. The techniques for collecting sediment data are described in two forms; the conventional sampling techniques (also known as traditional techniques) and the advanced technologies technique.

Use of conventional methods where measurements are taken from the field and analysed in the laboratories may be accompanied by errors up to 20 per cent from sampling and computation [2]. Sediment settlement by one hour accompanied by resuspension may result to increase in volume mean particle size up to 24 per cent [3]. Large sudden variability with time and space are usually not common with well-mixed suspended sediments (<0.062) within the cross-section of a river. Sand transport exhibits large variability with time and space. Measured coefficient of variation (COV) for 16 rivers and found sand concentration was to be as high as 70 per cent [4]. Laboratory analysis using flume under steady uniform flow with 0.5 mm sand showed that the COV for sand concentration data was 62 per cent on an average over a flow range [5]. Similar research on sand transport of Goodwin Creek Watershed in Northern Mississippi found that COV values were approximately 100 per cent [6].

A good understanding of sediment processes in the Koshi River is a pre-requisite for proper future management of the river. The Koshi River, located on one of the most active alluvial fans in the world, poses major challenges in flood management and in coping with the excessive quantities of sediment entering the alluvial plain. In this context, estimation of yearly sediment load in the Koshi River is the prevailing issue for policy makers and planners.

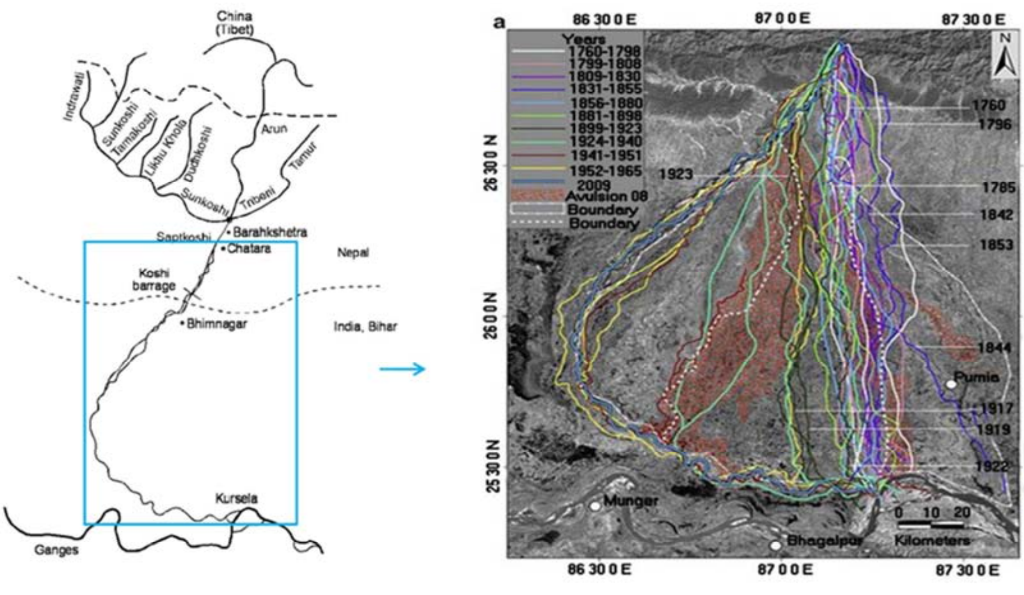
2. Study Area and Data

2.1. General Description

The Koshi River is one of the major rivers in South Asia having snow fed characteristics. The Koshi basin is roughly located between 85° to 89° east longitude and 25° to 29° north latitude. The Koshi is a trans-boundary river, originating in Tibet, flowing through the Himalaya, through the eastern part of Nepal and the flat plain of Indian north territory. The Koshi River drains 29400 km^2 in China; mainly the upper Arun basin north of the Mount Everest region, 30700 km^2 in Nepal and 9,200 km^2 in India. The Koshi has seven major tributaries: Sunkoshi, Tamakoshi or Tambakoshi, Dudhkoshi, Indravati, Likhu, Arun and Tamur. These rivers combined become the Saptkoshi, literally "Seven Koshis". Below Tribeni, which is the confluence of the Sunkoshi from the west, the Arun from the north and the Tamor from the east, the Saptkoshi crosses the middle mountains or Mahabharat Range in a narrow gorge, for 10 km. In Nepal, at Barahkshetra, it emerges from the mountains and becomes the Koshi [7].

Below the foothills the Koshi deposits huge quantities of sand, since it is unable to transport the sand all the way to the Ganges. A good understanding of sediment processes in the Koshi River is a pre-requisite for future management of the river. Basic questions to answer when developing management strategies for the Koshi River comprise average yearly sediment load at the site of the planned Koshi High Dam including contribution of the different tributaries, fluctuation of this yearly sediment load over the years, characteristics of the bed material, impact of land use changes and climate change on the past and in particular in the future on the sediment yield from the Koshi catchment etc.

Over 200 years, as the result of avulsions, the river has shifted its course over 120 km from east to west Figure 1 (b). To prevent the shifting of the Koshi River, to control the floods and to implement a large irrigation project, the Koshi Project with cooperation with India was designed. Under the project, barrage, irrigation facilities and embankments of many kilometres on both left and right sides were constructed. Since 1963, after the realization of the Koshi Project, the river was held fixed between embankments.



(a) Alluvial fan with tributaries (b) Shifting of Koshi River

Figure 1. *Koshi River and its tributaries.*

2.2. Origin and Characteristics of Sediment

The different regions including the high Himalaya, Mountains, Siwaliks and Terai which the Koshi River passes Figure 2 contribute to the high sediment load. In the high Himalaya region, moraine dammed glacier lakes are common and can result in catastrophic floods when moraines are breached. In the High Mountains region, the rocks are resistant to weathering. All valleys in this region were glaciated. Active river cutting enhanced by high river gradients has resulted in very deep canyons being carved since glaciations. The Middle Mountains are present north of the Siwaliks. The Koshi River is down-cutting this area. Mass wasting (rock falls and landslides) is present. The Siwaliks regions possess steep slopes and weakly consolidated layers of bedrock, subject to severe surface erosion. High intensity rainfall produces high erosion and torrent flows. Mass wasting is exceptionally high throughout the Siwalik. The Terai region is the flat land. It consists of gently sloping recently deposited alluvium. The soil is sandy. In the Terai, there is primarily sediment deposition. The percentages of contribution to the total load of the Koshi River from each of these regions are unknown. The source of sediment is primarily mass wasting, geologically controlled, such as landslides, debris flows, rock fall, avalanches, glacial lake outbursts, active down cutting of the river bed and bank erosion.

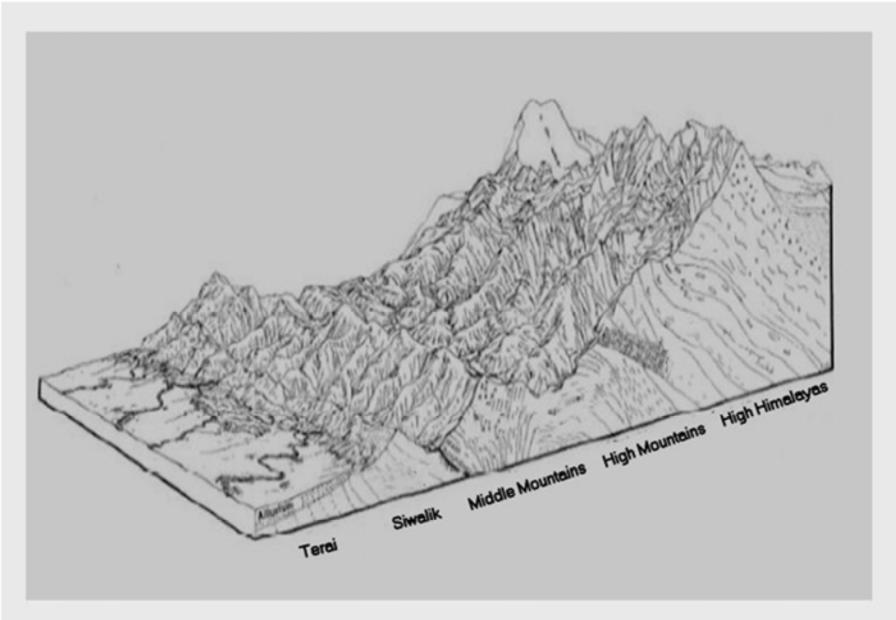


Figure 2. *Regions for sediment origin [10].*

3. Methodology

3.1. Koshi Sediment Transport Measuring Network

Figure 3 presents the hydrological network of the Koshi River. Moreover the hydrological stations are shown. The stations are identified by a 3 digit number. All stations in the Nepalese part of the Koshi River basin start with a 6. Chatra station has the number 695.

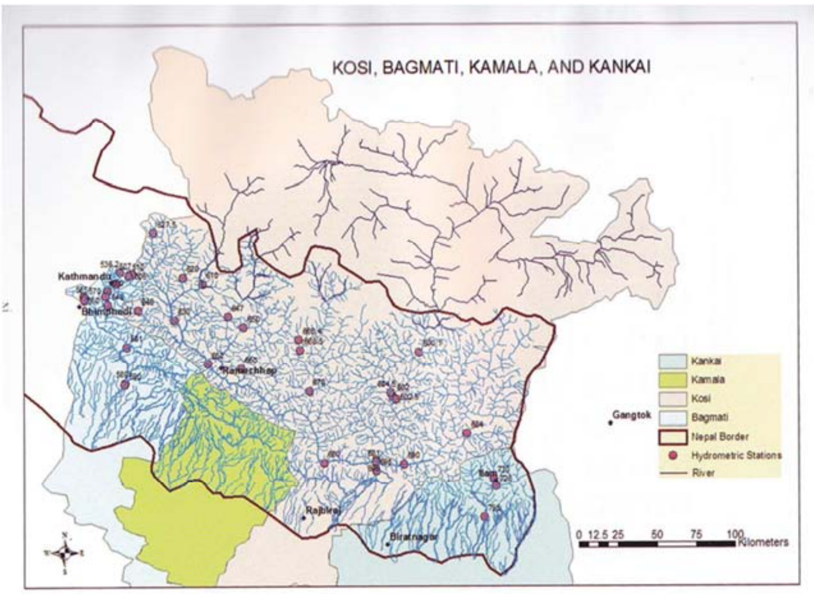


Figure 3. *Koshi catchment in China and Nepal (light pink) and (in different colours) neighbouring catchments of Bagamati, Kamala and Kankai Rivers with Nepalese hydrological stations.*

Sediment transport measurements are always carried out at stations where also hydrological data are collected. Hydrological data were provided by DHM on request. These data however date back only to 1977. The sediment data provided by DHM cover only the years 2001 through 2003, and it concerns three stations in the Koshi catchment, notably: 647 Tamakoshi, 690 Mulghat and 695 Chatra.

Information on earlier sediment transport measurements was found in two reports, notable Ganga Flood Commission (1983), which deals with the flooding problems of the Koshi in Bihar which reviews the availability of sediment transport data in the Nepalese Terai and their quality. Stations S. T. 13 in Table 1 is probably the Barakhshetra station, which later has been abandoned [8].

Table 1. *Overview of stations and available data in the Koshi basin before 1983 [8].*

River	Station	Distance from Chatra (km)	Year observations started	Later abandoned	Data available
Sun Kosi	Tribeni	13 u/s	1947	No	1948-55; 1980-81
Arun	Tribeni	12 u/s	1947	No	1948-55; 1980-81
Tamur	Tribeni	11 u/s	1947	No	1948-55; 1980-81
Sapta Kosi	S. T. 13	6.5 u/s	1947	No	1948-55; 1980-81
Sapta Kosi	S. T. 19	1 u/s	1953	Yes	No
Kosi	Galpaharia	17.5 d/s	1953	Yes	No
Kosi	Kushara	33.5 d/s	1953	Yes	No
Kosi	Koshi barrage	42 d/s?	1963	No	1963-ongoing (discharge only)
Kosi	Hanumanagar	51 d/s	1951	Yes	No

3.2. Sediment Transport Measuring Techniques

Sediment transport measurements in Nepal is not easy due to the steep slopes of the rivers and consequently high velocities. In a river like the Koshi River either wading in or sailing on the river is not an option during flood. In the past sediment transport measurements in Chatra were done via a cableway (see Figure 4 for the cableway at Chatra). The technique used was the so-called equal-discharge-increment (EDI) method in which samples were obtained from locations representing equal increments of discharge.

In the EDI method, samples were collected iso-kinetically and the vertical represents the mean concentration and particle-size distribution for the subsection sampled. Moreover, the discharges on both sides of the sampling vertical were predetermined proportions of the total discharge, which required information on the lateral distribution of discharge in the cross section.

Figure 4. *Cableway in Chatra for measuring of flow and suspended sediment.*

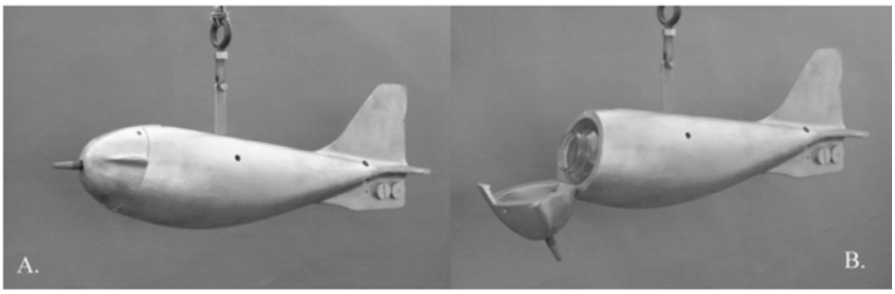


Figure 5. *Depth-integrated US D-74 sampler (modern version of US D-49 used for sediment measurements in Chatra in (a) closed and (b) open position with bottle inside) [8].*

In Nepal, usually five verticals were sampled and the sediment transport measurement was combined with a flow measurement, in accordance with ISO Standard 4363 (ISO, 1997). The instrument used is the depth-integrated sampler US D-49 (see Figure 5 where the US D-74 is shown, which is following up the US D-49, but working according to the same principle with bottles inside which are filled during the lowering and the heaving of the instrument). These instruments were designed to be suspended from a bridge, cableway or boat.

Since 1988, sampling in Chatra has been carried out in a different way. Only one sample has been taken from the surface of the water near the left bank. An important advantage of this technique is that it is less time-consuming and, when combined with a gauge reading and a rating curve to determine the flow, there is no need to do a flow measurement as is the case with the EDI method. However, despite these seemingly important advantages, this way of measuring sediment transport has some serious limitations such as theoretical adjustments for vertical distribution of sediment concentration and lateral variations in sediment distribution are required.

3.3. Prediction of Sediment Load

3.3.1. Historical Measurements

To collect relevant data for the design of the dam a measuring station was erected in Barakhshetra in 1947 and for a long period discharges and sediment transport were measured in this station. The original data might have been lost, but in the report of the Ganga Flood Control Commission (1983), a summary of the results is provided as a table presenting the annual sediment load in Koshi at Barakhshetra for different grades for the period 1948-1981 [8]. From the data set, it can be observed that total yearly sediment load varies between 49 and 283 million m^3, with an average of 95 million m^3. The coarse, medium and fine fraction contribute by respectively 19, 25 and 56% to the total sediment load of the Koshi River.

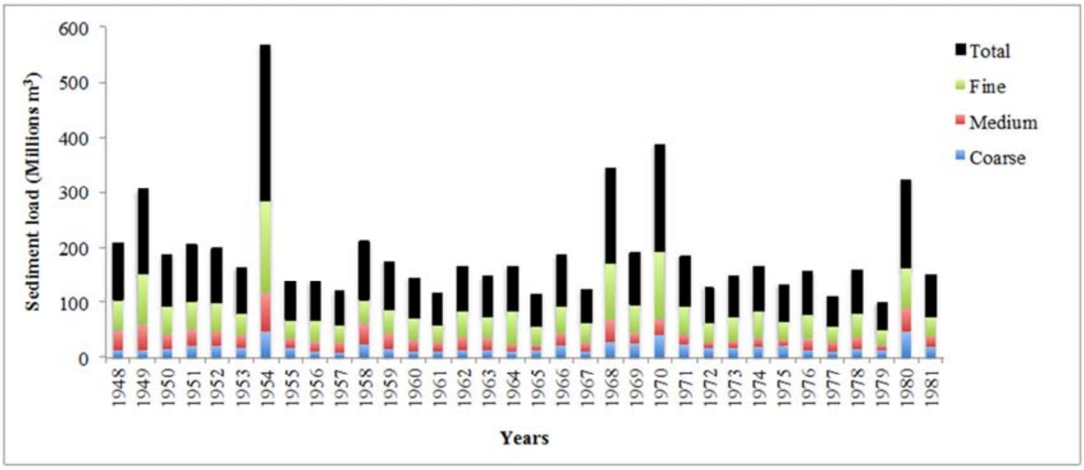


Figure 6. *Annual sediment loads in Koshi at Barakhshetra for different grades for years.*

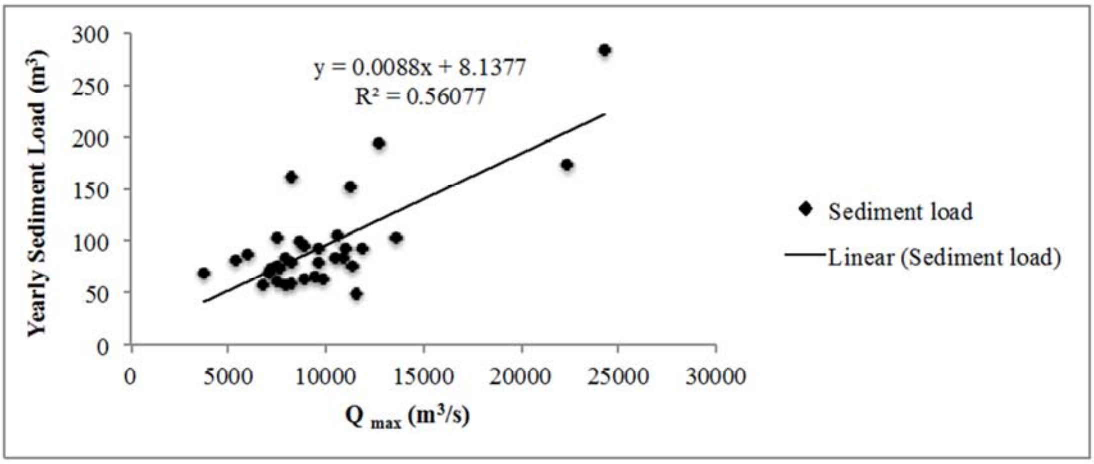


Figure 7. *Yearly sediment load of the Koshi River plotted versus the yearly maximum discharge in the period 1948-1981.*

3.3.2. River Bank and Surface Layer Sampling

i. JPO-SKSKI sediment sampling

Over the last years, frequent sampling of the sediment load of the Koshi River at Chatra has been carried out for the (Indo-Nepal) Joint Project Office- Saptakoshi-Sunkoshi Investigations (JPO-SKSKI) project. Also these samples were taken from the riverbank and from the surface layer of the river. Results of one year of sampling of the year 2005 are available for analysis. Almost daily sampling was carried out in the months July through and including November, so in total 5 months. In the period preceding the monsoon the sampling was done twice a week. In total the sampling was carried out 158 days out of a period of almost 7 months, or 221 days.

ii. DHM sediment sampling

Since 1988 the sediment transport measurements were not done anymore by cableway using the equal-discharge-increment (EDI) method but surface samples were taken from the bank of the river. Regular monitoring of flow and sediment transport in the main river basins by Department of Hydrology and Meteorology (DHM) were done for the Koshi

River in Chatra [11]. The process is in principle still ongoing but in practice stopped in 2003. DHM has three sediment transport measuring stations in the Koshi basin namely 647 (Tamakoshi), 690 (Mulghat) and 695 (Chatara). In this study, only the sediment data for the Chatra station are considered, as these are the most complete (at least in the period 2001-2003) and a comparison can be made with the historical data for Barakhshetra.

4. Results and Discussions

4.1. Historical Measurements

For the management of flooding problems, it is important to have a good estimate of the sediment supply of the river at its apex. Hence, in the case of the Koshi River not the sediment load at Barakhshetra is important, but the sediment load at Chatra has to be estimated. The sediment load at Chatra is higher than the figures given for Barakhshetra for a number of reasons. First the contribution of the kholas (steep tributaries) between Barakhshetra and Chatra has to be accounted for. Secondly, the sediment loads at Chatra include only the suspended load and the unmeasured bed load still has to be added. Hence the total sediment load at Chatara is estimated with three corrections.

1. A report mentions an appreciable increase in silt load between Barahkshetra and Chatra with contribution to the total sediment load in the river by 25% during flood. Moreover, the contribution to the coarse fraction of the sediment load is still higher, being about 39%. Based on this information, the sediment load of the coarse fraction is multiplied by a factor 1.39 [8].
2. Based on the sieve curves), the increase of sediment load between Barakhshetra and Chatra the medium fraction is assumed to increase by 25% [9]. An increase of the fine fraction with about 20% results in a total increase of about 25% as mentioned by Ganga Flood Control Commission (1983) [8].
3. The bed load is not yet taken into account. The contribution of the bed load is assumed to be 10% of the suspended bed material load. This is based on values measured in the Jamuna River in Bangladesh, which is a braided river with sandy bed material as well [12].

Based on these assumptions, and assuming that most of the sediment is transported during the flood period, the total yearly sediment load of the Koshi River at Chatra in the period 1948-1981 is estimated as:

$$(19 \times 1.39 + 26 \times 1.25 + 55 \times 1.2)/100 \times 1.1 \times 95 = 130 \text{ million m}^3$$

Coarse medium fine bed load

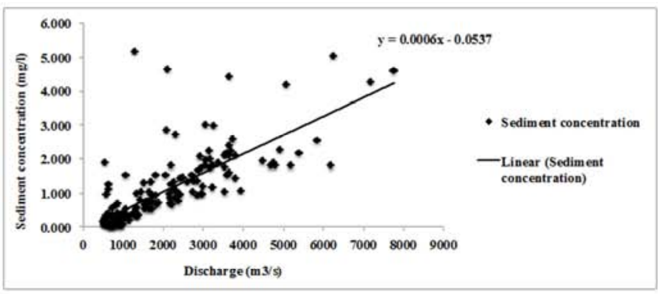
The average total bed material load at Chatra over the period 1948-1981 is estimated at:

$$(19 \times 1.39 + 26 \times 1.25)/100 \times 1.1 \times 95 = 60 \text{ million m}^3$$

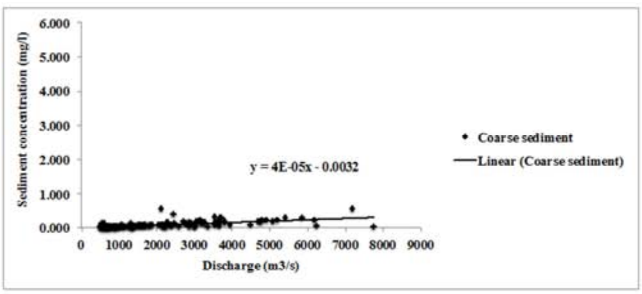
4.2. River Bank and Surface Layer Sampling

4.2.1. JPO-SKSKI Sediment Sampling

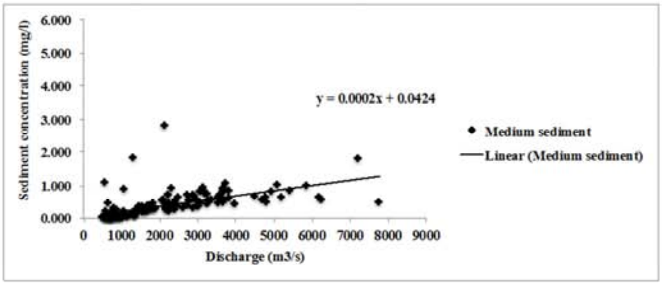
The JPO-SKSKI sediment data for 2005 were processed in different ways. Sediment concentrations were plotted versus the daily discharge, both for the different fractions separately and for the total sediment concentration. The results are shown in Figure 8 (a) through (d). The total sediment concentration shows a substantial scatter, but – as expected - this scatter is in particular due to the fine sediment, which corresponds to the fraction < 0.07 mm and hence behaves as wash load (not linked to the local conditions). The scatter in the medium and coarse sediment is less, probably because these fractions belong to the bed material transport. The concentrations of coarse sediment are almost negligible, whereas the concentration of the medium fraction is about half of the fine sediment concentration. Next the daily discharges and the daily sediment loads were plotted as a function of time. The results are shown in Figure 9 (a) through (d). In 2005, several discharge peaks did occur. Interestingly, many more peaks are noticeable in the fine sediment loads, which is typical for wash load. Also the medium sediment load shows some peaks which do not correspond to discharge peaks. This might be due to the complex interaction between bed material and sediment load in case of armoured river beds. Another explanation might be a contribution of the kholas. From Figure 9 it can also be concluded that the contribution to the sediment load of the coarse fraction is very minor.



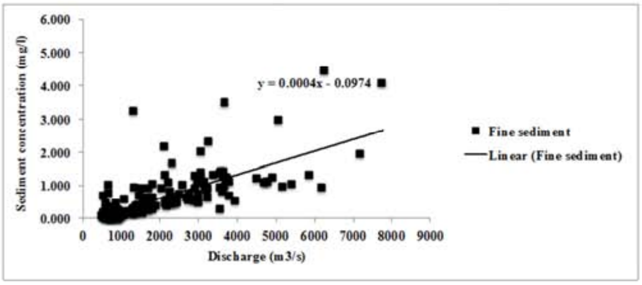
(a) Total sediment



(b) Coarse sediment

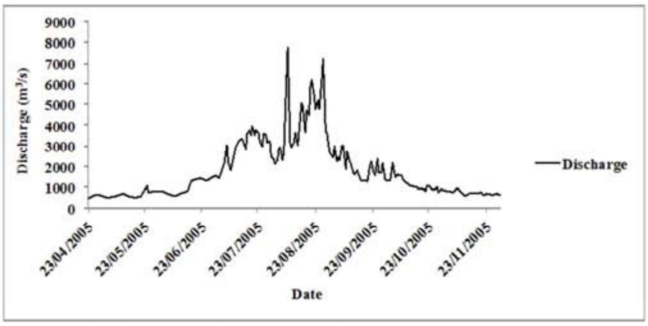


(c) Medium sediment

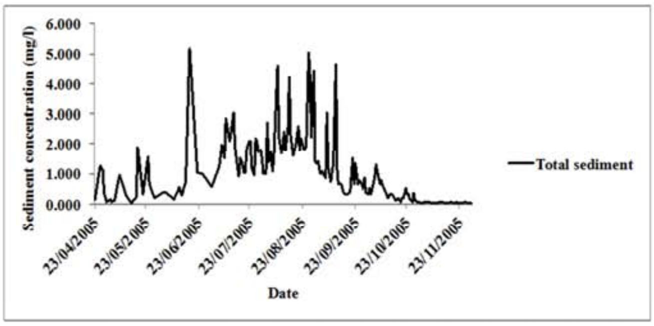


(d) Fine sediment

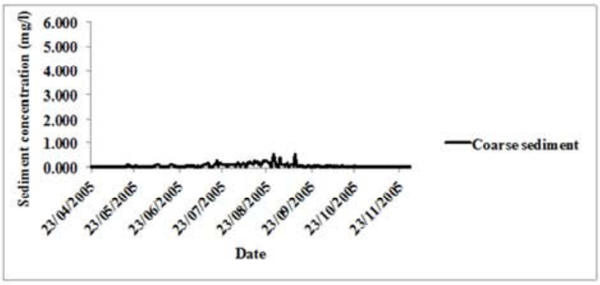
Figure 8. *Concentrations of total, fine, medium and coarse sediment versus discharge at Chatra in the monsoon 2005 according to the JPO-SKSKI measurements.*



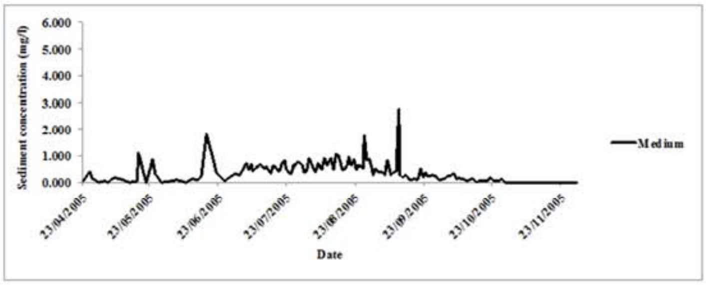
(a) Discharge



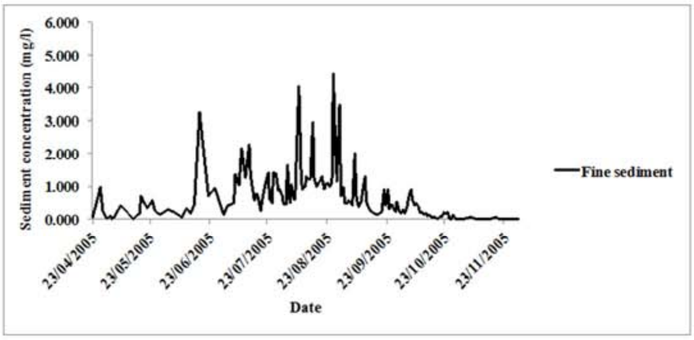
(b) Total sediment



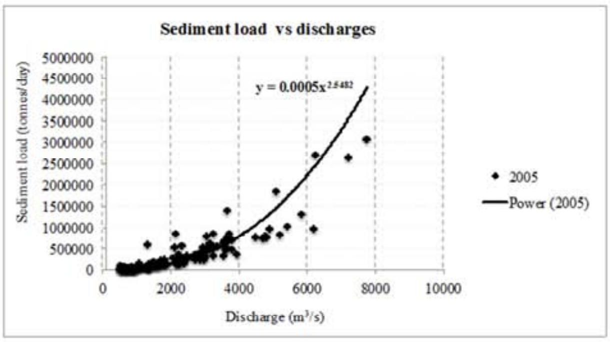
(c) Coarse sediment



(d) Medium sediment



(e) Fine sediment



(f) Sediment rating curve

Figure 9. *Discharge and concentrations of fine, medium and coarse sediment (a-e) & sediment rating curve (f) at Chatra in the monsoon 2005 according to the JPO-SKSKI measurements.*

Table 2. *Summed sediment load Koshi River for 158 days in 2005.*

Sediment	Coarse	Medium	Fine	Total
Total sediment load (million tons)	3.4	15.1	28.4	46.9
Percentage	7	32	61	100

Also here the main interest is in the yearly sediment load of the Koshi River for later comparison with historical data and the DHM measurements. Table 2 presents the summed sediment loads for the sediment measurements. This summation is done over the 158 days that samples were taken in the period 24 April – 31 November 2005. The total number of days in this period is 221, so the sediment loads in Table 2 have to be multiplied by a factor 221/158 to arrive at a true estimate of the sediment loads in the sampling period. To arrive at the yearly sediment load still the sediment transport in the 365-211 = 154 remaining days of the year. The average sediment load in this low flow period is estimated at about 0.0364 million tonnes/day. Hence the yearly sediment load on the basis of the water surface samples near the bank of the river collected for the JPO-SKSKI office is:

$$221/158 * 46.9 + 154 * 0.0364 = 70.9 \text{ million tonnes.}$$

This corresponds to 44.5 million m^3.

Based on the Barakhshretra data and using additional information also provided in Ganga Flood Control Commission (1983) the average yearly sediment load at Chatara was estimated as 130 million m^3. In the present analysis an average sediment load of 44.5 million m^3 was found for 2005. Hence this confirms that indeed the sediment sampling of the water surface layers of the Koshi from the bank results in serious underestimation of the sediment load of the Koshi River.

In Table 2 also the percentage wise contribution of the different fractions is given. In Table 3 a comparison is made between the percentages coarse, medium and fine sediment for the historical measurements and the JPO-SKSKI measurements. As can be concluded from this table sampling from the bank results in a serious underestimation of the contribution of the coarse sediment to the total sediment load of the river.

Table 3. *Comparison of percentage wise distribution of the sediment of the historical measurements for the period 1948-1981 and the JPO-SKSKI measurements in 2005.*

Source of data	Coarse	Medium	Fine	Total
Historical data (%)	19	25	56	100
JPO-SKSKI measurements (%)	7	32	61	100

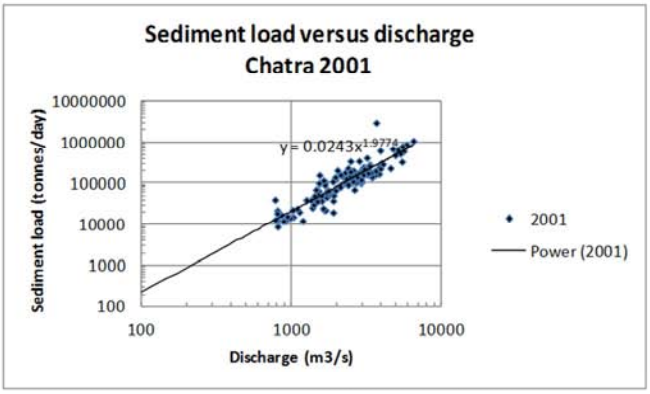
4.2.2. DHM Sediment Sampling

Sediment data were supplied by DHM in the form of a number of spread sheets. In these spread sheets only the date, the sediment concentration and the sediment yield are given. Multiplying the concentration with the discharge and integrating this over a day obtain the sediment yield. The discharge is obtained from a gauge reading and a rating curve. The present interest is the yearly sediment loads of the Koshi River in Chatara. For this the sediment transport has to be integrated over the whole year. In the period before and after the monsoon only one value per week is available. So it is required to fill in the blanks. This was done by extracting discharge data for 2001 – 2003 and entered into the spread sheets with sediment data. Subsequently the computed daily sediment loads were plotted versus the daily discharges, for each year separately (Figures 10 (a) through (c)) and for all three years together (Figure 10 (d)). Trend lines were added and it was noted that these trend lines do not differ substantially. Hence they were treated as one data set and the following trend line was determined as representative for the whole period 2001-2003 (Figure 10 (d)).

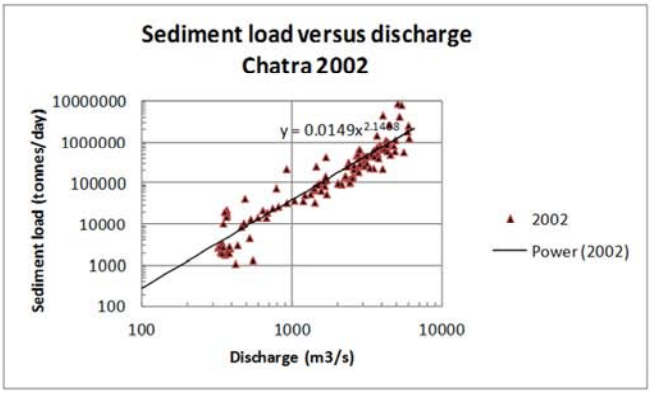
$$S = 0.0191\, Q^{2.0808} \qquad (1)$$

Where S = daily sediment load (tons/day) and Q = discharge (m^3/s).

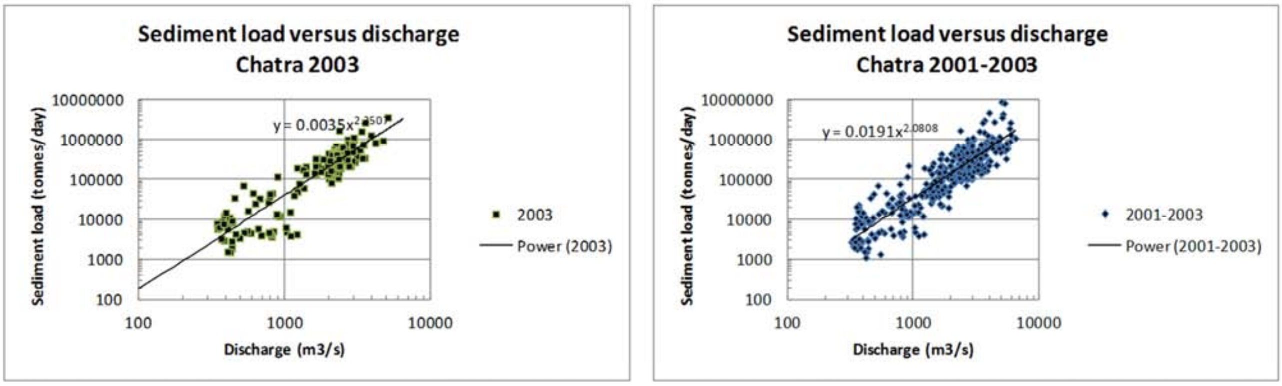
Equation (1) allowed to compute the daily sediment load for all days, hence also for dates when no sediment concentration was measured. Subsequently the daily sediment loads were integrated over the whole year to obtain the yearly sediment load for the three years.



(a) 2001

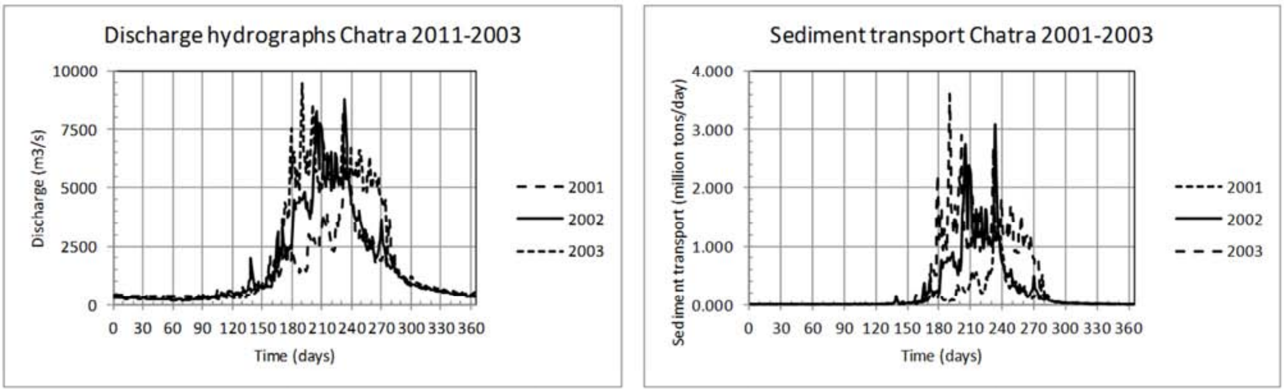


(b) 2002



(c) 2003 (d) 2001-2003

Figure 10. *Sediment rating curves for Chatra for the period 2001-2003 on basis of DHM measurements.*



(a) Discharges (b) Daily sediment loads

Figure 11. *Discharges and daily sediment loads in the Koshi River at Chatra as computed on the basis of the DHM sediment sampling.*

Table 4. *Yearly sediment loads Koshi River in period 2001-2003 as determined from DHM surface sampling.*

Year	2001	2002	2003	Average
Yearly sediment load (million tons)	41	92	137	90
Yearly sediment load (million m^3)	26	58	86	57

From the results it can be observed that the three hydrographs of daily discharges vary considerably. The year 2001 is a relatively minor monsoon, with only one peak in the order of 5000 m^3/s. The year 2003 is exceptional: for almost three months the discharge was in the order of 6000 m^3/s. The year 2002 was more normal with several peaks. The maximum discharges in the years 2001, 2002 and 2003 were 6500, 8780 and 9480 m^3/s, respectively. Moreover, the daily sediment loads in Figure 11 (b) reflect the same pattern as the discharges, with maximum daily sediment loads in 2001, 2002 and 2003 of 1.64, 3.07 and 3.60 million tons, respectively. The yearly sediment loads vary considerably from 41 to 137 million tons. The average yearly sediment load in the period 2001-2003 as determined by the bank sampling by DHM is about 90 million tons, which corresponds to 57 million m^3.

Table 5. *Sediment rating curves from different data sets.*

Origin and period of sediment data	Sediment rating curve
DHM 2001-2003	S (tonnes/day) = 0.0191 $Q^{2.0808}$
JPO-SKSKI 2005	S (tonnes/day) = 0.0005 $Q^{2.5482}$

5. Conclusions

The yearly sediment load on the basis JPO-SKSKI sediment data corresponds to 44.5 million m^3. Based on the historical measurements, the average yearly sediment load at was estimated 130 million m^3. The average yearly sediment load determined by DHM was about 57 million m^3. All the sediment loads were estimated with reference at Chatara. The sediment sampling for historical measurements were carried out by EDI method whereas the sediment data for both JPO-SKSKI and DHM were obtained through the surface sampling near the bank. This confirms that indeed the sediment sampling of the water surface layers of the Koshi from the bank results in serious underestimation of the sediment load of the Koshi River. Moreover, a comparison between the percentages coarse, medium and fine sediment for the historical measurements (EDI method) and JPO-SKSKI and DHM measurements (Surface sampling near the bank) concluded that sampling from the bank results in a serious underestimation of the contribution of the coarse sediment to the total sediment load of the river.

The sediment rating equations ($S= A Q^{B}$) showed different values for the coefficient A and the power B with some correlation between the values of A and B. Low values of A correspond to high values of B. The power A of the sediment rating curves varies between 2.1 and 2.5 and hence is substantially higher than the value of about 1.5 valid for un-constricted rivers. These results of higher values might be the fact that the sediment rating curves were derived for total sediment data including wash load, and the river at Chatara is quite constricted.

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