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Construction of sediment budgets in large-scale drainage basins: the case of the upper Indus River

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Abstract High rates of soil loss and high sediment loads in rivers necessitate monitoring and quantification methodologies so that effective land management strategies can be designed. Construction of a sediment budget can be a useful technique to address these issues since it provides a comprehensive accounting of the fluxes and fate of sediment in the drainage basin. Sediment budget studies in large river basins are usually hampered by inadequate data. Constructing a sediment budget using classical field-based techniques is too labour intensive, time-consuming and expensive for poorly gauged, large river basins. Remote sensing has emerged as a useful tool for studying large basins, and can be combined with GIS tools for identifying potential sediment source areas and quantifying their respective contributions. Such analyses, in combination with historic hydrological records and other auxiliary data, can be utilized for constructing a sediment budget. Following this approach, a framework is developed for constructing sediment budgets for large drainage basins that is prototyped on the upper Indus River basin in northern Pakistan.

Key words Himalayas; Indus River; integrating remote sensing and GIS; large drainage basins; Pakistan; sediment budget

INTRODUCTION

High mountain regions like the Himalayas are characterized by a high rate of denudation (Shroder, 1993) with river systems like the Ganges-Brahmaputra and the Indus acting as the export mechanisms for sediments. The large quantity of sediment produced and transported downstream creates a number of major water resources management problems such as siltation of reservoirs, damage to turbines, reduction in quality of water supplies, and transport of chemical pollutants (Johnson *et al*., 1998). Globally, rates of soil loss are increasing owing to natural and anthropogenic factors, which have important economic implications relating to on-site loss of soil productivity and to the off-site, downstream impact of mobilized sediment. As a result, there is a need for a global assessment of current rates of soil erosion and sediment yield, and their response to environmental change, as well as for more detailed regional assessment of the patterns and the rates involved (Walling & Webb, 1996).

Sediments budgets are a useful and powerful conceptual framework for examining the relationships between sources, sinks, fluvial transport and sediment yield, and investigating how these relationships are affected by changes in land use, climate, seismicity and isostatic adjustment (Wasson, 2002). Reid & Dunne (1996) have defined a sediment budget as an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from the drainage basin. In its full form, a sediment budget accounts for rates and processes of erosion and sediment transport on hills and in channels, for temporary storage of sediment in bars, alluvial fans, and other sites, and for weathering and breakdown of sediment while in transport or storage. Sediment budgets are a useful tool for addressing a number of scientific and management problems that involve predicting erosion and sedimentation in response to changes occurring on watershed hillslopes and in stream channels. Sediment budgeting allows the sediment yields to be estimated before the results of long-duration stream-sampling programmes are known.

Sediment budget construction requires identification of erosion processes and their controls, and estimation of process rates. Conventional sediment budget construction techniques include: (a) direct field measurements in experimental plots to establish basic principles and rates of erosion; (b) measuring sediment loads at catchment outlets and relating these to soil erosion using sediment delivery ratios; and (c) using radio-active fallout and naturally occurring radioactive elements. Field-based studies of sediment budgets are frequently hampered by the limited availability of data in quality and quantity, and raise the question of the representativeness of the dataset for larger or smaller basins over longer periods of time (De Boer & Ali, 2002).

Previous sediment budget studies have mostly dealt with relatively small drainage basins ranging from a few hectares to a few hundred square kilometres (Phillips, 1991). More such budgets are required, particularly in dryland and mountain regions where they are currently under-represented (Wasson, 2002). Construction of sediment budgets for large river basins poses quite a few challenges that include: (a) measure-ment of river loads; (b) identification of sediment source areas; (c) quantification of sediment source areas; and (d) data sparsity. Remote sensing has emerged as a useful tool for studying large basins (e.g. Lu & Higgitt, 1999; Gupta *et al*., 2002) and it provides new insights in sediment budgets (Wasson, 2002). A combination of remote sensing data analysis and geographic information systems (GIS) used for identifying potential sediment source areas and for quantifying their respective contributions has much to offer in this respect (Mattikalli & Engman, 2000). Such analyses, in combina-tion with historic hydrological records and other auxiliary data, can be utilized for constructing a sediment budget. The overall objective of this study is to develop a framework for constructing sediment budgets for large-scale drainage basins, with a case study of the upper Indus River basin in northern Pakistan.

STUDY AREA

With a drainage area of 860 000 km^2 and 2880 km length, the Indus River is one of the largest rivers in southern Asia (Fig. 1). The upper reaches of the Indus River flow through the Himalayan and Karakoram mountains down to the Tarbela Reservoir in northern Pakistan. Downstream of Tarbela Dam, the river opens out into the plains and flows all the way up to the Arabian Sea. The upper Indus basin includes the areas upstream of Tarbela Dam on the Indus River. Most of the basin is semiarid to arid, and surplus moisture is only available in northern areas where elevations reach above 4000 m. The 30-year mean annual precipitation is 132 mm at Gilgit and 202 mm at Skardu (Fig. 1). Due to the high elevations, most of the precipitation occurs as snow, which has resulted in extensive glaciation in the basin, covering an area of 16 300 km^2

in the Karakoram Range. The melt season occurs in the high temperature months from April to August. Thereafter, very little water is available in the Indus basin rivers. The western rivers (Indus along with its tributaries Kabul, Jhelum and Chenab) descend south towards the Arabian Sea with a 30-year (1967–1997) average annual discharge of 5500 $m^3 s^{-1}$. The upper Indus basin exhibits one of the highest rates of sediment transport (Milliman *et al.*, 1984) and the estimated average annual sediment yield of the Indus River reported in the literature ranges from 100 to 675 million tonnes. However, these values relate to the actual amount of Indus sediment reaching the ocean, and depend upon where, when and how they were obtained (Milliman & Meade, 1983).

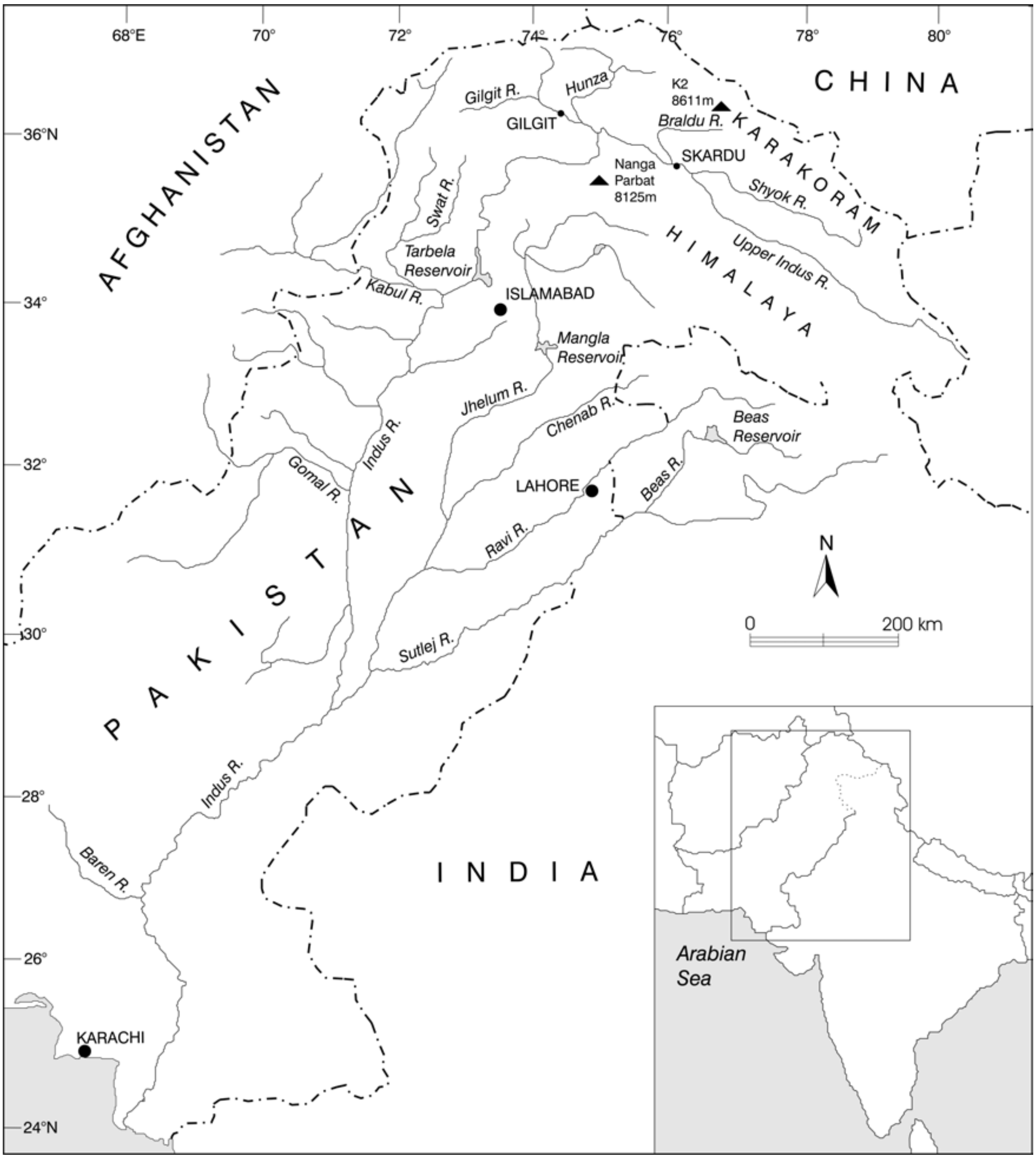

Fig. 1 The Indus River basin.

Although the Indus River is one of the world's largest rivers in terms of drainage area, discharge and sediment load, few people in Pakistan and even fewer in the western world, know much about this river (Milliman *et al.*, 1984). Considering the size of the basin, the hydrological database is relatively small. Apart from some long-term discharge records for the Indus and some of its major tributaries, hydrological measurements are very scarce (Young & Hewitt, 1990). The upper Indus exists in natural basin conditions without any significant human impacts. Since a number of dams are planned for future water resources development projects in the area, it is desirable that sediment studies are initiated in this region.

DATA REQUIREMENTS

This study utilizes a wide variety of hydrological, remote sensing, and auxiliary data classified into two broad categories, namely, the sediment transport data and the sediment source data.

Sediment transport data

The sediment transport data mainly consists of a long-term, hydrological database of the upper Indus basin and the hydrographic surveys of Tarbela Reservoir at the basin outlet. There are 12 gauging stations along the main upper Indus River and at the confluences of tributaries. Another 40 gauging stations have been installed and operated more recently at smaller rivers. A summary of hydrological stations is presented in Table 1 and their location is shown in Fig. 2. The Pakistan Water and Power Development Authority (WAPDA) have collected hydrological data since 1960. Daily gauge readings and discharge measurements exist for all the main stations in digital form in a hydrological data bank. In addition, suspended sediment data have been collected irregularly at the stations and included in the database. Water quality

Table 1 Summary of hydrological stations (arranged in downstream order).

Tributary	Station	Location Latitude	Longitude	Elev.(masl)	Area (km^2)	Years	Runoff (km^3)	Sediment yields (mill. tons)	($t\ km^{-2}\ year^{-1}$)
Shyok	Yugo	35º 11' 00"	76º 06' 00"	2469	33 670	18	10.7	25.4	754
Shigar	Shigar	35º 20' 00"	75º 45' 00"	2438	6610	4	5.1	16.8	2547
Hunza	Dainyor	35º 55' 40"	75º 25' 00"	1370	13 157	25	11.2	44.4	3375
Gilgit	Gilgit	35º 55' 35"	74º 18' 25"	1430	12 095	21	8.9	12.2	1008
	Alam Br.	35º 46' 03"	74º 35' 50"	1280	26 159	25	20.6	55.1	2108
Astore	Doyian	35º 32' 42"	74º 42' 15"	1583	4040	17	4.0	1.6	401
Gorband	Karora	34º 53' 31"	72º 45' 58"	880	635	16	0.6	0.9	1406
Indus Main	Kharmong	34º 56' 00"	76º 13' 00"	2542	67 858	5	15.4	33.7	496
	Kachura	35º 27' 00"	75º 25' 00"	2341	112 665	21	31.8	79.4	705
	Partab Br.	35º 43' 50"	74º 37' 20"	1250	142 709	28	55.1	138.9	973
	Shatial Br.	35º 31' 56"	73º 33' 52"	1040	150 220	7	62.3	106.5	709
	Besham Q.	34º 55' 27"	72º 52' 55"	580	162 393	22	76.2	218.4	1345

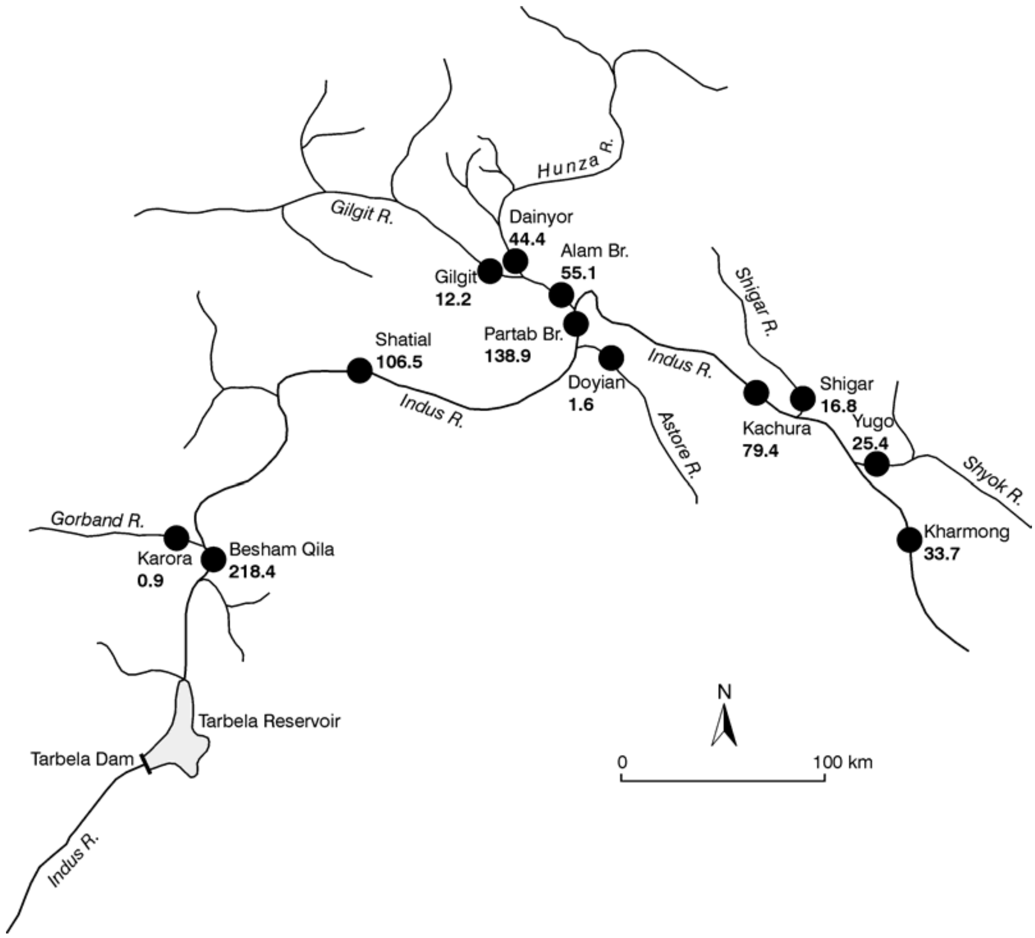

Fig. 2 Main gauging stations and mean annual sediment yields in the upper Indus basin (× 10^6 t).

data are available, but not in digital form. Since bed load sampling presents a difficult challenge in large mountain rivers, no field measurements have been done until recently in the project area. However, bed material data have been collected at a number of places in the basin. Hydrographic surveys of the Tarbela Reservoir have been carried out on a yearly basis, providing vital information regarding the storage of sediments at the outlet of the basin. This information is used for balance calculation and checking the results of sediment budget.

Sediment source data

The sediment source data consists of remote sensing data, digital elevation models (DEMs), and a variety of auxiliary data. Digital Landsat TM-Type satellite scenes have been acquired that cover the project area of the upper Indus in Pakistan, and these are utilized for a land use characterization of the basin. This information, in combination with the global DEM and auxiliary data, is planned to be used for the identification and evaluation of potential erosion-prone areas. Global DEM datasets of the Indus River basin, like HYDRO1k and GTOPO30, are available from the USGS. DEMs at finer resolutions of 100 and 25 m are also available for some parts of the basin. The utilization of remote sensing technology requires the availability of ancillary data for calibrating the remote sensing data and for performing unbiased accuracy assessment of the final results (Jensen, 1996). Therefore, a variety of auxiliary data, including the climatological, topographic, soil and geological data, forms an integral part of this study.

METHODOLOGY AND DISCUSSION

A methodology and analytical framework is presented for constructing sediment budgets in large river basins with the upper Indus River basin as a case study. This consists of: (a) identification and mapping of different geo-hazard types and sites, that act as sources and origins of catastrophic sediment flux; (b) quantification of the contribution of sediment source areas by processing remote sensing and auxiliary data in a GIS framework; (c) detailed investigation and processing of the sediment transport data for the evaluation of the contribution of various sub-basins; (d) carrying out the balance calculation and developing the sediment budget; (e) checking of results by the annual hydrographic surveys of Tarbela Reservoir at the basin outlet; and (f) testing the newly developed sediment budget independently by applying it to the Jhelum River basin. Figure 3 presents a schematic of this analytical framework.

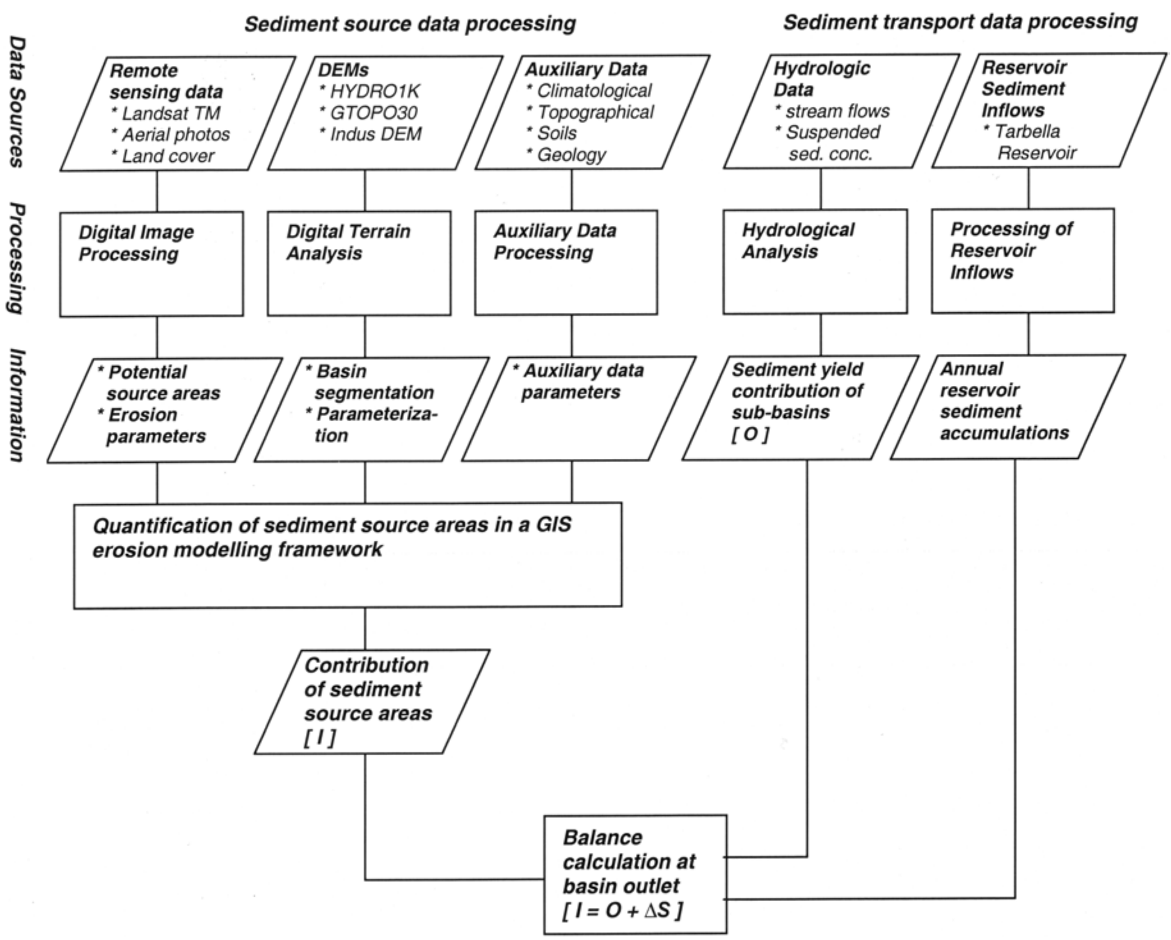

Fig. 3 Schematic representation of data flow and processing.

Processing of sediment source data

The main objective of the processing of sediment source data is the quantitative evaluation of potential sediment source areas in the Indus River basin. Considering the large extent of the basin and the lack of field-data, the choice of utilizing remote sensing techniques is the only viable solution in this respect. Remote sensing can detect and measure changes in spectral and physical properties of soil caused by erosion (Ritchie, 2000). This forms the basis of using remotely sensed data in such studies that can be accomplished by measuring radiance or spectral contrast of reflection values in a satellite band and relating it to soil erosion (Price, 1993; Fraser *et al.*, 1995). The Universal Soil Loss Equation (USLE) has been used extensively for determining the upland erosion (e.g. Trimble, 1981; De Roo, 1998), however, this concept has limitations regarding its use for large river basins. The problem of data sparsity for large basins can be resolved by using simplifications of plot-scale processes and utilizing the global datasets available at coarse scales that include, for example, topographic data from DEMs, and soil and vegetation data based on thematic maps and remote sensing. Remote sensing techniques also provide an approach for extracting variables concerning soil erosion at varying temporal and spatial scales. The integration of soil erosion models in a GIS can effectively store and process the large amount of spatial data provided by remote sensing and can effectively display the resulting spatial information.

The sediment source data processing module in Fig. 3 presents a schematic for the identification and quantification of sediment source areas of the Indus River basin. A detailed land use characterization of the basin is planned to be carried out by digital image classification of the Landsat TM satellite scenes. The HYDRO1k global DEMs are analysed using digital terrain analysis techniques for basin segmentation and the extraction of erosion related topographic parameters like slope and aspect. A subsequent analysis of land use characterization and topographic parameters in combination with auxiliary information from land cover, soil and geology maps, and precipitation from climatological data, results in a categorization of erosion-susceptible areas in the basin. Once these potential erosion prone areas are identified and the above mentioned parameters extracted from the remotely sensed data, DEMs and auxiliary data, the contribution of sediment source areas can be quantified by determining the rates and patterns of erosion for the upper Indus River basin from suitable erosion models processed in a GIS environment as shown in Fig. 3.

Processing of sediment transport data

The processing of the sediment transport data begins with developing relationships between discharge and suspended sediment concentration for determining sediment yields along the upper Indus River and at the confluences of main tributaries. An example of such relationships is presented for the Indus River at Besham Qila in Fig. 4. Considerable scatter around the straight-line relationship indicates that other variables, like seasonal effects, beside stream discharge, influence the level of concentration in the river. Such relationships have been developed for all the stream gauging sites in the Indus basin and respective sediment yields calculated. The sediment yields thus calculated are summarized in Table 1 and presented in Fig. 2, which constitutes a very preliminary sediment budget. The mean annual suspended sediment discharge of the Indus River is 214 × 10^6 t at Besham Qila near the basin outlet. The Shyok, Shigar, Hunza and Gilgit Rivers are the main tributaries that contribute nearly 60% of the sediment. According to Collins & Hasnain (1996), continuing tectonic instability, high relief, steep slopes with high rainfall, together with runoff from the glaciers in heavily ice-covered areas indicates that the potential sediment source areas are located in the Himalayan portions of the basin. The sediment yields along the main stem of the Indus River range from 496 t km^{-2} $year^{-1}$ at Kharmong to 1345 t km^{-2} $year^{-1}$ at Besham. This also shows a general increase of sediment yields with basin area, a trend observed by Church & Slaymaker (1989) in British Columbia at all the scales. The only exception is a stretch of 150 km between Partab Bridge and Shatial that exhibits storage on valley floors. Among the main tributaries, the Hunza River at Dainyor shows the highest sediment yield of 3375 t km^{-2} $year^{-1}$, which is amongst the greatest in the world for a drainage basin of its size, largely because of very high suspended sediment concentrations in summer meltwater discharges (Ferguson, 1984). This preliminary budget will be further refined once the contribution of potential source areas is evaluated.

Balance calculation, checking and testing of results

Sediment from the upper Indus basin is deposited in the Tarbela Reservoir. As the catchment areas of the Tarbela Reservoir and the next upstream gauging station of Besham Qila are nearly the same, a sediment balance calculation of the yearly measured sediment loads can be carried out. A part of this calculation is presented in Fig. 5, which compares the historic sediment accumulation in the Tarbela Reservoir and the sediment yields calculated at Besham Qila. This comparison shows a general trend of higher values of sediment yields at Besham Qila than the reservoir accumulations. This difference can be explained in terms of an 89% trap efficiency of the reservoir (World Commission on Dams, 2000) as some proportion of the sediment

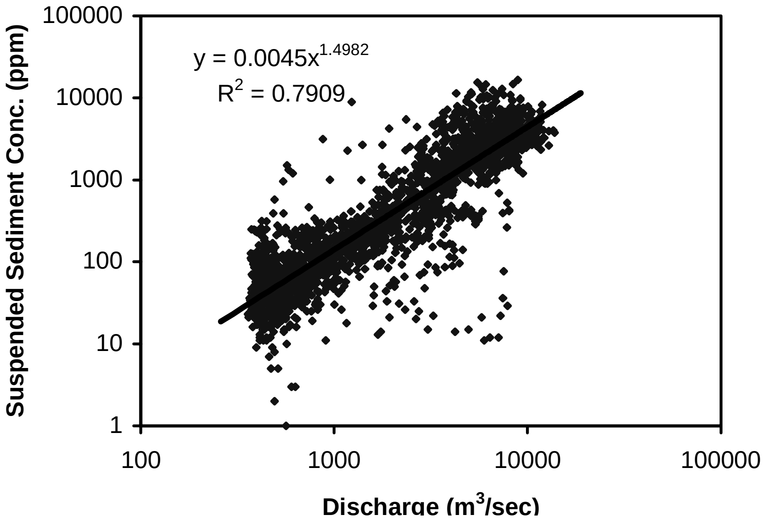

Fig. 4 Relationship between suspended sediment concentration and discharge of the Indus River at Besham Qila, 1969–1990.

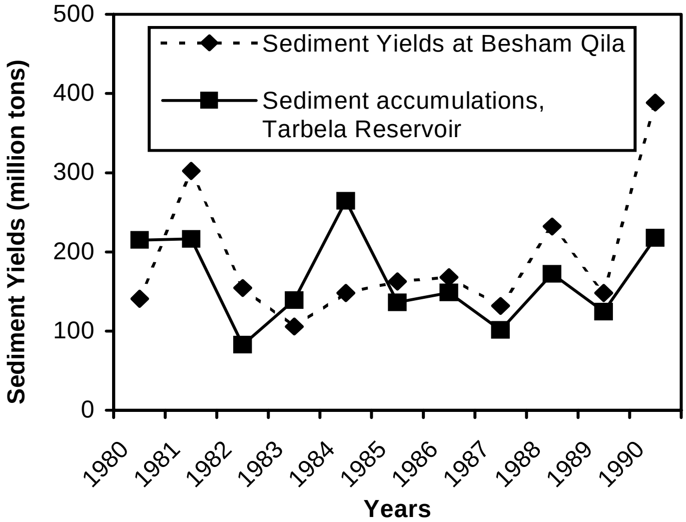

Fig. 5 Comparison of the sediment accumulations in the Tarbela Reservoir and sediment yields of the Indus River at Besham Qila, 1980–1990.

leaves the Tarbela Reservoir through the powerhouse turbines and the spillways. The trap efficiency, however, is primarily dependent on the detention time, with the deposition increasing as the time in storage increases. The sediment yields calculated from the hydrological data at a number of places in the basin also give an opportunity to evaluate the contribution of various sources, and to calibrate the sediment budget and check the results. Long-term hydrological data of the considerably large upper Jhelum River basin are also available. This basin is 33 000 km^2 from its outlet at Mangla Dam and is located adjacent to the Indus River basin. This dataset provides an opportunity to test the results of the newly developed sediment budget independently on a basin of considerable size situated in similar climatological, topographic and hydrological conditions.

CONCLUSIONS

Sediment transported by large river systems in high mountain areas causes serious water resources management problems. The magnitude and frequency of this sediment transport depend not only on the hydraulics of the river system, but also on the complex pattern of sediment availability from a variety of sources. However, little quantitative and qualitative information is available on the sediment released from these sources. Construction of sediment budgets is useful in this respect since it provides a comprehensive accounting of the sources and disposition of sediments in the drainage basin. This paper has demonstrated a conceptual framework and initial development of a sediment budget for a large drainage basin using a combination of discharge and sediment load records along with remote sensing and GIS techniques. Further work is planned for refining this sediment budget that will result in the risk assessment of the sediment sources on quantitative basis. This study will assist in planning the basic requirements for the fast growing population in remote areas of the Himalayan and Karakoram mountains, such as improving forecasting of food availability and clean drinking water supply, irrigation and hydropower. The results of this study will find an application in other large basins in mountain areas with similar topographic, seismo-tectonic and hydrological conditions.

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