4. SEDIMENT

Sediment transport is a natural phenomenon that directly or indirectly affects water resources projects and plays an important role in the assessment of technical and economic viability of hydropower projects. Sediments have a direct impact on the determination of the useful life of seasonal (deep) reservoirs, may significantly hamper the performance of shallow reservoirs, can damage and even drastically reduce the useful life of water turbines and induce high operational and maintenance costs in general.

The methods used for sediment sampling depend on the characteristics of the river course and type of sediment under consideration, i.e. suspended or bed load.

4.1 GENERAL

4.1.1 SEDIMENTS IN HIGH HEAD HYDROPOWER

Sediments play a critical role in the overall conception of hydropower projects, but especially in the planning and design of following project elements:

- Seasonal and daily reservoirs
- Intake structures
- Sand traps
- Waterways (canals and tunnels)
- Forebays
- Water turbines and pumps

For seasonal reservoirs, the total sediment load constitutes the main parameter to determine dead storage requirements and also to estimate the useful life of the project. At preliminary level, the trapping efficiency of the reservoir can only be roughly estimated. In the field, suspended sediment can be sampled more easily than bed load. Therefore, it is common that bed load is estimated in basis of available information on suspended sediment. For example, as a rule of thumb it has been a common practice to assume for alluvial rivers that the bed load amounts about 20% of the suspended load. However, it must be noted in steep mountainous rivers the bed load may even exceed the suspended load.

For design of sand traps, grain size distribution and mineralogic characteristics of the sediment are required. However, when data is not available, estimates based on regional analysis, comparison with similar catchments, and even experience may be applied to adopt a suitable value at identification and preliminary level. More detailed planning works invariably require data from the site.

The main problem faced with sediment data is the scarcity of the records and the difficulties faced with the application of regional analysis to estimate values at ungauged sites. The sediment regime in a river is affected by the morphology of catchment, geological conditions, etc. which may make regional analysis not always suitable.

Another factor, which is very important in mountainous regions is the relationship between sediment load and geotectonic activity. Large sediment concentrations are observed in those areas subject to high seismic activity. The main problem is that the concentration may be low during many years, when seismic events are few and/or of small magnitude. However, after a large seismic event the sediment load may significantly increase, changing completely the regime during some time.
The above mentioned problems should be carefully considered at the identification and design level, especially with respect to the possibility of formation of landslides. The problem is not

only of having landslides which may fall into the reservoir areas, but also those which could create dams in the upstream part of the river which later on can affect the project due to extraordinary sediment loads which may occur during a relatively long period.

Although the natural dams formed by landslides tend to fail suddenly, even a controlled release of water may increase the sediment load and affect the plant during many years. Records of sediment load should be critically evaluated to establish how well these describe the regime for the sites of interest. The study of the seismotectonism in the region may be helpful in this respect.

In order to diminish erosion and resulting sediment load the suitability of various control measures has to be studied, such as agricultural and forestry management, agricultural practices, animal husbandry, regulation of gullies and brooks, control structures and monitoring systems.

According to the type of transportation, the sediment loads are subdivided into two sub-groups:
- suspended load
- bed load

Total load is the addition of suspended and bed load.

4.1.2 SEDIMENT DATA

The following diagram illustrates the type, source, processing and purpose of sediment data collection in canals. By classifying the sediment into these two groups, loads can be calculated according to their transportation mechanism with physical as well as empirical relationships.

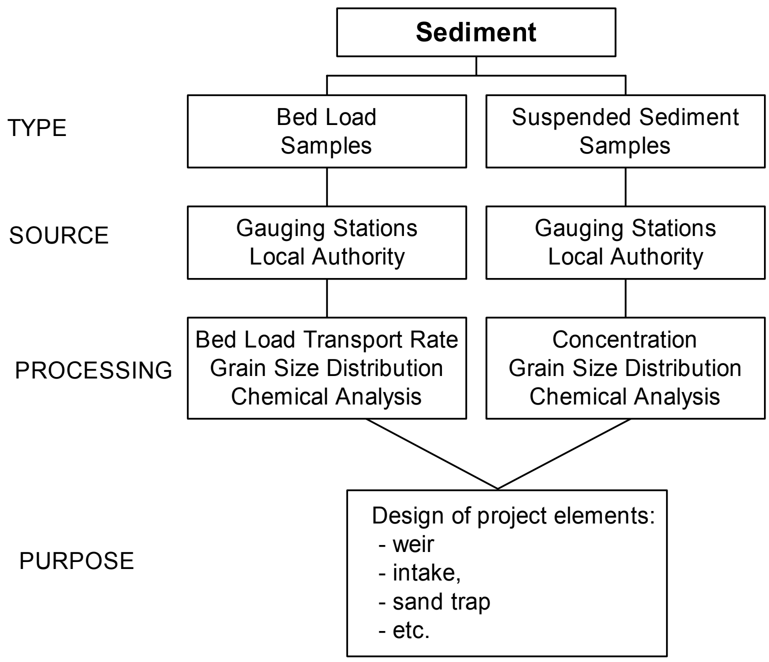


Fig. 4.1: Type, source, processing, and purpose of sediment data in canals

The sediment transport is more complex in rivers than for canals. In canals the maximum capacity is determined by the design and thereby also the maximum acting shear stresses on the canal bed are established. If the bed material is known from the consistency and with the sieve analysis, the resistance of bed load can be determined and the expected sediment transport calculated.

On the other hand, in natural streams the flows change with the availability of water in the catchment area. The discharge is not uniform and the availability of sediments from the sources can also be considered as a process of unknown probability. The design of sediment related structures in rivers has to take this into account, therefore the type, sources, processing, and purpose of sediment data in rivers is as follows:

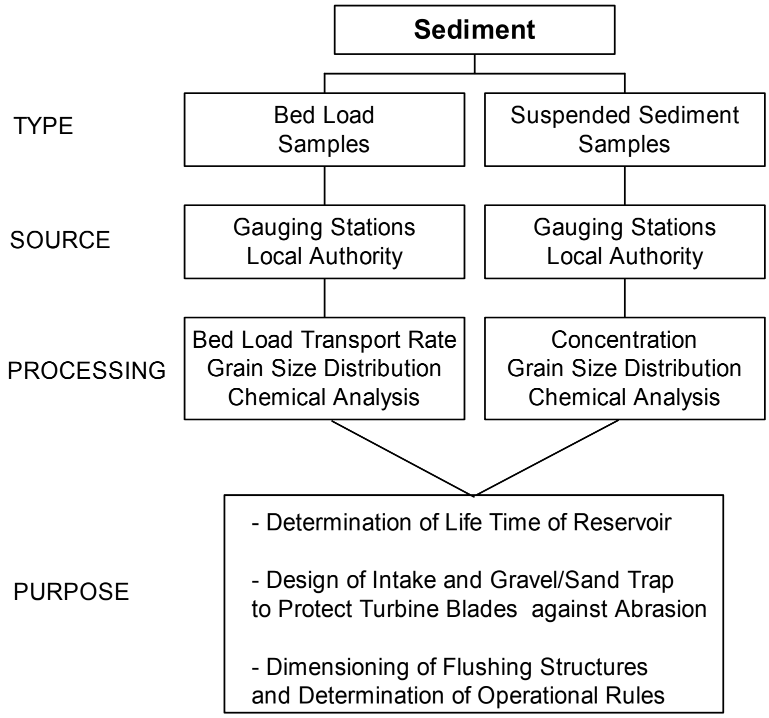


Fig. 4.2: **Type, source, processing, and purpose of sediment data in rivers**

4.2 DATA COLLECTION

4.2.1 CATCHMENT AREA

In mountain areas the characteristics of the catchment area have an important impact upon the sediment transport in the rivers. Depending on the development of the mountains and the climatologic conditions, different sediment sources can be distinguished. These include:

- Rains (especially tropical cyclones and monsoon)
- Glaciers
- Seismo-tectonic activity
- Slope failures
- Mass movements

Tectonic activity can be considered as the affecting force in this interdependent system of high mountains. With the seasonal melting of glaciers and snow covers, fine embedded sediment are washed out. In combination with seismic activities, glacier outbursts might occur, blocking rivers and causing floods after melt. This phenomenon is recorded especially in young mountain formats, such as the Himalayas in Asia and the Andes in South America. Additionally mass movements such as slope failures can cause enormous input into rivers, which transport the material downstream. Additionally rain causes erosion on mountain slopes. If these slopes have lost their vegetation cover through deforestation and agricultural activities, massive erosion can occur due to loss of stability of the soil cover. In some regions of the world, heavy precipitation associated with tropical cyclones, monsoon rains and typhoons has disastrous consequences.

All above-mentioned influences have a strong impact on the transported sediments in the mountain rivers. Nowadays modern survey methods such as satellite images can help to understand the interdependent mountain system and to assess each component quantitatively. Further research work is needed in this field.

4.2.2 FIELD INVESTIGATIONS

4.2.2.1 BED LOAD

Since the process deals with larger and heavier masses, sampling of bed load is generally more difficult than suspended load. Therefore, various procedures have been developed and are commonly applied in practice with different degree of success. Therefore, it is important to know in every case the requirements and expected results. Following methods are most commonly used:

- Tracer
- Sampler

4.2.2.1.1 TRACER

There are different methods to trace the material, such as

- Colour
- Magnetics
- Electronics

The material has to be taken from the bed and the tracer has to be installed. This implies a change in the bed morphology and the question remains, if the stones and boulders can be put to the river bed in the same position as they have been packed in the natural way.

The tracer method can be considered as a useful technique, if the transported length of particular gravels and stones is of special interest. It is useful in case of smaller rivers with a relatively small water depth, where stones can be easily identified again after some time. Magnetic and electronic receivers are used for identification. However, in case of large rivers with considerable high floods, considerable bed load transport might occur, where the marked material might be overtopped with a large amount of sediments. In these cases search of traced material is difficult and it might happen, that stones can not be identified any more.

4.2.2.1.2 SAMPLERS

The rate of bed load is generally difficult to measure. In mountain rivers and mountain torrents, bed load measurements can be considered as even more complicated, due to steep slopes of the riverbeds, high water velocities and large sediments, especially boulders.

Two basic types of sampling can be considered for rivers in mountain areas:

- moveable samplers
- trap samplers

The latter one is only applicable for small mountain torrents, therefore discussion will focus on moveable samplers.

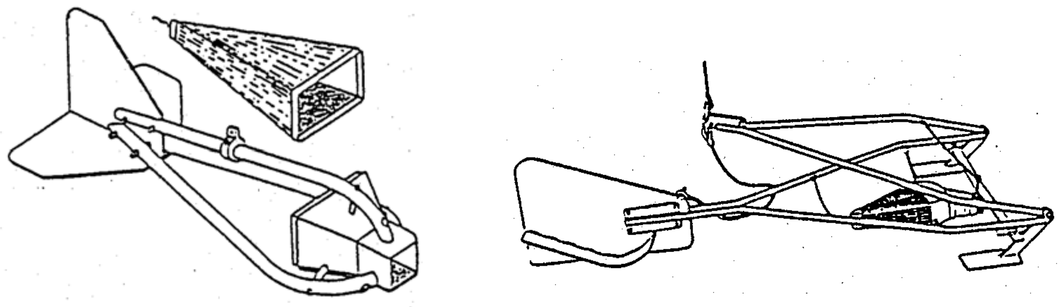


Fig. 4.3: **Examples for moveable bedload samplers Helley-Smith, BfG-Sampler [2]**

Many bed load samplers have been developed throughout the years, such as Muehlhofer, Arnhem, and Helley-Smith. Compared to the other models the sampler Mühlhofer has a solid bottom. The Dutch model Arnhem, as well as the American Helley-Smith-bedload sampler, is very useful for sandy channel grounds. For mountain rivers however, simple and heavy samplers are useful due to strong currents. If the sampler is not heavy enough it will be dragged by the current or it might even not be possible to drop the sampler down to the riverbed. Moreover, the entire cross-section of a bed load sampler for mountain rivers should be large enough to allow catching big boulders.

The bed load measurement in the field is similar to the discharge measurement. The total width where the bed load is moved should be measured at different locations in the cross section of the channel. It is important that the sampler lies flat on he riverbed, without disturbing the stream bed and the movement of the sediment. The sampler should also not be moved during the measurement, it should be held in position by a rod or a wire. It is useful to have the velocity distribution as well as the suspended load measured at the same time. For a first approach the number of verticals should be chosen close together. The denser the measurements the more accurate are the results.

At least three up to seven measurements should be taken at each vertical. The average of these samples can be considered as the instantaneous sampling at this location and the given discharge. It should be considered after measurement whether the distance between is sufficient to achieve the desired degree of accuracy. When insufficient, the density of the measurements may be increased. Alternatively samples may be taken every second vertical.

It must be ensured after every measurement that all the collected material is removed from the sampler and properly stored for transportation to the laboratory. Each sample should be dully identified, with indication of sampling site, vertical number and date.
In the mountain range of Karakoram and Himalayas first successful experience have been made with a heavy crane and a simple basket type bed load sampler of 70 kg weight. The discharges of the torrents during fieldwork were in the range between 20 m^3/s and 400 m^3/s with local flow velocities up to 6 m/s. Boulders with a diameter of up to 15 cm have been caught. However for mountain rivers of considerable magnitude, such as Indus and tributaries, this kind of measurement equipment is too small. Another box type sampler with a mouth of 0.5 m width is in the testing phase. Further experiments and research is urgently needed in this respect. With the availability of field data there might be the chance to evaluate empirical relationships for bed load movement with real data of nature.

Fig. 4.4: **Bed load sampling at mountain river with basket sampler**

Fig. 4.5: **Trapped bed load of a measurement**

The measurements have to be analyzed in a laboratory. With the help of a sieve analysis, the grain size distribution can be determined. This procedure is essential for the calculation of the sediment transport rates. The bed load comprises material of different size and is therefore often characterized by typical sizes. Several of the available formulae use the mean grain diameter to describe the sediment material. Mostly d_{50} is used, which stands for the particle size for which 50% by weight of the sediment is finer. The second important parameter for the determination of the transport rate is the density of the material ρ_s, which is also analyzed in the laboratory. Usually a density of 2650 kg/m^3 can be taken.

4.2.2.2 SUSPENDED LOAD

Suspended sediment sampling considers the determination of sediment concentrations. The measurements are mostly made at sites where gauging stations are operated. The reason is that besides having the possibility of using existing facilities, discharge data is needed to quantify the transported quantities.

The samplers used for the measurement of suspended load can be classified into three general types:

- Integrating samplers
- Instantaneous samplers
- Pumping samplers

Integrating samplers accumulate a water-sediment mixture over a period of time by withdrawing it from the ambient flow through a relatively small nozzle. Integrating samplers can be distinguished in depth- and point-integrating samplers.

Instantaneous samplers trap a volume of the suspension by instantaneously closing off the ends of a flow-through chamber.
Pumping samplers withdraw a mixture of the suspension through an intake by a pumping action. Their application in mountain rivers is limited.

Usually integrating samplers are preferred because they obtain a water-sediment mixture from a long filament of flow. These samplers can be traversed through the flow and thereby take sample at more than one point. One of the widely used measurement instruments for suspended load is the American depth-integrating sampler D-49 and the point-integrating sampler P-61. An example of an integrating sampler is given in the next figure.

The samplers are designed to sample isokinetically to ensure that the water-sediment mixture moves with no acceleration as it leaves the ambient flow and enters into the sampler intake. Inside the instrument a bottle with the volume of one pint is fixed where the mixture is continuously sampled. In the nozzle there are three openings which can be used with different diameters. The choice of the diameter influences the filling time of the bottle.

Fig. 4.6: Examples of integrating sampler P-49 during field measurement

The number and distribution of measuring stations for suspended sediments depends upon the conditions in the catchment area, as aforementioned. Gauging stations are advisable to use for suspended sediments, they should be combined with discharge measurements. If no gauge is installed, suspension bridges near the identified hydropower site should be used due to load of equipment, such as crane etc. Suspended load measurements should be combined with bed load and discharge measurements.

It is advisable to measure the suspended load daily when suspended sediment concentrations have large fluctuations. The main reason is that normally there is no proven relationship between water discharge and suspended sediment. If daily sampling is not possible, samples should be taken at least two up to five times a week. The frequency of the measurements depends upon the experiences regarding variability of suspended load data at the site.
In case of high variability due to snow-and ice melt, seismic activity and heavy rains large amounts of sediment can be transported within a couple of days. For this reason, during critical times whenever possible several times a day should be measured to record extreme loads. Depending on the variability of the concentrations, 250 up to 300 measurements a year provide a good basis to estimate the annual sediment load and especially extreme conditions.

The distribution of suspended sediments in a river is not uniform. Typically in a river cross-section more sediments are transported where water velocities are higher. Samples might not be representative for a site when only one measurement is taken in the center of the cross-section. To decrease the uncertainty of the measurements it is recommended to carry out suspended sediment measurements in several verticals of the rivers and to take at least three samples in each vertical to have an average representative sample in a vertical. If data processing shows, that the number of verticals can be reduced without loosing information, only a few, or even one vertical can be used as mean value. However, due to irregular changes in the regime of rivers, this procedure has to be controlled regularly by multi vertical measurements.

4.2.2.3 BED MATERIAL

Parallel to the samples of bed load and suspended load a sampling of the bed material of the river should also be carried out. The grain distribution of the riverbed gives information about armoring effects and helps to calculate the sediment transport rate. Especially in comparison to the bed load grain distribution information about the regime of the river can be gained.

The measuring equipment consists of a dredge or scraper and other auxiliary equipment such as cranes and boats. But as mentioned above, flow currents in mountain rivers are considerably high especially during floods, so that the usually applied techniques may not be suitable. In case of mountain rivers mainly two techniques are applicable:

- Sample pits
- Line-by-number-procedure

4.2.2.3.1 PITS

Therefore bed material samples can be taken from the banks of the rivers and torrents to establish the grain distribution of the transported material, which has been transported during floods. It is possible to take samples from the exposed riverbed when sampling is carried out during low flow season. The material is then representative for the riverbed.

On the other hand, subsurface pit samples can also be taken during low flow season. With help of the subsurface samples fine material is collected, which can not be covered by the line-by-number procedure, which is measuring the gravels and boulders on the bed surface. By combination of fine material obtained from subsurface pit samples together with the results of the line-by-number procedure, a complete grain size distribution curve of the bed material is obtained as shown in the chapter Data Processing.

Fig. 4.7: **Subsurface pit sampling at a mountain river**

4.2.2.3.2 LINE BY NUMBER

Another aspect in the determination of grain distribution of mountain rivers is the extreme wide variability of grain sizes. Fine material as well as big boulders deposits on the riverbed. The standard sieve analysis used in laboratories however covers only a small part of the variability of available bed material. Therefore a procedure for determination of the grain distribution for mountain rivers is developed by ETH Zuerich, which is widely used in the world today. The measuring technique is called "Line-by-number-procedure" (LBN), covering the range of all available stones in mountain rivers. Firstly a string is laid next to the river / on the exposed bed in the direction of flow. The concept is to measure the middle axis, so called b-axis of stones, which are touched by the string. Thereby a representative sample of the bed material is gained in short time without complicated and time-consuming laboratory tests.

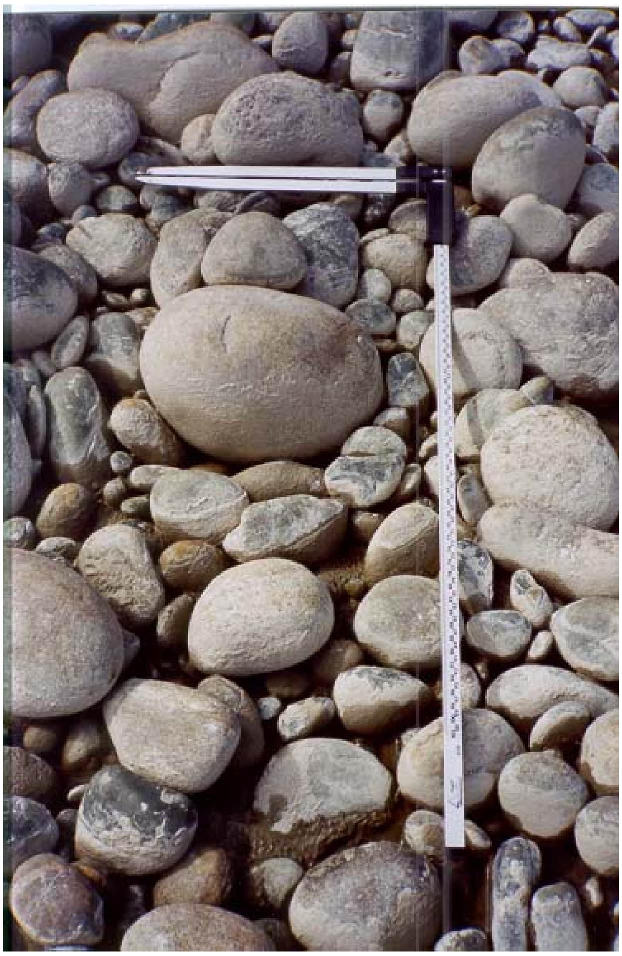


Fig. 4.8: **LBN measurement of armour layer, Kandiah, Karakoram**

4.3 DATA PROCESSING

4.3.1 BED LOAD

4.3.1.1 LABORATORY TESTS

The bed load samples of the field are analyzed in two respects:

- weight
- particle size analysis
- specific gravity

With help of the weight of the samples at each vertical, the bed load can be transformed into the standard unit of transported bed load per unit width and unit time [kg/ms]. For this reason the width of the sampler and the measured time duration of each sample has to be protocol led in the field. By application of this procedure for each vertical, the total transported bed load can be determined by interpolation in the cross-section at a certain discharge.

Sediment Sampling Dhubar Khwar			Discharge Q:		2550	[ft3/s]	72.35 [m3/s]
Date:	6/11/97		Velocity V:		10.4	[ft/s]	3.17 [m/s]
Location:	Aurangzeb Bridge		Area A:		245	[ft2]	22.79 [m2]
Sampler Widht:	0.25						
1. Measurement							
	Weight Sampler[kg]	Duration [min]	weight [kg/ms]	distance R/S WL		[kg/s]	[kg/d]
					32		
1.Vertical	0.08758	15	0.000389244		28	0.000778	
2.Vertical	5.689	15	0.025284444		24	0.051347	
3.Vertical	4.265	15	0.018955556		18	0.13272	
					14	0.037911	
				Sum:		**0.222757**	**19246.2**
2. Measurement							
	Weight Sampler[kg]	Duration [min]	weight [kg/ms]	distance bank		[g/s]	[kg/d]
					32		
1.Vertical	0.14521	15	0.000645378		28	0.001291	
2.Vertical	9.2362	15	0.041049778		24	0.08339	
3.Vertical	3.568	15	0.015857778		18	0.170723	
					14	0.031716	
				Sum:		**0.287119**	**24807.11**

Fig. 4.9: **Data processing of bed load measurements at Duber Khwar, Karakoram.**

With help of a mechanical particle size analysis, also called sieve analysis, the grain size distribution can be determined for each sample. The particle size analysis should determine the relative proportions of the different grain sizes, which are transported by the flow. There are different international sieve sizes according to the different standard specifications used in each country. The US sieve openings range from 100 mm to 0.038 mm, German specifications range from 63 mm to 0.04 mm. That part of sediments, which are smaller than the smallest sieve have to be analyzed by the hydrometer method, which will be discussed in the paragraph of suspended sediments.

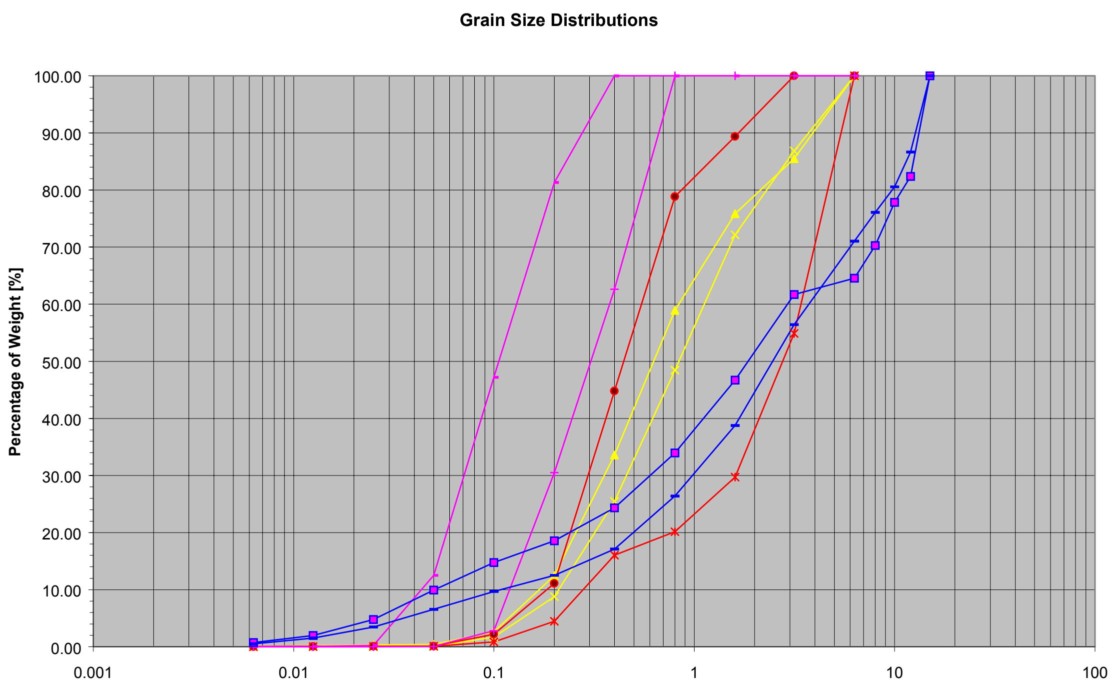


Fig. 4.10: **Grain size distributions of different verticals of bed load measurements**

Stones much larger than the greatest sieve the middle axis have to be measured by hand. The sieve analysis as well as the grain size distribution plot has to be extended accordingly. Especially in mountain rivers also bigger stones can be transported and caught in the sampler, therefore this situation might occur. If the grain size distribution is known, the sample can be described with characteristic coefficients, such as the sorting coefficient, the mean diameter d_{50}, the standard deviation and the skewness.

The specific gravity test is a well-known and simple laboratory test. In most cases the specific density of sediment transported as bed load can be assumed as 2650 kg/m^3. Seldom it is needed to carry out this test, detailed information is available in the training module “Bed Load”.

4.3.1.2 PUBLISHING

Until today only experimental bed load sampling tests have been carried out by GTZ. Therefore there is no systematic data collection available for processing and publishing purposes. However, the mean load transported in the cross-section should be published together with the discharge at that date and the result of the mechanical sieving in form of grain size distribution in form of a table.

Table 4.1: **Form of a table to be published for bed load**

Date	Discharge	Bed Load	d_{10}	d_{20}	d_{30}	d_{40}	d_{50}	d_{60}	d_{70}	d_{80}	d_{90}	d_{100}
	[m^3/s]	[kg/ ms]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]

4.3.1.3 DATA RELIABILITY

Following elements should be considered as far as the sources of error in the sediment computation concern.

- Field sampling procedure
- Field equipment
- Field operator technique
- Laboratory equipment
- Laboratory technique
- Laboratory operator
- Computation method
- Computation equipment
- Computation operation
- Local spatial variation

Different aspects of data reliability during measurement have already been discussed above. The work with data shows the quality of measurements and in some cases it might be necessary to repeat measurements. There should always be an interaction between data collection and processing. Every single measurement should be critically analyzed, especially those which largely deviate form the general pattern or from measurements for similar conditions made at the same site or even other sites

4.3.2 SUSPENDED LOAD

4.3.2.1 LABORATORY TESTS

The first step in data processing is the laboratory analysis of data. Suspended sediments consist of a mixture of fine material comprising sand, silt and clay. There are a number of laboratory tests, which should be carried out, for further data processing, such as:

- Concentration of samples
- Specific gravity test
- Particle-size analysis

With help of the concentration, which is measured in parts per million [ppm], the load of suspended sediment material can be calculated. The test is carried as follows: Firstly, the weight of the water-sediment mixture is determined. Afterwards the sample is dried in an oven and weighted again. Thereby the concentration of the sample can be determined.

Since the specific gravity of the mixture of sediments has an impact upon the sediment yield calculations, this laboratory test should also be carried out. Some detailed information on the used laboratory equipment and the detailed procedure of the test can be found in Ref. XX (*training material of suspended load*)

Furthermore the grain size distribution of the suspended sediments is also of interest. Since the material is so fine that standard sieves cannot be applied, a special particle-size analysis, the hydrometer test, has to be used. Particles, which pass the sieve No.200 (0.2 mm) have to be analyzed by the procedure mentioned above. The method is used to obtain an estimate of the distribution of soil particle sizes between 0.075 mm and 0.001 mm. Similar to the mechanical method for coarse material, result data are also plotted on semi-log graph of percent finer vs. particle diameter and may be combined with the data of the mechanical analysis. A hydrometer is needed, such as the one shown below.
The principle of the hydrometer is based upon the physics, that by mixing an amount of soil with water to a 1000 ml suspension, the mixture will have a specific gravity larger than 1.000. The hydrometer displays the specific gravity of the suspension at the center of the bulb. Any soil particles larger than those still in suspension in the shown figure and marked with L (distance between water surface and center of the bulb) have fallen below the center of volume.

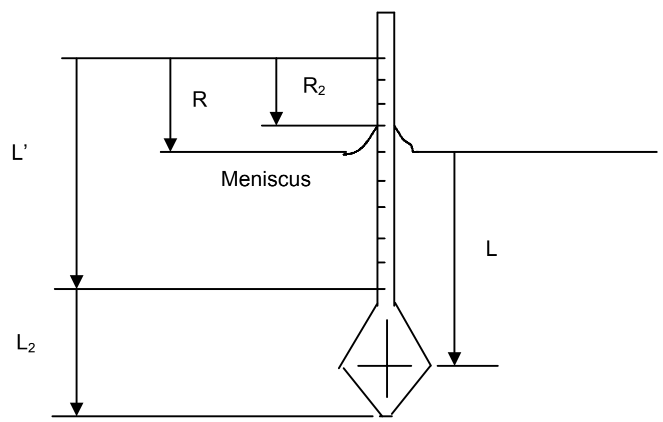


Fig. 4.11: **Hydrometer dimensions and terms**

This will constantly decrease the specific gravity of the suspension. Since the hydrometer is a constant mass, the less the specific gravity of the suspension, the deeper the hydrometer will sink into the suspension and the larger the distance L will become. Of course larger particles with a greater specific gravity will settle first, after this continuously smaller particles. By reading the distance L of the falling parameter and using Stokes' law of fall velocity, the distribution of the fine material can be determined.

4.3.2.2 PUBLISHING

After the laboratory tests have been completed, suspended sediment data are published in the hydrological yearbooks. The yearbooks give information on the date of measurement, the measured discharge, the temperature of the water, the measured value of suspended sediments and the result of laboratory analysis, divided in percentage of sand, silt and clay. It looks as follows:

Table 4.2: **Form of a table to be published for suspended load**

Date	Discharge	Temp.	Suspended Load	Sand	Silt	Clay
	[m^3/s]	[C]	[PPM]	[%]	[%]	[%]

4.3.2.3 DATA RELIABILITY

After the data collection in the field work has been finished and the samples have been analyzed in the laboratory, the data processing is continued. By using the data for calculation it is always necessary and important to check the data regarding their reliability. Because the data have been passed a long way to be published in the yearbooks or any other report and some mistakes might happen, for example:

- Improper measurement procedures
- Incorrect reading of the measurement
- Improper identification of the field samples
- Deficient analysis
- Incorrect reading of the equipment
- Mistaken calculation of the analysis
- Incorrect transcription of the data (typing mistakes)

Different aspects of data reliability during measurement have already been discussed above. The processed data should reflect the reliability of the measurements. In some cases it might be necessary to reject data and repeat measurements. There should always be an interaction between data collection and processing to find possible errors in data collection and /or processing.

4.3.3 BED MATERIAL

For the processing of bed material data the same laboratory test should be carried out as for bed load. Independently of whether a sample pit has been taken from the exposed riverbed during low flow or from the river bank, processing is the same. The samples should always be large enough to allow the determination of its grain distribution by mechanical methods.

However, if a 'line-by-number-procedure" (LBN) has been applied, the specific gravity is automatically assumed to be 2650 kg/m^3. In this case, it is usually not foreseen to analyze a

Line by Number Procedure

sample in the laboratory. The table from the data collection from the field is analyzed and transformed with help of regression analysis into a cumulative grain size distribution curve. Since sediment material smaller than 1 cm is not taken into account during measurement, fine material data from concrete engineering is artificially added to the sample to develop a grain size distribution similar to bed load procedures.

Fig. 4.12: **Grain size distribution curve, LBN procedure, Astore, Himalaya.**

The other possibility is, that a sample of the subsurface sediment material is taken from the site, analyzed with mechanical sieving and results are combined with the coarse material of the armour layer of the line-by-number-procedure. This procedure can be considered as more site specific and more reliable to natural conditions.

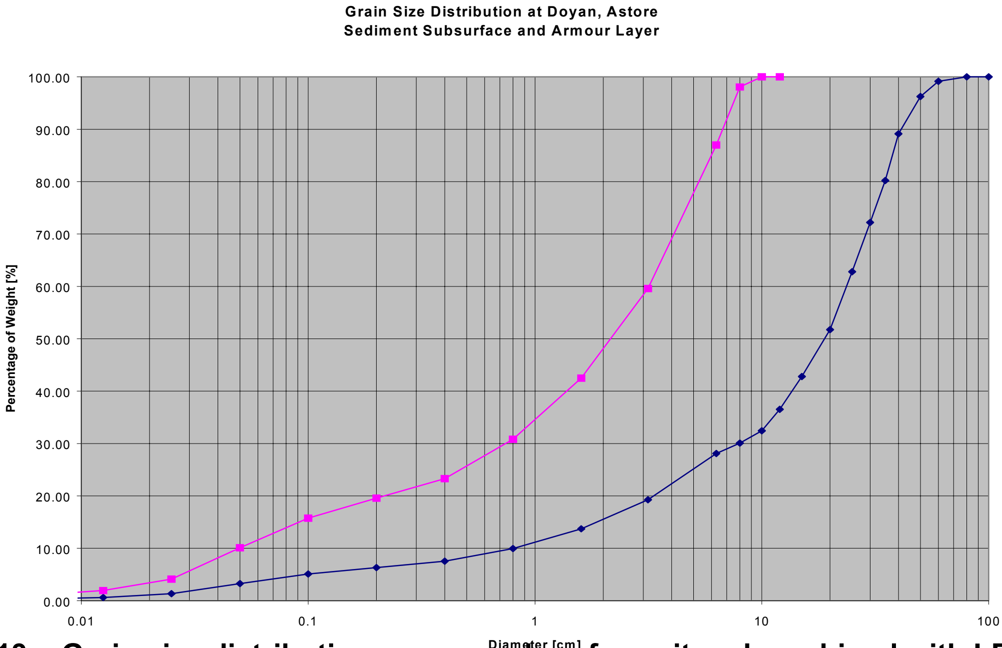


Fig. 4.13: **Grain size distribution curves, subsurface pit and combined with LBN procedure, Astore, Himalaya.**

4.4 APPLICATION

4.4.1 BED LOAD

There are mainly two issues which are of special interest concerning bed load:

- Incipient motion criteria for the beginning of bed load transport
- The amount of transported bed load

Once, the bed load has been started to move, the bed load transported in a river can be assessed basically by two methods:

- Bed load transport formula derived from field measurements
- Use of empirical formulae

4.4.1.1 INCIPIENT MOTION CRITERIA

The critical water depths for incipient motion can be determined and compared with classical approaches after Shields and Meyer-Peter/Mueller etc..

First test measurements are indicating that the existing formulae and approaches for incipient motion are not applicable to the rivers and torrents available in high mountain regions, such as Himalayas or Andes. According to the classical approach with a critical Shields parameter τ^* mountain rivers with a mean annual discharge between 15 and 30 m^3/s, a slope between 5 to 7% and a one year flood up to 100 m^3/s would have sediment transport all year long. This cannot be conformed from the field measurements, where incipient motion starts at a mean water depth of 1 to 1.5m. The following figure shows the existing actual Shields parameter of the two mountain rivers Golen Gol (Hindukush) and Duber Khwar (Kohistan) in comparison to the critical Shields parameter of 0.5 for rough turbulent flow conditions. Even at the lowest water depths of 0.2 m the sediments with a d_{50} in the range of 17 cm would be in motion according to the classical approach.

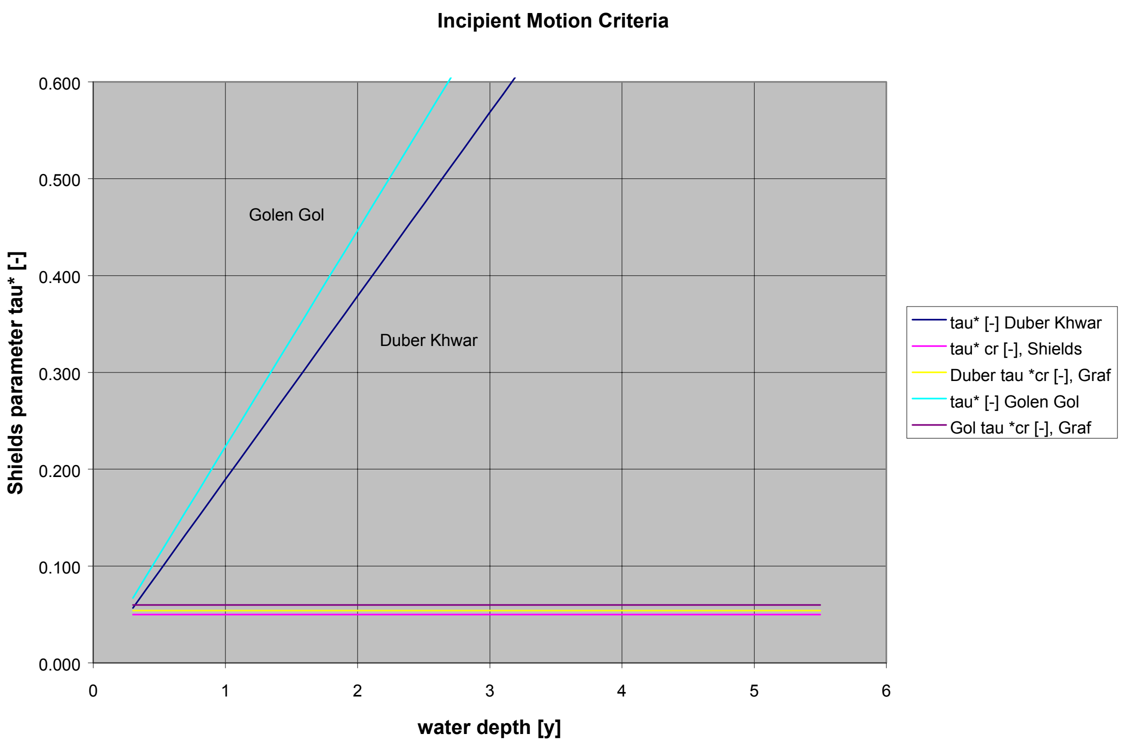


Fig. 4.14: **Application of critical motion criteria after Shields to mountain rivers.**

4.4.1.2 TRANSPORT FORMULA DERIVED FROM FIELD MEASUREMENTS

With help of the field measurements a relationship between the transported bed load and the discharge can be derived for one cross-section. Since many points have to be known of the graph, this procedure needs a lot of reliable data from the field. However several measurements at different sites of the river have to be done to gain a comprehensive view of the transport mechanisms of sediments.

With help of the derived bed load transport formula the expected sediment loads for other discharges can be calculated. The mean annual bed load can be computed on basis of the flow duration curve. The mean annual bed load can be applied to several years, which gives the mass of transported material for a given duration. Provided that the density of the sediments is known, the sediment volume can be calculated. In case of high-head hydropower projects with storage, the volume of the reservoir should be compared to the annual volume of transported sediment material. The useful life of such a reservoir will highly depend on the amount of transported bed load, even when flushing of deposited sediments is being considered.

The derived bed load transport formula can also be compared with other different empirical formulae to assess their range of application. Since the bed load sampling at mountain rivers is virtually at the initial stage, not enough information is available to give an example based on reliable analysis and processing.

Moreover the grain distribution of the transported sediment material in nature can be compared with the bed material or the material on the banks and any conclusions about the armoring processes of the river might be established.

4.4.1.3 EMPIRICAL TRANSPORT FORMULAE

There are various methods and formulae used to estimate bed load. Their applicability depends on the conditions under which the formulae were developed compared with the conditions of the river under study. Especially for mountain rivers characterized by steep slopes and coarse material, only two formulae are of special interest, the formula by Meyer-Peter/Mueller and the extended version of the formula developed by Smart and Jaeggi.

While Meyer-Peter/Mueller is limited to slopes of less than 2%, the latter formula can be applied to riverbed slopes ranging from 4% to 28%. Special literature on the prerequisites for applying these formulae can be seen in hydraulic publications on sediment transport and in journals.

For the application of both formulae the grain size distribution is needed. For this reason, empirical formulae have to be combined with results of bed material sampling by means of above mentioned methods.

In the following the bed load for Khan Khwar at Karora was estimated using the formula by Meyer-Peter/Mueller. To estimate the bed load the following procedure was adopted: The calculations have been carried out with the hydrological data bank DBHYDRO. However, by hand calculations follow the same procedure:

- Surveying of cross section and water level slope of Khan Khwar was undertaken. It should be mentioned in this connection, that the longitudinal water surface profile shows the morphological phenomenon of step pools, which is typical for mountain rivers and which is expected to have an enormous impact upon the stabilization of river bed.

Cross Section Khan Khwar

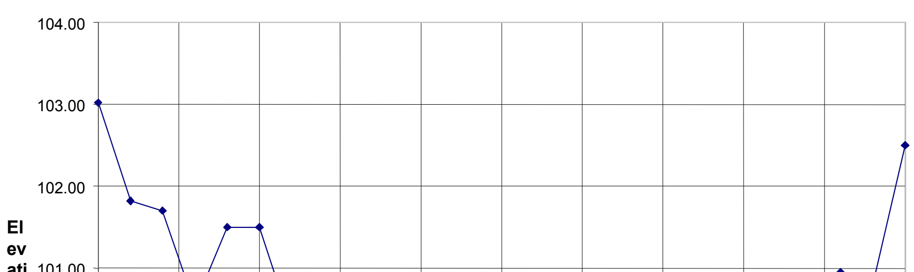


Fig. 4.15: **Cross Section of Khan Khwar, Kohistan**

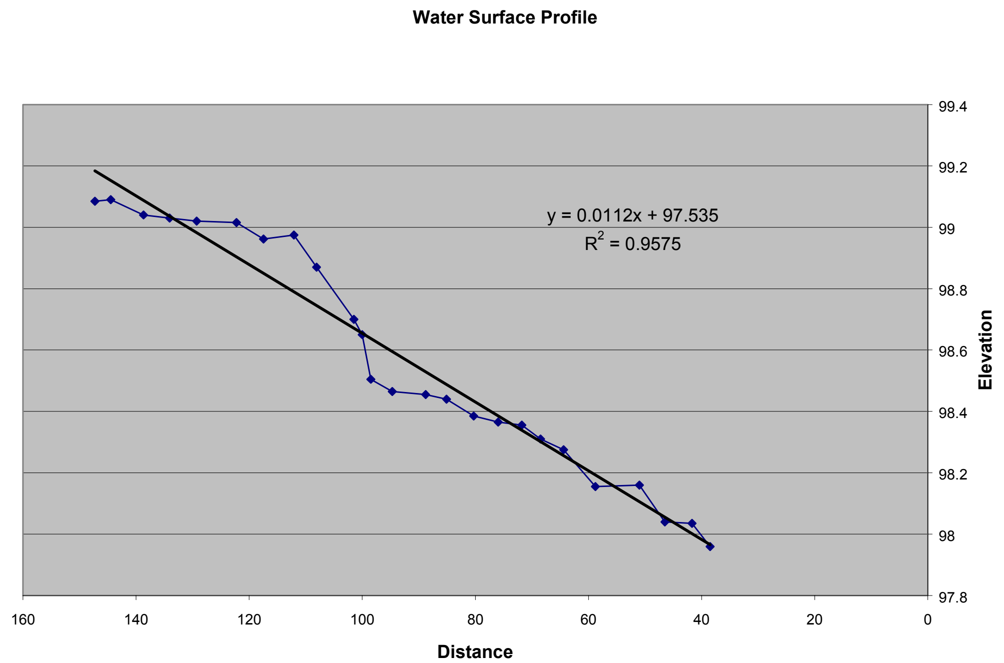


Fig. 4.16: **Water Surface Profile at Khan Khwar, Kohistan**

- A line-by-number procedure was taken from the surface riverbed, which shows the capability for armoring effects.

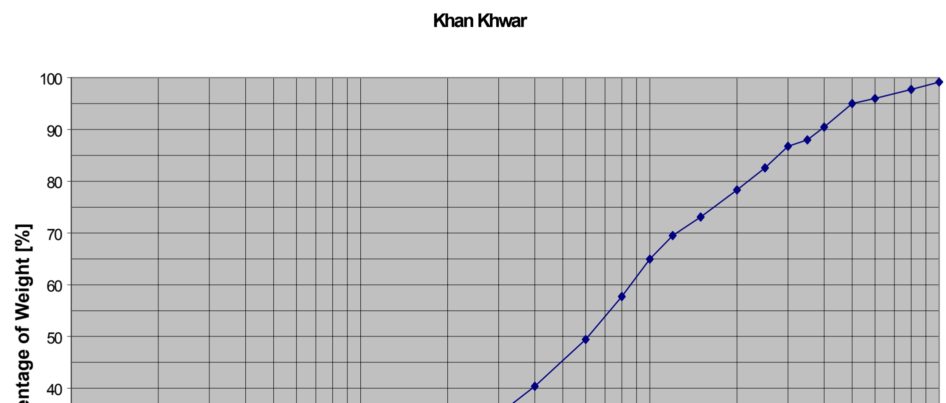


Fig. 4.17: Grain size distribution of bed material

- Bed load was estimated for various stages using the classical formulae after by Meyer-Peter-Mueller.
- A bed load rating equation was developed from the bed load and the respective water discharge for various stages.

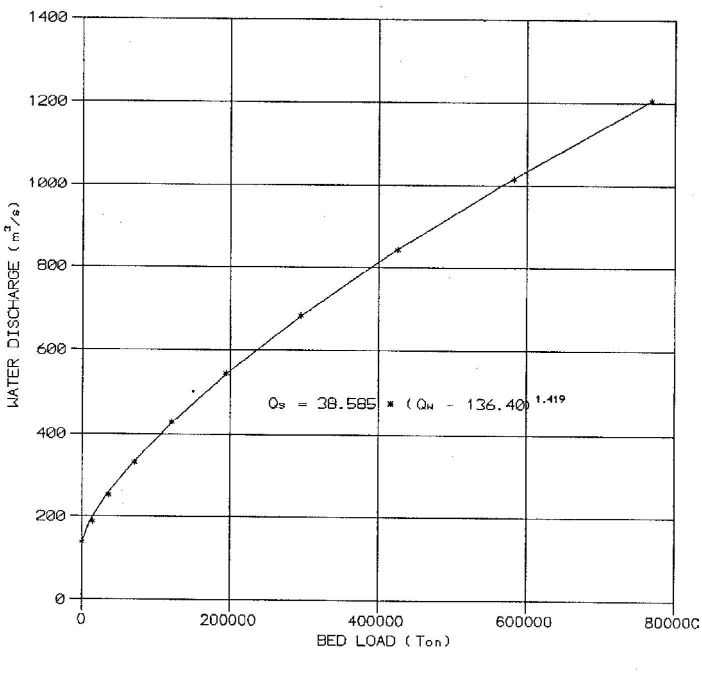


Fig. 4.18: **Bed load rating curve for Khan Khwar**

- Bed load was estimated applying the rating equation to the series of daily flows.
- Bed load was totaled to obtain monthly and annual totals.

- A mean annual value of bed load was estimated.

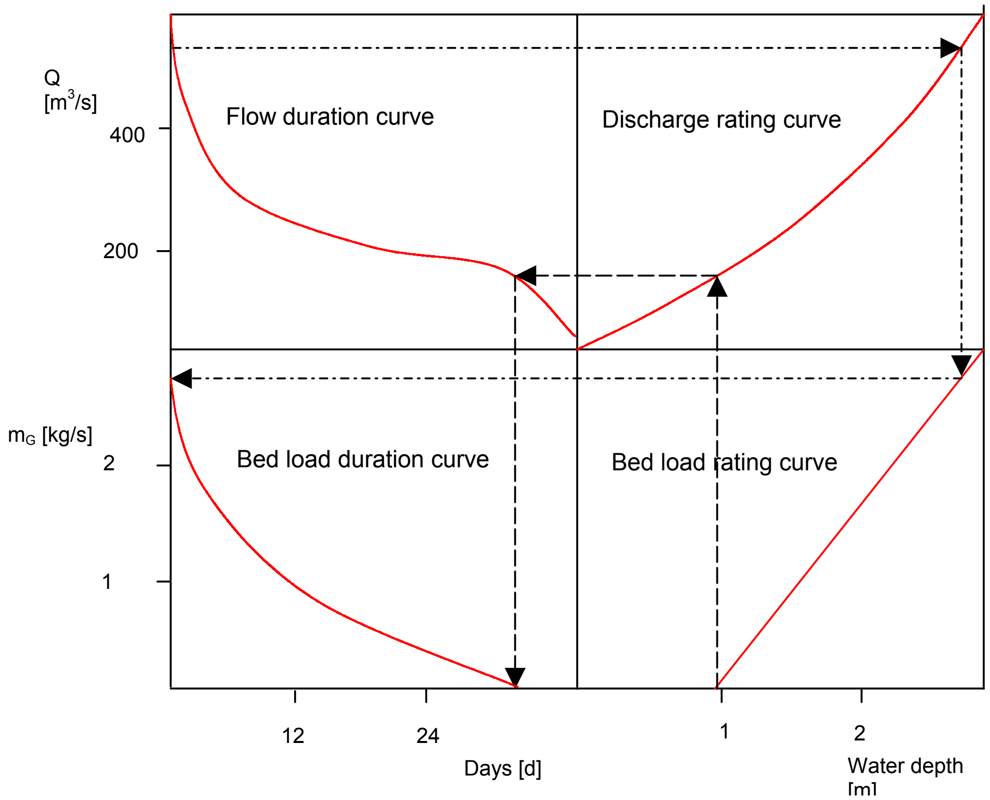


Fig. 4.19: **Diagram for determination of yearly bed load rates**

This procedure is illustrated in the graph above. For the determination of the yearly sediment discharge, the procedure starts with the flow duration curve in the square top left. Via the discharge rating curve top right and the sediment rating curve bottom right, by application of Meyer-Peter/Mueller or any other transport formula, the bed load duration curve can be obtained. The bed load discharge is equal to the area below the bed load duration curve. Together with the density of sediment materials, a volume of transported sediment material can be calculated.

With help of the relationship of Meyer-Peter/ Mueller a rating equation was obtained relating bed load to water discharge, the rating equations is shown on Figure 4.18. The rating equation was applied to the series of daily flows to obtain daily bed load discharges. The daily discharges were totaled to obtain monthly and annual values. The mean annual bed load was estimated to be 0.09 * 10^6 Ton/year. Monthly distribution of bed load is depicted on the Figure 4.20.

From Figures 4.18 and 4.20 it becomes apparent that bed load occurs only during high floods. Therefore, the recommendation that the reservoir should be flushed during the flood season was further strengthen.

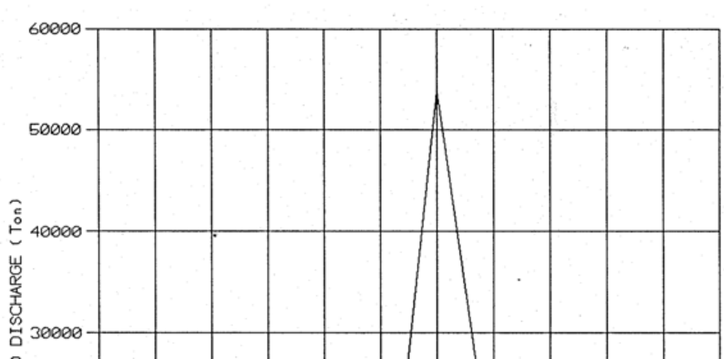


Fig. 4.20: **Monthly Distribution of Bed Load at Khan Khwar**

4.4.2 SUSPENDED LOAD

4.4.2.1 RATING CURVE

As already discussed, suspended load can be estimated from the suspended sediment samples. A commonly used method for estimation of suspended sediment is the development of a suspended sediment rating curve relating the discharge of suspended sediment to the water discharge. The suspended sediment discharge is then calculated applying the rating curve to the daily discharges. A rating curve used to estimate the suspended load of glacier fed Shigar River in the Himalayas is included on Figure 4.20.

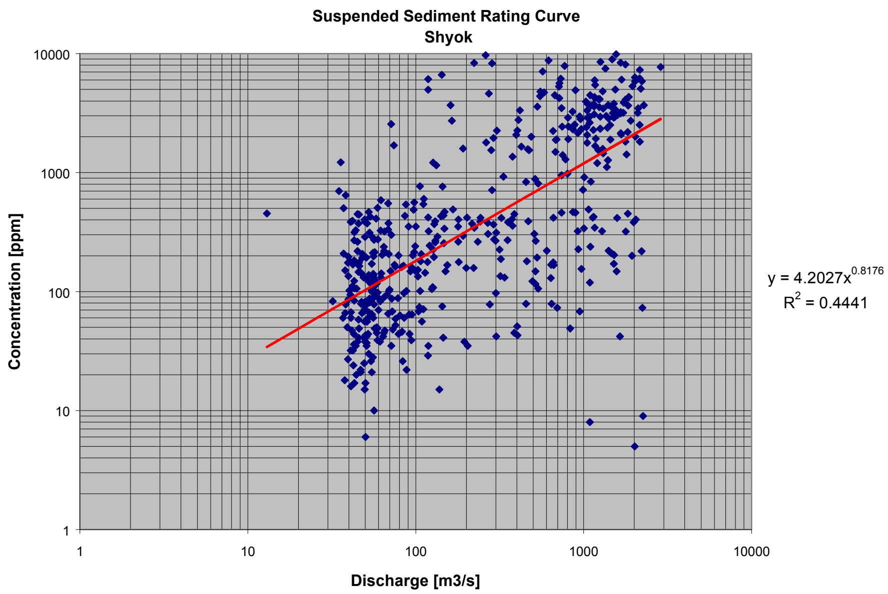


Fig. 4.21: **Suspended Load Rating Curve of Shigar River, Himalayas**

However, suspended sediment estimated by rating curve as described above has been found in some cases, to give suspended sediment rates below the expected amount. One possibility to overcome this circumstance is to divide the derivation of the suspended sediment rating curves into flow different flow regimes, like summer and winter. The discretization can also be done for each month, if sufficient data are available. An example for two month is given for the Peruvian River La Balsa in the Andes.

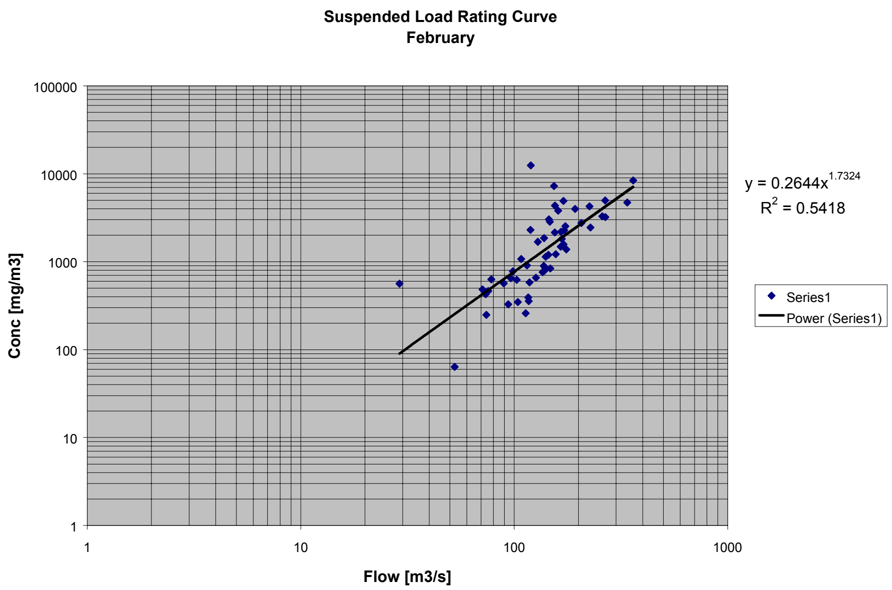


Fig. 4.22: **Derivation of Suspended Sediment Rating Curves, February, La Balsa, And**

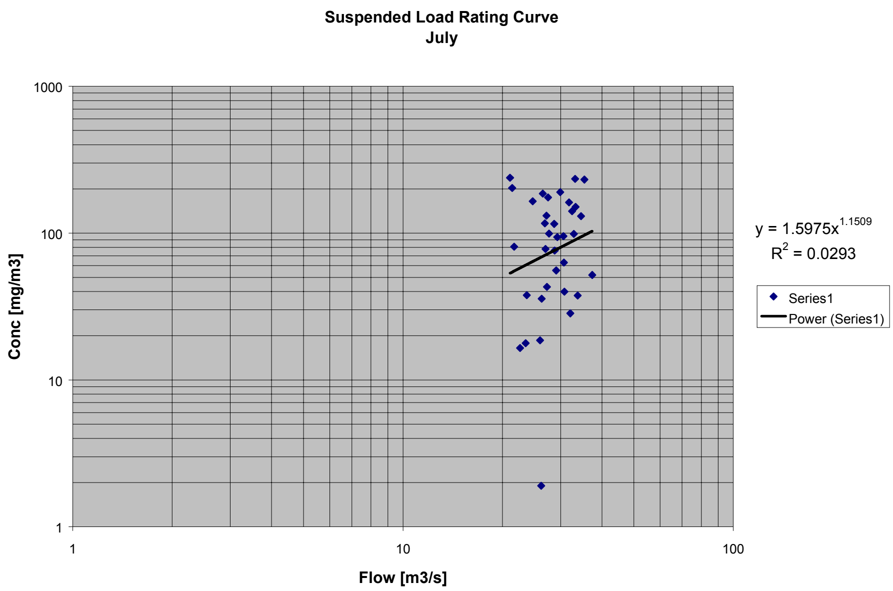


Fig. 4.23: **Derivation of Suspended Sediment Rating Curves, July, La Balsa, Andes**

The application of yearly as well as seasonal rating curves has shown, that suspended loads are underestimated. The underestimation of suspended load is probably due to the fact that the rating curve represents the mean condition of the river and does not represent the extreme conditions when the river carries the larger part of the sediment load.

4.4.2.2 INTERPOLATION (SHIFTING) METHOD

Alternatively, a method has been developed to estimate the suspended sediment following the concentrations of the sediment samples. The method comprises the calculation of the suspended load from the concentration of the samples. For the days when no sediment sample is available, interpolated values between the concentration of the previous and consecutive samples and the respective discharges are calculated:

- Shift is the correction applied to the discharge of a concentration measurement to bring the measurement to the standard curve.
- Shifts vary with time and fluctuations of concentrations

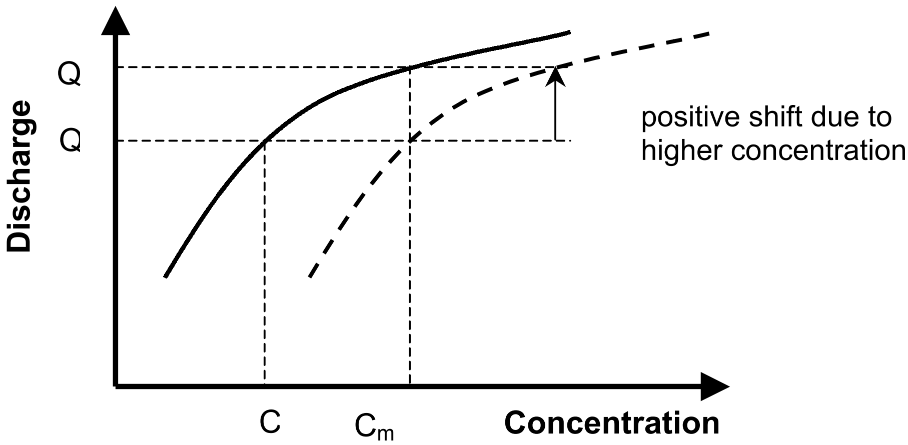
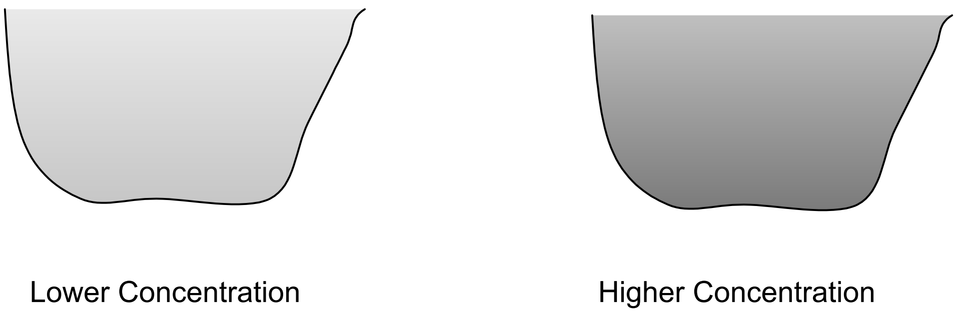


Fig. 4.24: **Shifting of discharge-concentration**

With:
Q_m, C_m: Discharge and concentration by measurement
Q_r, C_r: Discharge and concentration by rating curve
If:
$C_m > C_g$ => positive shift
$C_m < C_g$ => negative shift



Suspended sediment using the two methods mentioned above were performed for the Indus River at the hydrological station Besham Qila, upstream the multipurpose project Tarbela. The suspended load applying the rating curve method was estimated to be in average $155*10^6$ Ton/year. Suspended load calculated following the concentrations of the sediment samples was estimated to be $192*10^6$, which is considered to better represent the conditions of the catchment and show better agreement of sedimentation rates in Tarbela. This is a considerable difference, which has to be taken into account for the layout and design of the project. The expected useful life of a reservoir of a storage project can be drastically decreased due to an underestimation of the suspended sediment loads.

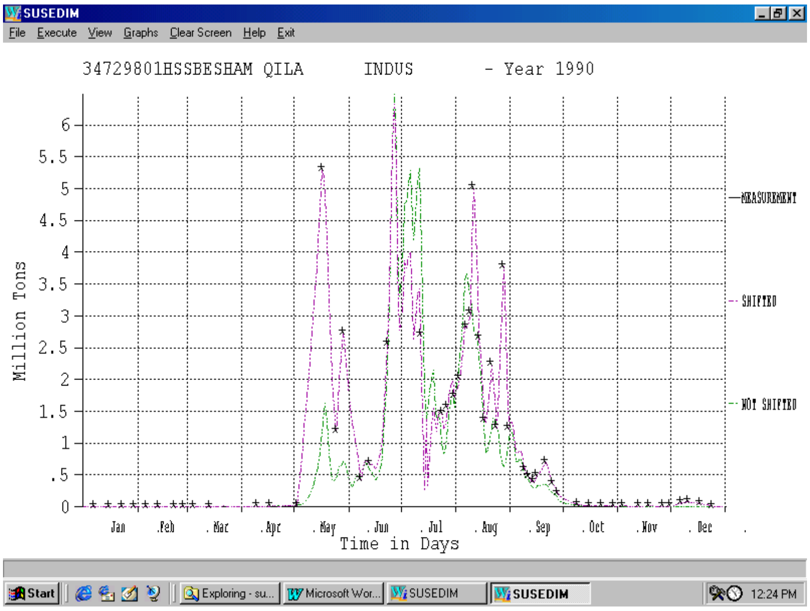


Fig. 4.25: **Comparison of Interpolation and rating curve method, Besham Qila, Indus**

Another example from La Balsa, Andes shows the monthly distribution of suspended sediment. The figure shows that the suspended sediment occurs in significant amounts only during the flood season, a very short time of the year. A large amount of sediments is even transported in several days of the flood season. If these peaks are not fully considered by the calculation, an underestimation is expected, as it can be seen in Figure 4.25. Therefore, to avoid siltation of the reservoir of the hydroelectric project flushing of the reservoir during the flood season may be considered.

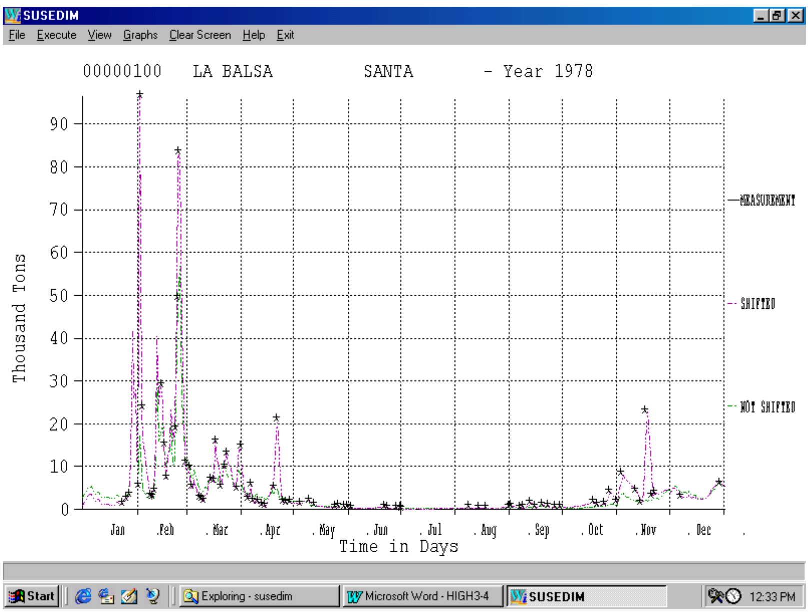


Fig. 4.26: **Suspended sediment peaks during flood at La Balsa, Andes**

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