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SEDIMENT TRANSPORTATION AND SORTING PROCESSES IN STREAMS

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The sediments at the beds of the Usri and the Dwarkeswar rivers, as in many other streams, progressively fine downstream and also develop lognormality in grain-size distribution. Flume studies suggest that the phenomena are related to the process of grain-sorting during bedform (sand dune or ripple) migration. The coarser grains, entrapped at the toes of bedforms, are gradually removed from the flow while the relatively finer ones are carried forward. Concentration of grains belonging to a narrow size range in the stream bed leads to lognormal grain-size distribution.

Flume experiments also indicate that grain sorting in a fluvial regime takes place in two stages : a preliminary sorting leading to concentration of grains around the mode of the distribution in the bed layer, and a secondary sorting due to lifting of the relatively finer grains from the bed layer into suspension as jets ejecting out of the ripple/dune crests. The range of grain-sizes abundantly available in the bed layer determines, in accordance to the Rouse equation, the sizes that will dominate the suspension. Lower the height of suspension, closer is the match between the modal sizes of the bed and the suspended load. A method, developed in partial modification of Hunt's equation, allows computation of the suspended load's grain-size distribution directly from that of the bed.

The grain-size distribution in suspension is generally skewed due to preponderance of fines. At appropriate combination of height and flow velocity, and after logarithmic conversion, the size distribution gives the impression of lognormality. Such a distribution might also develop through a process of grain sorting as a special case of hyperbolic distribution. At the stream bed lognormality, once attained, is maintained until the hydraulic conditions change drastically, as in floods. In suspension however, lognormality, attained at a particular combination of height and flow velocity, is likely to be modified with further transportation downstream. For experiments with suspended loads `close-circuit' hydraulic flumes of uncommon designs were needed for retaining particular grain-size distributions in suspension for desired lengths of time.

Log (phi)-probability plots of sediment populations transported either at bed or in suspension show mixtures of two or more linear segments with sharp inflections. These inflections disappear as the process of sorting is completed either after prolonged transportation in bed or at high flow velocity in suspension. The segments, commonly found in such plots of ancient and present day fluvial sediments, therefore, do not necessarily represent mixtures of sediments transported in different modes—traction, saltation, and suspension—as is commonly believed. The degree of lognormality attained, on the other hand, might provide a clue to the flow velocity of ancient streams. A relationship worked out between height of suspension and shear velocity for lognormally distributed sediment populations of known (mean) grain-sizes aid palaeohydraulic analysis.

All grain-sizes in suspension are deposited simultaneously when the flow velocity is reduced. This provides an explanation for the presence of large proportion of fine matrix in coarse grained turbidites. Hindered settling apparently prevents exponential decay of the coarser grains from suspension. For mathematical modelling introduction of a dampening factor' in the conventional Rouse equation was necessary to obtain results matching the experimental observations. Such phenomenon should be operative in natural streams and density currents also.

The observation that sediment concentration in suspension sharply increases with decrease of mean grain-size of the bed material, and that usually the modal grain-size of the bed dominates the suspension, will be of help in transporting sediment loads through natural or artificial canals. Experimental result indicating the influence of bed on deposits from suspension is also remarkable.

Key Words: Sediment Transportation; Sorting Process in Streams; Grain Size Distribution; Lognormality; Sediment Suspension; Weight Frequency Distribution

Introduction

A large part of the turbulent energy in a flowing stream gets converted to heat. Only a small part of it is utilised for transportation of sediments derived from erosion of source areas as well as river banks. These sediments range in size from boulders

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(>256 mm) through sand (2 mm-0.063 mm) to fine clay (<0.004 mm). When the velocity of water flowing over a non-cohesive sediment bed exceeds a certain threshold value, called the critical erosion velocity (or entrainment velocity), the grains are put into motion. The relationship between critical erosion velocity and grain-size was revealed by diagrams compiled by Hjulström[1], Shields[2], and Sundborg[3] for grains of specific gravity equivalent to that of quartz. Those for some other minerals were later experimentally investigated by Ljunggren and Sundborg[4]. Shields' threshold values were subsequently modified by Miller *et al.*[5].

Once entrained, the insoluble sediments are transported by running water in four different ways: sliding, rolling, saltation, and suspension. The grains dragged or rolled on the stream bed, constitute the traction load. A suspension load is the one in which the weight of the particles is continuously supported by the fluid. Saltation load is an intermittent phenomenon where the particles leap forward in a state of temporary suspension, describing projectiles, until the force of gravity brings them back to the bed. A saltation load, eventually, is preserved as a part of the bed load.

Most of the early experiments on sediment transportation were confined to the study of particles of uniform grain-size. Only in more recent years some attempts have been made to study the process of transportation of heterogeneous (grain-size wise) sediment loads [6-9]. So far as heterogeneous sediment loads are concerned, two problems have been of particular interest to the present authors and their associates: the process of sorting responsible for:

1. Progressive downstream decrease of mean grain-size of the materials transported, and
2. Modification of the grain-size distribution pattern with transportation.

The following pages review the current ideas on these topics and also summarise the investigations conducted during the past few decades in the field and also, under controlled conditions, in the laboratory. The problems concerning the bed and suspended loads are discussed below under separate heads.

Transportation at Bed

Grain-size Reduction

Downstream decrease of mean grain-size of sand and gravel populations in fluvial regimes is a well known phenomenon. The Ganga River in India may be cited as an example[10]. The mean grain-size of the channel sediments in this river is of medium to fine sand size in the upstream sector (300-470 km from the source), whereas further downstream (1680-2020 km from the source) it belongs to fine to very fine sand size[11]. An example of pronounced fining over a short distance in a Scottish river appears in Ferguson *et al.*[12]. Some examples of clast size reduction with increasing distance of transportation in alluvial fans are discussed by Wilson[13].

More than a century back Sternberg observed that both the mean and maximum pebble sizes in a fluvial regime steadily decrease with prolonged transportation. The rate of decrease of pebble size was expressed by Barrell[14] by a negative exponential: $w = w_0 e^{-ax}$ where w=weight of the fragment at a given point, w_0 is its initial weight, a=coefficient of size reduction, and x is the distance of transportation.

Bed load transport phenomenon of mixed sand and gravel populations were studied by a number of previous workers[6-9]. The general observation is that for low flow strengths only the sand size grains are transported. The size distribution of the bed load approaches the bed material only when the flow strength is competent enough to transport grains of all sizes present in the bed. The net effect is segregation of sand and gravel fractions in the river bed. Clusters of coarse grains accumulating at the leading edges of thin sheets of sediments (named 'bedload sheets') were noted by Whiting *et al.*[15].

In spite of these studies, the precise reason for downstream decrease of sand size has not been clear. Local base level control, a sharp drop in stream power due to a decrease in the river gradient[11], excessive supply of relatively fine sediments, selective sorting are some of the explanations generally provided[16]. In some cases, as in the Gomati River of India, this has been thought to be the result of decrease in transporting capacity as well as velocity downstream[17]. However, it is not so in many other cases. Observations in about 6000 stream gauging stations in USA, for example, have shown that the mean velocity either remains constant, or increases due to increasing contributions from the tributaries downstream[18].

Field Studies

The problem of downstream decrease of sediment size was investigated firstly in the Usri River of Bihar, and subsequently in the Dwarkeswar River of West Bengal, India. These two rivers were chosen because they are relatively easily accessible and are not affected by human interference.

Originating out of a number of streamlets flowing off the hillocks located north and northwest of Kharagdiha in the Hazaribagh Plateau of Bihar, the Usri River flows past the township of Giridih in a southerly direction for a distance of

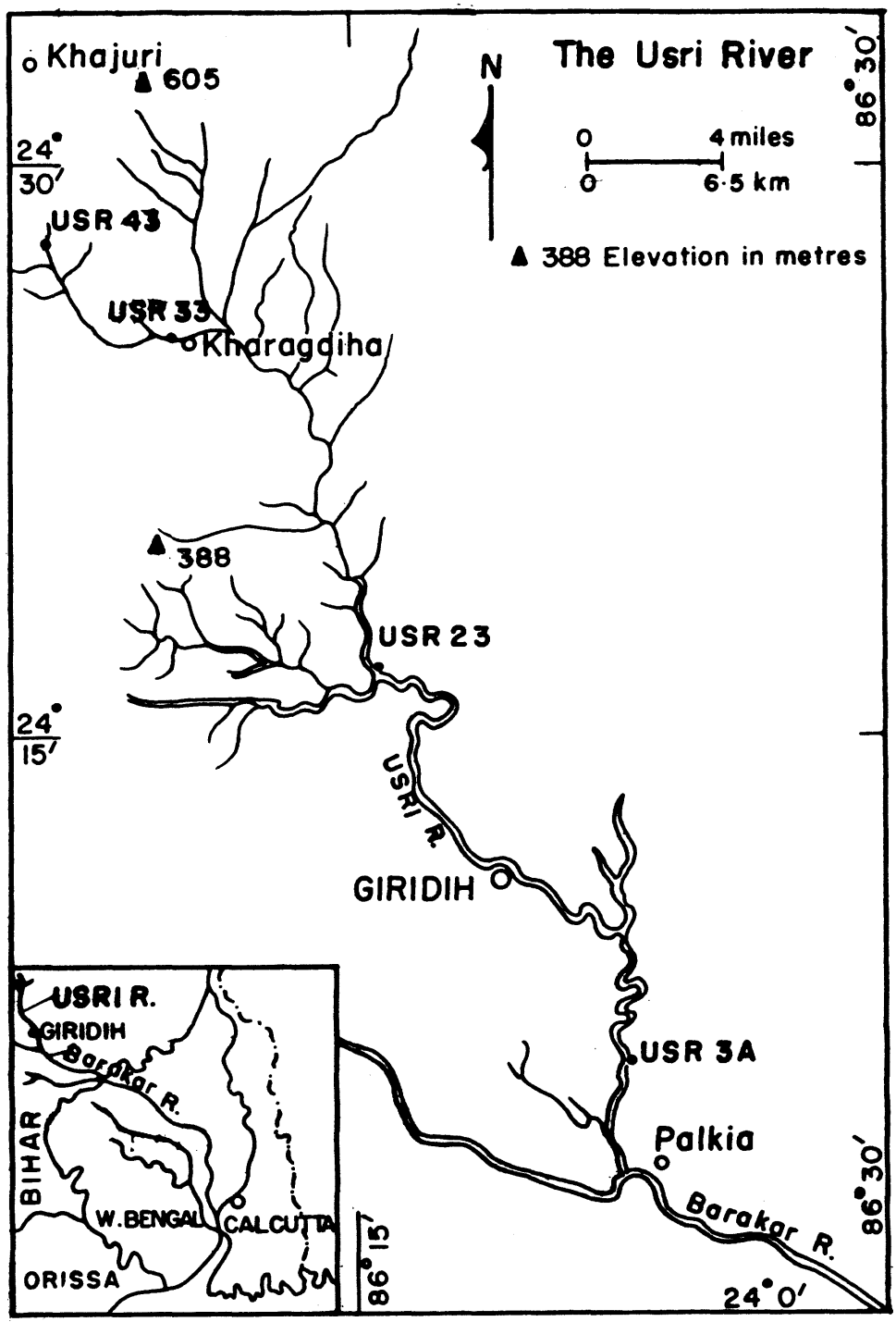

Fig. 1 The Usri River basin, Bihar, India showing sample locations (e.g. USR 23)

about 90 km to debouch into the Barakar River south of the village Palkia (Fig. 1). The maximum discharge in this river, which carries water mostly during the monsoon season (June to August), is estimated to be of the order of 500 m^3/s. During the winter months the river nearly dries up, exposing the point bars and also parts of its channel[19].

The Dwarkeswar River originates in the elevated western part of West Bengal and flows in a southeasterly direction for a distance of about 200 km through Bankura, Bishnupur and Arambag to debouch into the Rupnarayan River south of Dongal (Fig. 2). This river, which is also ephemeral in nature, carries water during the monsoon season only (estimated maximum discharge ~300 . m^3/s), exposing the point bars during the winter months.

In the Dwarkeswar valley sediment samples were collected from eleven selected point bars spread along the whole length of the river. The surface sediments of these bars depict a series of sand dunes. Sediment samples were collected from trenches dug across these dunes. At four locations in the upstream part of the river, where bedforms are not well developed, samples were collected from trenches dug randomly on the point bars. In one of the locations where no point bar is developed, a sediment sample was collected directly from the river bed. Wherever bedforms are well developed two samples, one from the upper part, and another from the lower part of the sand dune were collected with a view to investigating the nature of vertical variation in grain-size. The Usri River bed samples were collected from about 2 inches below the surface.

Grain-size distribution of representative river bed samples were determined by sieving. `Graphic mean' and `inclusive graphic standard deviation' of these samples were computed by Folk and Ward formulae[20]. The results are presented in Table I. In both the rivers a progressive decrease of the mean grain-size with increasing distance of transportation is noticed. Slight inconsistencies, noted in this table, are either due to local changes in elevation or to contributions of the tributaries.

From the source area to Kenjakura, a distance of 60 km, where the Dwarkeswar river bed is steep (gradient ~1.5 m/km) the mean grain-size shows many irregularities indicating that the sediment populations within this reach are not properly

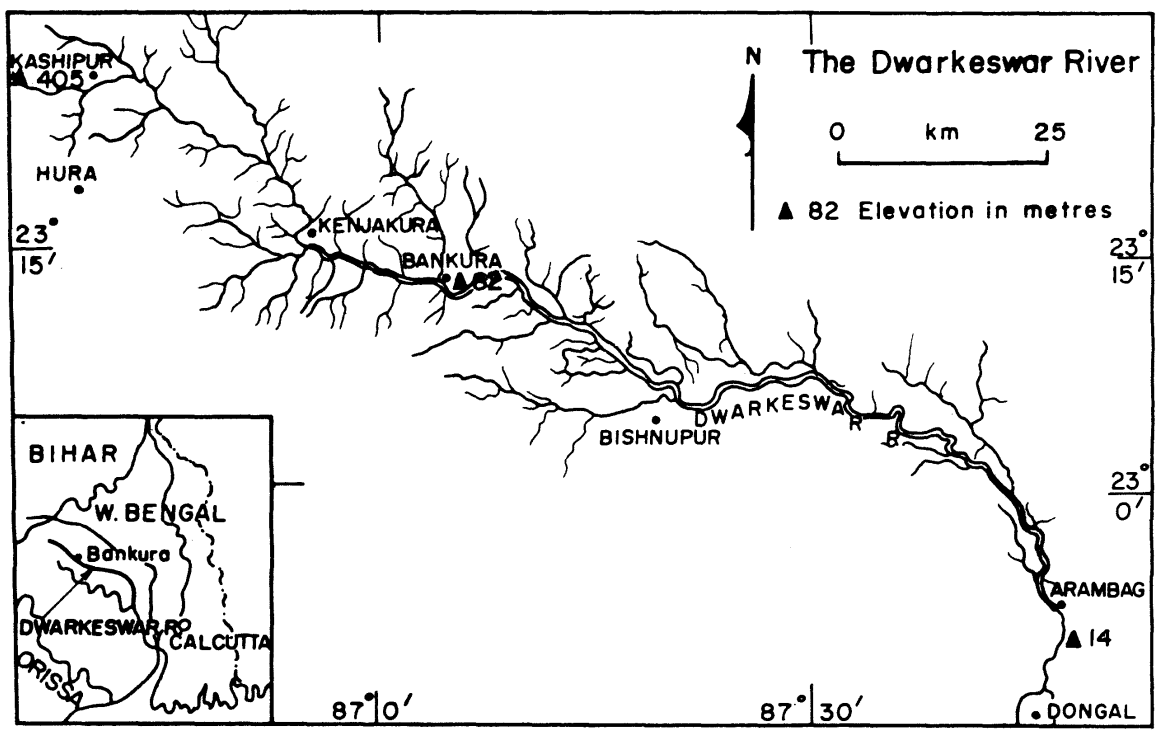

Fig. 2 The Dwarkeswar River basin, West Bengal, India. Samples were collected from point bars nearest to the townships shown

sorted (Fig. 3). Appreciable sorting starts only when the river profile becomes graded (gradient ~0.28 m/km) further downstream.

Between Kenjakura and Dongal, a distance of 143 km, the mean and the modal sizes of the samples steadily decrease indicating the influence of distance of transportation on grain-size. That this size decrease is not due to the influx of silt and clay is shown by the presence of only a very small proportion (<0.5%) of particles finer than the sand size in all the samples analysed. The size reduction between these two locations is due neither to abrasion nor to attrition of the grains. Measurements by Mukhopadhyay[21] showed that roundness and sphericity of the sand grains in the Dwarkeswar River do not change appreciably downstream, but abrasion or attrition would have drastically modified these parameters with increasing distance of transportation. Interestingly, in each of the point bars between Kenjakura and

Table I

Downstream change in grain-size and sorting of the sand at the beds of the Usri and the Dwarkeswar rivers

THE USRI RIVER

Sample No.	USR 43	USR 33	USR 23	USR 3A
Distance from source (km)	0	11.3	43.5	70.8
Inclusive graphic mean (M_z) ϕ	-0.233	-0.033	0.70	0.50
Sorting, Inclusive graphic standard deviation (σ_1) ϕ	1.583	1.186	0.834	0.905

THE DWARKESWAR RIVER

Location	Hura	Kashipur	Kenjakura	Bankura	Bishnupur	Arambagh	Dongal
Distance (km)	5	16	60	86	114	188	203
Mean (M_z) ϕ	U - 0.28	0.13	1.38	1.16	1.42	2.29	2.32
	L -	0.04	0.27	0.56	1.02	1.64	2.75
Sorting (σ_1) ϕ	U 1.61	1.11	0.83	0.63	0.79	0.34	0.35
	L -	1.26	1.41	1.18	1.04	0.77	0.47

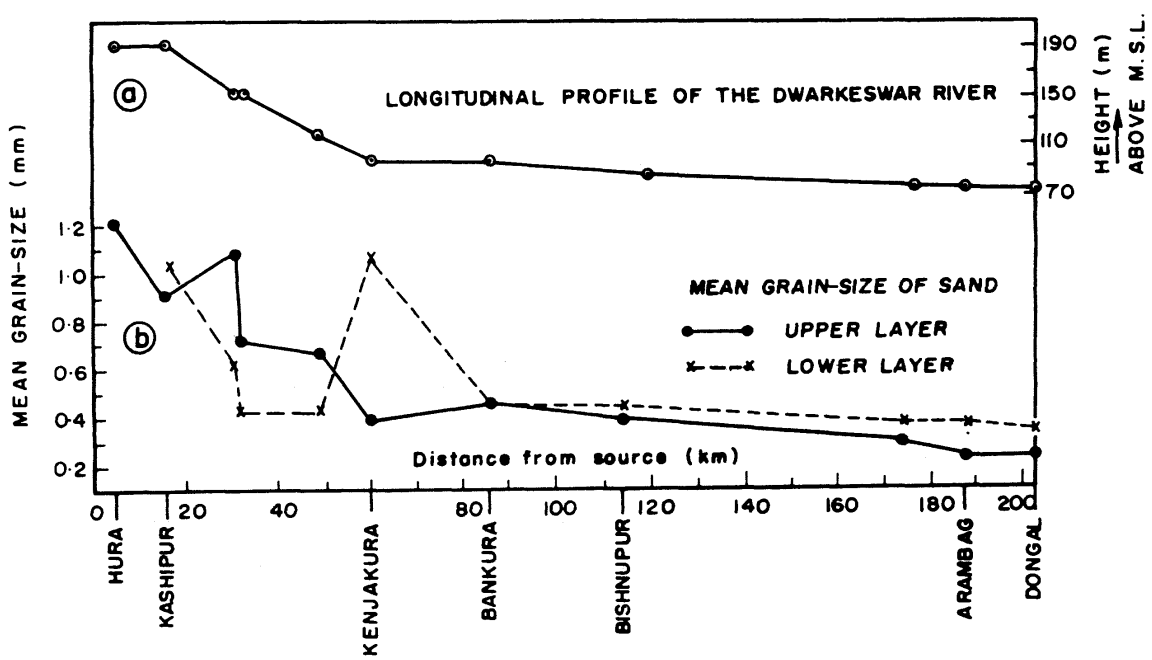

Fig. 3 Longitudinal variation in (a) the Dwarkeswar river profile (b) mean grain-size of the river bed sediments

Dongal the mean grain-size of the upper layer of the bar is appreciably smaller than the lower one (Table I). Apparently, the coarser grains accumulated in large quantities at the base of the sand dunes leaving only the finer ones to be transported. However, the mechanism of entrapment of the coarser grains at the base of the sand dunes remained unclear from field studies alone.

Experimental studies conducted in laboratory channels on earlier occasions suggested that bedform migration can play a significant role in the process of grain sorting. Whether such a phenomenon could be responsible for entrapment

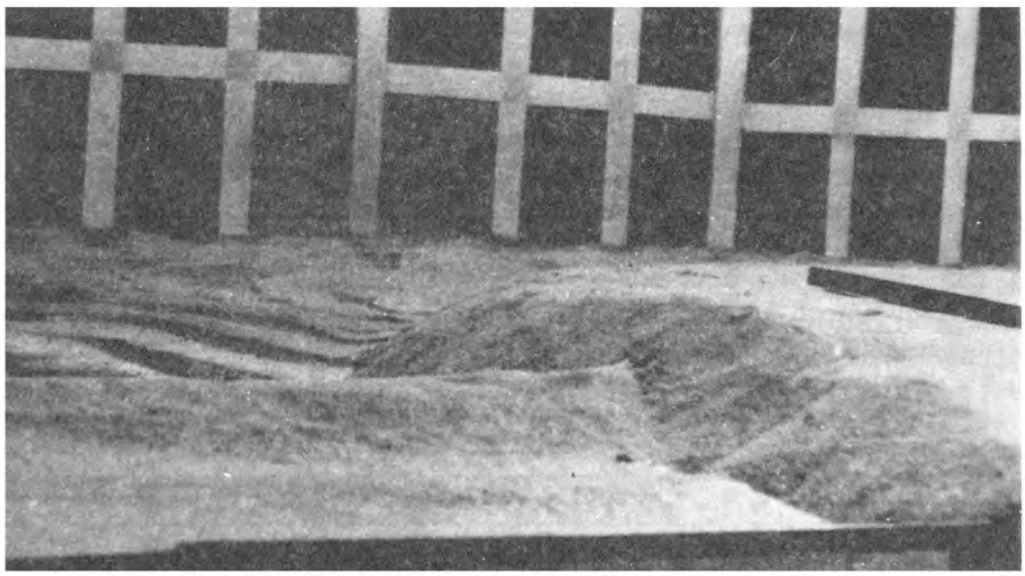

Fig. 4 Photograph of a large sand dune with a spur generated in a 2m wide flume at IIT, Kharagpur. Black bar on top is ~45 cm long. Flow from right to left

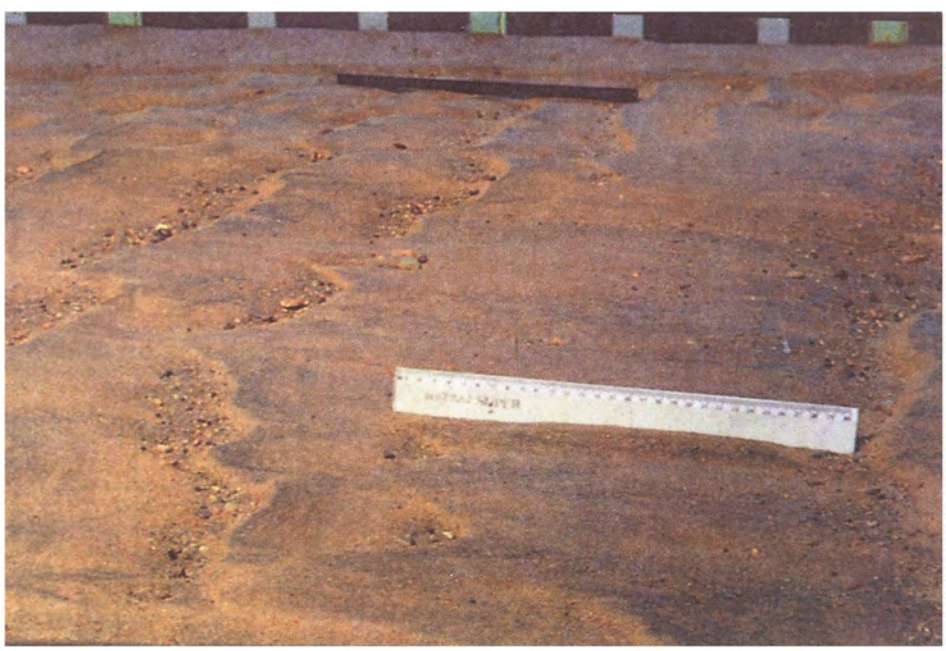

Fig. 5 Photograph showing accumulation of coarse sand and pebbles in front of subaqueous sand dunes in a 2m wide flume at IIT, Kharagpur (white scale in front is 30 cm long). Flow from right to left

of the coarser grains in a fluvial regime was investigated in a two-metre wide laboratory channel at IIT, Kharagpur. The results of this study are discussed below.

Laboratory Studies

In each of these flume experiments water was allowed to flow unidirectionally over a bed (~8 cm thick) of mixed sand and gravel at speeds (~0.5 m/s) exceeding the entrainment velocity of the mixture. Soon after this velocity was reached, in each case, the whole body of sediment was thrown into a pattern of large sand dunes (H~10 cm, L ~1.1 to 1.3 m), each having a distinct stoss and a lee face and a spur in front of the lee (Fig. 4). After 10 to 15 hrs of run a distinct accumulation of coarse sand and gravel took place on the lee side of this sand dune. Particularly, clusters of gravel accumulated at the toe of the dune (Fig. 5). With continuous feeding of material from behind, and migration of the dune front downstream, these coarser grains were buried below the lee faces. This layer of coarse sediments, entrapped below the rows of cross-beddings, became visible only when the sand dune was cut open (Fig. 6).

The effect of this grain sorting was revealed by a comparison of the mean grain-sizes of sediment samples collected from the crests as well as toes of sand dunes. The results of two such representative measurements are shown in Figs 7 & 8. In each case a progressive downstream decrease of mean grain-size of the sediments constituting the dune crest is noted. In each case again, the grains trapped at the toe of the dune are coarser than those present at the crests. These experimental results match the field observations in the Dwarkeswar as well as the Usri Rivers where coarser grains were found in large quantities at the base of sand dunes. In the Usri River particularly, where longitudinal sections of the point bars morphologically resemble large dune forms, the coarser grains accumulated in large quantities at the base of the lee faces of the mega dunes (B. Purkait and S. Sengupta, unpublished work). Thus, from field as well as experimental studies, progressive downstream decrease of grain-size seems to be the result of entrapment of the coarser grains at the toes of sand dunes.

Concentration of temporarily immobile clusts of pebbles in the troughs of bed-load sheets and bars were noted by some of the previous workers

Fig. 6 Longitudinal section of the sand dune in Fig. 4 showing accumulation of the coarser sediments at the base of cross-bedding foresets (scale on top is 30 cm long). Flow from right to left

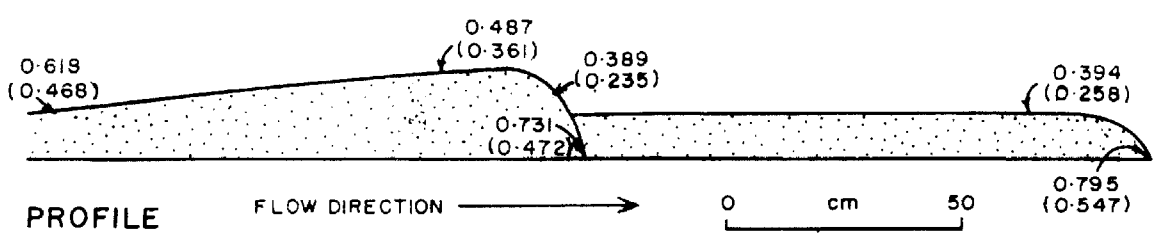

Fig. 7 Mean grain-sizes (in mm) and sorting (shown in parenthesis) of sand within a sand dune and spur generated in a laboratory flume. Flow velocity ~0.5 m/s, water depth =61.5 cm above sand bed no. IIT-7.2

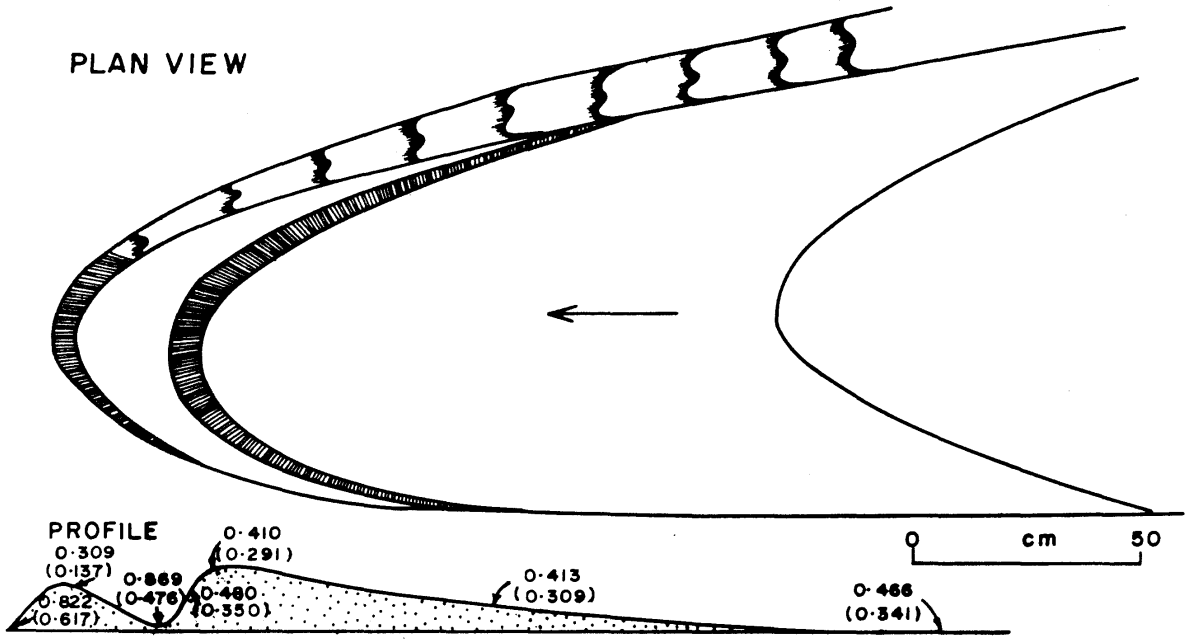

Fig. 8 Mean grain-sizes (in mm) and sorting (shown in parenthesis) of sand within a sand dune generated over bed no. IIT-7.2 at a flow velocity of ~ 0.5 m/s, and water depth of 72.5 cm. Arrow indicates flow direction

Table II

Grain-size distribution of sand beds used for experiments at IIT, Kharagpur

Bed No. → mm	IIT-1.1 wt (%)	IIT-2.1 wt (%)	IIT-2.2 wt (%)	IIT-3.1 wt(%)	IIT-4.1 wt (%)	IIT-4.11 wt (%)	IIT-7.2 wt (%)
4.00				2.68			
3.36				0.45			
2.83				6.00			
2.36	0.43			4.98			
2.00	0.30	0.02	0.03	6.42			0.05
1.40	1.23	0.15	0.21	8.01		0.03	2.22
1.00	1.60	0.24	0.24	8.02	0.02	0.10	2.59
0.71	3.68	0.83	0.74	9.36	0.07	0.05	6.02
0.50	9.79	2.91	2.95	9.78	0.20	0.14	11.95
0.36	27.61	8.84	8.90	11.90	0.75	0.62	21.24
0.25	42.78	36.71	37.57	16.46	6.15	6.59	31.92
0.18	10.55	33.14	33.80	11.13	28.26	27.19	16.27
0.13	1.81	12.33	11.84	3.81	47.65	46.96	5.78
0.09	0.20	3.15	2.77	0.77	13.62	14.67	1.47
0.063	0.01	1.19	0.61	0.13	2.18	2.68	0.32
0.045	0.01	0.47	0.25	0.07	0.72	0.66	-
0.01 *	0.00	0.02	0.09	0.01	0.37	0.32	0.19
Total (%)	100.00	100.00	100.00	99.98	99.99	100.01	100.02
Total weight (kg.)	17.50	19.95	20.0	10.13	34.40	50.31	30.00
Roughness (k_s/30) mm	0.0138	0.0086	0.0086	0.0333	0.0063	0.0060	0.0142
Mean grain-size (mm)	0.42	0.27	0.28	1.14	0.175	0.174	0.427

* Includes all grains < 0.05 mm.

also[22,23]. The bedforms in those cases had relatively fine grained crests and coarse grained troughs together with well mixed grain texture along the stoss sides—observations matching the present experimental findings. In marked contrast to these observations was the finding by Bridge and Best[24] that the bedload is often coarsest at the crest of the dunes. Accumulation of the coarser grains at the toes of sand ripples in the present set of experiments seems to be the result of avalanching from the dune crest. The finer grains occurring on top of the coarser ones, in such cases, might have been carried further downstream in suspension, in a manner suggested by Whiting[25]. These experimental results also indicate that downstream fining is not due to a simple process of selective deposition as was experimentally demonstrated by Paola *et al.*[26]. Sambrook Smith and Ferguson[27], who experimented with a bimodal, gravel-sand bed in a hydraulic flume, noticed a progressive change from coarse gravel to fine sand with decrease of slope, but these results are not applicable to the present set of experiments where the flume base was essentially horizontal.

Gravitational sliding of sediment masses down the lee faces of sand dunes is a well known phenomenon. Bagnold[28], who worked out the physics of these movements in eolian dunes, demonstrated how the bigger particles tend to accumulate at the bottom in large quantities. The present experiments show that the same principle works for subaqueous dunes also.

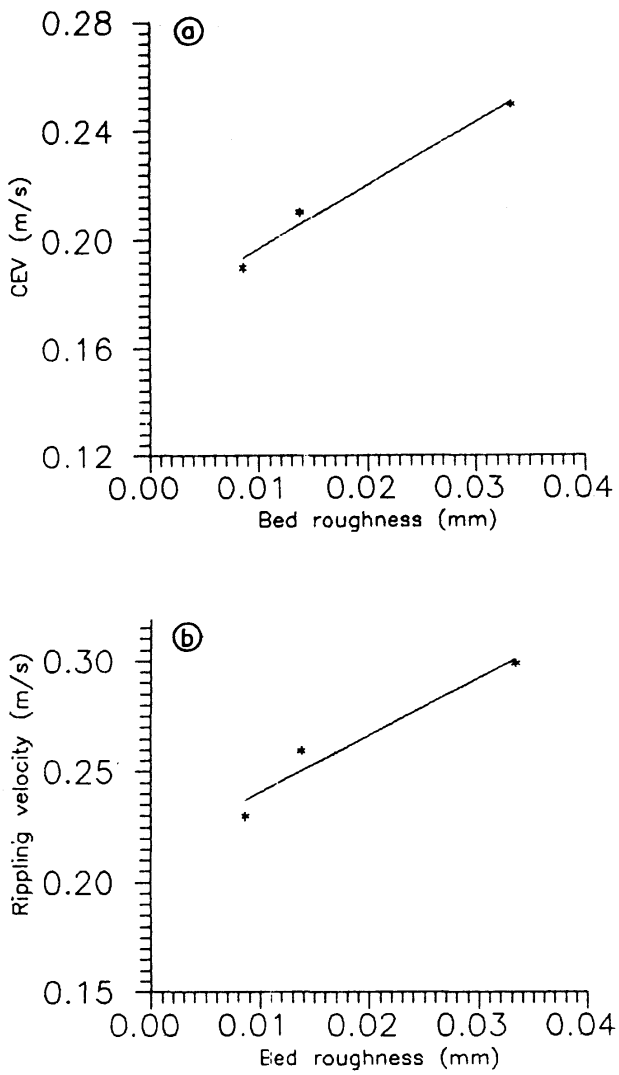

Fig. 9 (a) Bed roughness vs. critical erosion velocity (CEV), (b) bed roughness vs. velocity for initiation of sand ripples

The Effect of Bed Roughness

The influence of bed roughness on sediment transportation was broadly investigated in course of the present experiments. Roughness values of the sediment beds used for the experiments were calculated as $k_s/30$, where k_s is that sieve size of which 65% of the mixture, by weight, is finer[29]. Bed IIT 3.1 was prepared out of bed IIT 2.1 by adding coarser grains to it so as to increase its roughness without altering the modal size of the distribution (Table II). The results of this change on various parameters of sediment transportation are shown in Figs 9a & b. The critical erosion velocity (CEV) needed to move even the finer grains of a heterogeneous sand bed is higher for beds having greater roughness (Fig. 9a). The velocity at which sand ripples were initiated was also higher (Fig. 9b). This was so because increase of bed roughness also involved an increase of the mean grain-size of the bed.

Modification of Grain-size Distribution

It is well known that the patterns of grain-size distribution in river beds get modified with prolonged transportation. The problem received attention of sedimentologists ever since the introduction of the phi (ϕ) scale by Krumbein[30] ($\phi=-\log_2 d$, where d is the grain diameter in mm), when it was discovered that logarithmic transformation of fluvially transported particle sizes lead, in many cases, to a normal distribution even

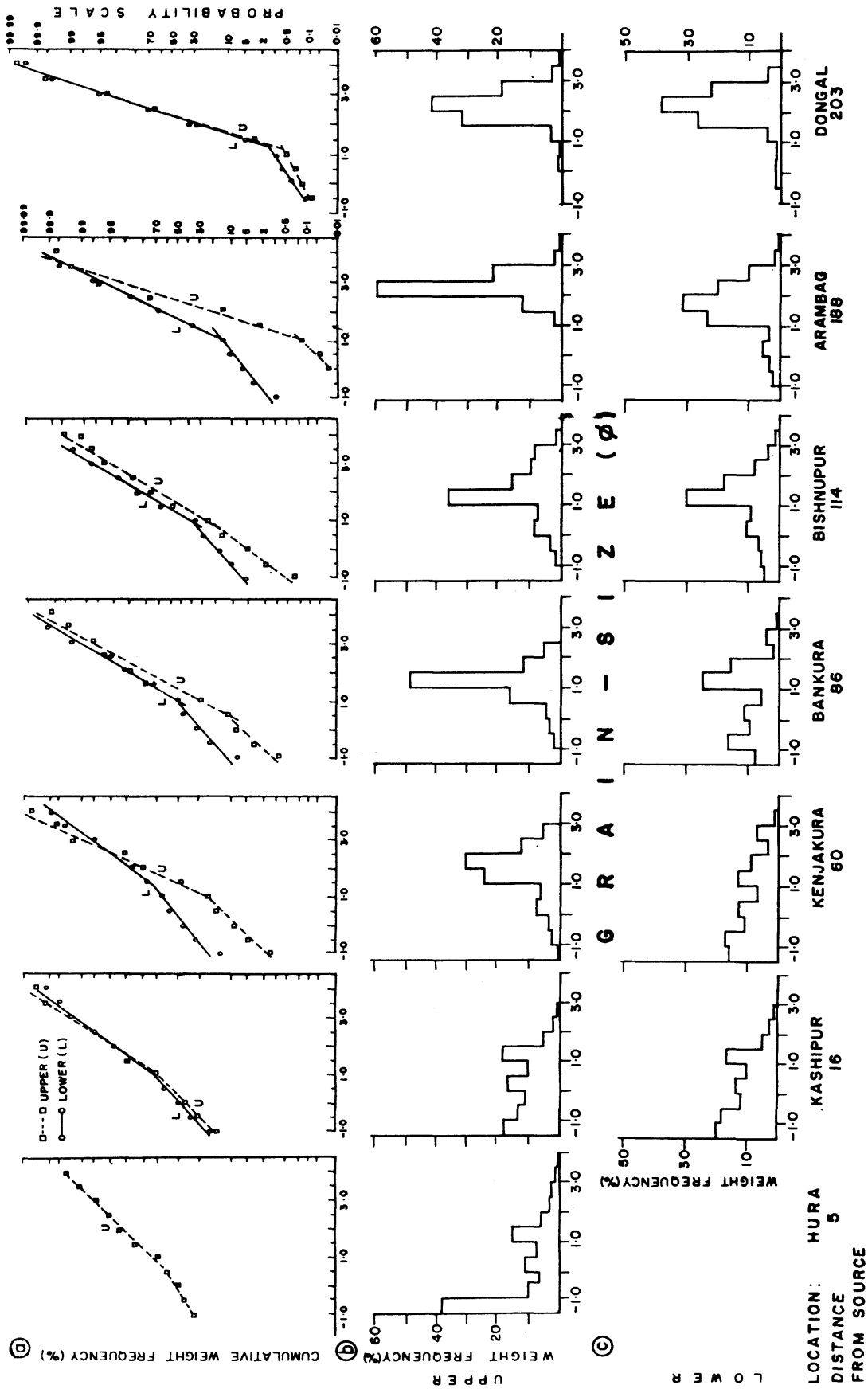

Fig. 10 Downstream change in grain-size frequency distribution of sand at the bed of the Dwarkeswar river (a) probability plots (b) histograms of the samples from the upper layer (c) histograms of the samples from the lower layer

though the materials at the source areas are not normally distributed.

Field Studies

The pattern of histograms of grain-size distribution of the Dwarkeswar River samples (Fig. 10b) suggests progressive development of unimodality and symmetry, the essential criteria for lognormality, with increasing distance of transportation. These visual impressions however, were not enough and further tests were needed to ascertain that lognormality was actually attained with progressive transportation.

It should be noted here that the technique of sieving, used for grain-size analysis, classifies sediment samples according to the total weights of grains within narrow size classes. The resulting distribution is designated `weight frequency distribution'. Since mathematical tests for lognormality of the 'weight frequency' data are not easy, sedimentologists are accustomed to testing the normality of distribution by plotting the cumulative grain-size frequency on a specially prepared graph paper (called the `probability paper') which squeezes the central part of the curve while stretching both the tails to infinity. A symmetrical ogive, which is the cumulative curve corresponding to a normal frequency distribution, thus attains linearity on a probability plot. Better the fit of a straight line through the plots, closer is the match to a perfectly normal distribution. When grain-sizes are plotted on logarithmic (phi) scale on a probability paper a straight line fit indicates that the distribution is lognormal.

Probability plots of the Dwarkeswar River samples are shown in Fig. 10a. Each of these plots shows intersection of two straight lines indicating mixtures of two populations of sand, each of which is lognormally distributed. With increasing distance of transportation a tendency was noticed in these plots to develop into only one lognormally distributed population. For example, 98.4% and 99.5% of the samples collected respectively from the lower and upper layers of the point bar at Dongal, located 203 km from the source area of the river Dwarkeswar, display linearity in probability plots while at a distance of 16 km from the source these proportions are only 27% and 30% respectively. The same feature was also seen in the Usri bed samples collected at increasing distances from the source. Bed samples (USR 43 in Fig. 11), showing mixtures of two linearly distributed populations near the source of the river became nearly perfectly distributed linearly on log-probability graphs after about 71 km of transport (USR 3A).

Log-probability plots of many ancient and recent fluvial sands depict straight line segments which are abruptly joined together. Some examples of such segmented plots from the present day river

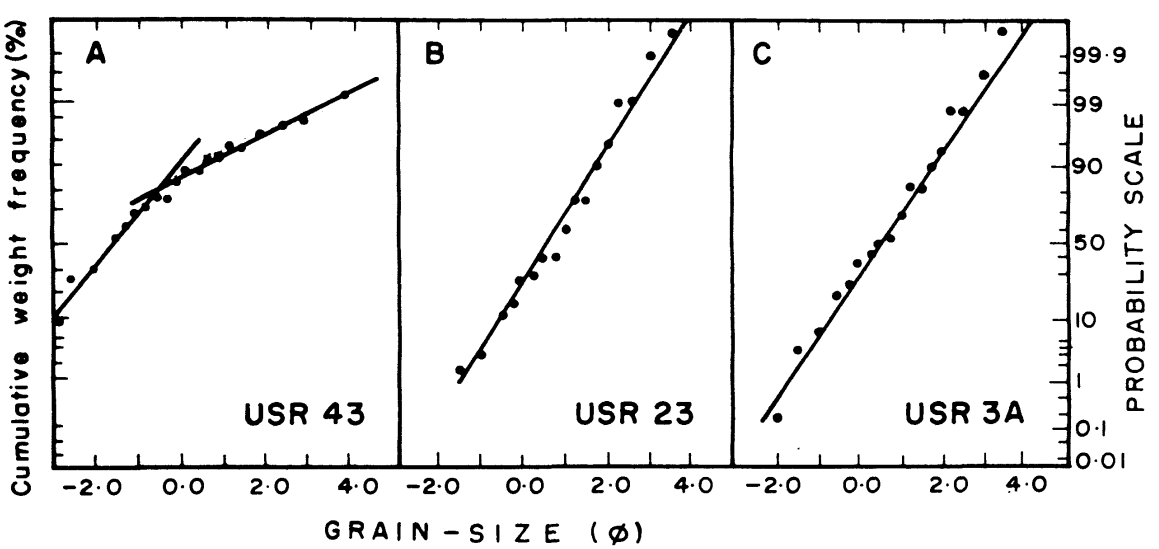

Fig. 11 Grain-size distributions of the Usri river bed samples showing development of lognormality with increasing distance of transportation. Samples collected (A) from the source (B) after 44 km of transport (C) after 71km of transport (redrawn from Sengupta[44])

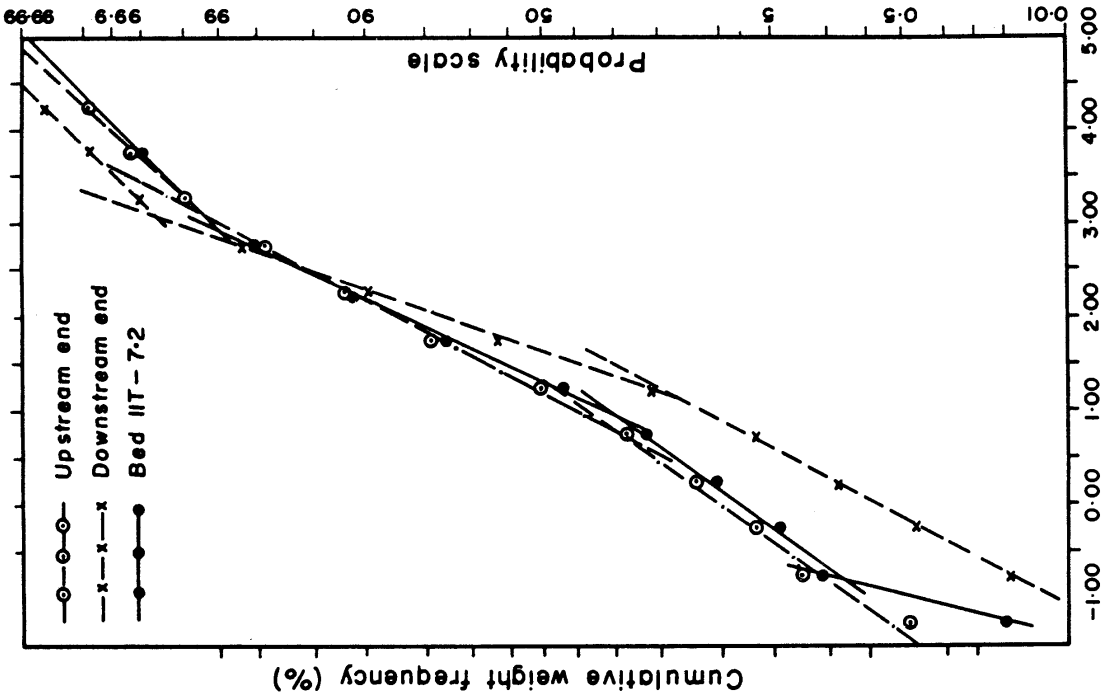

Fig. 13 Log(phi)-probability plots showing modification of grain-size distribution of a fluvial sand (IIT-7.2) after ~10 hours of run in a flume at ~0.5 m/s

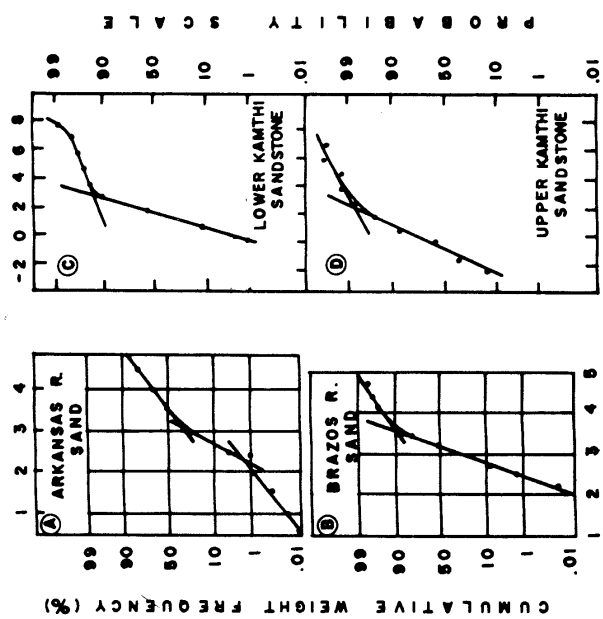

Fig. 12 Probability plots of grain-size distributions of two Recent river sands of USA (A & B after Visher[31]), and two Permian Gondwana (Kamthi) fluviatile sandstones from India (C&D after Sengupta[32])

sands of USA[31] and ancient Gondwana (Kamthi) sandstones of India[32] are presented in Fig. 12. Visher[31], who studied such distributions extensively, inferred that the inflection points in these plots might be related to transport dynamics–the result of intermixing of "traction carpet and saltating sand grains and a suspension population of slightly smaller grains" (compare similar observations by Moss[33]). It was also suggested that such intermixing might be the result of trapping of finer particles in the interstices of coarser grains, or interlamination of two sub-populations of sand.

Generation of Lognormality

The mechanism responsible for modification of grain-size distribution with transportation at bed was also investigated in a laboratory flume. The sand used for these experiments (IIT-7.2) was of fluvial origin. This sand showed mixtures of three linear segments on log-probability plots. Samples collected from the upstream and downstream ends of the sand dunes generated in the flume after about 10-15 hrs of run showed no appreciable change from the initial grain-size distribution (Fig. 13) indicating that short distance transportation is not enough for a drastic modification of the grain-size distribution pattern. The modifications observed in natural stream beds are apparently the effect of transportation over much larger distances. Since experimental studies did not throw light on the mechanism of generation of lognormality the problem had to be approached from a theoretical point of view.

Many attempts have been made from time to time to provide explanation for generation of lognormality with progressive transportation in streams. The phenomenon was attributed, for example, to a process similar to that of crushing of particles for a sufficient length of time[34], to multiple stage abrasion processes[35], or to repeated sorting events[36]. The model proposed by Kolmogorov[34], as early as 1941, assumed progressive change in grain-size distribution following crushing of grains. Assuming that the grains break up physically during transportation, one may, in that case, end up in a lognormal distribution following the Central Limit Theorem. Observations in present day streams, however, do not support the idea of physical attrition. As has been mentioned already, measurements on the Dwarkeswar River samples indicated no appreciable change in roundness and sphericity of the sand grains away from the source area, whereas attrition would have modified these parameters appreciably.

A more plausible explanation for generation of lognormality offered by Ghosh[37] assumed that the process of grain sorting by prolonged transportation over long distances leads to concentration of only a narrow range of grain-sizes in the bed. A rigorous proof for generation of lognormality, in a different context, was provided by Clarke and Ghosh[38]. The assumption of concentration of a narrow range of sizes by a process of sorting due to prolonged transportation in river beds is confirmed by field observations. The coarser grains get buried below the advancing bedforms during transportation, while only the finer ones are carried forward leading to concentration of a narrow range of sizes. This model can be used as an explanation for the lognormality observed in the Dwarkeswar and the Usri river bed samples.

In a separate study[39], following the line of argument provided by Barndorff-Nielsen[40], it was suggested that lognormal distribution in the stream bed samples of the Usri River developed as special cases of hyperbolic distribution by a process of grain sorting during prolonged transportation downstream. However, it remains to be seen if mixtures of three linear segments in log-probability plots, found in some stream bed materials (see, for example, Fig. 13), can also be explained by the hyperbolic model.

A question may be raised at this stage about preservation of the lognormal grain-size distribution generated in a stream bed by a process of grain sorting. How is it that lognormality, once attained, does not change with further transportation downstream? Flume studies conducted in a different context[41] demonstrated that prolonged exposure to a particular flow condition brings an end to the sorting process as the subaqueous angle of repose of a dune attains its limiting value (35°)[42]. At this stage the dimensions of bedforms also do not change till the flow parameters are altered. In an analogous situation in a natural stream the grain-size distribution attained at a certain distance from the source, under a particular flow condition, will be preserved as long as the

hydraulic parameters remain stable. However, as will be discussed later, this argument does not apply to grain-size distributions of suspension loads generated in natural streams.

Transportation in Suspension

Grain-size frequency distributions of particles in suspension could hardly be studied in natural streams because of the difficulties involved in collecting samples of suspension load from rivers which are in spate. The problem of size sorting during suspension transportation was therefore, investigated under controlled conditions in laboratory flumes. Hydraulic flumes of uncommon designs were required for conducting these experiments. Following is a brief account of the type of equipment used for the experiments.

Equipment & Methodology

In hydraulic flumes of conventional design water flowing through the experimental channel from an overhead tank is stored into an underground reservoir from where it is pumped back to the overhead tank (Fig. 14a). These flumes, although often used for conducting experiments on bed load transportation, are unsuitable for simulation of fluvially transported suspended loads because a suspension, generated within the experimental channel at a high flow velocity, will be lost as soon as the flow gets into the settling tank. Kuenen[43] used circular flumes (circular in plan) for generating suspension loads of high density within closed systems. However, centrifugal forces and spiral motions developed within such flumes caused problems which were difficult to tackle.

To improve on this situation a number of recirculating, 'close-circuit' flumes were designed in different laboratories. Two such flumes, constructed in the Department of Physical

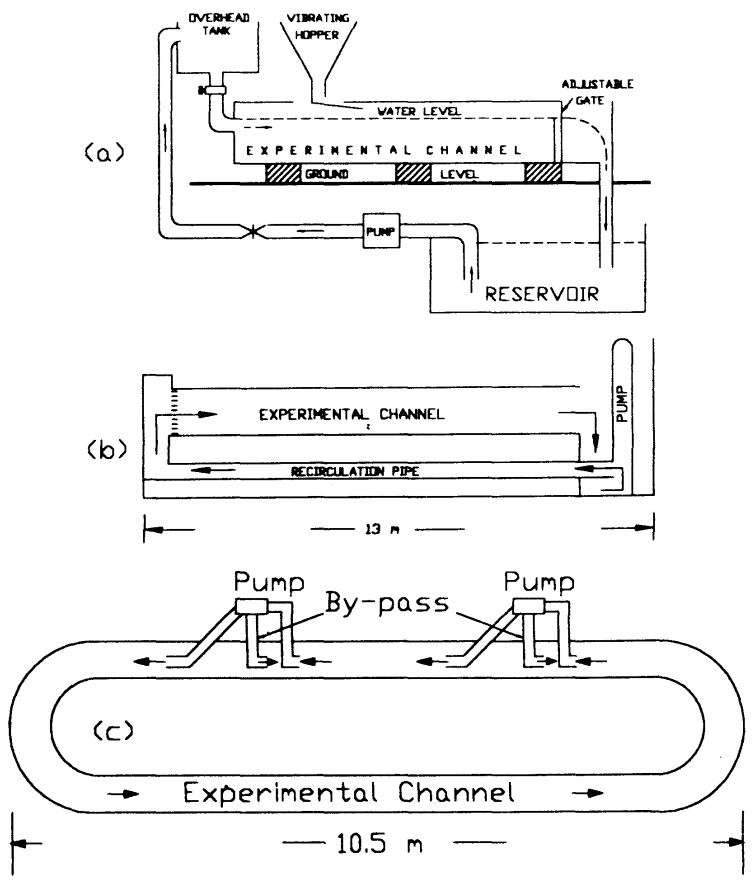

Fig. 14 Schematic diagrams of hydraulic flumes of different designs: (a) a flume of conventional design (b) a close-circuit' flume constructed at the Uppsala University, Sweden (c) a `close-circuit' flume constructed at the Indian Statistical Institute (ISI), Calcutta

Geography, University of Uppsala, were described earlier[44-46]. The more efficient one of these two had a straight, 10 m long experimental channel with a width of 60 cm, and a height also of 60 cm (Fig. 14b). Two submersible centrifugal pumps, each having a discharge capacity of about 80 l/s maintained an endless flow within this channel. The speed of water flowing through the experimental channel could be set anywhere between 20 and 150 cm/s. Suspended sediments could be drawn from any desired height by inserting draw tubes through the bottom of the experimental channel.

Experiments on suspension in this flume were conducted with sand beds of five different grain-size distributions: bimodal, with a coarse mean size (bed 0), positively skewed (bed 1), nearly uniform (bed 2), bimodal with medium mean size (bed 3), and negatively skewed (bed 4). Suspension loads generated over these sand beds at various flow velocities and heights above the base were sampled, dried and analysed by sieving.

Recirculation in the Uppsala flume was effected with the help of two metal pipes, each of 10 cm diameter, placed below the experimental channel. The cross-sectional areas of these pipes, being much smaller than that of the experimental channel, a sharp drop in flow velocity took place as soon as the flow entered the experimental channel. Consequently, a part of the sediment transported through the pipes was dumped at the entrance of the flume channel during the experiments.

An improved version of a `close-circuit' flume, with experimental and recirculation channels of equal width (50 cm), was constructed at the Indian Statistical Institute (ISI), Calcutta (Fig. 14c). Recirculation of water in this flume was effected with the help of two centrifugal pumps located outside the channel. By manipulating the valves in the outlet and the bypass pipes the flow could be set at any desired speed up to a maximum of 125 cm/s for a water depth of 30 cm. Experiments were performed in this flume with beds of polymodal grain-size distribution. The flow velocities at Uppsala and Calcutta were measured by Ott laboratory type current meters.

The experiments conducted at Uppsala and Calcutta provided useful information on the nature of grain-size distribution in suspension with respect to the bed material, height of suspension and flow velocity but the mechanisms responsible for grain suspension still remained unclear. This was investigated by a series of experiments conducted in a newly designed, `close-circuit' flume at the Department of Ocean Engineering & Naval Architecture, IIT, Kharagpur. This fully transparent, all perspex flume allowed continuous monitoring of the process of sediment transportation at different flow velocities. This flume has a straight experimental and a tapering

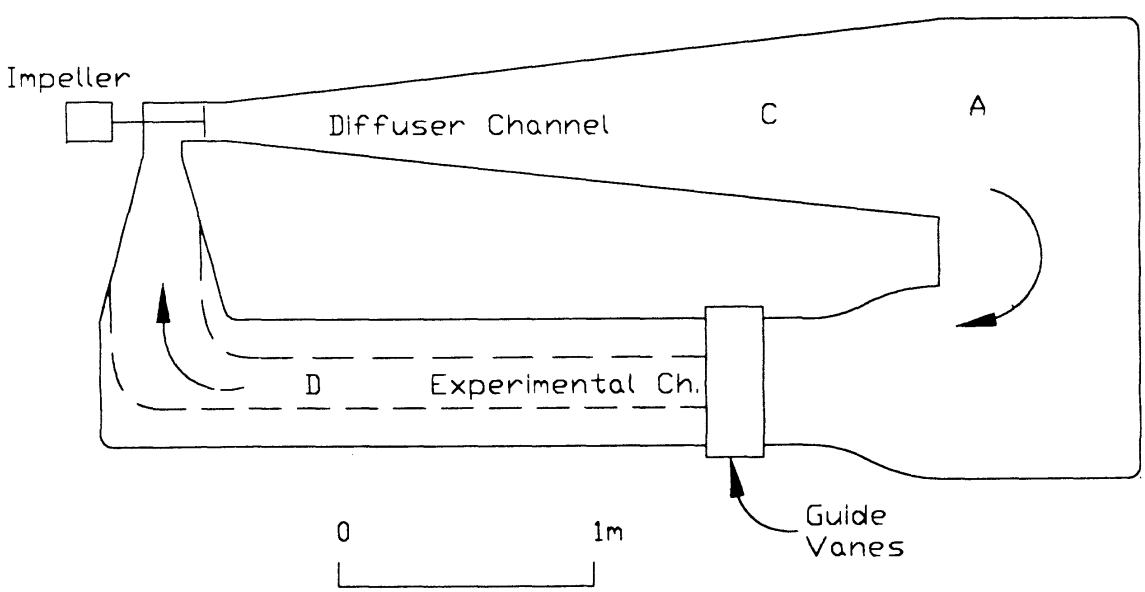

Fig. 15 Schematic (plan) view of the newly constructed `close-circuit' hydraulic flume at the Department of Ocean Engineering & Naval Architecture, IIT, Kharagpur. A, C, and D are locations for sampling in experiment X1

Fig. 16 Photograph of the flume shown in Fig. 15, viewed from the diffuser side

Table III

Weights of Sediments in Suspension and Deposits in Experiment IV.

Sandbed: IIT-2.1. Initial bed thickness 3cm. Initial water depth 20.2 cm.

v (cm/s)	28.0	28.0*	32.0	32.0	32.0*	32.0	32.0*	39.0	39.0*
h (cm)	7.5	-	5.0	10.0	-	7.5	-	7.5	-
Bed	rippled	-	rippled	rippled	-	rippled	-	rippled	-
S/D	S(E-ch)	D	S(E-ch)	S(E-ch)	D	S(E-ch)	D	S(E-ch)	D
Gr.size (mm)	1	2	3	4	5	6	7	8	9
1.40									0.0067
1.00									0.0421
0.71			0.0010	0.0004	0.0198			0.0023	0.1257
0.50		0.0042	0.0028	0.0024	0.0410	0.0009	0.0104	0.0022	0.7031
0.36	0.0039	0.0109	0.0090	0.0045	0.1642	0.0015	0.0157	0.0244	3.2990
0.25	0.0066	0.0447	0.0708	0.0124	2.1688	0.0158	0.0844	0.1788	29.3813
0.18	0.0062	0.0564	0.1748	0.0235	7.1858	0.0251	0.2161	0.2904	39.2025
0.13	0.0065	0.0570	0.1906	0.0471	7.8440	0.0298	0.3119	0.2097	22.7774
0.09	0.0043	0.0322	0.0764	0.0283	2.6863	0.0171	0.2112	0.0995	5.7519
0.06	0.0039	0.0166	0.0339	0.0217	0.9244	0.0125	0.0879	0.0399	1.5481
0.05	0.0024	0.0130	0.0246	0.0175	0.3340	0.0082	0.0595	0.0386	0.4104
0.01**	0.0420	0.0264	0.2156	0.1885	0.5052	0.0959	0.1218	0.4078	0.5765
Total	0.0758	0.2614	0.7995	0.3463	21.8735	0.2068	1.1189	1.2936	103.8247

Note: All sample weights are in gms. Volume of sample collected=10 litres in each case unless otherwise mentioned. V=maximum flow velocity (cm/s). Initial water depth and height of sampling (h) were measured above flume base in cm. S(E-ch)=suspension sample in experimental channel. D=deposits in diffuser channel collected after several minutes. D(imm)=immediate deposits in diffuser channel.

*Corresponding velocity in experimental channel, estimated velocity in diffuser channel was about $1/10^{th}$ of the velocity.

**Includes all grains <0.05 mm.

diffuser channel (Figs. 15 & 16). The width of the experimental channel, about 48 cm initially, was reduced to 20 cm in some experiments by partitioning in order to increase the flow velocity. The width of the diffuser channel however, remained 74 cm at the sampling point althrough. The diffuser section was of greater depth than the experimental channel and hence contained a much larger volume of water. Consequently, a sharp drop in velocity took place in the diffuser channel, depositing a large part of the suspended load. This allowed *simultaneous* sampling of the suspended load and deposits from two different arms of the flume—a facility not available in flumes of any other design.

Experiments were performed in this flume with sand beds of five different grain-size distributions (IIT-1.1 to 4.1 in Table II). In each case a sand bed

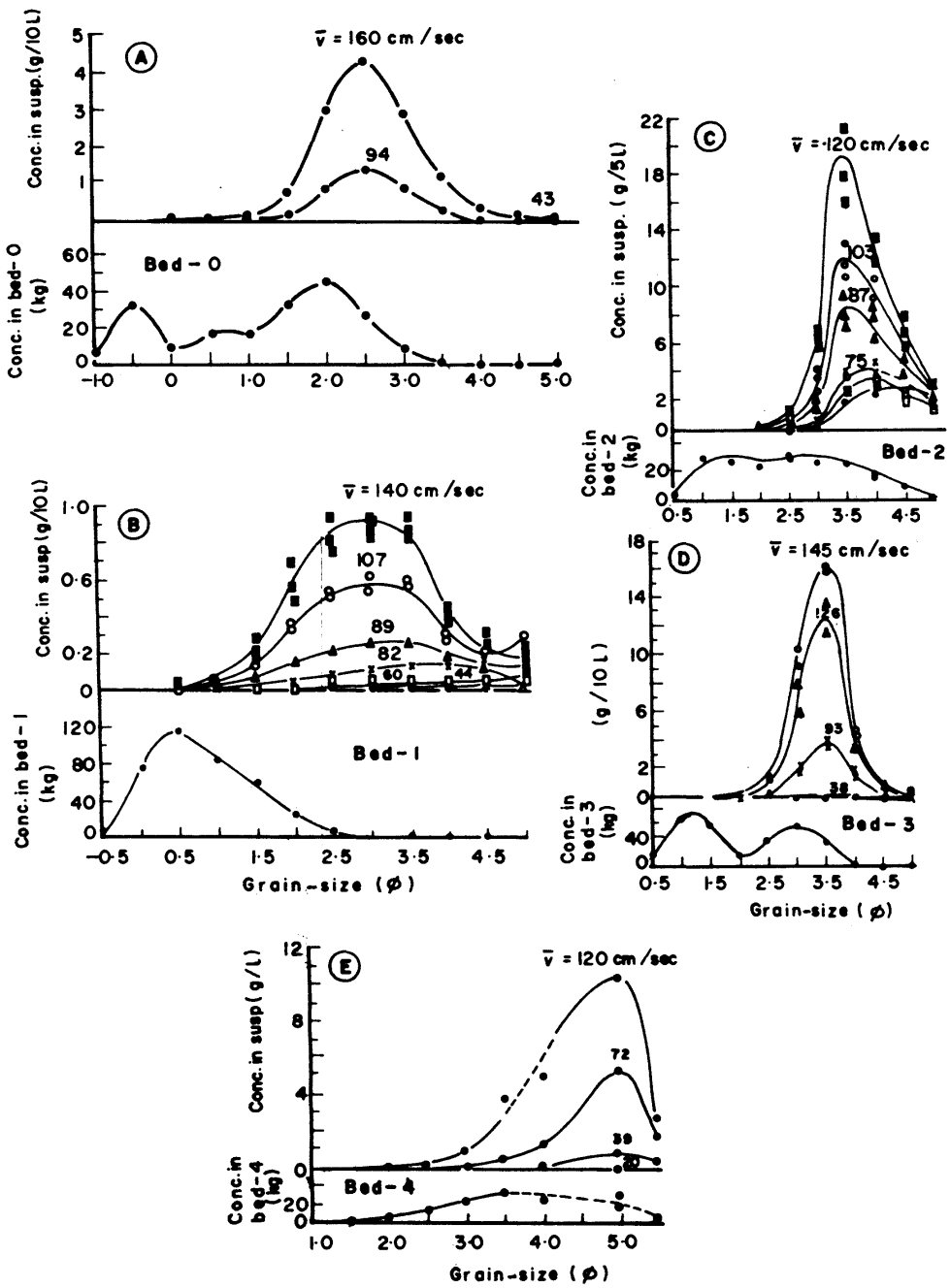

Fig. 17 Results of the Uppsala experiments. Grain-size distributions in suspension at 20 cm above sand beds of different types at various flow velocities (redrawn from Sengupta[44-46])

of small thickness (2.0-5.5 cm) was placed on the experimental channel of the flume and samples of suspension load generated over this bed at known heights and flow velocities were siphoned out and analysed by sieving after evaporation of water. The flow velocities were measured either by an Ott or by a Lynx laboratory current meter recalibrated at IIT, Kharagpur.

Results of Experiments

The results of all the experiments conducted at Uppsala are summarised in Fig. 17. Irrespective of grain-size distribution in the bed, the distribution in suspension was always unimodal and also nearly symmetrical when plotted in logarithmic (phi) scale. Moreover, the concentration in suspension always increased with increase of flow velocity. At appropriate combination of height and flow velocity the suspended load depicted the degree of symmetry and peakedness (skewness = 0, kurtosis=3) necessary for lognormality. In fact, nearly 95 to 98% of the suspended load produced at a high flow velocity (>120 cm/s) displayed linearity in phi-probability plots suggesting that log-normality was attained when the process of grain sorting was completed (Fig. 18).

The results of experiments conducted at IIT, Kharagpur are presented in Tables III to VIII. Some representative plots of these data are shown in Figs. 19 and 20. Broadly speaking the results of these experiments are similar to those noted at Uppsala. As in the Uppsala experiments, height remaining constant, the concentration in suspension increased with increase of flow velocity (see columns 1, 6 and 8 of Table III). For comparable flow velocities, concentration decreased with increase of height of suspension (compare, for example, columns 3 and 4 of Table III, columns 1 and 2 of Table VI). At any particular flow velocity the proportion of the coarser grains was higher at the lower heights of suspension and that of the finer fraction was lower. This relationship was reversed at greater heights of suspension. In each case, irrespective of the nature of the grain-size distribution of the bed, the suspension load was unimodal, with the mode approaching, within

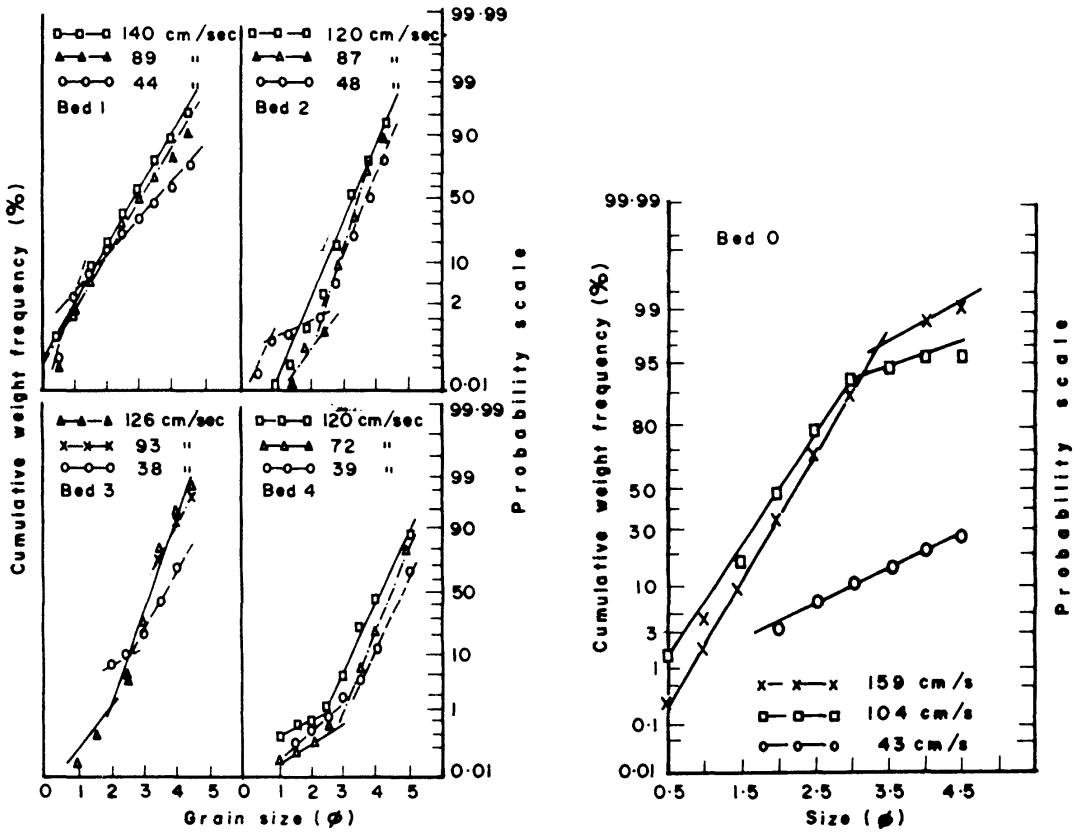

Fig. 18 Log-probability plots of the suspension load samples shown in Fig. 17

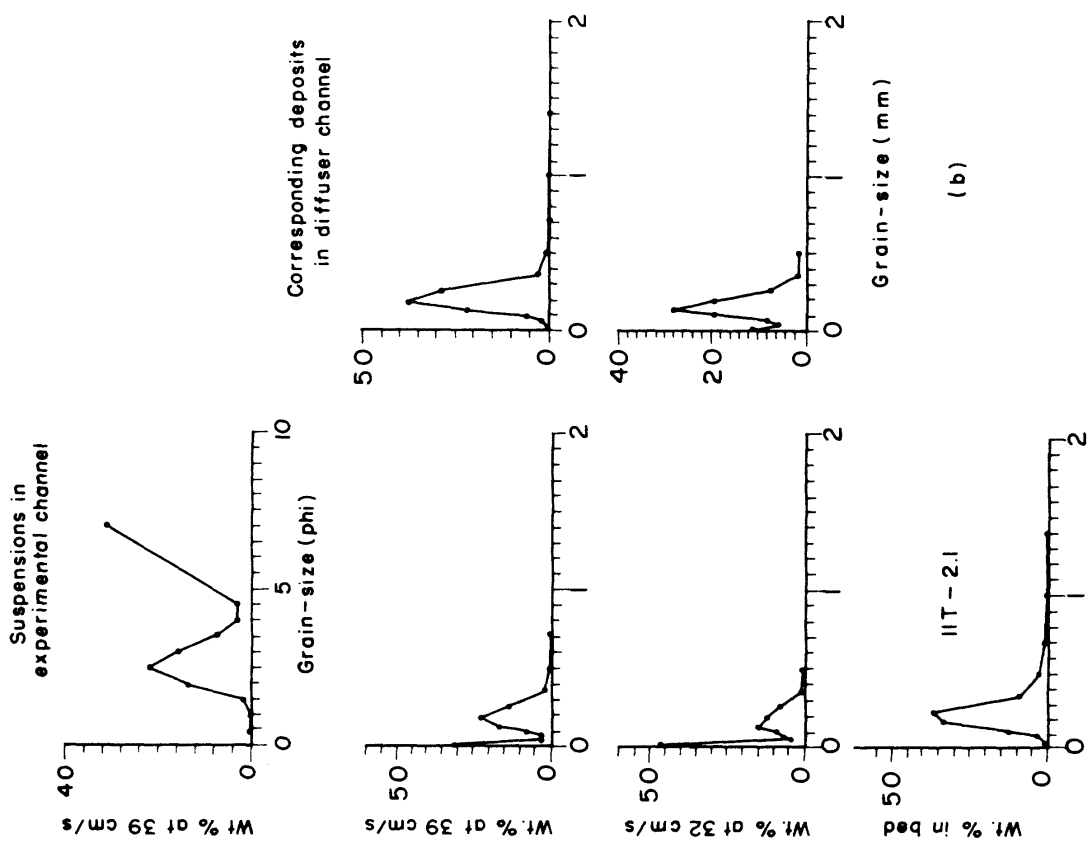

Fig. 19 Grain-size distributions of the suspension loads at different flow velocities at 7.5 cm above sand bed No. IIT-2.1 and the corresponding deposits in the diffuser channel (experiment IV, Table III)

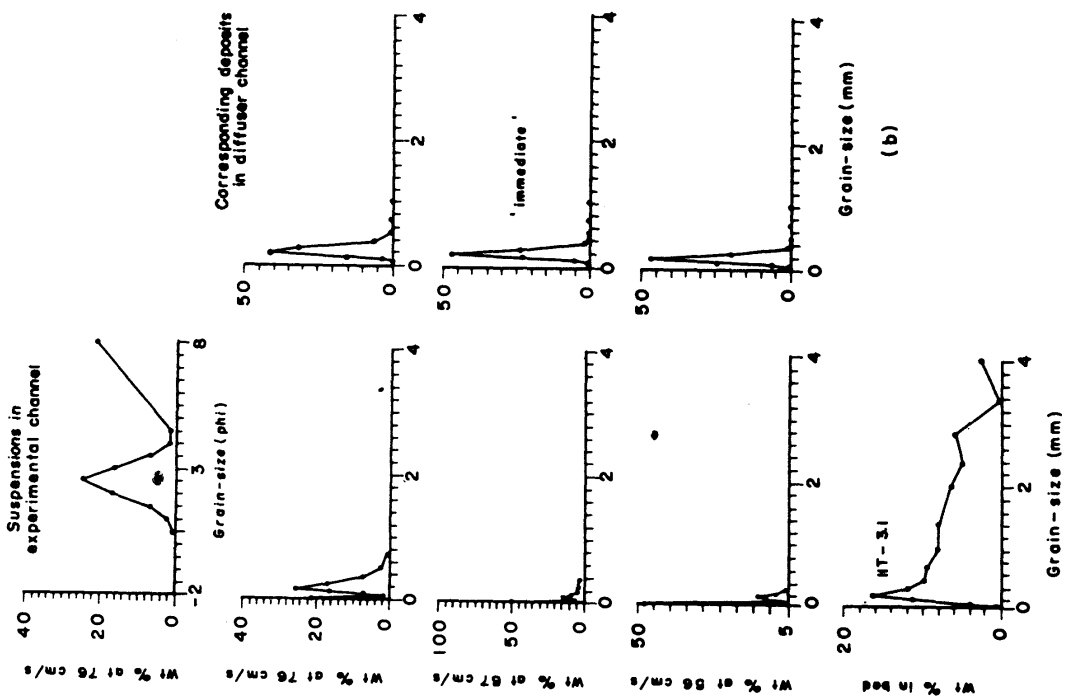

Fig. 20 Grain-size distributions of the suspension loads at different flow velocities at 6.0 cm above bed No. IIT-3.1 and the corresponding deposits in the diffuser channel (experiment VI, Tables V and VI). 'Immediate' refers to the sample collected as soon as it was deposited

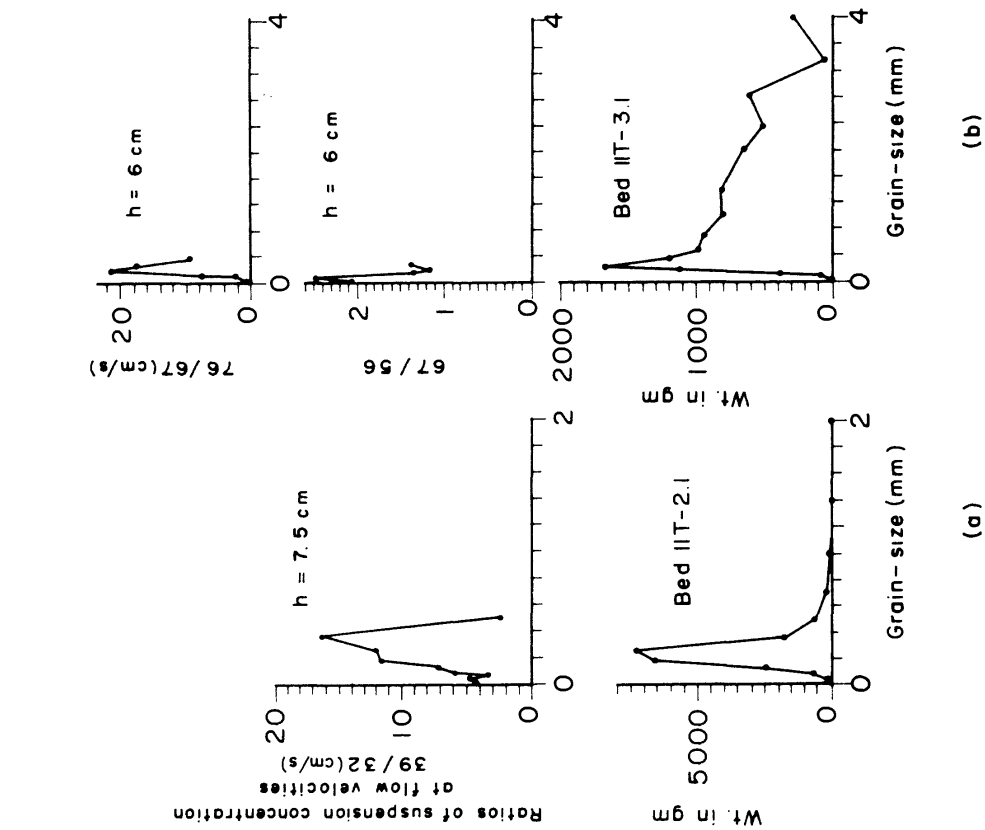

Fig. 22 Ratios of suspension concentration with increase of flow velocity above sand beds (a) IIT-2.1 (b) IIT-3.1

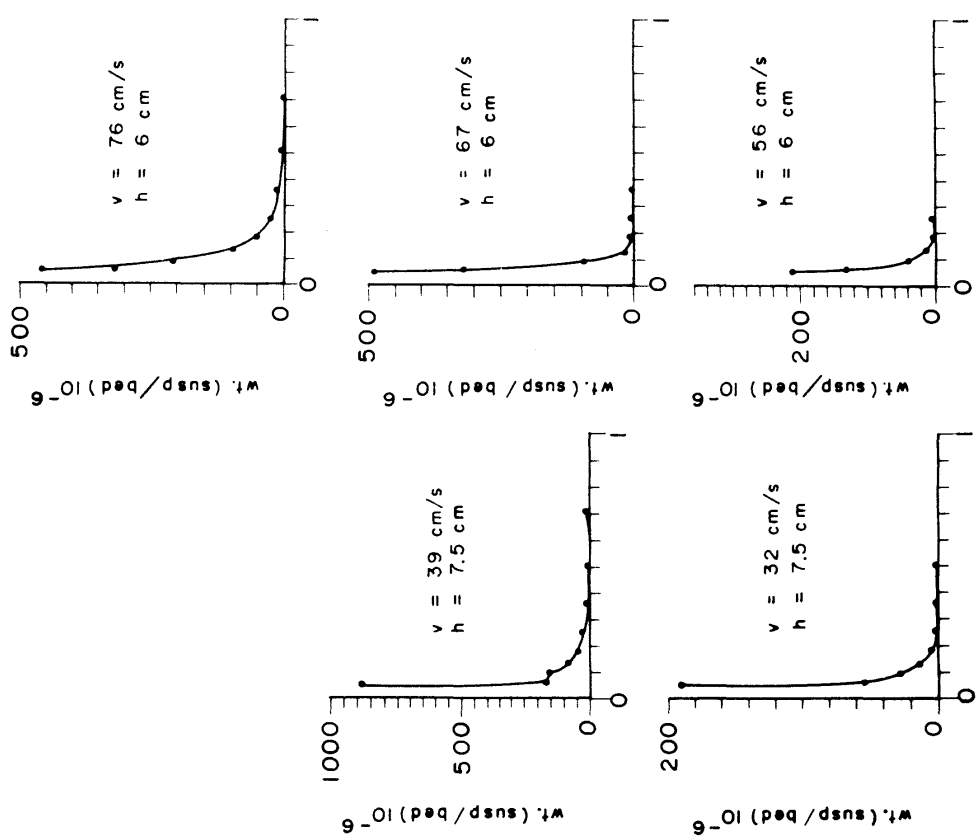

Fig. 21 Proportion of bed materials taken into suspension over sand beds (a) IIT-2.1 (b) IIT- 3.1.

limits of experimental error, the modal grain-size of what was available in the bed Figs. 19 & 20. The exceptions to this rule were mainly due to experimental errors—the sample size being very small, precise measurement of the sieve fractions was difficult in some cases. It must also be remembered that the second modes in the finest size grade in these figures are not real—these being the cumulative weights of all grains finer than 0.045 mm (>4.5ϕ).

The most interesting fact revealed by these experiments is that the current was never filled to capacity by the finest grains only although these were abundantly available in the bed. In each case a significant proportion of what was available in the bed in large quantity also went into suspension together with the fines. Hence the suspension load was dominated by the grains corresponding to a size that was intermediate between the finest size available and also the modal size of the bed material. This was brought out by plots of the proportions of bed materials in suspension at known heights (Fig. 21a & b). The plots of the ratios of suspension concentration at successively increasing flow velocities also confirmed that with each increment of velocity the fraction which went into suspension in the largest quantity was closest to the one most freely available in the bed (Fig. 22 a & b). Slight shifts in the modal size of the suspension load from the mode of the bed material, noticed in these diagrams, are presumably due to the limitations of the sampling facility—the intake velocity in the sampling tube being not always the same as the flow velocity in the flume.

The phenomenon of sediment suspension has been traditionally described in terms of capacity

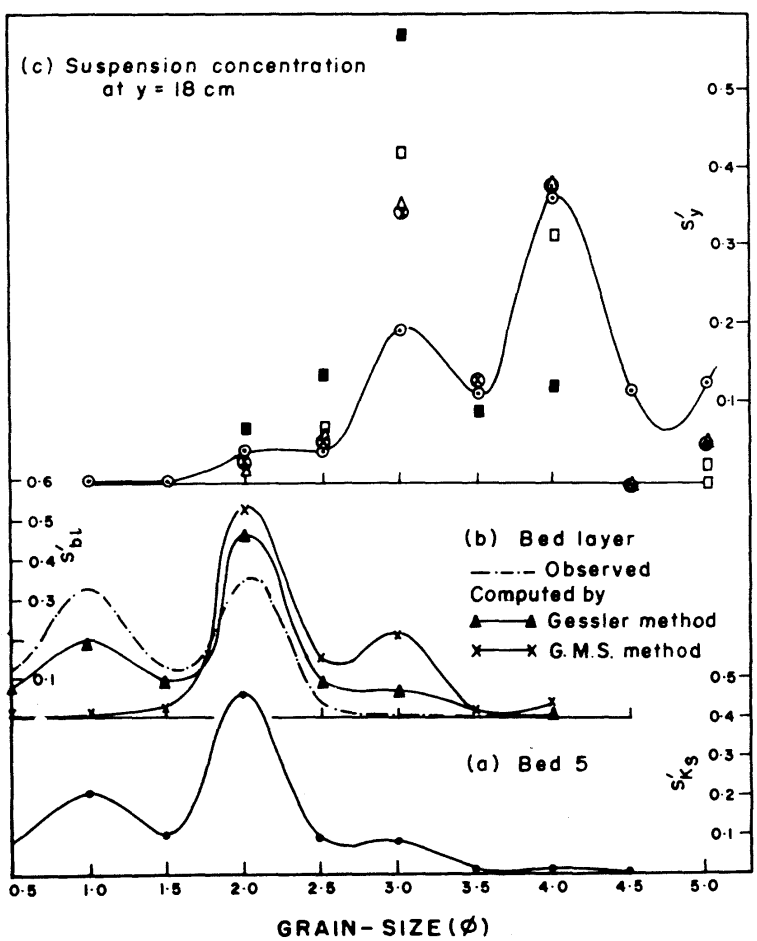

Fig. 23 Grain-size distributions in: (a) the bed (b) bed layer, and (c) suspension above bed no. 5. ⊙ observed, ⊗ computed[55], △ computed (Gessler and Rouse equations), ■ computed by Einstein (with ξ-correction) and Rouse equations, □ computed by Einstein (without ξ-correction) and Rouse equations (redrawn from Ghosh *et al.*[55])

(the amount, kept in suspension, expressed in gm/l), and competency (the coarsest grain in suspension). The present set of experiments shows that availability also plays an important role in controlling the grain-size distribution of the suspension load-the grains moved at the bed layer and taken into suspension in large quantities, are the ones most freely available in the bed, provided the current is competent to lift them.

The stages of sorting leading to concentration of particular grain-size distributions in suspension were investigated at ISI, Calcutta. The sand bed used for this study was a specially designed, bimodal one, covering a large range of grain-sizes (bed 5, Fig. 23). These experiments demonstrated that sorting in suspension takes place in two stages. At or near the bed layer, which is defined as a `two grain diameter thick flow layer immediately above the bed'[29], the grain sorting is controlled mostly by availability, provided the current is competent to move all the grains present in the bed. This is shown by the presence of both the modal sizes in the bed layer. The distribution at this level could be closely approximated by one of the well known bed load equations[29,47]. The finer one of these two modal sizes has a greater influence on suspension because it is easier for the vertical component of a turbulent flow to counteract the settling velocity of the finer grains. This conclusion was confirmed by carrying out the same exercise on one of the bimodal beds used for the Uppsala experiments also[55].

The physical process of grain sorting responsible for the observed grain-size distribution in suspension was monitored in course of the experiments conducted at IIT, Kharagpur. The flat sand bed with which each experiment was initiated, was converted into a series of rhythmic bedforms soon after the entrainment velocity was exceeded. Sediments transported over the gentler stoss faces of these bedforms sorted out into two fractions on reaching the ripple crests. While the coarser grains slided down the lee faces, the relatively finer ones went into suspension in the form of jets (Fig. 24). The grain-size which dominated these jet streams was the one corresponding to the modal size of the bed material, these being available in large quantity at the crests of the sand ripples. In each case, the modal sizes of the suspension load and that of the sediments ejecting out of the ripple crests matched closely whereas the materials accumulating at the toes of the sand ripples were coarser (Fig. 25). Apparently, the coarser grains sliding down the lee faces got buried below the advancing bedforms. Endo *et al.*[48] obtained similar results by allowing sediments to flow over an artificially created micro delta. The experiments conducted at IIT suggest that such micro deltas or sand dunes generate over flat sediment surfaces in course of sand movements by unidirectional flows. This process is presumably active in natural streams also.

Macroturbulent events, popularly known as `kolks' or boils, have been, for a long time, thought

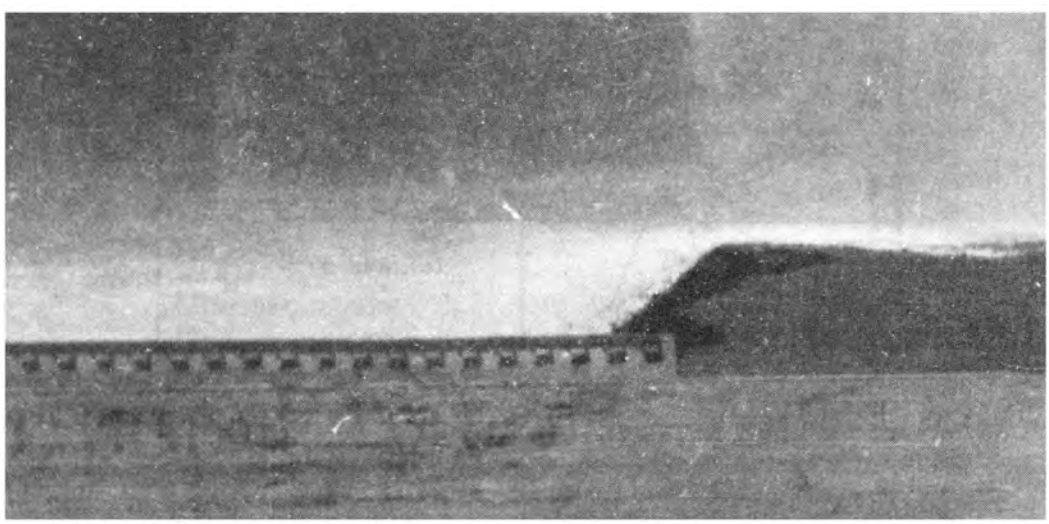

Fig. 24 Photograph showing ejection of sediments into suspension from the crest of a sand dune generated in the flume. Scale in cm. Flow from right to left.

to be responsible for the process of sediment suspension[49-51]. More recent studies by Bennett and Best[52] suggest that the dune related macroturbulent events are likely to be the result of 'Kelvin-Helmholtz instabilities' developed at the zone of flow separation in front of ripple lee. Through an ingenious set of experiments these authors have been able to document the 'ejection events' associated with this zone of instability. These are similar to the 'ejections' photographed during the current experiments.

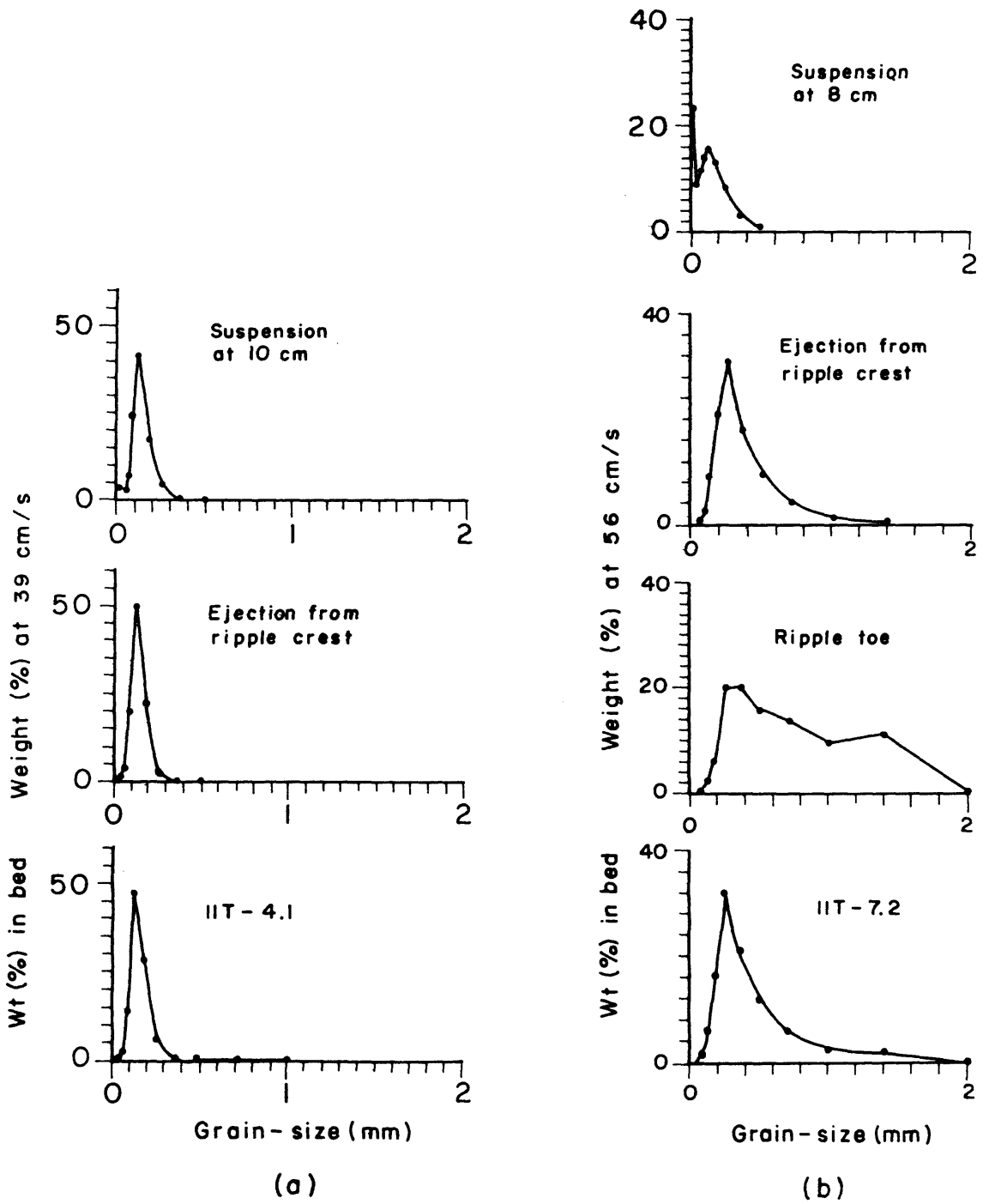

Fig. 25 Diagrams illustrating close match between grain-size distributions of sediments ejected out of the crests of sand ripples and the suspension loads over sand beds (a) IIT-4.1 (b) IIT-7.2. The sediments accumulated at the toes of the ripples were coarser (experiments VII & X, Tables VI and VII)

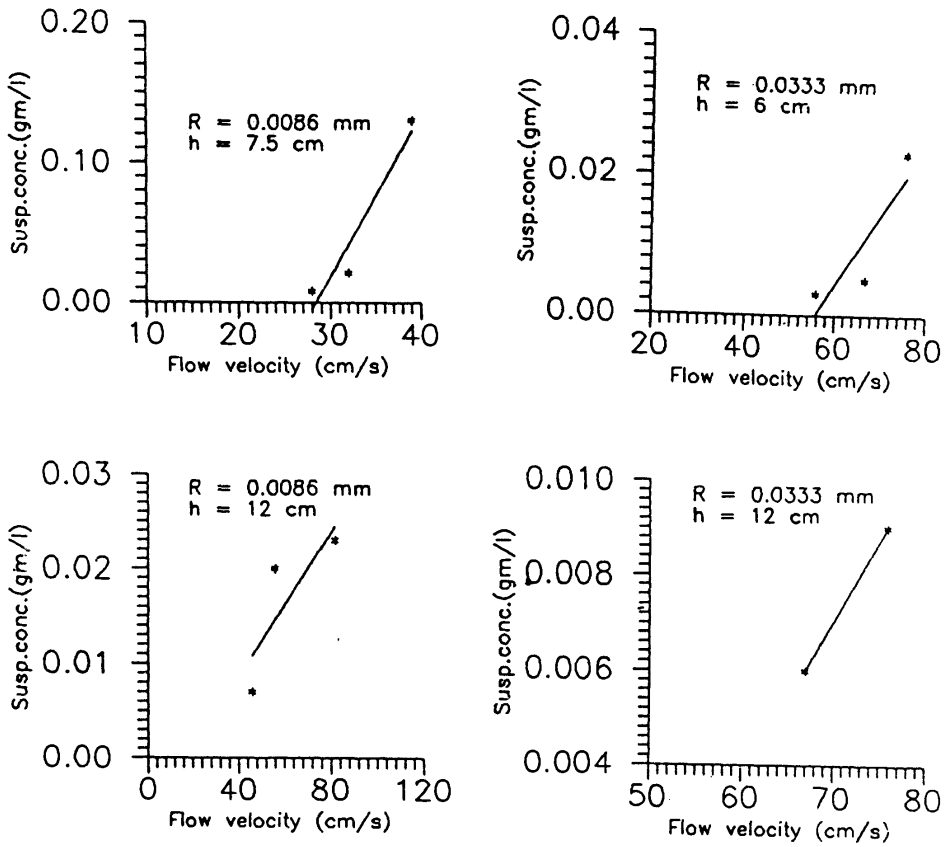

Fig. 26 Flow velocity (cm/s) vs. suspension concentration (gm/l) at various heights of suspension (h) for different values of bed roughness

Influence of Bed Roughness on Sediment Suspension

The influence of bed roughness on suspension concentration was investigated during the present set of experiments by comparing the suspension loads over two beds, IIT-2.1 and IIT-3.1, which have the same modal size but different values of roughness. Fig. 26 shows plots of suspension concentration (gm/l) against flow velocity arising out of these experiments. At comparable heights of suspension a higher flow velocity was needed for suspending comparable amounts of sediments when bed roughness was increased (compare a & b; c & d of Fig. 26).

Modelling the Suspended Load

Flume experiments demonstrate that the controlling factors in sediment suspension are: grain-sizes of the particles available, flow velocity, and height of suspension. The way these parameters influence a suspension load is brought out by the equation of relative suspension concentration of Rouse[53]. This equation assumes that in a turbulent flow the grains are kept in suspension by the vertical component of turbulence which counteracts the fall velocity of the particle concerned. The equation allows computation of suspension concentration at any desired height (y) when the concentration at a reference level (a) is known:

$$\frac{c_y}{c_a}=\left(\frac{d-y}{y}\cdot\frac{a}{d-a}\right)^z \qquad \ldots (1)$$

The exponent z in this equation is given by $v_s/\chi u_*$, where c_y and c_a are sediment concentrations at heights y and a above the bed respectively, d is the total depth of water, v_s is the settling velocity of the grain, u_* is the shear velocity, χ, the von Kármán constant, is given by 0.40.

Various other expressions for the exponent z of this equation are also known. In the form proposed by Sundborg[3], $z=6.25c \ln (d/z_0)/U_{max}$, where U_{max} is the maximum velocity in the profile, c is the

settling velocity of the grain, z_0 is a measure of the roughness of the bed given by $k_s/30$[29]. The Rouse equation provides a simple method for estimation of the concentration of the suspension load. The method is applicable to natural streams also.

A good fit between the computed and observed data in case of the Uppsala experiments (Fig. 27) convincingly demonstrates the applicability of the Rouse equation in computing suspension loads at levels located not too near the bed. Traditionally, computation of the suspension load, using this equation, has been done in two stages—firstly from the bed to bed layer, and secondly, from the bed layer to suspension.

A formula, developed in partial modification of a method proposed by Hunt[54], now affords direct computation of the bed and the suspended loads from the bed's grain-size distribution, given the flow parameters[55]. This formula for computing the suspended sediment concentration (s_y) is given by:

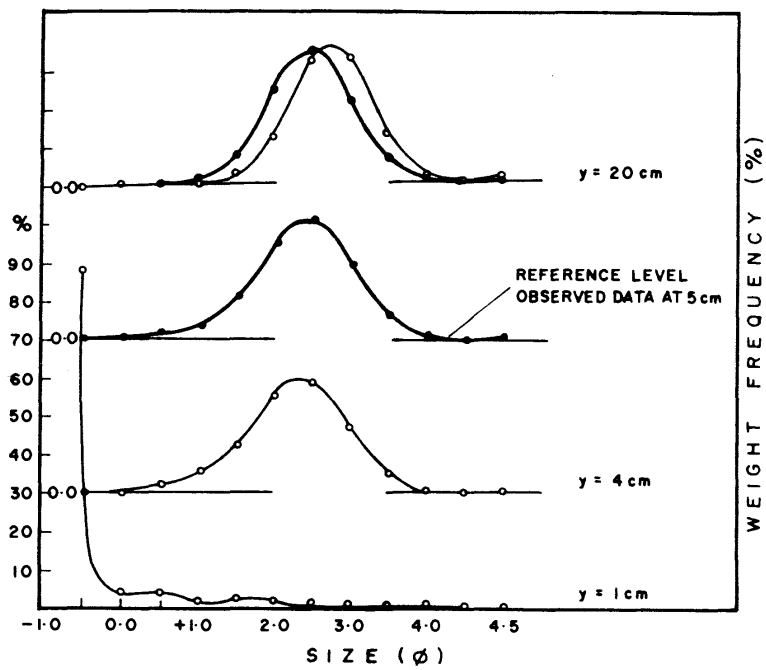

Fig. 27 Close match between the observed and computed (by Rouse equation) suspension concentrations in the Uppsala experiments (redrawn from Sengupta[44]). Thick lines represent observed and thin lines the computed values

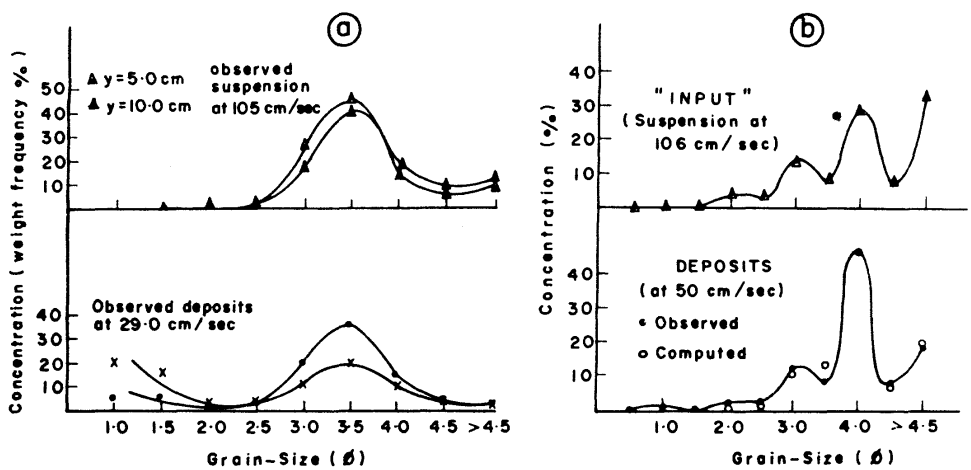

Fig. 28 Deposits from suspension in the experiments conducted at (a) Uppsala (b) Calcutta (redrawn from Ghosh *et al.*[58])

$$\log_e \frac{S_y\,(1-S_{ky})}{S_{ky}\,(1-S_y)} = K_1 \log_e \frac{(d-y_1)}{(d-k_s)} + K_2 \log_e \frac{\sqrt{(1-y/d)}}{\sqrt{(1-y_1/d)}} \times \frac{B-\sqrt{(1-y_1/d)}}{B-\sqrt{(1-y/d)}} \quad \ldots (2)$$

where $K_1 = \frac{c(\phi)\,du_{y1}}{(u_*)^2\,(y_1-k_s)}$, $K_2 = \frac{c(\phi)}{B\chi u_*}$.

Hence the relative sediment concentration at height y (S'_y) is given by:

$$S'_y = \frac{S_y(\phi)}{\Sigma_\phi S_y(\phi)} \quad \ldots (3)$$

(explanation of notations in the Appendix).

With the help of this equation it is possible to calculate the suspension concentration of materials of a particular size at any height $y > y_1$ above the bed if its concentration in the bed (S_{ky}) is known. The efficiency of this theoretical model was tested by comparing the observed and computed suspended load concentrations over three different sand beds used in the Uppsala and Calcutta experiments[55]. The method seems to be as good as any other method for computation of suspended load (Fig. 23). The applicability of this equation was further tested in a natural stream—the Niobrara river, Nebraska, USA where observed data for suspension load are available[56]. The computed and the observed distributions, particularly, the modal sizes, match well[39].

Generation of Lognormality in Suspension

The process of grain sorting may lead to the development of lognormal grain-size distribution in suspension even when the source (bed) materials are not lognormally distributed. That lognormality may actually be attained in this way is seen from Fig. 18, redrawn from results of the experiments conducted at Uppsala. More than 90% of the materials collected from suspension here are linearly distributed on log (phi)-probability plots, whereas the corresponding bed materials (beds 0-4) did not have lognormal distribution. It was shown elsewhere[39] that lognormality in these cases developed at a high flow velocity as a special case of hyperbolic distribution through a process of grain sorting. The symmetry in grain-size distribution pattern, brought about by logarithmic (phi) conversion, could also be responsible for creating the impression of lognormality (compare, for example, the topmost curves in Figs. 19 & 20 with the lower ones).

In a close-circuit flume, of the type used for the experiments, lognormality, once produced, is likely to be maintained as long as the hydraulic conditions remain unchanged—the mechanism of grain sorting, responsible for generation of lognormality, being related to the process of bedform migration. However, this is not so in a natural stream flowing unidirectionally. Thus, in course of an earlier experiment[45], it was noted that "lognormality of weight frequency distribution of grain-sizes is a transitional phenomenon occurring within a critical range of velocity and height above a sand bed of a given composition. It follows that the materials deposited by streams from this critical velocity-height zone will have lognormal grain-size distribution. This explains why sand size distributions in nature are not ubiquitously lognormal".

Deposition from Suspension

A part of the suspension load carried by a stream in spate is deposited during the waning phase of flood. These deposits are of particular interest to geologists because these are the ones preserved in geological record. In fact, much of the sandstones found in nature are the products of sand deposited either by rivers or by suspension currents of high density within the sea or large lakes. A series of controlled experiments were performed in different laboratories with a view to obtaining information on the nature of the deposits formed from suspension when the flow velocity is reduced. The ultimate aim of this study was to investigate into the relationship between the grain-size distribution patterns of the deposits and the flow parameters so that the same may be used for palaeohydraulic analysis.

Equipment and Methodology

In one of the early experiments conducted in a circular flume at Gröningen sand grains were taken into suspension at a high flow velocity and subsequently dropped back to the bed at a decelerated velocity. The grains, thus deposited, could not be separated from the pre-existing bed.

The nature of the deposits had to be estimated indirectly, by subtracting, what remained in suspension at a decelerated flow velocity, from what went into suspension at a higher velocity[57].

Getting rid of the preexisting bed material had always been a difficult problem in these experiments. At Uppsala this was achieved by performing the experiments in two stages. The suspension generated at a high flow velocity was initially stored in an auxiliary tank and then pumped back into the main flume after it had been thoroughly cleaned of the pre-existing bed material. The flume was then run at a high speed for some time to take all the grains back into suspension. The flow velocity was subsequently lowered and samples of deposits siphoned out of the base of the experimental channel.

In the experiments conducted at Calcutta a mixture of known grain-size distribution (anticipated to be kept in suspension on the basis of prior experimental results) was inserted into a clean body of water running at a high velocity in the flume. The velocity was subsequently reduced and the deposits formed on the flume base were collected by siphoning

In spite of all the precautions taken problems arose both at Uppsala and Calcutta due to partial mixing of the deposits with the pre-existing bed materials. At Uppsala this happened due to release of a part of the coarser sediments into the experimental channel by recirculation pipes of much smaller diameter. At Calcutta a part of the material was dropped in the initial stage of suspension apparently because it exceeded suspension capacity.

The problem of mixing of the deposits with the pre-existing bed materials was solved to a large extent in the newly constructed flume at IIT, Kharagpur (Fig. 15). As has been stated already, most of the grains taken into suspension in the experimental channel of this flume settled down on entering the diffuser channel of wider cross-sectional area. This allowed sampling of the suspensions and deposits simultaneously from two different arms of the flume. The diffuser arm was generally free from any bed material excepting in the cases when, at high flow velocity, some of the grains rolled into the diffuser channel from the experimental section. To ensure non-mixing of the deposits with these bed materials samples of deposits, in these experiments, were siphoned out of clean trays placed at the base of the diffuser channel. The samples collected from these trays, *the moment the grains were dropped* from suspension, are marked `immediate' (D imm) in the Tables and Figures.

Results of Experiments

Grain-size frequency distributions of the suspensions and deposits sampled during the experiments conducted at Uppsala and Calcutta are shown in Figs. 28 a & b. The most interesting feature revealed by these samples is that *all* grain-sizes were dropped *simultaneously* when the flow velocity was reduced. This is contradictory to the common belief that the coarsest grains are the first to be discarded from suspension. In the experiments conducted at Uppsala and Calcutta a doubt regarding this conclusion remained because the experiment, in each case, was conducted in two stages. It was not certain whether grains of all sizes were dropped because the time lag between deceleration of flow velocity and collection of deposits in these experiments exceeded the settling time of even the finest grains present in suspension. This doubt was dispelled when simultaneous sampling of suspensions and deposits at IIT, Kharagpur confirmed deposition of *all* grain sizes at the same time. The deposits collected instantly (marked`D imm' in Fig. 20(b), and Tables IV, V, VI) contain materials of all grain-sizes, including the finest ones present in suspension. Since the fall velocities of the finer grains are very small (< 0.18 cm/s) it is obvious that these were deposited from the lowest level of suspension.

In all the experiments conducted so far grain-size distribution of the deposit matched the distribution in the lowest level of suspension. The modal sizes of these two distributions matched well in most cases; but at higher levels of suspension the mode shifted to a finer size (see Fig. 29 and Table V columns 5-7, Table VI columns 3-5). Particularly striking is the result of the experiments where the mode of the deposit is the same as the mode of the bed (Figs. 19 & 20).

In Fig. 30, ratios of suspension concentration at different levels in the diffuser channel corresponding to bed IIT-3.1 have been plotted to demonstrate that the grains corresponding to the

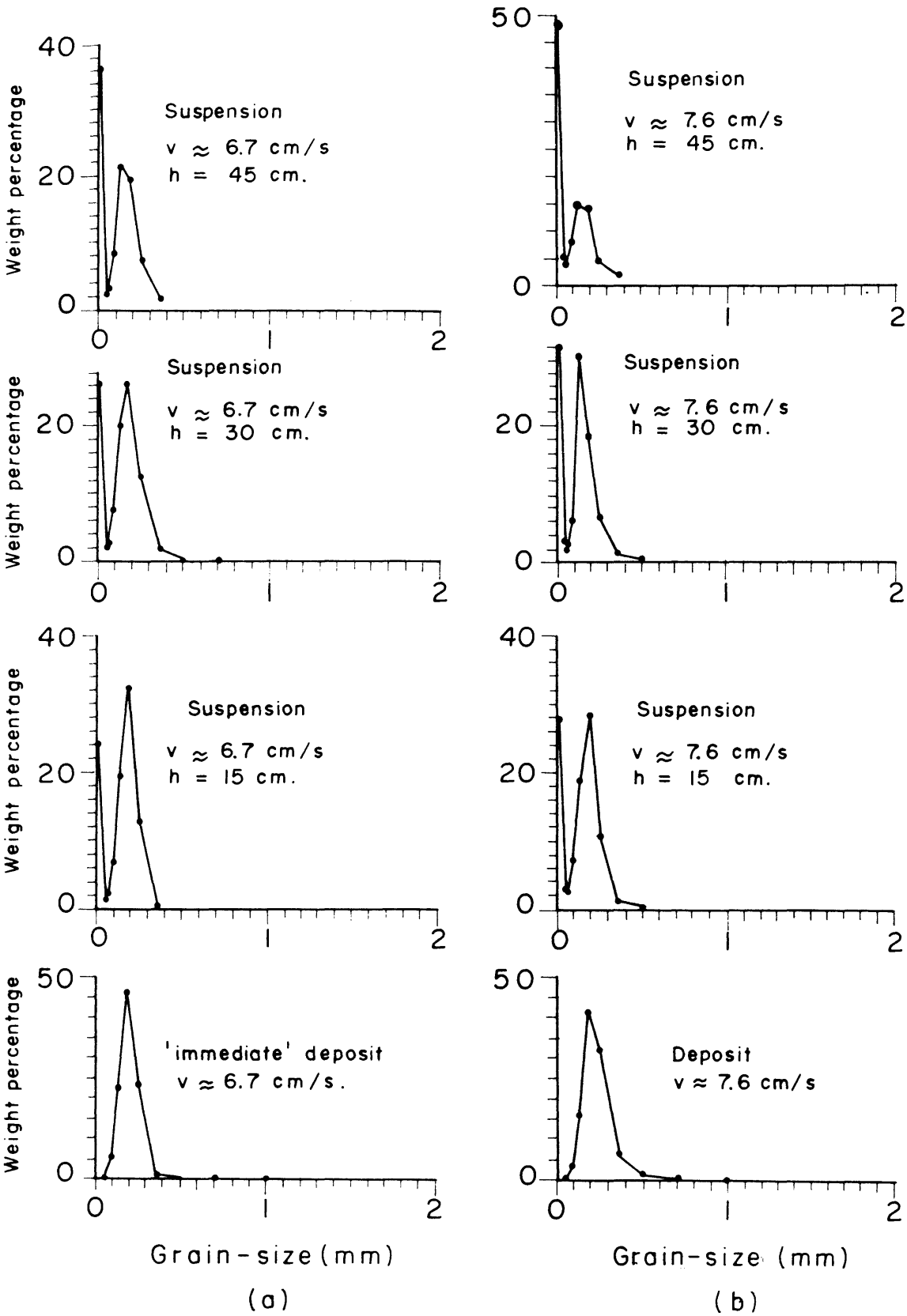

Fig. 29 Grain-size distributions in suspension at 15, 30 and 45 cm above the deposits in the diffuser channel (experiment VI, Tables V and VI).

Table IV

Weights of Sediments in Suspension and Deposits in Experiment V.

Sand bed IIT-2.2. Initial bed thickness 5.5 cm. Initial water depth 20 cm.

v (cm/s)	46.0	46.0*	46.0*	46.0	46.0*	56.0	56.0*	56.0*	56.0*	74.0	74.0*	82.0	82.0*	82.0*
h (cm)	12.0	-	-	-	-	12.0	-	-	-	12.0	-	12.0	-	-
Bed	rippled	-	-	-	-	rippled	-	-	-	very	little	bed	-	-
S/D	S(E-ch)	D(imm)	D(imm)	D	D	S(E-ch)	D(imm)	D	D(imm)	S(E-ch)	D	S(E-ch)	D(Imm)	D
Gr.size (mm)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.40											0.0009			
1.00								0.0106			0.0075		0.0099	0.0037
0.71					0.0034		0.0022	0.0113			0.0038		0.0645	0.0058
0.50	0.0007	0.0006	0.0004	0.0010	0.0213		0.0219	0.2549	0.0013		0.0596	0.0011	0.3715	0.1441
0.36	0.0010	0.0009	0.0078	0.0042	0.3686	0.0018	0.3633	2.9461	0.0089	0.0028	0.8931	0.0059	1.9837	1.7377
0.25	0.0053	0.0088	0.1295	0.1615	9.8875	0.0048	5.3902	28.3991	0.4916	0.0032	8.8546	0.0176	10.9436	17.8825
0.18	0.0049	0.1155	0.3365	1.1127	18.3596	0.0078	8.0236	30.7089	1.8758	0.0016	9.0222	0.0072	9.3138	18.5255
0.13	0.0031	0.2025	0.2160	1.4713	9.6323	0.0134	3.3869	11.4821	1.1178	0.0042	2.6675	0.0083	2.9406	6.0846
0.09	0.0028	0.0604	0.0580	0.6115	2.4904	0.0107	0.7662	2.2708	0.2703	0.0109	0.5233	0.0065	0.6200	1.3303
0.06	0.0032	0.0080	0.0081	0.1395	0.4487	0.0060	0.1123	0.3869	0.0398	0.0123	0.0733	0.0038	0.0892	0.2402
0.05	0.0077	0.0029	0.0036	0.0772	0.1805	0.0099	0.0308	0.1707	0.0206	0.0191	0.0330	0.0049	0.0289	0.0657
0.01**	0.0367	-	-	0.0100	0.1273	0.1447	0.0028	0.0239	0.0028	0.2405	0.0028	0.1790	0.0013	0.0060
Total	0.0654	0.4000	0.7599	3.5889	41.5196	0.1991	18.1002	76.6653	3.8289	0.2946	22.1416	0.2343	26.3670	46.0261

Note: All sample weights are in gms. Volume of sample collected=10 litres in each case unless otherwise mentioned. V=maximum flow velocity (cm/s). Initial water depth and height of sampling (h) were measured above flume base in cm. S(E-ch)=suspension sample in experimental channel. D=deposits in diffuser channel collected after several minutes. D(imm)=immediate deposits in diffuser channel.

*Corresponding velocity in experimental channel, estimated velocity in diffuser channel was about $1/10^{th}$ of the velocity.

**Includes all grains <0.05 mm.

Table V

Weights of Sediments in Suspension and Deposits in Experiment VI (continued to table VI)

Sand bed No IIT-3.1 Initial bed thickness 2 cm. Initial water depth 20 cm.

v (cm/s)	56.0	56.0*	67.0	67.0	67.0*	67.0*	67.0*	67.0*	67.0
h (cm)	6.0	-	6.0	12.0	15.0	30.0	45.0	-	-
Bed	rippled	-	rippled	rippled	-	-	-	-	-
S/D	S(E-ch)	D	S(E-ch)	S(E-ch)	S(D-ch)	S(D-ch)	S(D-ch)	D(imm)	D
Gr.size (mm)	1	2	3	4	5	6	7	8	9
1.40									0.0004
1.00		0.0005						0.0049	0.0008
0.71		-				0.0005		0.0010	0.0026
0.50		0.0012			-	-		0.0103	0.0407
0.36		0.0378	0.0017	0.0012	0.0010	0.0030	0.0020	0.2622	0.6669
0.25	0.0016	0.9114	0.0022	0.0012	0.0243	0.0205	0.0089	5.6482	6.8864
0.18	0.0023	2.1387	0.0027	0.0021	0.0610	0.0432	0.0238	11.2134	11.4417
0.13	0.0037	1.1243	0.0050	0.0018	0.0367	0.0328	0.0256	5.4445	4.6166
0.09	0.0030	0.2680	0.0073	0.0030	0.0128	0.0126	0.0102	1.1814	0.9694
0.06	0.0017	0.0495	0.0042	0.0028	0.0037	0.0043	0.0038	0.1999	0.1605
0.05	0.0015	0.0159	0.0035	0.0038	0.0022	0.0037	0.0030	0.0449	0.0362
0.01**	0.0129	0.0158	0.0268	0.0442	0.0456	0.0430	0.0444	0.0447	0.0337
Total	0.0267	4.5631	0.0534	0.0601	0 1883	0.1636	0.1217	24.0554	24.8555

Note: Please see footnote on next page (i.e. Page No. 197).

modal size of the suspension load were transferred to successively lower levels to be eventually discarded from suspension.

Modelling the Deposits from Suspension

The processes of suspension and deposition were found to be controlled, in course of an early study[57], primarily by the capacity of the current to hold grains in suspension and secondarily by the current's competency to keep grains of certain sizes in suspension. These two parameters again, were thought to be interrelated, because the ratios of grams per litre in suspension at two different flow velocities varied with the size class involved. It was postulated, on the basis of this study, that deposition of grains belonging to a particular size class takes place as soon as the capacity of the current to hold materials of that size class is exceeded. This led even to the speculation that "a current overloaded with silt will, with lowering of flow velocity, deposit silt first, instead of a few coarse grains of sand which might be present in suspension". The current set of experiments reveal that the grain-sizes most conspicuous in the ratios of suspension at varying flow velocities are the ones available in the largest quantity in the bed. This size fraction shows up in the deposits also. This leads to the conclusion that availability plays as important a role as capacity and competency in suspension and deposition of sediments.

Mathematical modelling of the process of deposition from suspension has not been easy. When the settling velocity (v_s) of the grain concerned is high, or when the shear velocity (u_*), is low, i.e. when $v_s / u_* \chi > 1$, the exponent in the Rouse equation increases substantially, indicating exponential decay of the grains from suspension. In an attempt to obtain a match with the experimental observations Ghosh *et al.*[58] modified the conventional Rouse equation by introducing a dampening factor $\beta\,(\beta > 0)$. This modified equation allows computation of the deposits within acceptable range of the observed values. The errors between the computed and the observed values are particularly small when *proportions* of the deposited materials are considered. This technique, developed for the relatively coarser grains and low velocities, works also for the finer grains and high velocities. A detailed study of the deposits from suspension, sampled during the current set of experiments (Tables X-XII), is underway with a view to developing an efficient method for estimating the deposits.

Table VI

Weights of Sediments in Suspension and Deposits in Experiment VI (continued from Table V).

Sand bed No IIT-3.1 Initial bed thickness 2 cm. Initial water depth 20 cm.

V (cm/s)	76.0	76.0	76.0*	76.0*	76.0*	76.0*	77.0	77.0	77.0*	77.0*	77.0*
h (cm)	6.0	12.0	15.0	30.0	45.0	-	6.0	12.0	15.0	-	-
Bed	rippled	rippled	-	-	-	-	Very little bed in experimental channel				
S/D	S(E-ch)	S(E-ch)	S(D-ch)	S(D-ch)	S(D-ch)	D					
							S(E-ch)	S(E-ch)	S(D-ch)	D	D(imm)
Gr. size (mm)	1	2	3	4	5	6	7	8	9	10	11
1.40											0.0134
1.00						0.0013					0.0006
0.71	0.0019					0.0119				0.0018	0.0056
0.50	0.0051		0.0006	0.0007		0.1082	0.0014	0.0010		0.0147	0.0605
0.36	0.0161	0.0008	0.0024	0.0021	0.0023	0.6498	0.0034	0.0029	0.0014	0.1523	0.6434
0.25	0.0393	0.0011	0.0214	0.0129	0.0054	3.4218	0.0056	0.0056	0.0067	1.3511	4.9466
0.18	0.0582	0.0017	0.0570	0.0364	0.0176	4.4550	0.0098	0.0047	0.0113	2.2162	6.7824
0.13	0.0378	0.0045	0.0377	0.0596	0.0185	1.6838	0.0156	0.0044	0.0079	0.9560	2.3446
0.09	0.0160	0.0027	0.0143	0.0117	0.0096	0.3531	0.0228	0.0021	0.0039	0.2077	0.4522
0.06	0.0042	0.0024	0.0053	0.0042	0.0049	0.0555	0.0032	0.0013	0.0015	0.0319	0.0630
0.05	0.0033	0.0041	0.0054	0.0054	0.0063	0.0146	0.0029	0.0018	0.0018	0.0101	0.0302
0.01**	0.0492	0.0723	0.0553	0.0622	0.0605	0.0020	0.0710	0.0580	0.0697	0.0014	0.0022
Total	0.2311	0.0896	0.1994	0.1952	0.1251	10.7544	0.1356	0.0818	0.1042	4.9432	15.3447

Note: All sample weights are in gms. Volume of sample collected=10 litres in each case unless otherwise mentioned. V=maximum flow velocity (cm/s). Initial water depth and height of sampling (h) were measured above flume base in cm. S(E-ch)=suspension sample in experimental channel. D=deposits in diffuser channel collected after several minutes. D(imm)=immediate deposits in diffuser channel.

*Corresponding velocity in experimental channel, estimated velocity in diffuser channel was about $1/10^{th}$ of the velocity.

**Includes all grains <0.05 mm.

Table VII

Weights of sediments in suspension and deposits in experiment X (continued to table VIII)

Sand bed IIT-7.2 Initial sand bed thickness 3.5 cm. Initial water depth 16 cm, Width of E-ch 20 cm.

v (cm/sec)	48.0	48.0	48.0	48.0	49.0	49.0	56.0	56.0	56.0	56.0
Sample ht.(cm)	0.0	15.0	30.0 rippled	45.0 rippled	3.5 rippled	8.0	8.0	3.5	0.0	
Bed Susp./ dep.	D	S(D-ch)	S(D-ch)	S(D-ch)	Eject	S(E-ch)	S(E-ch)	Eject.	Rip.toe	D
Gr.-size (mm)	1	2	3	4	5	6	7	8	9	10
2.00									0.0358	
1.40								0.1061	0.5970	
1.00	0.0042							0.1577	0.5115	0.0051
0.71	0.0033				0.0053			0.4796	0.7216	0.0137
0.50	0.0191				0.0284	0.0029	0.0012	1.0387	0.8336	0.1361
0.355	0.0972	0.0020	0.0040	0.0018	0.1096	0.0058	0.0033	1.9263	1.0525	0.8280
0.25	0.6731	0.0053	0.0117	0.0027	0.4202	0.0165	0.0084	3.3811	1.0495	3.4292
0.18	1.5854	0.0199	0.0134	0.0050	0.5766	0.0275	0.0131	2.2446	0.3154	4.0364
0.125	1.5071	0.0895	0.0169	0.0170	0.3220	0.0231	0.0153	0.9860	0.1016	2.4919
0.09	0.7651	0.0527	0.0181	0.0225	0.1066	0.0230	0.0142	0.2511	0.0278	0.9072
0.063	0.1904	0.0232	0.0160	0.0149	0.0269	0.0168	0.0115	0.0435	0.0060	0.2127
0.045	0.0835	0.0160	0.0110	0.0087	0.0172	0.0076	0.0092	0.0282	0.0019	0.0765
0.01**	0.0457	0.0183	0.0031	0.0157	0.0583	0.0186	0.0227	0.0070	0.0083	0.0380
Total	4.9741	0.2269	0.0942	0.0883	1.6711	0.1418	0.0989	10.6499	5.2625	12.1748

Table VIII

Weights of sediments in suspension and deposits in experiment X (contd. fromTable VII).

Sand bed IIT-7.2 Initial sand bed thickness 3.5cm. Initial water depth 16 cm. Width of E-ch 20 cm.

v (cm/sec)	57.0	57.0	57.0	57.0	57.0	57.0	57.0
Sample ht.(cm)	8.0	3.5		15.0	30.0	45.0	0.0
Bed Susp./dep.	rippled S(E-ch)	rippled Eject	rippled Rip.toe	- S(D-ch)	- S(D-ch)	- S(D-ch)	- D
Gr.-size (mm)	11	12	13	14	15	16	17
2.00			0.0013				
1.40		0.0334	0.4995				
1.00	0.0234	0.0769	0.5583				0.0091
0.71	0.0059	0.1018	1.0054				0.0266
0.50	0.0040	0.3421	1.7003	0.0012	0.0014		0.1453
0.355	0.0102	1.0510	2.0904	0.0020	0.0018	0.0008	0.5436
0.25	0.0351	3.1170	2.4211	0.0119	0.0081	0.0052	2.7710
0.18	0.0571	2.8733	1.2736	0.0280	0.0215	0.0172	4.9231
0.125	0.0484	1.3187	0.4332	0.0609	0.0337	0.0317	3.4689
0.09	0.0255	0.3434	0.0940	0.0494	0.0371	0.0422	1.1743
0.063	0.0214	0.0558	0.0143	0.0413	0.0244	0.0247	0.2577
0.045	0.0146	0.0281	0.0021	0.0329	0.0278	0.0243	0.1074
0.01**	0.0145	0.0260	-	0.0390	0.0405	0.0501	0.0656
Total	0.2601	9.3675	10.0935	0.2666	0.1963	0.1962	13.4926

Note: All sample weights are in gms. Volume of sample collected=10 litres in each case unless otherwise mentioned. V=maximum flow velocity (cm/s). Initial water depth and height of sampling (h) were measured above flume base in cm. S(E-ch)=suspension sample in experimental channel. D=deposits in diffuser channel collected after several minutes. D(imm)=immediate deposits in diffuser channel.

*Corresponding velocity in experimental channel, estimated velocity in diffuser channel was about $1/10^{th}$ of the velocity.

**Includes all grains <0.05 mm.

Table IX

Weights of sediments in suspension and ejection in experiment VII

Sand bed IIT-4.1 Initial bed thickness 3.2cm. Initial water depth 20.2cm

v (cm/sec)	37.0	37.0	39.0	39.0	39.0	39.0
Sample ht.(cm)	10.0	15.0	Rip.crest	Rip. cr	Rip. cr	10.0
Bed	–		rippled	rippled	rippled	rippled
Susp./dep.	S(E-ch)	S(E-ch)	Eject.	Eject	Eject	S(E-ch)
Vol. water	(10l)	(5l)				(5l)
Gr-size (mm)	1	2	3	4	5	6
2.00						
1.40						
1.00						
0.71	0.0013				0.0054	
0.50	0.0041	0.0018	0.0074	0.0024	0.0135	0.0007
0.355	0.0038	0.0012	0.0262	0.0126	0.0704	0.0047
0.25	0.0070	0.0024	0.2804	0.0931	0.5009	0.0296
0.18	0.0216	0.0049	1.0289	0.7319	1.7544	0.1202
0.125	0.0957	0.0201	1.4626	1.6524	2.1012	0.2871
0.09	0.0940	0.0270	0.5249	0.6467	0.6512	0.1674
0.063	0.0334	0.0144	0.0846	0.1285	0.0800	0.0386
0.045	0.0248	0.0131	0.0318	0.0427	0.0256	0.0199
0.01	0.1524	0.0834	0.0244	0.0228	0.0125	0.0232
Total	0.4381	0.1683	3.4712	3.3331	5.2151	0.6914

Note: Please see footnote on prepage under Table VIII (P. 198).

Table X

Weights of sediments in suspension and deposits in experiment XI (Set-1)

Sand bed IIT-4.11 Initial thickness 6.5cm. Initial water depth 20 cm, Width of E-ch 47.7cm

v (cm/sec)		48	48	48*	48*	48*	48*	48*	48*	48*
Sample height (cm)		10	15	0	15	30	45	0(bed)	15	30
Bed						rippled				
Susp(S)/ Dep(Dp)		S	S	Dp	S	S	S	Dp	S	S
Location		D	D	A	A	A	A	A	C	C
Volume (l)		10	10	1.56	10	10	10	0.55	10	10
Intake time (sec)		113	127	120	374	618	159	60	416	397
Sample No.		1	2	3	4	5	6	7	8	9
Gr. Size (mm)	Bed 4.11 (kg)	1	2	3	4	5	6	7	8	9
2.00										
1.40	0.016									
1.00	0.051	0.0018						0.0015		
0.71	0.024	0.0048	0.0013		0.0029			0.0021	0.0006	0.0003
0.50	0.069	0.0020	0.0019	0.0023	0.0013	0.0019	0.0004	0.0046	0.0011	0.0005
0.355	0.310	0.0081	0.0044	0.0063	0.0049	0.0039	0.0037	0.0127	0.0029	0.0038
0.25	3.316	0.0888	0.0089	0.0405	0.0213	0.0174	0.0129	0.0978	0.0252	0.0260
0.18	13.678	0.8149	0.0492	0.4046	0.2429	0.2225	0.1547	1.1121	0.2809	0.2945
0.125	23.621	2.6308	0.2846	1.4467	1.1393	1.1225	0.9469	3.6222	1.2730	1.3418
0.09	7.377	1.4834	0.3379	0.8059	0.8796	0.8019	0.7805	1.6424	0.8981	0.9595
0.063	1.347	0.3478	0.1509	0.1520	0.2491	0.2584	0.2654	0.2406	0.2655	0.2745
0.045	0.334	0.1435	0.0882	0.0463	0.1541	0.1328	0.1211	0.0642	0.1372	0.1467
0.01**	0.162	0.1724	0.1361	0.0402	0.1589	0.1988	0.1998	0.0389	0.1586	0.1756
Total	50.305	5.6983	1.0634	2.9448	2.8543	2.7601	2.4854	6.8391	3.0431	3.2232
Presieving wt.(gm)		(5.7422)	(1.0744)	(2.9548)	(2.8684)	(2.7544)	(2.4299)	(6.8647)	(3.0776)	(3.2617)

Note: Please see footnote on page 202 for reference.

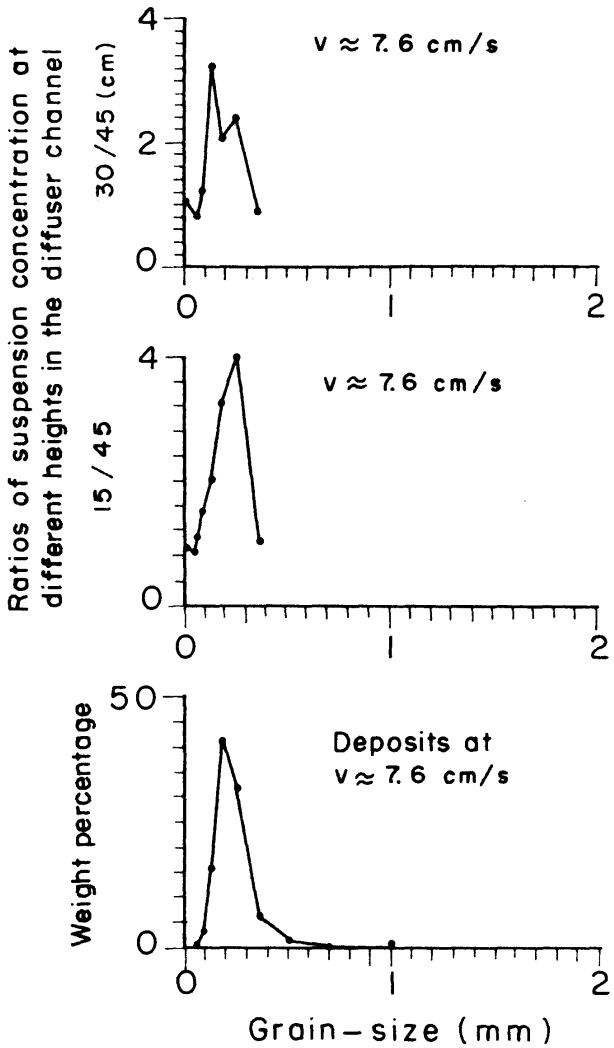

Fig. 30 Ratios of suspension concentration at different heights in the diffuser channel and the corresponding deposits (experiments VI, Tables V & VI)

The physical nature of the `dampening factor' introduced in the earlier work is only a matter of speculation at present. It is possible that in the experiments, and presumably also in nature, the settling velocities of the coarser grains are reduced by increase of fluid density due to silt suspension[59]. Hindered settling of the coarser grains due to collision between the particles in a dense suspension, turbulent fluctuations within the fluid, `vertical density currents'[60], `settling convection'[61], are some of the other phenomena tentatively suggested to explain hindered settling.

In a separate study Ghosh *et al.*[62] provided a stochastic physical interpretation of the process of deposition. It was postulated that the flow carries up some materials which, after being deposited to the bottom, are partially redistributed into suspension by a process of reflection and jump. "Stochastically, in such a situation, one can think of a particular grain being displaced according to a Markovian law specified by the diffusion equation. Its behaviour at the lower boundary is of partial reflection and partial jump to a new height". It was also noted that the Rouse equation gives the stationary distribution of the corresponding Markov process when the lower boundary is completely reflecting. The modified equation involving the dampening factor approximates the stationary distribution of this set up[63].

Applications

The results obtained in course of the studies enumerated above may be used in the analysis of log-probability plots of fluvially transported sediments, in palaeohydraulic studies, in transportation of sediments through canals as slurries, and also in the interpretation of textures of sediments deposited by density currents.

Log (phi)-probability plots of cumulative grain-size distributions of sediments transported in nature often depict intersections of two or more linear segments with sharp inflections. Following the conventional line of approach it has been customary for geologists to interpret these segmented plots as mixtures of sediment populations transported as traction, saltation and suspension loads[64]. The present study leads to the conclusion that such intersections may occur also in sediment samples collected either from the river bed, or wholly from suspension. The Usri and the Dwarkeswar river bed samples are examples of the former and the samples collected from suspension during the flume experiments illustrate the latter case. The inflections in the log-probability plots disappear when the process of grain sorting is completed either by prolonged transportation in the river bed, or at high flow velocity in the flume. In both the cases there is a tendency for the grain-size to be lognormally distributed. Thus the degree of lognormality attained seems to reflect the stage of completion of the process of grain sorting rather than the mode of sediment transportation.

The observation that usually the modal grain-size of the bed is reflected in the lower level of suspension and also in the deposits, allows

estimation of (palaeo) flow velocity of an ancient stream from the deposits preserved in geological record. The relationship worked out by Ghosh and Mazumder[63], between height of suspension (y) and shear velocity (u_*) for lognormally distributed sediment populations of known (mean) grain-sizes, may be utilised for this purpose. The height of suspension in such an analysis is estimated from the relationship $H=0.086\ d^{1.19}$ provided by Allen[65]. H in this equation is the dune height. The bankfull depth (d) determines the maximum range of height of suspension possible.

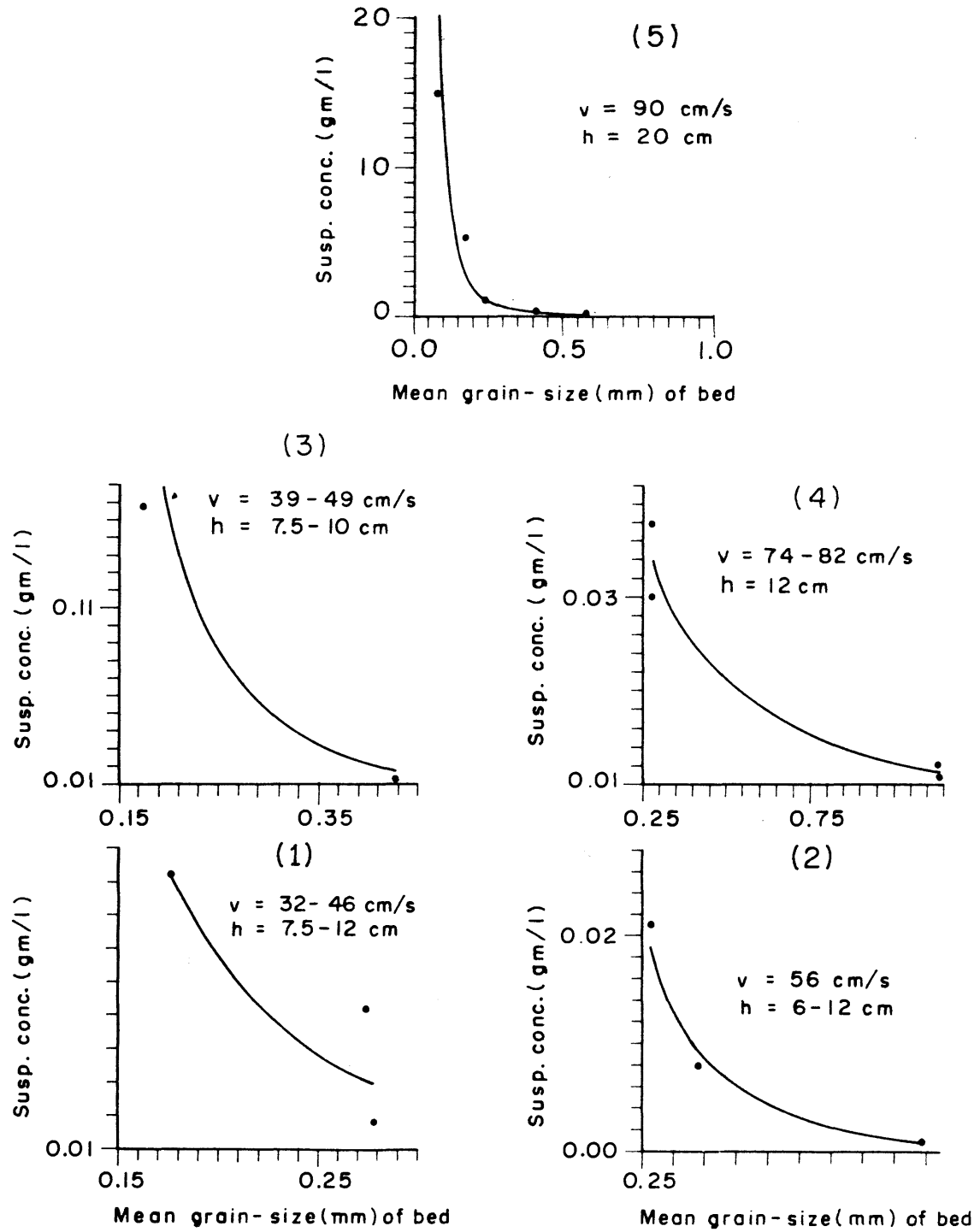

Fig. 31 Diagrams illustrating variation of suspension concentration with mean grain-size of the bed material (1-4: results of IIT experiments, 5: results of Uppsala experiments)

Table XI

Weights of sediments in suspension and deposits in experiment XI (Set-2)

Sand bed IIT-4.11 Initial thickness 6.5cm. Initial water depth 20 cm. Width of E-ch 47.7cm

v (cm/sec)		49	49	49*	49*	49*	49*	49*	49*	49*
Sample height (cm)		10	15	0	15	30	45	0(bed)	15	30
Bed						Rippled				
Susp(S)/ Dep	(Dp)	S	S	Dp	S	S	S	Dp	S	S
Location		D	D	A	A	A	A	A	C	C
Volume (l)		10	10	0.96	10	10	10	0.49	10	10
Intake time (sec)		127	114	180	378	662	160	60	398	403
Sample no.		10	11	12	13	14	15	16	17	18
Gr.size (mm)	Bed 4.11 (kg)	1	2	3	4	5	6	7	8	9
2.00										
1.40	0.016									
1.00	0.051							0.0008		
0.71	0.024	0.0007		0.0005			0.0014	0.0015		
0.50	0.069	0.0009	0.0005	0.0025	0.0010	0.0009	0.0017	0.0059	0.0025	0.0008
0.355	0.310	0.0024	0.0020	0.0048	0.0025	0.0026	0.0022	0.0204	0.0042	0.0055
0.25	3.316	0.0141	0.0029	0.0378	0.0191	0.0175	0.0138	0.1558	0.0385	0.0516
0.18	13.678	0.1491	0.0119	0.4819	0.2465	0.2552	0.1830	1.2862	0.3409	0.3849
0.125	23.621	0.6730	0.0951	1.4111	1.0468	1.0818	0.9239	3.6556	1.1921	1.3079
0.09	7.377	0.5003	0.1640	0.5991	0.6875	0.6649	0.6535	1.4266	0.7369	0.7508
0.063	1.347	0.1629	0.0998	0.1120	0.2238	0.2164	0.2096	0.2380	0.2177	0.2329
0.045	0.334	0.1250	0.0924	0.0466	0.1227	0.1188	0.1442	0.0883	0.1179	0.1361
0.01**	0.162	0.1284	0.1669	0.0299	0.1987	0.1998	0.2073	0.0460	0.2191	0.1993
Total	50.305	1.7568	0.6355	2.7262	2.5486	2.5579	2.3406	6.9251	2.8698	3.0698
Presieving wt(gm)		(1.7879)	(0.6566)	(2.7314)	(2.5749)	(2.5931)	(2.3733)	(6.9401)	(2.9055)	(3.1035)

Note: Please see footnote on next page (203p).

Flume experiments indicate that height has an important influence on the size of the grains transported. In the Niobrara River in Nebraska, for example, grains of 0.25 mm (2.0 phi) diameter were transported in suspension at a height of about 34 cm at a flow velocity of 152 cm/s[56], but to transport grains as large as 0.75 mm (0.5 phi) at a height of 20 cm during the flume experiments a flow velocity of only 146 cm/s was needed[45].

Contradictory information exists in literature on the influence of water discharge on the capacity and competency of streams to transport sediments in suspension. In the Clyde River of Scotland, Fleming and Poodle[66] observed that competency depends more on availability than water discharge. On the other hand, Reid and Frostick[67] found suspension capacity to increase with increase of water discharge. The flume studies described in the present work lead to the conclusion that both capacity and competency of a current to transport particles in suspension can be enhanced either by increasing flow velocity, or by reducing the height of suspension, provided materials of appropriate sizes are available in the bed. It was demonstrated in course of an earlier study that competency of a suspension current can be substantially enhanced by increasing the effective density of water by adding salt or lutum to it[57]. Results of flume experiments compiled in Fig. 31 demonstrate that the capacity of a stream to carry sediments in suspension increases considerably with decrease of the mean grain-size of the bed material. This, together with the finding that materials around the modal grain-size of the bed are transported in the largest quantity in suspension, will be of use to those interested in the transport of slurries through natural or artificial canals.

The observation that all grain-sizes present in suspension are dropped simultaneously when the flow velocity is reduced help solve a long standing

Table XII

Weights of sediments in suspension and deposits in experiment XI (Set-3)

Sand bed IIT-4.11 Initial thickness 6.5cm. Initial water depth 20 cm.Width of E-ch 47.7cm

v (cm/sec)		46	46	46*	46*	46*	46*	46*	46*	46*
Sample height (cm)		10	15	0	15	30	45	0(bed)	15	30
Bed						Rippled				
Susp(S)/ Dep(Dp)		S	S	Dp	S	S	S	Dp	S	S
Location		D	D	A	A	A	A	A	C	C
Volume (l)		10	10	0.655	10	10	10	0.335	10	10
Intake time (sec)		117	146	120	397	698	161	60	432	407
Sample No.		19	20	27	22	23B	21	26	25	24
Gr. size (mm)	Bed 4.11 (kg)	1	2	3	4	5	6	7	8	9
2.00										
1.40	0.016									
1.00	0.051									
0.71	0.024			0.0016				0.0018	0.0009	
0.50	0.069	0.0009		0.0038	0.0009	0.0012		0.0125	0.0016	0.0002
0.355	0.310	0.0014	0.0009	0.0094	0.0020	0.0061	0.0019	0.0290	0.0064	0.0026
0.25	3.316	0.0076	0.0031	0.1221	0.0176	0.0334	0.0113	0.2706	0.0284	0.0270
0.18	13.678	0.0647	0.0121	1.4732	0.1886	0.3272	0.1777	2.2218	0.2101	0.2384
0.125	23.621	0.3402	0.0904	4.4081	0.6619	0.6521	0.6815	6.1315	0.6568	0.7469
0.09	7.377	0.2708	0.1511	1.7030	0.4146	0.3653	0.3824	2.3375	0.4017	0.4403
0.063	1.347	0.1549	0.0704	0.2326	0.1218	0.1115	0.1396	0.3719	0.1119	0.1528
0.045	0.334	0.1347	0.1162	0.0574	0.0828	0.0614	0.1069	0.1136	0.0681	0.0954
0.01**	0.162	0.0984	0.1824	0.0444	0.2163	0.1968	0.1398	0.0688	0.2889	0.2184
Total	50.305	1.0736	0.6266	8.0556	1.7065	1.7550	1.6411	11.5590	1.7748	1.9220
Presieving wt		(1.1067)	(0.6451)	(8.0851)	(1.7404)	(1.7909)	(1.6871)	(11.6084)	(1.8055)	(1.9650)

Note: All sample weights are in gms. A, C, D represent sample locations shown in Fig. 15. Initial water depth and height of sampling (h) were measured above the flume base in cm. S=suspension sample in experimental channel. Dp=deposits in diffuser channel collected after several minutes.

Velocities measured at location A in diffuser channel=16 cm/s (at 52 cm above base), at location C=14 cm/s (at 43 cm above base), 11 cm/s (at 38 cm above base), 5 cm/s (at 23 cm above base).

*Indicates flow velocity (cm/s) in experimental channel (E-ch).

**Includes all grains <0.05 mm.

geological problem, namely, the presence of large proportion of fine matrix in coarse grained turbidites—the products of deposition from suspension currents of high density. Traditionally, materials of such varying sizes were assumed to be deposited under different hydraulic conditions. Diagenetic alteration of the coarse sand size grains, deformation and squashing of the pelitic fragments, were some of the explanations provided for secondary enrichment of matrix of an essentially coarse grained rock[68]. Experimental results indicating simultaneous deposition of the coarse and fine fragments from a decelerating flow provide a solution to the matrix problem of turbidites.

Summary and Conclusions

Insoluble sediments are transported by streams as traction, saltation and suspension loads. In the Usri and the Dwarkeswar Rivers, as in many other streams, a general decrease in the mean size of the traction load in the downstream direction is noticed. A steady change in the pattern of grain-size frequency distribution of the traction as well as the suspension loads, leading to a lognormal grain-size distribution downstream, is also

observed. This article summarises the work done by the authors and their associates on these problems, in the field and in laboratory, for the last three decades.

Controlled flume experiments suggest that the mechanism responsible for downstream fining is related to the process of migration of bedforms (sand ripples or dunes). These rhythmic patterns generate on the bed soon after the entrainment velocity is exceeded. The sediments transported over the gentler stoss faces of these bedforms are sorted out into two parts. The coarser ones, sliding down the steeper lee faces of the dunes, are buried and removed, while the finer fractions are carried forward, causing a progressive downstream fining. This mode of grain sorting, leading to accumulation of only a selected range of grain-sizes in the bed, has been theoretically shown to generate lognormality. Such a distribution, once attained in a stream bed, will be preserved as long as the concerned bedforms remain stable under a particular hydraulic condition.

The nature of suspension loads, generated by unidirectional flows, over sand beds of known grain-size distributions, was experimentally investigated in different laboratories using specially designed hydraulic flumes. These flumes are capable of maintaining the same suspension concentration within closed systems for desired lengths of time. The concentration in suspension in these experiments increased with increase of flow velocity and/or decrease of the mean grain-size of the bed material. A higher flow velocity was required for taking comparable amounts and sizes of sediments into suspension when the bed roughness was increased.

The grain-size distribution in suspension was always unimodal irrespective of the size distribution in the bed. This was due to a two stage sorting process: 1. from bed to bed layer, and 2. from bed layer to suspension. The former process enhanced concentration of the grains around the modal size of the bed material provided the current was competent to move them. The latter process lifted the relatively finer of these grains into suspension as jets ejecting out of ripple/dune crests. This explains why the concentration in suspension is guided not only by the finer grains present in the bed but also by availability, i.e. the modal size of the bed material. Lower the level of suspension, closer is the match between the modal grain-sizes of the bed and the suspended load.

The sorting from bed to bed layer is computed by one of the well known bed load equations. The equation of relative suspension concentration formulated by Rouse allows computation of the suspension load. An equation developed in partial modification of the one offered by Hunt allows direct computation of suspension concentration from the grain-size distribution of the bed. This equation works well for natural streams and experimental channels.

The suspension is generally skewed due to preponderance of fines. At appropriate combination of height and flow velocity, and after logarithmic (phi) conversion, the distribution in suspension gives the impression of lognormality. The conditions necessary for generation of unimodality, symmetry and lognormality of grain-size distribution in suspension were worked out by Ghosh and Mazumder. It was also shown that lognormality can generate as a special case of hyperbolic distribution by a process of grain sorting.

Lognormal grain-size distributions in suspension, once generated in a close-circuit flume, at an appropriate combination of height and flow velocity, is sustained till the flow condition is drastically altered. In a natural stream however, lognormality, once developed, is likely to be modified with progressive downstream migration.

The observation that sediment concentration sharply increases with decrease of the mean grain-size of the bed material, and that the modal grain-size of the bed usually dominates the suspension, will be of help in the transportation of sediments as slurries through natural and artificial canals.

Sediment populations transported either in the beds of streams, or in suspension, plot as mixtures of several segments on log-probability graphs. These segments disappear as the grains get sorted either by prolonged transportation on the river bed or by transportation in suspension at high flow velocity. At this stage the log-probability plot of the cumulative grain-size distribution attains linearity. The degree of lognormality attained, therefore, may provide a clue to palaeoflow condition. Experimental results indicating influence of the modal grain-size of the bed on suspension as well as deposits are significant

because they allow estimation of palaeoflow condition from grain-size distribution of the deposits using a relationship developed by Ghosh and Mazumder.

All grain-sizes in suspension are deposited simultaneously when the flow velocity is reduced. This empirical observation solves a long standing geological problem—the presence of large quantities of fine grained matrix in essentially coarse grained turbidites.

Mathematical modelling of the deposits from suspension has not been easy because the conventional equations predict exponential decay of the coarser grains from suspension with lowering of flow velocity. Introduction of a 'dampening factor' in the conventional Rouse equation produced results matching the experimental observations within reasonable limits. Hindered settling of the coarser grains in a dense suspension and similar other processes are likely to be responsible for retarded settling of the coarser grains. Such processes must be operating in fluvial regimes and also in density currents generated in nature.

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Mathematical modelling of the experimental observations was undertaken by Professors J K Ghosh and Prof. B S Mazumder at the Indian Statistical Institute (ISI), Calcutta. The authors are grateful to Prof. Ghosh and the anonymous referees of INSA for their comments and suggestions on an earlier version of the manuscript.

Appendix

(Notations)

- B Integrating constant
- c Settling velocity of a particle
- d Initial depth of water as measured from flume base
- H Height of sand ripple/dune
- L Wave length of sand ripple/dune
- M_z Inclusive graphic mean size[20]
- S_y Concentration of material per unit volume
- S_{ks} Relative concentration distribution at k_s, where k_s is the bed roughness
- S'_y Relative concentration distribution at height y above the bed
- u_* Shear velocity
- u_{y1} Extrapolated velocity at $y=y_1$
- y Vertical height above the bed
- ϕ $-\log_2 D$ where D is the grain diameter in mm
- χ von Kármán constant (0.4)
- σ_1 Inclusive graphic standard deviation[20]

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