SOME FACTORS CONCERNING THE TRANSPORT OF SEDIMENT BY RIVERS[1]

By J. B. AUDEN, *M.A., Sc.D. (Cantab.), F.N.I., Superintending Geologist, Geological Survey of India, Calcutta.*

SUMMARY

The paper discusses the problem of capacity and competence of rivers in transporting sediment, based on the pioneer work of Gilbert, and subsequent elaborations by Rubey, Quirke and Mackin. It is suggested that sufficient attention has not been paid in silt studies, as they effect engineering projects, to the power functions between capacity and competence with bed velocity, and indirectly therefore with discharge. Data collected by the River Research Institute, West Bengal, and by the CWINC research stations at Hirakud and Barahakshetra, indicate that the silt contents of the Damodar, Mahanadi and Kosi rivers are higher than the normal upper limits provided by A. N. Khosla's formula. The special geological conditions relevant to the Kosi and other Himalayan catchments are outlined. The possibility is then considered of the erosion and transport of the bed sands of these rivers under conditions of peak discharge, and the increased cross-sections thus developing which should be considered in estimating flood discharges. Finally the paper discusses the effect of the construction of dams on the retention of silt, and the fact that the flood waters which will spill over the dams will not be flowing to full capacity or competence. From this consideration it is suggested that the 'fixed' sand deposits below the Maithon and Panchet dams, which are now used for sand-stowing, may be eroded. Another effect of retention of sand as deltas in the headwaters of the reservoirs will be the aggrading of river beds upstream. Such aggrading might be a menace to structures such as the Sindri Fertilizer Plant, were it not for the proposed upstream control of the silt charge by construction of dams nearer the tributary headwaters.

CONTENTS

1. INTRODUCTION

Nearly four years ago the writer prepared a small report for the then Department of Labour, Government of India, to assess on limited evidence the quantity of silt brought down by the Damodar river, and the effect which the construction of dams would have on sand supplies used for sand-stowing in the coalfields. It cannot be said that our knowledge has much increased since then, but it is thought worth while to review the data once more from the slightly different approach of the geological principles underlying the argument.

My colleague, Mr. A. B. Dutt, has discussed in a separate contribution to this Symposium the quantities of sand now present in the beds of the Damodar and related rivers and the amounts required for sand-stowing operations. This present paper is concerned more with questions of the capacity of rivers to transport sand and the effects of dam construction on the annual increments.

---

[1] Published by permission of the Director, Geological Survey of India.

VOL. XVI—No. 6 (November—December) 1950.

The problem of sand supplies for stowing operations in the Jharia coalfield was discussed 20 years ago by C. S. Fox (1930, p. 106), who classified the sand into two categories:—

(*a*) 'Fixed' deposit perennially present in the river bed; regarded as 80 m. tons between Amlabad and the end of the coalfield.

(*b*) 'Current' deposit brought down annually by floods; regarded as 25 m. tons.

The designation 'fixed' deposit was not intended to imply that the sand in the river bed was immovable. Fox himself suggests that the top 6, or even 8, feet of sand in the river bed would be in movement during floods. The sand of the river bed must indeed be carried down both as suspended and as tractional (or bed) load during floods, and further sand would be dropped from upstream as discharge and velocity diminished. In this sense only is it permissible to regard these deposits as fixed, for in reality the sand must be for ever changing and renewed, and is not necessarily of constant thickness from year to year. The sand-stowing operations remove large quantities of sand annually from the river beds and the areas of extraction are invariably filled up by the subsequent monsoon floods. For instance, as much as 1·5 million tons of sand are required annually by only 3 collieries in the Raniganj coalfield.

2. Capacity and Competence

The question of the quantity of silt carried annually by rivers is highly involved, since it is connected not only with the hydraulics of river flow over beds of varying gradient, hydraulic radius, and bottom conditions, but on the geological nature of the catchment, on climate, and on the effects of human action, such as de-forestation and unsound systems of cultivation. Very divergent estimates have been made, partly as a consequence of the many different types of catchment studied, but partly because experimental studies of suspended load have varied in accuracy. The primary difficulty is to make any reliable estimate of suspended silt content during periods of peak floods and high flood velocities. Estimates of tractional or bed load are even more uncertain.

Two basic conceptions involving velocity coefficients were developed by Gilbert 36 years ago, and have been elaborated by Twenhofel, Rubey, Quirke and Mackin in more recent years.

Capacity may be defined as the maximum load that a stream can carry in suspension. Much depends on the conditions of the stream: whether or not the stream flows over a sandy bottom; the grade size of the silt; and the settling velocities of the largest particles carried. Relevant to most rivers of peninsular India is Rubey's statement that 'in a stream free to pick up much sand and gravel as its velocity is increased, the unit width load will vary roughly as the third power of the "bed" velocity'.

Competence may be defined as the ability of a stream to transport load in terms of dimensions of particles. Rubey gives the rule as follows:—

> 'The weight of the largest debris moved by a stream varies as the sixth power of the "bed" velocity.'

The largest particles moved in a stream would form the tractional load, while the smaller particles moved would be transported as suspended load.

Rubey discusses in detail the meaning of the term 'bed' velocity, showing that it is reduced by a low hydraulic radius, such as is common to many rivers of the Indian peninsula, and by a decrease in channel smoothness. He points out (p. 132), however, that bed velocity is most sensitive to changes in the mean velocity and only very slightly sensitive to changes in the roughness ratio.

Quirke (1945, p. 129) elaborates the conception of capacity and expresses the effective energy of a stream carrying a load in terms of $V-x$, in which 'V' equals the velocity of flow unimpeded by any load, while 'x' represents the reduction in velocity due to the load. In shallow rivers, supplied with an abundance of sand load smaller in size than the maximum for which the stream is competent, such as are prevalent in peninsular India, Quirke remarks that the factor 'x' must be large and that the capacity may vary as $(V-x)^{3\pm}$. He also cites the formula developed by Lechalas, and earlier discussed by Gilbert (1914, p. 195), for movement of rivers over sandy bottoms in France as:—

$$C = K\left(V_m^2 - k\right)$$

where capacity varies as the square of the mean velocity, with two empirical constants. Even with an assumed exponent as low as 1·5, a fourfold increase in the velocity involves an eightfold enlargement of the power product to which capacity would be related. Whatever the actual exponent may be for particular local conditions, it is clear that the curve of silt load as a function of velocity is parabolic, and that the load of suspended silt during short periods of exceptional peak floods may be extremely large.

Leighly (1934, p. 463) has also stressed the importance of turbulence in stream transportation, and has shown that in the case of a normal symmetrical cross-section of a stream with relatively large hydraulic radius, the most active erosion of bed deposits is below two areas of maximum turbulence near the stream bottom and lateral to the axial zone of maximum surface velocity. Most peninsular rivers have a low hydraulic radius almost approaching the relatively small mean depth of the river and the zones of turbulence in them are clearly much more irregular. Turbulent flow itself varies with a power of the velocity.

Few data are available in this office regarding velocities of flood discharge flow. It is said that the Kosi river, which flows through a narrow gorge in the Nepal Himalaya, reached a surface velocity of 28 ft./sec. in 1948. In the case of wide flat-bottom rivers, such as the Damodar, discharges of the order of 500,000 cusecs are accompanied by surface velocities of 15 ft./sec. and analogous bed velocities. The maximum recorded velocity of the Mahanadi at Sambalpur in 1948 was 8·03 ft./sec. for a discharge of 948,000 cusecs. Observations of suspended load are presumably not very reliable in the case of discharges exceeding 5 ft./sec., and may be almost impossible during times of peak floods, such as occurred in June 1950 on the Teesta river, which is said to have passed a record discharge of 600,000 cusecs through a gorge from a mountain catchment of only 4,800 sq. miles.

3. Data about Suspended Load

According to the Report of the Advisory Committee on the Hirakud Dam Project (June 1948), the total run-off at Hirakud in 1947 was 39·18 m. acre-feet, and the silt yield was 33,235 acre-feet, for a catchment area of 32,200 sq. miles. The mean annual run-off at Hirakud is taken to be 50 m. acre-feet and, on the assumption that the mean silt charge of a catchment is carried in a year of mean annual run-off, the silt yield for the latter year was estimated proportionally to be 42,500 acre-feet, or 1·32 acre-feet per square mile. Subsequent data obtained by the Hirakud Research Station under the charge of Dr. R. C. Hoon indicate that for the three years 1947–49 the average discharge was 35·75 m. acre-feet, with an average suspended silt content of 29,891 acre-feet, and a silt intensity of 0·93 acre-feet per square mile. If 50 m. acre-feet is still regarded as the average run-off, proportionality would suggest that the average intensity of silting would be 1·3 acre-feet per square mile. The figures given below for the Barakar river suggest, however, that it is unsafe to assume simple proportionality, since the silt content may be related to exceptional short periods of high-intensity precipitation and run-off, rather than to the total annual run-off.

On page 29 of the Preliminary Memorandum on Unified Development of the Damodar River it is stated that observations made during the monsoon seasons from 1939–41, inclusive, indicated that the proportion of silt carried by the Barakar river at Barhi amounted to approximately 1/350 of the average flow. It was assumed that for the Damodar catchment as a whole the proportion would be 1/500. If this proportion is applied to the mean annual run-off at Rhondia of 8·04 million acre-feet, the quantity of silt would be 16,080 acre-ft., equivalent to 28 million tons at 90 lbs./c.ft. Since the catchment area above Rhondia is 7,690 sq. miles, the intensity of silting on the above assumptions would be 2·09 acre-ft. per square mile per annum. These data have now been supplemented by fuller silt observations carried out by the River Research Institute, West Bengal, under the guidance of Dr. N. K. Bose (1949, p. 39):

Monsoon volumes of discharge of Barakar river near Giridih and Kulti together with silt charge, for June to October inclusive

Catchment Area	Barakar (Giridih) 1,540 sq. miles			Barakar (Kulti) 2,500 sq. miles		
	Discharge in million acre-feet.	Silt charge in acre-feet.	Siltation Intensity: acre-feet per sq. mile.	Discharge in million acre-feet.	Silt charge in acre-feet.	Siltation Intensity: acre-feet per sq. mile.
1945 ..	1·100	2,511	1·64	1·803	..	..
1946 ..	2·121	4,439	2·88	3·027	5,806	2·32
1947 ..	1·653	4,399	2·86	2·501	3,056	1·22
1948 ..	1·058	1,437	0·96	2·330	2,171	0·87
Average 4 years and 3 years		3,205	2·08	..	3,678	1·47

The intensity of siltation for the whole catchment based on the reduced value of the Barhi determination agrees exactly with that subsequently found in the Barakar river at Giridih, but is too high for the Barakar further downstream at Kulti. It is likely therefore that siltation intensity on the Damodar at Rhondia would be even lower than on the Barakar at Kulti, and might be of the order of 1·3 acre-ft. per square mile.

Finally, data may be given for silt content during periods of flood discharge, the data being obtained from Buckley (1928, p. 148) and Bose (1948, p. 3; 1949, p. 37):

	Ounces per cubic ft. or grammes per litre.
1. Sutlej 7-7-1894 (Buckley)	29·4
13-6-1895	25
2. Kistna 27-7-1900 (Buckley)	20
22-6-1901	23·8
3. Barakar, Giridih 1-8-1947 (Bose)	14 10 for more than 13 hours.
4. Damodar, Ramgarh 7-7-1946 (Bose)	22·77
7-7 to 8-7-1946	11·78 for 24 hours.

At Ramgarh on the Damodar river the silt charge volume during 2½ days in June 1948 was 335 acre-feet, for a catchment of 1,250 sq. miles, and was equal to about 30 per cent of the total monsoon silt charge. In a single day (1-8-1947) at Barakar (Giridih) the volume of silt charge was 2,568 acre-feet, which was higher than the total volume of silt charge for the individual years 1945 and 1948. On this day the silt content exceeded 14 oz./c.ft. for a maximum discharge of 260,000 cusecs, and was greater than 10 oz./c.ft. for more than 13 hours during the high stage.

These figures demonstrate the immense activity of rivers during peak floods, throughout which periods, lasting only a few hours, the full implications of the power function become manifest, and the greater part of the geological work is done. When it is remembered that the figures refer only to suspended silt, and not to bed load, it is clear that the total activity of rivers during floods is even more impressive.

4. COMPETENCE.

Work done by CWINC on the suspended silt of the Mahanadi river in 1947 shows that 76 per cent of the total observed load was below 0·075 mm., 13 per cent between 0·075 and 0·20 mm., and only 11 per cent greater in size than 0·20 mm. Data concerning the grading of the Mahanadi bed sands are lacking. Similar small percentages have been found in the river waters of the Damodar basin with respect to the coarser particles above 0·611 mm. in diameter. The maximum percentage of such particles recorded for the monsoon discharges was 7·7 per cent at Barakar (Kulti) in 1946 (Bose, 1949, p. 40). The bed sands of the Damodar river from Argada to Champadaga over a distance of 200 miles were found by A. K. Roy (1942) to be as follows:—

	1	2	3	4	5
>0·421 mm. ..	30·60	32·20	9·00	28·00	20·12
0·211–0·421 ..	46·50	49·01	69·02	62·05	63·64
0·139–0·211 ..	18·00	5·14	17·21	3·77	8·77
<0·139	4·20	13·01	4·09	5·47	5·06
Greater than 0·211 mm.	77·1	81·2	78·02	80·05	83·76

The critical bed velocity at which movement of sand greater than 0·20 mm. diameter starts is of the order of 0·05 ft./sec., whereas sand particles with diameter 4 mm. begin to move with a velocity of 1·4 ft./sec. (Rubey, p. 133). It is evident therefore that the coarser fractions of these Damodar sands begin to be eroded with relatively insignificant bed velocities.

It is seen that the Damodar bed sands have higher percentages of coarse grades than the silt obtained from suspension in the river itself. The silt analyses refer only to suspended load near the water surface and do not indicate the true picture of material transported during flood periods in the lower depths of the moving water.

5. TRACTIONAL LOAD

The quantity of tractional or bed load moved by streams is known with even less certainty than the suspended load. Twenhofel (1950, p. 222) cites estimates in Europe of tractional as a percentage of bed load which vary from 14 to 30 per cent, whereas in some exceptional American rivers the tractional and suspended loads have been considered to be almost equal. It is probable that the ratio will vary in the same stream according to different velocity conditions, since the size of particles moved by traction varies with a higher power of the bed velocity than the load carried in suspension. It is difficult of course to relate the amount of bed load directly to competence, since competence refers to the maximum size of particles that can be moved and not to the quantity, but it has been shown that in the case of a river able to put into motion progressively coarser grain sizes, there is a moderately close relationship between the quantity of debris in motion and the largest grain size that is being translated (Mackin, 1948, p. 469). During low winter discharges of many rivers the sand may be seen through the clear shallow water being moved as bed load without any suspended load being present at all, whereas under flood conditions the suspended load is abundant, but the turbidity arising from it obscures any direct observation of the quantity being moved as bed load.

The ratio will vary also between different streams, depending on the size of the bottom materials. Mackin (1948, p. 470) has pointed out that the total load carried will be greater for a given velocity for small sizes than for larger sizes, and has argued that for rivers such as the Damodar, which have particle sizes clearly not up to the full competence of the river during peak discharges, it is capacity which is the critical factor, and the total load carried per unit width may vary as a power of the bed velocity which is higher than the third power. In such a case, with bottom sands of relatively small particle size, it is probable that tractional load may be relatively unimportant under large discharges, and suspended load forms the major part of the total load. On the other hand, with rivers such as the Kosi, which have abundant coarse boulders distributed in rapids throughout the montane course, the fraction of bed load which moves under high velocity conditions may increase relative to the suspended load, and increased competence is in a sense a measure of the amount of tractional load.

6. Work of Rivers during periods of Flood Discharge

Dr. N. K. Bose has suggested to me that the experiments on velocity have only been carried out within a very limited velocity range, and that extrapolation to the higher velocities encountered during large discharges is probably unsound. The maximum velocity in Gilbert's laboratory experiments appears to have been 3 ft./sec. While it is possible that the exponent may change with very high velocities, the geological evidence for major activity at times of high discharge and velocity is unequivocal, and does not suggest that the rule is significantly modified in the direction of diminished capacity under such conditions. To account for the lack of correspondence between theory and experimental results it might be assumed either that the silt supplies from the catchments are small, or that the experimental results are not representative for the higher ranges of discharge and velocity. It is true that some Indian rivers do not yield much silt, such as the Cauvery at Mettur. But since soil erosion is prevalent in the catchments of most Indian rivers, and since these rivers are proved to be very silty during flood periods, it is unlikely that there is a shortage of silt supply during periods of concentrated precipitation and run-off. Moreover, the rivers in their lower reaches flow over 20–80 feet of wide sandy bottom, part at least of which is perennially water-born, and these sands are witness therefore of higher grade sizes being moved than are recorded in the silt tests.

What rivers are capable of doing during peak discharges is clear from the nature of the Colorado river at the Boulder (Hoover) dam. An inner gorge 75–80 feet deep below the rock benches on either side, and some 120 feet below river bed level, was found to be pitted, fluted and pot-holed. Moreover a sawn plant of wood was found embedded in gravels at the edge of the inner gorge. It could only have reached this position provided the whole mass of gravels from top to bottom had been in a condition of buoyancy and turbulent movement, during a historically recent flood.

Corroborative evidence has very recently come to light of the same feature to the Kosi dam site in Nepal. My colleague, Mr. M. S. Jain, informs me that a piece of fresh wood has been found in diamond drill hole No. 201, which is the centre hole of the toe alignment, at a depth of 42 feet below the top of the bed sands and 3½ feet above ledge rock below the sands. The average thickness of the bed sands, which lie below 15 feet of quiet water during periods of low discharge, is 43 feet, with a range from 26 to 64 feet in 15 holes. The occurrence of such wood, almost at the bottom of the bed sands, clearly indicates that during flood discharges the whole of the thickness of these sands must be in a state either of suspension or of movement sufficient for the wood to have been left in that deep position. Another piece of wood was found from 21½ to 25½ feet below the top of the bed sand, and 10 feet above bed rock, in wash-boring No. CD4.

As already stated, Fox considered that the top 6–8 feet of the bed sands of the Damodar may be under suspension during floods. This is probably an under-estimate for large discharges and it is conceivable that the whole thickness of sands may periodically be in motion. From data provided by Mr. A. B. Dutt, the average thickness of the bed sands of the Barakar river between its confluence with the Damodar and the Kalyaneswari temple, near Maithon, is 43 feet, with cross-sectional ranges between 36 and 54 feet. But at the Maithon dam site, in the section where the river is at its narrowest (1,000 ft. wide) the bed sands are found from detailed drilling at 200 ft. centres to average 62 feet, with a range of 38 to 85 feet. It is of course arguable that the deeper scour at the narrowest section of the river took place during an earlier regime of the river, and has subsequently been filled up by mainly non-scouring sands. But it is also possible that, as in the case of the Colorado and Kosi rivers, the whole thickness of bed sands at Maithon may be scoured out and transported during floods such as occurred in 1823, 1840, 1913, 1935 and 1942, and that the deeper scour in the Maithon defile belongs to periodic peak discharges of the present river regime. The drill records at the Maithon site do not indicate any break in the nature of the bed sands throughout their depth, but suggest rather an essential continuity and a single regime.

This problem is of relevance to estimates which are made of peak discharges, for it may be necessary to calculate the cross-sectional area of moving water not only upwards from bed-sand level, as it occurs during small discharges, but from the base of the bed sands resting on rock. In the case of the Maithon cross-section, this would involve an additional area of some 62,000 square feet, while in the Kosi gorge, Nepal, the additional peak flow area would be of the order of 12,000 sq. feet.

This enlarged cross-sectional area, set in motion during floods, will naturally involve greater flood discharges than are normally accepted on the basis of a cross-section taken down only to the top of the bed sands. If all the factors involved in discharge are correctly assessed, the ratio of the calculated run-off to the actual run-off should approximate to unity. After allowance has been made for discharge into rivers from springs and diffuse effluent seepage from the ground water, and for increments due to snow-melt and glacier-melt water, the discharge from streams should not exceed the actual precipitation over the catchment. This will set a limit to the actual discharge which can be expected from the enlarged cross-section, and may lead to the conclusion that the bed velocities are much smaller than the surface velocities. Such considerations apply to the Damodar river, where the total discharge below the main tributaries over the Anderson Barrage is known, and forms a check to calculations based on enlarged cross-sections. But uncertainty may exist about the representative character of the raingauge stations over a catchment, particularly in the almost unknown regions of Nepal, Bhutan and Upper Assam, and it seems advisable to consider the possibility of the real discharges in times of flood being greater than those hitherto accepted in the little studied rivers of the eastern Himalaya.

It may be noted that, whereas the bed sands of the Kosi river at the dam site are relatively fine, with only occasional boulders, the boulder gravels downstream thereof at Chatra are very coarse. These gravels have been derived from upstream of the dam site and must have passed through the gorge during periods when river competence was much higher. This points to the complete flushing out of all the fine bed material at the dam site during periods of flood discharge. The fact that only sands are dropped at the site during declining discharges, while gravels are confined to the rapids above and below the site, is admittedly difficult to explain.

Alternations of rapids and still sections in the longitudinal profile of a river imply sudden changes in velocity, with acceleration and deceleration. It is possible that the deceleration which arises where water passes from the rapids to the still sections has a greater influence during a waning flood on competence than on capacity, since competence is more sensitive to changes in velocity than capacity. This would indicate that the coarse detritus carried and moved by a river in flood tends to be deposited with declining discharges in the rapid sections, where the deceleration is at a maximum.

7. Siltation Formulae

From a study of over 200 reservoirs A. N. Khosla has developed an empirical rule for silting from catchments exceeding 1,000 sq. miles in area. This states that the annual rate of sedimentation per 100 square miles of catchment has a *normal upper limit* of 75 acre-feet. It is probable that the majority of reservoirs from which this rule was derived are located in the temperate climatic zone. Many of the reservoirs are located in the Western States of the U.S.A. where climatic and geological conditions are broadly similar.

The average rate of silting in the Mahanadi at Sambalpur, for the years 1947–1949, is considered to be 0·93 acre-feet per square mile per annum, and possibly 1·3 acre-feet for an average discharge. The average observed silt content of the Barakar river near Maithon for 3 years is 3,678 acre-ft. or 1·47 acre-ft. per square mile, which is double of that indicated from the formula. In the case of the Kosi river in Nepal, the annual silting rate is now determined by CWINC to be 5·18 acre-feet per square mile per annum, for the 3 years 1947–1949, which is almost 7 times the rate derived from the empirical rule.

The Kosi river is of interest in showing a combination of peculiar conditions:—

(*a*) the Himalaya is a region of very recent overthrusting and folding, and the river profiles indicate active downcutting concomitant with even more recent isostatic elevation;

(*b*) many of the southern tributaries of the Sun Kosi river have catchments in outcrops of Siwalik clay, sand-rock and cobble conglomerates. These rocks are very poorly compacted and both the argillaceous and arenaceous facies are eroded with the greatest of ease;

(*c*) the Arun catchment in Tibet flows through extensive areas of Jurassic shales without vegetal cover;

(*d*) within the catchment of the Sun Kosi, Arun and Tamur rivers lie the highest peaks of the Himalaya, with extensive snow fields and many large glaciers. The glaciers effect strong abrasion of their rocky beds, and the rock flour is carried down during the months of snow and ice melt;

(*e*) much deforestation has taken place in the lower ranges.

These factors all conspire to make the Kosi a very silty river. The Kosi has indeed built up a sub-delta of coarse sands and gravels, over 3,000 square miles in area, upon the Gangetic plain, and it is likely that the capricious deposition of coarse detritus, where the river debouches into the plains south of Chatra, is one of the factors responsible for the shifting course of the river. Another factor has been briefly mentioned elsewhere (Auden; 1949, p. 328). The Tista river has also had a very variable course south of Sevoke, which is probably due in part to erratic deposition of gravels at the débouchure.

Similar geological conditions apply with slight modifications to many Himalayan rivers in the catchments of which occur Siwalik outcrops and glaciated ranges. The Karnali river has a catchment area of 20,600 sq. miles in the western Nepal Himalaya in which are present both high peaks, many glaciers, and extensive areas of Siwaliks. West of longitude 77° the glaciers of the Himalayan range are somewhat less important, but the outcrop of Siwalik and Middle Tertiary rocks expands to 30–50 miles in width and forms considerable areas in the catchments of the Sutlej, Beas, Ravi and Chenab rivers. The very extensive and thick terraces of boulder gravels along the flanks of the Kali Gandaki river in central Nepal point to an earlier, but still recent, regime of the river when capacity and competence must have been exceptionally high.

It must be accepted therefore that the rate of silting in Northern India is exceptionally high, and does not conform to conditions characteristic of more temperate climates and orogenically less active terrains. This departure from temperate norm must be allowed for in estimating the life of reservoirs.

8. DEPOSITION DURING THE PLEISTOCENE

The Siwalik rocks (Middle Miocene to Lower Pleistocene) which form a zone of outer foothills at the foot of the Himalaya for a distance of 1,500 miles of arc, represent an orogenic facies deposited in front of the rising Himalayan chain. These rocks vary from 15,000 to 20,000 feet in thickness and die out radially, away from the mountain arc, under Gangetic alluvium. It would be safe to assume a total average width of Siwalik formations, exposed in present outcrops, and concealed below the alluvium, of 50 miles. The whole of this mass of sediments has been deposited probably well within 10 million years.

After early Pleistocene folding and faulting had thrown up the Siwaliks and caused their partial erosion, the Gangetic alluvium accumulated in a downwarp just in front of the Siwaliks. The Gangetic alluvium reaches a maximum thickness in North Bihar, where it may be over 6,000 feet. This pile of sediments has been deposited within the Pleistocene period of about 600,000 years' duration. If a prism of alluvium 100 miles wide is taken radially from the Himalayan arc, one mile wide, and 2,000 feet thick, the volume of sediment is 5,580 billion c.ft. Assuming that this has been eroded from a rectangular area across the Himalayan arc 100 miles long and one mile wide, during a period of at most 600,000 years, the rate of sedimentation is approximately 2 acre-feet per square mile per annum, which is 40 per cent of that of the present Kosi river. The closeness of the figures is of course fortuitous and depends on the assumptions made. It may be objected that the southern part of the Gangetic alluvium is derived from the peninsula, while some of the Himalayan drainage now comes from across the Himalayan axis. Nevertheless, the assumptions made are conservative, because only a part of the width of the alluvial Gangetic alluvium has been taken into account, and the thickness of the alluvium is likely over most of the zone extending 100 miles outwards from the Himalaya considerably to exceed 2,000 feet. Moreover, the period of 600,000 years is probably excessive since the pre-alluvial Siwaliks extend up into the Pleistocene, and the alluvium cannot represent the whole time considered to be covered by the Pleistocene, This calculation has been put forward not for any precise quantitative purpose, but merely to provide an approximate indication of magnitudes when dealing with orogenic sedimentation.

9. EFFECT OF CONSTRUCTION OF DAMS

The limitations of space imposed on this Symposium do not permit of any extended discussion of the effects of the dams on the migration of sand to the places from which it is now extracted for stowing.

There is no doubt that the whole of the gravel and sand brought down by rivers will be retained by the reservoir basins, mainly as deltas in the headwaters where the higher velocity water enters the relatively still impounded waters. It is probable that some of the finer silt grades may pass over the spillways, but the water which is spilled over the dams will most certainly not be transporting to full capacity or competence.

In so far as the reservoirs are designed for flood control, peak floods will be eliminated except in the event of a second cyclone occurring in the catchment immediately after a reservoir has been filled by run-off from a previous one. Nevertheless, in the latter part of the monsoon considerable discharges must be expected from the reservoirs.

Since these waters will be almost silt-free, they will be flowing over the bed sands downstream of the dam with potential ability to take up sand to satisfy the particular velocity and volumetric conditions of the regulated flow. It would appear therefore that the effect of the construction of dams will be to cause erosion of the bed sands below them, of comparatively fine particle size, by the almost silt-free spill waters, and a gradual diminution in the reserves of the so-called fixed deposits, which under the new conditions would receive little or no increments from upstream. In the probably not too rare event of a storm hitting the Damodar basin within a month after the reservoirs have been filled by a previous one, large discharges of the order of 200,000–300,000 cusecs may be expected over the Maithon and Panchet dams which could, according to theory, remove a great deal of the bed sands below them. This is a factor which the coal companies should bear in mind in future planning. It may be advisable to shift the locations of sand supply to the deltas which will grow at the headwaters of the reservoirs, though this will involve a greatly increased haulage. The quantity of sand reaching these deltas will certainly be diminished, however, by construction of dams upstream of the Maithon and Panchet reservoirs.

Another point may be stressed. As the deltas build outwards into the reservoirs, they also aggrade. In a very able discussion Mackin (1948) has shown that the aggradation spreads with great rapidity for long distances upstream, and may effect lines of communication and also towns. The Sindri fertilizer factory will be near the headwaters of the Panchet reservoir and, without upstream development, a delta would be built up considerably above the elevation of full supply level of the reservoir. But in this case, the construction of the Aiyar and Konar reservoirs upstream of Panchet should materially control the entrance of silt into the Panchet reservoir and lessen the tendency of aggradation. Aggrading delta formation should also be under observation at the headwaters of the Hirakud reservoir up the Ib river. If construction of the Dudh Kosi dam is delayed, intensive gravel formation at the headwaters of the main Kosi reservoir will tend to fill up the valley and increase the excavation necessary for the foundations of the Dudh Kosi dam.

Finally, the question of navigation below storage reservoirs may be raised. Mackin (p. 495) showed that the reduction of peak discharges may result in aggradation of the trunk stream below major tributary junctions, since the controlled discharges are no longer able to move much of the detritus delivered to the main channel by flash floods in the tributaries. This case is an exception to the general rule of greater down-cutting in trunk streams below storage dams, but may be very relevant to the question of navigation. For aggradation at the confluences of silty uncontrolled tributaries with main rivers on which storage reservoirs have been built may render navigation at those points more difficult. The Tel river below the Hirakud dam, and the Adjai river below the Maithon and Panchet dams, are cases in point. The construction of the Tikapara dam below the Tel confluence with the Mahanadi would of course eliminate the difficulty on that river by creating a navigable reservoir.

CONCLUSION

The object of this discussion has been partly to emphasize the power functions of capacity and competence with velocity, and partly to suggest the modifications which the structure, recent tectonic activity, and climate of northern India, are likely to impose on empirical rules of silting derived from other, in the main less revolutionary, environments. In so far as the life of reservoirs is concerned, it would appear necessary in many catchments in northern India to allow for a greater rate of siltation than would be indicated from the rule under discussion.

10. References

Auden, J. B. (1946). Silting on the Damodar Basin and Sand-Stowing. Unpublished Report of the Geological Survey of India.

——————(1949). A Geological Discussion of the Satpura Hypothesis and Rajmahal Group. *Proc. Nat. Inst. Sci. Ind.*, 1, p. 315.

Bose, N. K. (1948). Appendix to the Annual Report of the River Research Institute, West Bengal, 1946.

——————(1949). Annual Report of the River Research Institute, West Bengal, 1948.

Fox, C. S. (1930). The Jharia Coalfield. *Mem. Geol. Surv. Ind.*, 56.

Gilbert, G. K. (1914). The Transportation of Debris by Running Water. *U.S. Geol. Surv.*, Prof. Paper, 86.

Khosla, A. N. (1947). Mahanadi Valley Development; Hirakud Dam Project: Government of India.

—————— (1949). Special Techniques in Water Storage Conservation: Sand Storage, Sedimentation Control, U.N.E.S.C.O. (Water 5 (c)/1).

Leighly, J. (1934). Turbulence and the Transportation of Rock Debris by Streams. *Geog. Review*, **24**, p. 453.

Mackin, J. Hoover (1948). The Concept of the Graded River. *Bull. Geol. Soc. Am.*, **59**, p. 463.

Quirke, T. T. (1945). Velocity and Load of a Stream. *Journ. Geol.*, 53, p. 125.

Roy, A. K. (1942). On the Heavy Mineral Assemblages of the Damodar River. *Rec. Geol. Surv. Ind.*, **77**, Prof. Paper, 6.

Rubey, W. W. (1938). The Force required to move Particles on a Stream Bed. *U.S. Geol. Surv.*, Prof. Paper, 189-E.

Twenhofel, W. H. (1950). Principles of Sedimentation, New York.

Preliminary Memorandum on the Unified Development of the Damodar River: Central Technical Power Board, Government of India, 1946.