RIVER MECHANICS AND MORPHOLOGY

Dacca Southwest Project

East Pakistan

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Chapter I

Introduction

The Dacca Southwest Project (DSW) is bounded by the Jamuna, Dhaleswari, Kaliganga, and Padma Rivers. The project area is very flat and consists of mixtures of clays, silts and sands which have been deposited by the river system. The majority of the land area is cohesive. However, large silt and sand deposits are common along the rivers, particularly in the northern part of the project area. During the monsoon season these and other rivers overflow their banks. Then most of the project area is inundated to depths ranging up to 10 feet or more.

The major purposes of the project are (1) to protect this land from flooding, (2) to pump excess rainfall from the project area during the wet season, (3) to take water from the adjacent rivers and deliver it to the project for irrigation during the dry season. The construction of the project would greatly enhance the agricultural productivity of the project and the welfare of East Pakistan.

From a river development point of view the project requires the construction of perimeter dikes and possibly a system of interior dikes to hold out the rivers flood waters and the installation of pumping plants in the dikes to remove excess water during the monsoon period and to supply water to the area from the adjacent rivers during the dry season.

The purpose of this report is to discuss the major factors which may affect the feasibility of the project from a river mechanics point of view. The principle topics considered include a general discussion of:

1 - The response of the rivers to water resources development;

2 - The effects of sediment transported by the river system;

3 - The location and safety of the flood control embankments;

4 - The pumping plant locations;

5 - The characteristics of the rivers bounding the project area;

6 - Specific recommendations concerning the feasibility of the dikes, pumping plants, and supply canals considering the characteristics of the rivers, and

7 - The long-term need for hydrologic and related river data.

Chapter II

RIVER RESPONSE TO DEVELOPMENT

Before the response of rivers to confinement resulting from the proposed project development can be evaluated, certain facets of river morphology should be studied and understood. With this fundamental information the potential changes that may result from various degrees of river development can be investigated. This requires consideration of the effect of development on channel geometry, flow characteristics, sediment discharge, and other important factors. Then a realistic appraisal can be made of river response, embankment set-back distance, embankment alignment, height of embankments, and pumping plant locations.

River Form

The general forms of rivers, meandering, straight and braided, are illustrated in Figure (1) (for the figures refer to Appendix A). There are many transitional forms sandwiched between these types.

Figure 1. General classification of rivers.

Meanders. A meandering river has more or less regular inflections that are sinuous in plan. It consists of a series of bends connected by crossings. In the bends deep pools are carved adjacent to the concave bank by the relatively high velocities. The centrifugal force in the bend causes a transverse water surface slope and helicoidal flow in the bend. These transverse currents, with a magnitude of about 15% of the average channel velocity, flow toward the convex bank. In so doing, they sweep the heavier concentrations of bed load toward the convex bank where they are deposited to form the point bar. The bends are connected by crossings (short straight reaches) which are quite shallow compared to the pools in the bendways. At low flow, large sand bars form in the crossings if it is long and if the channel is not well confined. The scour in the bend causes the bend to migrate downstream and sometimes laterally. Much of the sediment eroded from the outside bank is deposited in the crossing and on the point bar in the next bend downstream. Meandering rivers have relatively flat slopes.

Braiding. The river channel is wide, the banks are poorly defined and unstable. There are two or more main channels that cross one another giving the river bed a braided appearance at low flow. Between sub-channels there are numerous sand bars and islands. These sub-channels and sand bars rapidly change position with time and stage and in an unpredictable manner. At flood stage the flow straightens, most of the sand bars are inundated or destroyed and the river has a canal-like appearance except that the river is much wider and has a higher flow velocity. Such rivers have relatively steep slopes and carry large concentrations of sediment.

Straight. The channel has negligible sinuosity at bankful stage. At low stage the channel develops alternate sand bars and the thalweg meanders around them in a sinuous fashion. Straight channels are often considered as transitional to meandering. If the channel is unconfined more than one channel develops, there are middle bars as well as point bars and the river is braided. This classification of channel has characteristics common to both meandering and braided rivers.

Bed configurations. Sand bed rivers have well recognized forms of bed roughness. The accepted forms of bed roughness are ripples, dunes, a transition region, plane or flat bed standing waves, and antidunes. These forms were studied and identified by Simons and Richardson (1)*. Their characteristics depend on depth of flow, velocity of water, and suspended sediment characteristics including viscosity, size, density and gradation of the bed material. Figure 2 shows these forms of bed roughness as reported by Simons and Richardson (2).

Figure 2. Forms of bed roughness in alluvial channels.

These forms of bed roughness are subclassified into a lower and upper regime. In the lower regime the bed forms are ripples and dunes; in the upper regime the bed is plane or there are standing waves and antidunes. In the lower regime resistance to flow is large, velocities are small, and bed material transport is small. In the upper regime resistance to flow is small, velocities are relatively large and transport rates of bed material are large. The shift from lower regime through transition to upper regime occurs at a Froude number of about 0.17 - 0.18 for fine sands such as occur in the Dhaleswari and Jamuna Rivers.

It is very important to note that as river stage rises much of the river bed shifts from lower regime flow to upper regime flow. In so doing Mannings n values drop from 0.025 - 0.030 to 0.012 - 0.017. Hence, the decrease in resistance with rising discharge permits the river to handle large increases in discharge with much less increase in stage than one normally expects. For example, the stage at Hardinge bridge on the Ganges rose only 5 ft for a change in discharge from 1,350,000 cfs

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* The references are found at the end of this report.

to 2,585,000 cfs. The increase may have been less except for the partial control of the flow by rock placement and the bridge.

Sand bars. In addition to the bed forms illustrated in Figure 2 large three-dimensional sand waves are important features in sand bed rivers--particularly in the unstable ones with large width to depth ratios. The accepted classification includes point bars, alternate bars, and middle bars. The latter may become semi-permanent islands. These large scale features are illustrated in Figure 3 for a confined river.

Figure 3. Point, middle and alternate bars.

In well confined channels their positions are predictable. In wide, unstable braided and straight channels it is difficult to predict their dimensions, characteristics, and positions. These bars are a function of channel geometry, hydraulics, and sediment transport. They greatly affect channel stability and channel geometry. Bars are most noticeable in wide-straight or wide-braided unstable channels and in long crossings of meandering channels at low stage. They cause dramatic changes in cross-section at any station, rapid cutting and filling along the banks, and rapid changes in channel width, and they affect the ability of the channel to convey water and sediment.

The amplitude of bars can extend upward to the water surface. With falling stage they are exposed and the submerged portions are subject to scour and deposition which changes their location and geometry. The amplitude of these features is closely related to the width-depth ratio of the channel as shown schematically in Figure 4, Simons (3).

Figure 4. Relation of bar amplitude-depth ratio to the width-depth ratio.

This figure illustrates the importance of locating the DSW pumping stations adjacent to relatively narrow stable reaches of rivers. In these reaches the bars will be of smaller amplitude and should not cause serious blockage of the canal entrance. In wide shallow reaches of rivers the bars will always be a serious problem. In this case river training works and dredging may be required.

Observed Channel Changes

The plan and profile of sand bed rivers are subject to changes of varying magnitude during an annual cycle. These changes are even more noticeable when the profile and banklines are compared over several years.

Bank stability is greatly affected by the type of river, the characteristics of the sediment load, and the river bed response to changing hydraulic conditions. The meandering river changes its position relatively slowly and it maintains its sinuous pattern. Hence, its future behavior and geometry are easier to predict. One can select the position of flood embankments, pumping stations, and the canals adjacent to a stable meandering channel with some confidence that large and rapid changes in river geometry and alignment will not endanger the works.

The plan and profile of braided rivers may change continuously. Erosion and deposition along the bankline and within the river channel are much less predictable. Both river banks may be attacked simultaneously and the pattern of alternate bars, braided channels, and middle bars and islands experiences large and random changes with time and river stage. Summarizing, the major reasons for river bank instability are: rising and falling stage, several braided channels, impingement of the thalwegs on the banklines, deposition of sediment, the formation and movement of sand bars, the variability of the composition of the banks, bank slumping and the presence of old river channels. All of these and other related factors greatly affect the bankline position and river configuration. With the braided river and its unpredictable geometry the flood embankments, pumping stations and canals located adjacent thereto should be set back further from the river to provide safety from changes in alignment. Such locations should be avoided when its feasible to do so. This type river causes special problems for the canals. A continuous water supply will not be available at the offtake. From time to time the water may be adjacent to the opposite bank. At other times the entrance to the canal may be partly or totally blocked by sand bars and the sediment load carried into the canal with the water may cause aggradation and may require periodic cleaning, particularly near the offtake from the river. When possible avoid locating the pumping stations adjacent to braided reaches of the rivers. The Jamuna River is primarily a braided river.

Map studies of the bankline configuration and a comparison of aerial photos taken at different times have been compiled and compared for the Brahmaputra and Jamuna Rivers. The report, "Channel Processes and Sedimentation," by Acres documents a study of bankline configuration for the Brahmaputra River. Thirteen maps dating from 1830-1963 were studied. In addition, the most recent maps published (1952 and 1963) were checked using aerial photos. These photos verified that the maps were accurate.

Thirty-two river sections spaced 3 to 5 miles apart were studied. Figure 5 presents the results of the analysis.

Figure 5. Rates of bankline migration for the Brahmaputra, Coleman (4).

Unstable and stable reaches of rivers tend to remain so except subjected to catastrophic events. Earthquakes, accompanied by subsidence or upheaval and very large floods, may cause major changes in both stable and unstable reaches. In fact such events may completely change the course of a river.

Because of limited documentation of bankline migration and large potential changes in river alignment during flood events the banklines should be defined and compared annually by aerial photography or other types of remote sensing. With this information the river changes could be studied in greater detail and used with hydrologic, hydraulic, and soils data to provide knowledge of interrelations between projects and the river. This study would also provide a history of river changes after project development which would help to predict river response to development of the extensive water resources of East Pakistan.

Project Effects on Rivers

The general aspects of river morphology, sedimentation, hydrology and hydraulics have been discussed for undeveloped rivers.

All rivers respond to modifications imposed by man, some significantly, others in a negligible way depending on the degree and type of river development. Consider possible river responses to the DSW project.

River Stage

The backwater analysis conducted by ECI established water surface profiles for the Jamuna and Padma Rivers and for the Dhaleswari, Kaliganga and Buriganga Rivers. The increase in stage as determined from the analysis was based on the assumptions of (1) the 100-year flood, (2) existence of the right embankment, (3) embankment set back distances of 1 mile along the Jamuna and Padma Rivers and 1/2 mile along the Dhaleswari, Kaliganga, and Buriganga Rivers, (4) Mannings n values based on field measurements, and (5) verification of computational procedures and assumptions by using 1966 flood levels and verifying them by computations. Profiles thus determined are probably on the safe side for two reasons: (1) As the stage rises the boundary shear stress $\tau = \gamma DS$ is increased. This will cause a larger percent of the river bed to shift from dunes and bars to a plain bed which will reduce the Manning n value to about 0.015. This will result in a higher average velocity and less rise in stage than has been computed; (2) With the increase in velocity in the channel the rate of bed material transport will be increased. Actually the rate of bed-material discharge increases approximately in proportion to the cube of the velocity. This increased capacity to transport sediment should degrade the channel slightly and contribute to an additional reduction in stage.

River geometry. As previously stated the basic types rivers are meandering, straight and braided. The increase in flood stage due to confinement, may cause a higher average velocity and the increased ability to transport bed material could have the following effects:

(1) It may cause the meandering and straight reaches to become slightly more unstable. Some reaches may become braided.

(2) The ability to transport more bed material at flood stage may make it possible to develop more stable, better defined channels which will be easier to control and develop. Much of the observed instability in reaches is due to excess coarse sediment.

(3) It should have no effect on the channel during periods of low flow.

In summary, the effects of confinement should be small. It will require careful observations to relate channel changes to the confinement of flow that result from construction of proposed flood embankments.

River banks. During flood stage the small increase in average velocity, depth, and transport capacity may cause a small increase in bank scour. At low flows the embankments will not affect flow and transport phenomena in the main channel.

Figure 6 illustrates the type of bank failures that occur in rivers and the general influences of the geology of river bank, soils on bank failure, and lateral migration of the river channel.

Figure 6. General influences of the geology of riverbank soils on the mechanics of bank failure. Potamology Investigations Report 12-15, Corps of Engineers, Vicksburg.

Chapter III

RIVER SEDIMENTATION

A river network consists of a highly organized system of physical and hydraulic features that transport the water and sediment downstream. The continuity of the river systems must be maintained for both water and sediment. If river development reduces or increases the river's ability to transport bed material, major detrimental consequences may result. For example, by degradation stream gradients may be reduced causing rivers to change form, or by aggradation river braiding, channel filling, and major river shifts may be the consequences.

The importance of the sediment discharge, its characteristics, and its movement as related to project development rivals the hydrologic data in importance.

The sediment is transported as suspended load and bed load. The suspended material is that transported with the water above the bed. It has been suggested that sediment in suspension, more than a few grain diameters above the bed, should be classed as suspended. The remaining material moving on and adjacent to the bed (within a few grain diameters of the bed) is bed load. This rather arbitrary subdivision is sometimes further subdivided to include a saltation load which bounces along the bed. This form of transport is transitional between suspended and bed load.

Generally speaking, these classifications are descriptive. We do not have sediment samplers which can measure bed load and suspended load according to these definitions. The samplers used are capable of measuring the suspended sediment to within 1/2 to 1 foot of the bed depending on the depth of flow, velocity, and size of weight required to sample the column of water above the bed. This requires a different classification system. That amount of suspended sediment that can be measured is called the measured load or measured suspended load and the remainder moving within one foot or less of the bed is referred to as the unmeasured load. The limited records of sediment discharge for the Jamuna and other rivers is of the measured suspended load. No measurements or computations have been made to evaluate the magnitude of the unmeasured load. Hence, total sediment discharge is equal to the measured suspended sediment load plus the unmeasured load. The unmeasured load can be computed using the U.S. Geological Survey Modified Einstein procedure (5) or the Colby method (6), provided the necessary variables are known or can be estimated.

The unknown fraction of the total load includes a large percent of bed materials (sand) and is equal to about 10-20% of the measured suspended sand load. The amount depends on the characteristics of the bed material, the depth of flow and hydraulic conditions in the river. In many instances, the unmeasured sediment load, which includes the bed load and some suspended sediment moving in the unsampled zone, is the most important part of the total sediment discharge. It is this fraction that is most responsible for bar formations, aggradation, degradation, and other phenomena which cause major changes in river systems.

There is yet another subclassification of the total sediment load that is important. The total sediment discharge is composed of the wash load or fine sediment load and the bed material load. The wash load consists of sizes not found in appreciable quantities in the bed material (silts and clays; usually small enough to pass the #225 sieve which has openings of 0.0625 mm). The wash load is quite uniformly distributed throughout the depth and width, in small width-depth ratio channels. The total bed material load is that material moving through the river cross-section as bed load and that material in suspension which is coarser than 0.0625 mm. Sometimes the dividing size is 0.074 mm because splitting a sample on the 200 mesh sieve is easier than doing so on a 225 mesh sieve.

The energy required to transport the wash load is much smaller than the energy needed to transport the bed material load. Rivers such as the Jamuna, Ganges, Padma, Dhaleswari and Kaliganga have an almost unlimited capability to transport wash load in the main channels. In fact, the presence of the wash load in suspension increases the apparent viscosity of the water-sediment discharge. This reduces the fall velocity and fall diameter of the sand sizes making it more susceptible to transport and making it possible for the river to carry more sand than would otherwise be the case. This is an important concept and it has other important ramifications which will be discussed in more detail in subsequent paragraphs.

Climatological and Hydrological Observation Stations

The location of all climatological and hydrological observation stations on the rivers adjacent to the DSW project have been tabulated by ECI. The sediment discharge records are rather incomplete and only available for short periods at a few locations.

Characteristics of Measured Sediment (Suspended) Discharge

During the period of flood flows the suspended sediment consists of clay, silt, and sand with a predominance of clay and silt. Even during the low flow season a significant percentage of the measured suspended load may be clay and silt in some rivers.

The quality and quantity of the suspended sediment discharge in the rivers is best appreciated by studying the data. The monthly suspended sediment moving through the sampled zone is given in Table I for the Meghna River, the Brahmaputra-Jamuna River at Bahadurabad, the Padma River at Hardinge Bridge, and the Dhaleswari River at Sabhar. (The tables are also in Appendix B.)

Table I - Data obtained from "Sediment Study," DSW Project - Pink cover (Rough Draft copy)

a - Meghna River, bottom of page 2 and top of page 3.

b - Brahmaputra River at Bahadurabad, bottom of page 3.

c - Padma River at Hardinge Bridge, bottom of page 6.

d - Dhaleswari River at Sabhar, middle of page 7.

* All tables should be brought up to date!

The suspended sediment discharge in the Meghna River is small in comparison with loads in other rivers; in some months it is even nil. This is apparently because of its flatter gradient and more resistant banks.

Study of the measured suspended load for the Bahadurabad station on the Jamuna-Brahmaputra River shows that the maximum sediment load is about 720 million tons per year for 1957 and the minimum load is about 530 million tons per year for 1961. The average annual sediment load at Bahadurabad is about 630 million tons. The magnitude of sediment discharge is quite similar and uniform during the low flow periods for all years. On the other hand, there is large variation in sediment discharge during flood periods. This is related to bank cutting, degradation and local instability of the river channel caused by peak flows. From the table, the maximum sediment load occurs on the rising stage during July, August, and September. From the available data, the maximum annual suspended sediment discharge is 570,880,000 tons. This occurred in 1961. From a comparison of the measured suspended sediment discharge of the Jamuna-Brahmaputra River with the sediment discharge of the Ganges River at Hardinge Bridge for the same year, the Ganges carries much less sediment, even though the maximum monthly measured suspended sediment discharge carried by the Ganges is 241 million tons which is higher than the Jamuna's one-month record. The minimum monthly sediment load is 440,000 tons and it occurred during the month of April in 1961. The average annual sediment load is 418,900,000 tons. This value is based upon six years of record and it is about 2/3 of the annual load transported by the Jamuna River at Bahadurabad.

Factors Affecting Sediment Transport

The mechanics of sediment transport is reasonably well understood but because of the extreme sensitivity of transport to small changes in velocity, precise values for a particular environment and at a given time cannot be accurately computed. Longer term average values based on several determinates, preferably supported by direct measurement of the suspended sediment discharge, yields much better results. The most accurate determinations of total sediment discharge are achieved when the suspended sediment discharge is measured and the unmeasured load is calculated by the U.S. Geological Survey's Modified Einstein procedure and added to the measured suspended load (5). These computations require knowledge of the velocity distribution, the stream cross section, and the characteristics of the measured suspended load, the water, and the bed material.

As a second choice, the total sediment discharge can be estimated using Colby's (6) procedure. This concept states that

$$Q_{ST} = f(V, D, d, Cw, T)$$

in which

Q_{ST} is the total sediment discharge,

V is the average velocity in the channel,

D is the median fall diameter of the bed material,

d is the depth of flow,

Cw is the concentration of wash load (silts and clays for sand bed streams), and

T is the temperature of the water-sediment mixture flowing in the channel.

For increased accuracy, the channel may be subdivided into increments for analysis.

The most significant variable in the transport relation are velocity and depth. Velocity integrates the effect of many variables as indicated in the functional relation

$$V = f(D, S, T, d, \text{bed roughness})$$

in which

D is depth of flow,

d is median diameter of bed material,

S is slope of energy gradient, and

T is the temperature of the water-sediment mixture.

These preceding relations show that if the project development alters the channels so that any of the variables which affect sediment discharge are changed, the response of the river to development may be significant and should be realistically evaluated.

Sedimentation and Channel Response

A meaningful evaluation of river response to development can be made using the simple relation

$$QS \propto Q_s D$$

which states that the product QS is proportional to the product $Q_s D$, in which

Q is water discharge,

S is slope of energy gradient,

Q_s is bed-material discharge, and

D is the representative fall diameter of bed material, usually the D_{50} size.

This relation was first proposed by E. W. Lane (7) and has been modified and extended by Simons and others. For example, in the original relation D was expressed as a sieve size, but it is more meaningful to use the fall diameter as presented here because size thus defined includes the effect of water temperature and suspended sediment on viscosity of the water-sediment mixture. The change in effective size can be very significant. With large concentrations of silts and clays the fall diameter of the bed material may be reduced as much as 50 percent. Figure 7 illustrates the delicate balance existing in rivers and river response to changes in water discharge, channel slope, the discharge of bed material or the effective size of bed material.

Figure 7. Channel response to development (after W. E. Borland, USBR).

Channel Scour and Fill

To illustrate the application of the preceding geomorphic relation illustrated in Figure 7, assume that due to embankment construction the flood stage or depth is significantly increased, which means that the discharge Q per feet of width is increased. Then in order for the relation to become balanced again, one or more of the other three variables must adjust. In this case, it is most likely that Q_s , the rate of bed material discharge, will increase. Secondly, degradation may decrease the slope of energy gradient of the channel. It does not seem possible, for this case, that the size of the bed material could be significantly decreased. Hence, it can be concluded that the constriction of the flow by dikes will increase the discharge per feet of width and increase the ability of the main channel to transport sediment. There will be very little change in stage due to constriction because the usual rise in stage will be largely offset by a reduced resistance to flow caused by more of the channel bed shifting from lower regime bed configurations to upper regime configurations.

In general, river development should increase the ability of the main channel to convey sediment at high stage. At low stage the embankments will have no effect on the transport of bed material; the possible changes in alignment and channel cross-section caused by the slight confinement of flood flows may however, slightly affect hydraulic conditions and transport rates at low stage.

Figure 8 illustrates the annual variations in discharge, mean velocity, depth of scour below the water surface, maximum deposition, and channel width for an entire flood cycle on the Brahmaputra River. These relations would show similar trends for other rivers adjacent to the project.

Figure 8. Total width of the Brahmaputra River influence during the period 1830-1963.

The probable effects of flood embankments on these relations are: (1) The channel discharge will increase (this must be qualified in terms of embankment effect on the overland and river flows). (2) With an increase in discharge the resistance to flow should decrease causing a small increase in average velocity. (3) With increased discharge and velocities slightly larger depths of scour may be experienced. (4) If the channel width remains about constant the maximum deposition should decrease. (5) Channel width may slightly increase due to bank scouring caused by the increased discharge and velocity. (6) The overall ability of the system to handle the sediment should improve, provided the main channels are not allowed to scour, widening the channel.

Chapter IV

FLOOD CONTROL EMBANKMENTS

Introduction

Flood control embankments for the Dacca Southwest Project will be constructed to surround and protect the project area. They will protect the project from overbank flow which occurs annually during the monsoon season. Pumping stations will be constructed, as required, at the flood embankments, to remove drainage water from the project area to the rivers during the wet season and to supply irrigation water from the rivers to the project area during the dry season.

Flood Control Embankment Foundations

The flood embankments will be constructed adjacent to the rivers on the natural alluvium. This material consists of very heterogeneous and complex soil of mainly clay, silt, and sand which has been deposited by the rivers. The foundation materials may consist of: combinations of layers of clay, silt and sand, old river channels filled with residual sand bars and silt-clay plugs, crevasse-splay sand deposits, which are very common along the Brahmaputra River. Because of this varied nature of the soils the alignment of the flood control embankments should be investigated to identify locations where, due to permeable sand deposits, the foundation may fail due to seepage forces, piping, and settlement. Poor quality foundation materials may require removal and backfill, and, in some instances, a clay blanket may be required on the river side of the embankment to lengthen seepage paths and to control piping. Based on limited field information, which should be supplemented with foundation borings, a major part of the embankment foundation consists of relatively stable, homogeneous silt-clay soils that seem sufficiently impermeable to under-embankment seepage. However, this, as well as other foundation properties such as potential subsidence under load, must be varified by borings and soil mechanics analysis. Subsidence is an important problem. To establish embankment heights, knowledge of rates and amounts of subsidence should be determined by inspection of existing dikes and by field testing to obtain accurate estimates.

Resistance to Erosion-Foundation

Varying soil conditions extend from the river to the embankment area, and with rapidly changing river stages the banks of the river come under varying intensities of attack. Clay and silt-clay soils are resistant to erosion, when exposed to river flows they tend to erode slowly unless the main current of the river directly impinges against the bank. Under this onslaught even the toughest bank materials are eroded at a rapid rate. So, to assure reasonable safety for the embankments the river bank material between the river channel and the embankment should consist of a large percentage of clay and silty-clay soils to a depth greater than the bed of the river. If, for example, sand crevasse-splay deposits, old sand filled channels, or layers of sand are sandwiched in between the silt-clay soil deposits extending from the existing river bank to the embankment area, the river is capable of making major lateral shifts within short time periods and may eventually undercut the embankments.

Embankment Materials

The embankments will be constructed of material, in general, available adjacent to the embankment on the river side. The material should be selected so that a Modified Proctor Density equal to or greater than 95 percent can be obtained in the embankment by moisture control and compaction. This quality control of the embankment is essential to limit seepage and to maximize their resistance to scour from rainfall and overbank flow. The natural growth of grass and other vegetation on the embankment will help control erosion of the embankment faces. Steps should be taken to promote growth of grass by turfing or seeding of the embankments in locations where erosion would occur before the natural vegetation could develop.

Borrow Areas

The embankment material shall be taken from the land between the river and the embankment. The borrow areas should be at least 100 feet away from the toe of the embankment, should be relatively shallow (no more than 4-5 feet deep), and should be discontinuous so that flow is not encouraged parallel to the embankment. Such flow could cause channelization and failure of the embankment due to erosion. If the borrow pits expose sand layers that extend under the embankment area the pits should be backfilled with compacted silt and clay to prevent excessive seepage beneath the embankment and possible piping and seepage failures.

Set-Back Distance of Embankment

The establishment of set-back distances embankment of the flood from the river bank is affected by many interrelated variables and requires careful consideration.

The flood embankment should be constructed on good foundation material to minimize seepage and to resist erosion. Placing the embankment on the typical clay-silt soils will be satisfactory but the magnitude of expected subsidence must be investigated. Based on limited field observations most of the soils are rather heavy and cohesive. However, as previously discussed, there may be old point, middle and alternate sand bars, extensive lenses of sand, sand crevasse-splay deposits, old channel fills and areas of sand that have accumulated by aggradation. Where sand deposits of any type can be identified by field observations, aerial photos, soil borings, or vegetative indices they should be avoided by shifting the embankment alignment or by excavation and backfill with suitable impermeable materials adjacent to and beneath the embankment area.

The embankment should be set back sufficiently from the river so that it is relatively safe from river channel shifts and subsequent direct attack by the flow in the main channel. If the river flood plain, between the river channel and the proposed embankment, consists of essentially cohesive silt-clay soils to depths below the river bed it may be feasible to move the embankment to within one-fourth mile of the smaller rivers on the east and within one-half mile of the Jamuna, Padma, and Meghna Rivers on the west and south of the project. When more erosive sandy soils form the river bank and the flood plain these distances should be doubled. However, before accepting these somewhat arbitrary distances let us first consider river characteristics that play a significant role in logically determining the set back distances.

The flood embankments should be set back so that they will be relatively safe from direct attack by the river due to channel changes which are very common to these rivers. The magnitude of possible lateral shifting of the river channels is closely related to the type of river.

If the channel is meandering, confined by relatively stable cohesive banks, and sufficiently narrow so that alternate and middle bars do not choke the channel at low stage, the reach is quite stable and the embankment would be quite safe if located not closer than one-fourth mile from the river.

If the channel is essentially straight, has cohesive banks, and is sufficiently narrow so that it is not partly plugged with exposed sand bars during low flow the same criteria as for the meandering channel may be applied although it is slightly less safe from river attack.

If the channel is straight or braided, relatively wide so that alternate bars, middle bars, and islands choke the channel during low flow, and the banks are poorly defined and caving, the channel is unstable. In such a reach there may be two or more main channels that shift rapidly with time and the banks on both sides are subject to intermittent attack. In this case, rapid changes of large magnitude can occur in the main channel so it is necessary to use about twice the set-back distance prescribed for the more stable meandering and straight reaches of channels confined by well defined banks of cohesive material (about one mile).

These suggested set-back distances can be verified by studying sequential maps and photos of the area which document major river shifts that have occurred in the past. In the "DSW Hydrology Annex", some historic channel changes are documented for the rivers adjacent to the project and provide a useful guide to establishing set-back distances. Analysis of these and other data show that rivers do not often move laterally more than one-channel width within several years of the flood plain consists of silt-clay soils. Defining channel width with the well-known regime relation

$$W = 4.88 \sqrt{Q}$$

the regime width can be computed using an arbitrary channel forming discharge, say Q_{90} which is the discharge in cfs equaled or exceeded 90 percent of the time. It should not be necessary to set the embankments back more than W but in no case should the set-back distance be less than previously suggested -- that is 1/4 mile adjacent to stable reaches of the Dhalaswari and Kaliganga Rivers, 1/2 mile adjacent to unstable braided reaches of these rivers, 1/2 mile adjacent to relatively stable reaches of the Jamuna, Padma and Meghna Rivers, and 1 mile adjacent to the braided less stable reaches of these rivers.

For suggested embankment locations at pumping station sites refer to "Pumping Plant Location".

Embankment Location and Flood Stage

If the final location of the embankment is closer to the river network than was assumed for the backwater surface computations the water surface elevations should be recomputed for the new conditions to establish height of embankments.

It is suggested that the embankments should not be placed closer to the main river channels than as specified by the preceding procedure since they would restrict overbank flow, perhaps cause a slight increase in stage, increase the velocity of flow adjacent to the embankment and in the main channel, and increase bank instability and bed material transport.

After adhering to the minimum set-back distances as established in previous paragraphs, the location of the flood protection embankments should be also considered from the points of view of hydraulics and economy: 1) Hydraulics. In order to avoid flow concentrations with resulting high flow velocities along the embankment the alignment should be such as to eliminate sharp, projecting kinks and exposed corners. 2) Economy. Straightening of the embankment will reduce embankment length and construction cost. The savings, of course, must be compared with the loss of revenue that would be attributable to the reduction of the protected polder area.

Villages

There are numerous villages adjacent to the river banks. There may be requests to place the embankments close to the river to include the villages in the project area. This should not be done if it requires moving the embankments closer to the river banks than specified in the preceding paragraphs. Such action would endanger the embankments.

There is some concern that construction of the embankments will greatly increase the unrestricted river stage at peak floods endangering the villages. The backwater computations show that the embankments proposed for the DSW project will increase the water surface elevation at flood stage one-half foot. This will not significantly affect conditions for the villages.

Conclusions

The following specific recommendations are made, based on an analysis of existing limited data and field observations.

1. A simplified embankment alignment should be selected using the existing data, the recommendations presented in this report, aerial photographs of the river and its adjacent

flood plain, and a thorough field inspection of the soil materials along the alignment.

2. The aerial photos should be particularly useful to:
    - a. avoid the villages, insofar as possible.
    - b. determine required setback distances where the embankments are adjacent to unstable reaches of river.
    - c. identify stable and unstable reaches of river.
    - d. identify major sand and clay deposits comprising the flood plain adjacent to the rivers.
3. The flood embankment should be of cohesive borrow materials and should be compacted to a modified Proctor density of 95 or greater.
4. Compaction of the embankment is necessary to make it more resistant to scour. Uncompacted embankments of cohesive materials will only withstand water velocities of 1 to 1/2 feet per second while well compacted cohesive embankments can withstand velocities of 3 to 4 feet per second and even more when sodded.
5. The borrow area should not be immediately adjacent to the toe of the embankment, should be shallow and the pit should be discontinuous to avoid possible channelization by overbank flows.
6. When excavation in the borrow areas exposes foundation materials that are permeable (lenses of sand or sand pockets) the permeable foundation material must be removed and backfilled with suitable cohesive materials or
    - a. the side slopes of the embankment must be flattened to

increase the flow line so that excessive seepage and/or piping cannot occur; or

b. a clay blanket of sufficient width and thickness must be placed along the embankment to achieve the same objectives.

7. The upstream end of the embankment should be investigated to determine whether or not it requires special protection from overland flow that may impinge on it and flow along it either from the Jamuna River to the Dhaleswari River or in the opposite direction.

Chapter V

PUMPING PLANT LOCATION

Introduction

The DWS pumping plants will serve two main purposes:

(1) During the low-flow periods they will pump water from the rivers to the irrigation distribution systems within the flood embankments.

(2) During the wet season they will be utilized to help evacuate excess water from within the polder to the river.

The pumping stations will be located at strategic positions in the flood embankments. Their locations must be selected considering such factors as: the available water supply; the water distribution system for the project; embankment and pumping plant foundation conditions; availability of suitable borrow material for embankment construction; the characteristics of the river including such variables as type (meandering, braided, etc.), bank materials, width-depth ratios, and stability, and intake channel design, construction, performance, and maintenance.

Location Considering River Characteristics

The set-back distance of the flood embankments was discussed in the previous chapter. Because of the high cost of pumping stations extra precautions should be taken to insure their adequacy, safety and efficiency. In all cases the final location of each pump station should be made after a detailed field inspection of foundation conditions and river characteristics.

Foundation Analysis

When the set-back distance to the dike is established and the tentative location of the pumping stations has been made, detailed foundation borings should be taken and analyzed. The foundation material has been water-deposited in areas that had been criss-crossed by old river channels. This results in very heterogeneous foundation conditions. Borings may identify clay plugs, old point, middle or alternate bars that may be predominately fine sands. In many instances, the foundation may be highly stratified consisting of layers of sand, silt, and clay of unequal thickness and density. Such locations should be avoided.

River Characteristics. The classic types of rivers, meandering, straight and braided, and transitional forms have been observed on the Dhaleswari, Kaliganga, and Jamuna Rivers. The type of river significantly affects the selection of flood embankment and pumping station location.

Applying the relation between river characteristics and flood embankment location to the selection of the location of pumping stations along the rivers, the following points should be considered:

1. The river channel should be relatively narrow and should have stable banks formed of silt and clay.
2. The reach of river should be free of large exposed sand bars, multiple channels, and rapidly changing thalwegs.
3. If it is necessary to locate a pumping station adjacent to a braided reach of river it should be opposite node points where the river has a relatively small width-depth ratio. Such nodes are formed where the river banks consist of silt and clay and are quite stable.
4. A location adjacent to the concave bank of a long radius bend is acceptable if the banks are stable and there is local and photographic evidence of stability. Such a location is favorable

in that the heavy concentration of bed load is swept away from the outside bank toward the point bar. The water diverted to the canal from this location will have a relatively low sediment-water ratio.

5. Locations on the outside of short radius bends where the current of the river strongly impinges on the concave bank should be avoided. Such bends are subject to strong erosive forces and may migrate laterally toward the embankment and downstream.
6. Intakes should not be located at the convex bank or inside of a river bend where a large point bar is maintained by the transverse currents. Its slope and location changes with time and a intake channel intercepting water in the point bar area would be continually plugged with sand and the sediment-water ratio would be large.
7. Wherever possible determine by field inspection, comparison of maps and photos, and from the historical records of the villages that the reach of river adjacent to the pump station has been relatively stable.
8. Existing channels that may, with minor development, convey water to the pumping station should be utilized. Such channels should be stable with cohesive banks.
9. Locations adjacent to braided reaches of rivers should be avoided if at all possible. These reaches are unstable and in general are aggrading during low flow periods. These reaches are choked with sand bars and the location of the thalweg is subject to frequent and large changes in lateral position. At one time the

water is adjacent to one bank. A short time later it may have moved hundreds or even thousands of feet away to the opposite bank. With these conditions it would be nearly impossible without dredging and/or channel improvement to supply water continuously by channel to the pumping station.

Sediment Transport. By using the above guidelines to locate the pumping stations, large sediment concentrations at the mouth of the intake channels may be avoided. There are numerous detrimental effects from the sediment, in particular with sand sizes. For example:

1. The sediment may drop out in transit to the pump station, thereby clogging the intake channel.
2. The presence of sands in the water will cause a more rapid deterioration of the pumps.
3. The sand and silts delivered to the irrigation conveyance system of the project will aggrade the distribution system, particularly near the pumping station, thereby reducing the canal capacity.

Intake Channel Design

If the pumping stations are located in accordance with the established guidelines it should be possible to design and construct the intake channels for the pumping plants so that maintenance costs will be low.

Location. The location of the channel should, in general, lead directly from the pumping plant to the vicinity of the river. The last few hundred feet of channel location should be selected to enhance stability at the junction, reduce sediment inflow to the channel, provide an ample supply of water, and avoid, insofar as possible, blockage of the intake channel by deposition in the entrance and/or development of large sand bars in the river at the channel entrance:

1. If the intake channel is constructed to the outside of a river bend large scale eddies and turbulence are formed at the junction. These may accelerate erosion and migration of the bend. Some sediments may be swept into the entrance of the channel. On the other hand, this is the most favorable location to reduce inflow of sediment to the channel and pumping station because of the favorable transverse river currents which sweep the bed load toward the point bar on the convex side of the bend. Conditions of the channel entrance could be improved by stabilizing the river banks adjacent to the channel and by using submerged guide vanes to carry the bed material past the channel entrance. This, however, involves major river training works and hydraulic structures which would require detailed studies and economic evaluation.
2. If the canal is constructed to a relatively straight reach of river the reach should be reasonably narrow with the stable clay banks and devoid of exposed sand bars. Under these conditions the canal entrance can be kept relatively free of sediment although the sediment concentration in the flow into the channel will be larger than for a canal entrance on the concave side of a bend. Also, submerged alternate bars of small amplitude may intermittently partially block the channel entrance requiring removal by dredging or other means to maintain intake channel capacity to the pumping plant.

3. Constructing the channel to the inside of a bend should be avoided. The point bar and adverse sediment conditions would make maintenance costly.

4. Constructing the channel to a wide-shallow braided or straight reach of river should be avoided. As with canal construction leading to the inside of the bend, the sand wave formations will intermittently block the entrance and adverse sediment load conditions. The river bed and the thalweg are in continuous flux making it a high-maintenance cost location.

Maintenance. The intake channels will require maintenance to keep favorable conditions at their junctions with the rivers. Bank stabilization techniques may be required at the entrance and along the river banks adjacent to the entrance. Also, small mobile dredging units will have to be employed from time to time, to remove sediment from the mouth of the channel, for periodic cleaning of the channel and to open waterways across river sand bars that may partially or totally block the channel entrances.

Conclusions

In summary the sites for the pumping plants should be carefully selected. In so doing certain conditions should be emphasized:

1. The river reachs adjacent to the pumping plant locations should be relatively narrow, the banks should be stable and well defined, and the alignment should insure a continuous water supply to the pumping plant supply-canal.

2. The flood plain between the river bank and the flood embankment should be formed of silt-clay soils that are resistant to erosion. Sand deposits are prone to scour.

3. The foundation conditions, in the vicinity of each pumping plant, should be investigated to determine that its structural and hydraulic properties are suitable to support the structure, control seepage, and limit settlement.

4. The embankment should be thoroughly compacted.

5. The canal intake should be located near the initiation of a bend on the concave side, or as a second choice, in the bank of a well confined, relatively straight reach of river.

6. It should be recognized that all supply canals will require maintenance to cope with deposition of sediment, scour at their intersection with the river, changes in river alignment and bar development, and migration in the river channel.

7. Continual surveilance of the rivers adjacent to the pumping plants should be implemented so that remedial steps can be taken to protect the stations if channel migrations endanger them.

8. A detailed analysis of the potential low water supply for the project is necessary. River training works channel stabilization and dredging may be required, particularly in the head reach and at the offtake of the Dhaleswari River from the Jamuna River to insure an adequate low water supply.

Chapter VI

THE RIVER SYSTEM

The field trips along the Jamuna and Dhaleswari Rivers made it possible to identify important characteristics of the rivers that are of significance to the DSW project and verify the previous conclusions.

The Jamuna River. The channel is very wide, braided, mostly unstable, subject to rapid change and choked with sand bars and islands. The historic observed maximum rates of bank scour and bank build-out were 2,600 ft/yr and 2,800 ft/yr, respectively. Based on recent records this river is shifting slowly to the southwest, away from the project area. Additional analysis of the data indicates that the flood embankments should be set back at least one mile from the present bank alignment of the Jamuna River--particularly where the banks are poorly defined, unstable, and subject to continuous attack by the river.

A similar study of the historic channel positions of Jamuna, Padma and Dhaleswari Rivers was presented by ECI in the "DSW Hydrology Annex."

Similar data for the Kaliganga River has not been identified and documented. Considering the characteristics of the rivers, the flood embankments should be set back from any recently abandoned river channels, even if the distance is large, unless the flood plain between the abandoned channel and the present location of the river is formed of cohesive silt-clay soils and is devoid of large sand deposits which are easily eroded.

The only parts of the banks of the Jamuna River that are reasonably stable are those formed of cohesive clay-silt soils. Along these banks, it may be feasible to locate portable pumping plants to supply water to the project if an adequate low water supply is not available, without major channel improvements, on the Dhaleswari River.

For example, a pumping station could be mounted on a barge. The barge could be anchored and when the channel shifts, the barge could be moved as required to pump water through a portable, pipeline to the project area. Site selection for the barge should be adjacent to a stable bank where the curvature of flow would minimize the sediment-water ratio. Such pump stations would eliminate canal construction and maintenance but would require higher-head pumps to overcome the pipe friction loss. Also, the pumping plant could not be used to discharge drainage water from the project area during the wet season.

Even with a stable clay bank the braided, unstable nature of the Jamuna River may allow the main water supply to shift westward adjacent to the right bank. This may require abandonment of the site on the stable left bank because thousands of feet of sand filled channel may separate the stable bank from the earlier water supply which shifted westward. Hence, if economically possible water from the Dhaleswari should be utilized.

Sedimentation. The results of a sediment concentration study of suspended sediment samples collected from the Jamuna (West Channel) at Sirajganj, the Jamuna (Dhaleswari Channel) at Sirajganj, the Jamuna (Main Channel) at Nagarbari, and the Jamuna (West Channel) at Nagarbari are presented in Tables II through V respectively.

Table II = Table I
Table III = Table II
Table IV = Table III
Table V = Table IV

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The suspended concentrations vary from 332 to 1582 ppm by weight. The concentrations of sediment vary quite markedly in the cross-section and with discharge.

The size distribution of the suspended samples, as determined by visual tube analysis (V.A. tube), is given in Table VI. Note that 70 to 93 percent of the materials are finer than 0.0625 mm. At peak floods the percentage is higher. Figure 9 shows the measured suspended sediment load in millions of tons per day and the percent of clay, silt, and fine sand for the main channel of the Jamuna at Nagarbari. The measured suspended sediment load is about 5 percent sand, 10 percent silt, and 85 percent clay. The wash load (clay plus silt) accounts for about 95% of the total measured load. This record is for a two month period, late September through late November of 1965.

Table VI = Table V - (same reference as above Tables II thru V)

Figure 9 = Figure 4-9 from DSW Hydrology Annex

The sand load in the rivers can be approximated by assuming that 5 to 10% of the measured suspended sediment discharge is sand (in accordance with Figure 9). Then further assume the water moving in the unmeasured zone, adjacent to the bed, carries about 15% of sand that is moving in suspension. Add these two quantities together to obtain a rough estimate of total sand transport. This unmeasured sediment discharge can be more accurately estimated by using the U. S. Geological

Survey Modified Einstein Procedure. However, width, depth, velocity, and the characteristics of the suspended sediment and the bed material must be known.

The Bed Material

The East Pakistan Water and Power Development Authority, Dacca, reported the results of laboratory analysis of 53 bed material samples. These were collected from the Jamuna River six miles below Sirajganj and near Nagarbari. At Sirajganj the river has three channels and at Nagarbari two channels. At Nagarbari the channels are the Main and West channels. Of the 53 bed material samples, 17 were collected from the Sirajganj site and 36 from the Nagarbari site. The samples were collected with a U.S. BM54 bed material sampler.

A typical gradation curve for the Jamuna River, Main Channel, downstream of Sirajganj is shown on Figure 10. A summary of the size analysis of all data is presented in Table 7.

Figure 10 = Sheet 1 of 2, Anexure B, "Analysis of bed and suspended materials of river Jamuna ---"East Pakistan Water and Power Dev. Authority.

In summary, the bed materials at the sampled stations on Januma River is quite uniform. The median diameter ranges from 0.340 to 0.028 mm and the average median diameter is about 0.172 mm. This bed material can be set in motion with little effort. At the velocities which occur at flood stage the bed material discharge is relatively large and much of the bed will be plain or molded into sand waves with large amplitudes and great lengths. Under these circumstances the resistance to flow in the channels is relatively small.

Very little data were found that describe the bed material at other stations. However, field observations show that the bed material has similar characteristics in the other rivers and that the median diameter of bed material becomes finer downstream. This reduction of size is caused by hydraulic sorting and possibly limited attrition. The rate of reduction can be described by a relation of the form

$$D_x = D_o \, e^{-\alpha x}$$

in which D_x is the median diameter at any station x downstream of the zero station, D_o is the median diameter at the zero station, and x is the distance downstream of the zero station in miles. The α term is a coefficient of size reduction and is best determined by field observations. In a similar manner the slope of energy gradient becomes flatter with distance measured downstream. Figure 11 schematically illustrates the bed-material and slope of energy gradient trends for all sand bed channels.

Figure 11 - Typical change of median size of bed material and slope of energy gradient with distance measured from some zero station downstream.

Of course, these relations may experience discontinuities at confluences if the characteristics of the bed material in the joining streams have different characteristics.

The Dhaleswari River. At the offtake from the Jamuna River the Dhaleswari River is also very wide, unstable and populated with numerous, large, shifting sand bars. For the first few miles below the offtake the two rivers are essentially parallel to each other. They are separated by only a narrow, erodable embankment which is a geomorphic feature of the two rivers. There are several overflow channels connecting the two rivers across this alluvial embankment. It is obvious that this embankment could be breached, leaving the Dhaleswari with little low water flow unless protective measures are taken.

Water Supply Limitations. The proposed pumping stations are located on the Dhaleswari and Kaliganga rivers. The Kaliganga is a branch of the Dhaleswari which derives its flow from the Jamuna (Brahmaputra). Downstream of the Dhaleswari offtake the Jamuna has three major channels referred to as the west channel, the main channel and the Dhaleswari. In this region the Jamuna is unstable. Because of the unstable, extremely complex behavior of the Jamuna, it is vital to study, in detail, the low flows of the Dhaleswari and its most probable future flow characteristics.

An analysis of available hydrologic data and information presented in "The Preliminary Draft, Dacca Southwest Project, Hydrologic Annex" indicates that the absolute amount of water that flows in the Dhaleswari during the low-flow in the Jamuna River has fallen off rather rapidly in recent years. It is unlikely that the river channel will aggrade to such an extent that low-water discharge will approach zero. On the other hand, the Gorai River which takes off from the Ganges and forms the Southwest boundary of the Faridpur project is a similar case. Observed minimum annual flows have ranged from 5 cfs to about 10,000 cfs.

During a field trip to the Dhaleswari on March 4, 1970, it was determined that the discharge was 3,000 to 4,000 cfs. With such low flow, when the DSW project is fully developed, there may be dry seasons when the supply of water in the Dhaleswari may be inadequate to meet irrigation demands. The nearly complete utilization of the available water supply would also affect the use of the Dhaleswari for navigation.

In the event that the long range water supply is judged as questionable these alternatives exist:

1. By dredging, it may be possible to increase the low flows of the Dhaleswari River through the improved and deepened channel. The dredged material could be deposited in the high stage spill channels that connect the Dhaleswari with the Jamuna.

2. It may be possible to construct river training works in the vicinity of the origin of the Dhaleswari River to insure a more adequate supply of water during the low flow period.

3. Some of the pumping stations could be constructed to take water from the Jamuna River on the west side of the project area.

The third alternative has serious limitations, not in terms of the water supply, but in terms of the complex, unstable nature of the Jamuna River. There would be complicated problems related to conveying water from the river to the pumping station, large shifts in river alignment, higher concentrations of sediment, and a greater embankment set-back distance due to the vagaries of the large, braided river. Nevertheless, the difficulties are by no means insurmountable. Ultimately, such diversions will be made from the major rivers of East Pakistan. An example of this is the suggestion already made for the Jamuna River regarding a portable pumping station mounted on a barge.

Suspended sediment discharge. The sediment data for the Dhaleswari River at Sabhar are available for only a few months, June, July, August and September of 1959-62. The maximum measured monthly load is 5,117,000 tons and the river's minimum monthly sediment discharge is 498,000 tons during this brief period of record. From field observations, the sediment discharge of the river during the low water period is relatively insignificant. It is largely sands and silts associated with minor channel changes and the migration and shifting of sand bars. The clays are more predominate during periods of high flow when the banks of the river are subjected to maximum attack by high velocity flow.

Diversion of water. Most of the low-water discharge in the Dhaleswari and Kaliganga Rivers will be diverted to the proposed pumping stations for delivery to the project. The water that is diverted will be quite free of sand. Sand which is taken from the river with the water will usually drop out before reaching the pumping plant. This material must be removed and will be deposited on the flood plain adjacent to the canal or returned to the river. Consequently, (1) the amount of water remaining in the river will be small when project needs are being fully met, (2) essentially all of the sediment in the sand sizes that is carried into the project area will remain in the main channels causing some aggradation. Fortunately, the amount of sand transported during the low flow period is relatively small and should not reduce low flow discharge in the Dhaleswari and Kaliganga Rivers.

Pumping plant locations. In the head reach the bed and banks of the Dhaleswari are mostly sand. The accompanying river pattern as already discussed is wide, unstable and braided, with poorly defined banks. As one proceeds downstream the banks and the adjacent flood plain gradually change to a heterogeneous mixture of silt-clay and sand deposits. Near the beginning of the DSW embankments the river is still braided and unstable. There are only two suitable locations for pumping plant 1A1 where banks are cohesive and stable and the river has a width-depth ratio small enough to assure a flow of water during the dry season adjacent to the right bank and pumping station. The plant is presently shown at an unstable site. Hence, it will be necessary to change the location of the first pumping plant from station 75.5 to about station 80 or another alternate location. With the newly proposed location it may be necessary to build a special pumping plant to remove the drainage from the upper segment of the project area.

The Dhaleswari River retains its braided and unstable form to the bifurcation forming the Kaliganga River and beyond.

The Kaliganga River. The channel is wide, braided and unstable to about Station 34. Here the banks are more cohesive. The channel is relatively deep and narrow and it meanders. With a meandering river, which is relatively stable, the location of the next two pumping plants are generally satisfactory. Other pumping sites have not been inspected recently.

The Jamuna-Dhaleswari Bifurcation. Both rivers are braided, wide, unstable and subject to major changes in alignment. The entrance to the Dhaleswari can be greatly affected by the conditions in the Jamuna. If, at falling stage, the Jamuna drops and maintains a large sand bar at the inlet to the Dhaleswari the main flow of the Jamuna may be moved several thousand feet away along the right bank of the Jamuna, opposite the offtake. This may temporarily limit the low water discharge in the Dhaleswari to a negligible quantity.

To insure a continuous and adequate supply of water for the DSW project in the Dhaleswari and Kaliganga Rivers during the dry season an active dredging effort may be necessary in the head reach of the Dhaleswari and in adjacent parts of the Jamuna River. Only by such an effort can an adequate low-water supply for the project be reasonably certain on a continuous basis. Even then a catastrophic flood could induce such large channel changes at the offtake that:

1. The Dhaleswari channel may be abandoned or
2. It may cause such a large increase in discharge in the Dhaleswari that subsequent channel changes in the Dhaleswari and Kaliganga may endanger the project.

However, the second possibility is less likely to occur.

Chapter VII

COLLECTION OF HYDROLOGIC AND RELATED DATA

Water and land are two of the major resources of East Pakistan. To develop and utilize these resources efficiently it is necessary to obtain more comprehensive records pertaining to both resources. Also, new techniques must be developed to assist with water resources and land development.

This will require:

1. Expansion and utilization of the net of climatological and hydrologic stations.
2. Continuous records of precipitation, river stage water discharge, sediment discharge, and water quality.
3. At each sediment discharge station the necessary hydraulic, geometric, and water and bed material characteristics should be collected so that the unmeasured sediment load can be computed and added to the measured suspended sediment discharge to yield the total sediment discharge. Computer programs have been developed and are widely used to complete the sediment record.
4. Complete aerial photographic coverage of the major rivers should be collected and analyzed continuously to: establish river geometry, response to annual floods, and response to river development. Such records are indispensible for river development, flood control, irrigation, navigation, and to establish short and long term river trends.
5. A program of channel control using bank stabilization structures coupled with channel improvement by dredging and realignment

should be initiated. This could be initiated in the headreach of the Dhaleswari River where channel improvement is essential.

6. A comprehensive water and land resources development program should be formulated.
7. The response of the river system should be analyzed using hydraulic, hydrologic, and related data to continuously improve the mathematical model developed to predict river system response to overall development.
8. A more detailed geologic study of East Pakistan should be completed. In most cases, river form and response to development are, in part, controlled by major geological features.

With reference to the climatalogical and hydrologic data, it would be possible and should be economically feasible to establish a comprehensive net of climatalogical and hydrological stations that would use remote sensing, radar, climatalogical techniques, hydrological data and systems analyses to provide an improved base for flood control, navigation, and water and land resources development in East Pakistan.

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APPENDIX A

FIGURES AND TABLES

TABLE VII

GRADATION OF BED MATERIAL - JAMUNA RIVER

Station	Channel	Location	Depth ft	D_{65} mm	D_{35} mm	D_m mm
Sirajganj	Main	3,000' LBT	10.5	.250	.225	.285
Sirajganj	Main	4,200' LBT	39.3	.130	.115	.137
Sirajganj	Main	5,000' LBT	30.0	.160	.149	.166
Sirajganj	Main	5,700' LBT	23.3	.230	.202	.222
Sirajganj	Main	6,300' LBT	20.9	.200	.175	.204
Sirajganj	Main	7,000' LBT	34.0	.250	.220	.242
Sirajganj	West	600' LBT	9.5	.165	.160	.168
Sirajganj	West	800' LBT	19.0	.154	.149	.158
Sirajganj	West	1,200' LBT	41.6	.120	.089	.139
Sirajganj	West	1,800' LBT	44.8	.180	.130	.180
Sirajganj	West	2,200' LBT	45.3	.260	.200	.244
Sirajganj	Dhaleswari	600' LBT	14.0	.155	.149	.165
Sirajganj	Dhaleswari	1,250' LBT	22.3	.115	.110	.118
Sirajganj	Dhaleswari	1,950' LBT	18.1	.149	.149	.151
Sirajganj	Dhaleswari	2,600' LBT	24.6	.115	.100	.122
Sirajganj	Dhaleswari	3,250' LBT	20.8	.180	.135	.187
Sarajganj	Dhaleswari	4,000' LBT	11.3	.150	.081	.112
Nagarbari	West	4,030' RBT	18.0	.168	.143	.153
Nagarbari	West	3,790' RBT	20.0	.030	.017	.029
Nagarbari	West	2,640' RBT	12.0	.033	.020	.031
Nagarbari	West	1,700' RBT	25.0	.090	.074	.086
Nagarbari	West	1,180' RBT	32.0	.096	.084	.105
Nagarbari	West	4,360' RBT	19.0	.185	.170	.194
Nagarbari	West	3,735' RBT	20.0	.224	.200	.200
Nagarbari	West	3,165' RBT	15.0	.044	.031	.040
Nagarbari	West	1,750' RBT	20.0	.090	.075	.088
Nagarbari	West	1,185' RBT	29.0	.100	.085	.107
Nagarbari	West	4,120' RBT	14.0	.176	.153	.178
Nagarbari	West	3,400' RBT	13.0	.100	.090	.100
Nagarbari	West	2,450' RBT	11.0	.029	.016	.028
Nagarbari	West	1,490' RBT	18.5	.092	.082	.095
Nagarbari	West	1,035' RBT	24.0	.114	.101	.123
Nagarbari	Main	14,600' LBT	51.5	.034	.017	.033
Nagarbari	Main	13,850' LBT	22.5	.083	.062	.085
Nagarbari	Main	12,350' LBT	38.0	.167	.138	.156
Nagarbari	Main	11,250' LBT	36.0	.208	.170	.196
Nagarbari	Main	10,415' LBT	58.0	.260	.230	.253
Nagarbari	Main	9,540' LBT	33.0	.149	.128	.152
Nagarbari	Main	7,240' LBT	17.0	.165	.130	.174
Nagarbari	Main	6,970' LBT	8.5	.097	.080	.105
Nagarbari	Main	8,150' LBT	22.0	.123	.095	.123
Nagarbari	Main	9,255' LBT	34.0	.157	.140	.161
Nagarbari	Main	10,090' LBT	55.0	.234	.186	.219
Nagarbari	Main	11,830' LBT	42.0	.245	.170	.224
Nagarbari	Main	12,840' LBT	22.0	.060	.042	.052
Nagarbari	Main	14,535' LBT	5.0	.024	.013	.028
Nagarbari	Main	7,690' RBT	19.0	.287	.149	.238

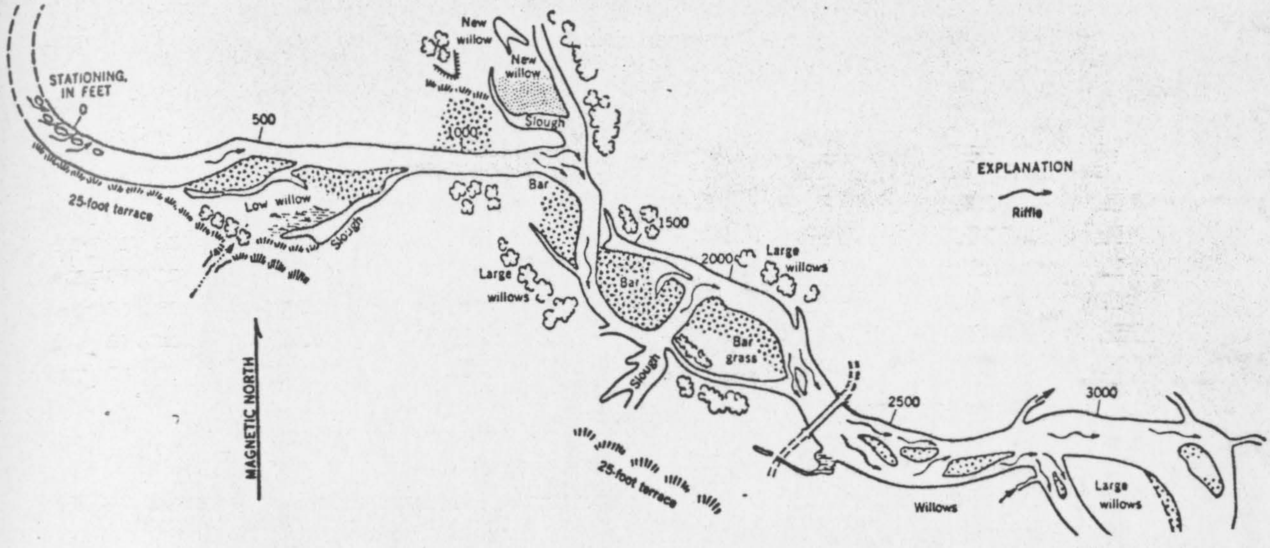
TABLE VII Continued

Station	Channel	Location	Depth ft	D_{65} mm	D_{35} mm	D_m mm
Nagarbari	Main	6,255' RBT	27.5	.108	.088	.107
Nagarbari	Main	5,315' RBT	54.0	.186	.147	.185
Nagarbari	Main	4,060' RBT	44.0	.273	.200	.241
Nagarbari	Main	2,980' RBT	21.0	.174	.074	.143
Nagarbaro	Main	2,115' RBT	19.0	.060	.044	.061
Nagarbari	Main	1,245' RBT	45.0	.028	.014	.027

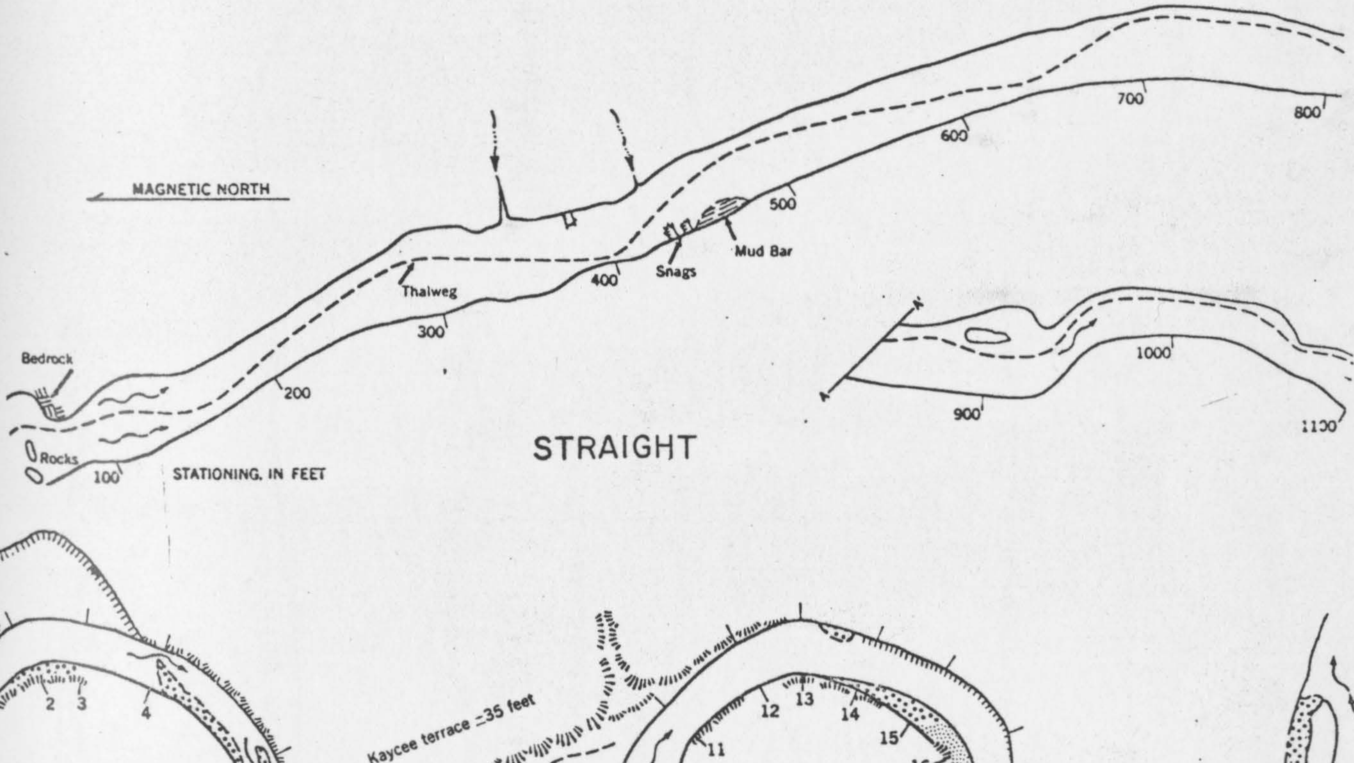
The D_{65}, D_{35} and D_m are in mm.

LBT - Tower on left bank - locations are relative to these towers.

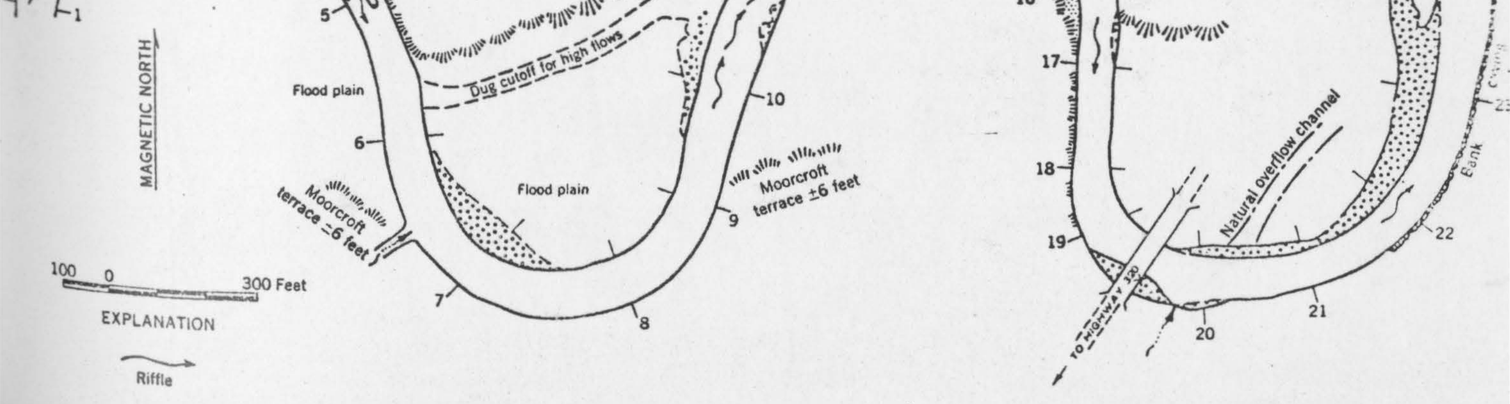
RBT - Tower on right bank - locations are relative to these towers.



BRAIDED

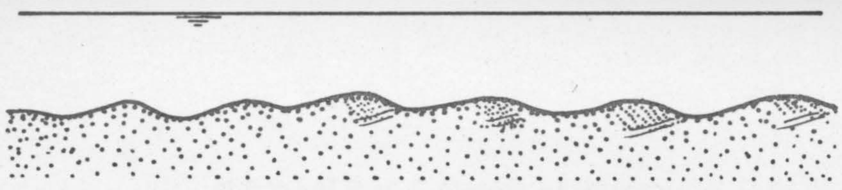


STRAIGHT

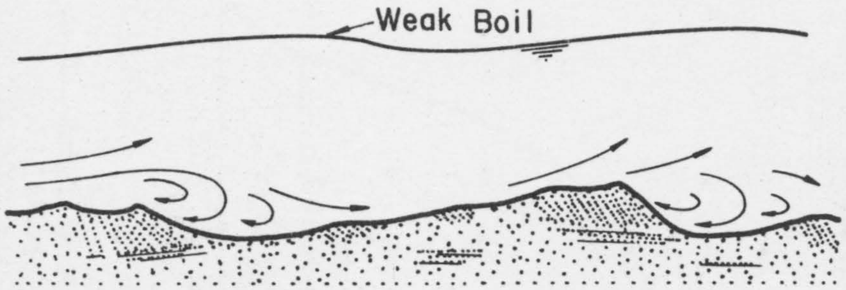


MEANDERING

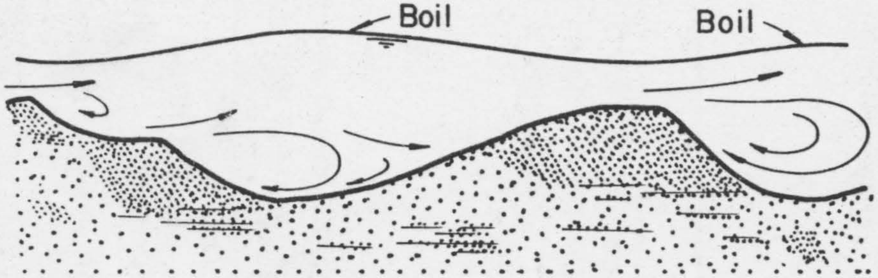
Figure 1 - General Classification of Rivers



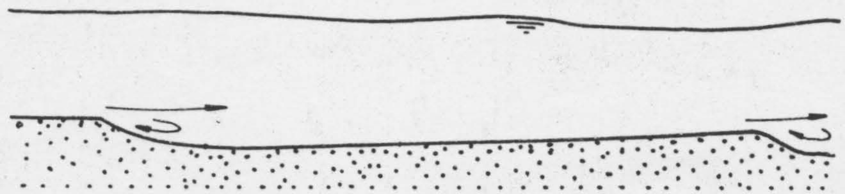
(a) Typical Ripple Pattern, $Fr \ll 1$



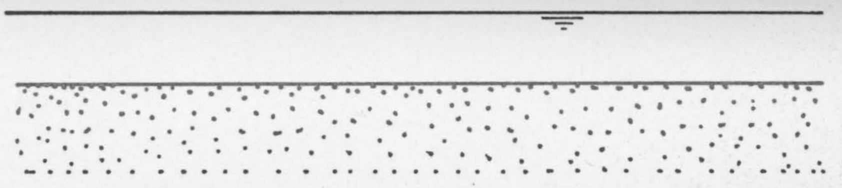
(b) Dunes with Ripples Superposed, $Fr \ll 1$



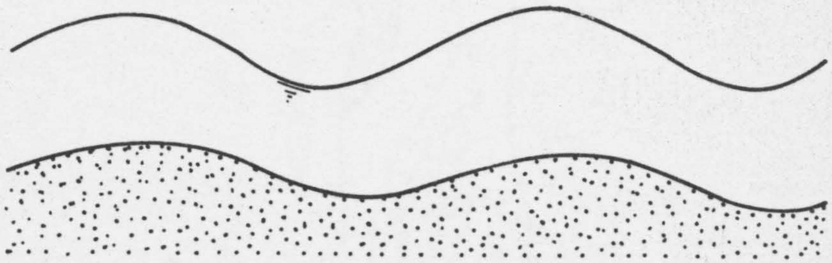
(c) Dunes, $Fr < 1$



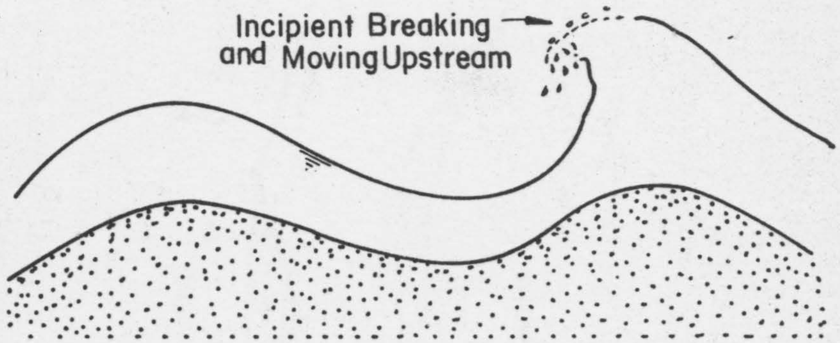
(d) Washed - out Dunes or Transition, $Fr < 1$



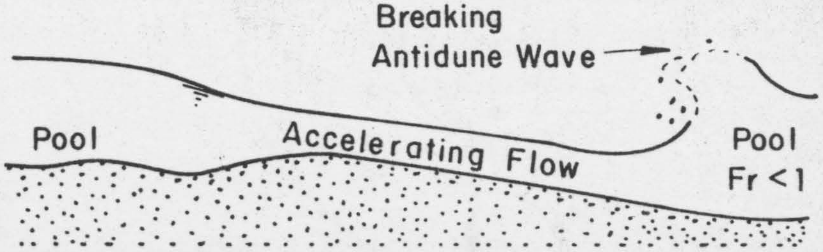
(e) Plane Bed, $Fr < 1$ and $d \leq 0.4$ mm



(f) Standing Waves $Fr > 1$



(g) Antidunes, $Fr > 1$



(h) Antidunens, $Fr \gg 1$

Figure 2 - Forms of Bed Roughness in Alluvial Channels

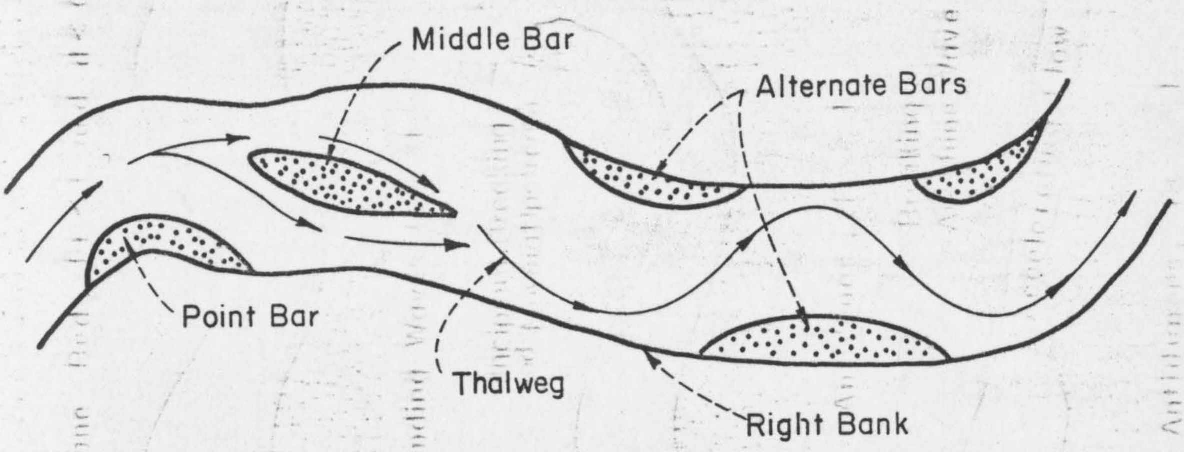


Figure 3 - Point, Middle and Alternate Bars

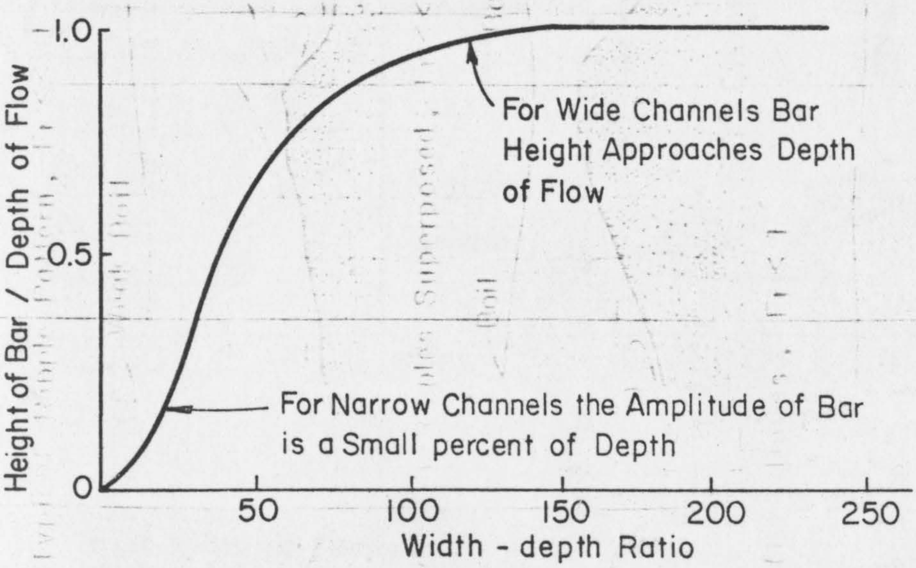


Figure 4 - Relation of Bar Amplitude-Depth Ratio to the Width Depth Ratio

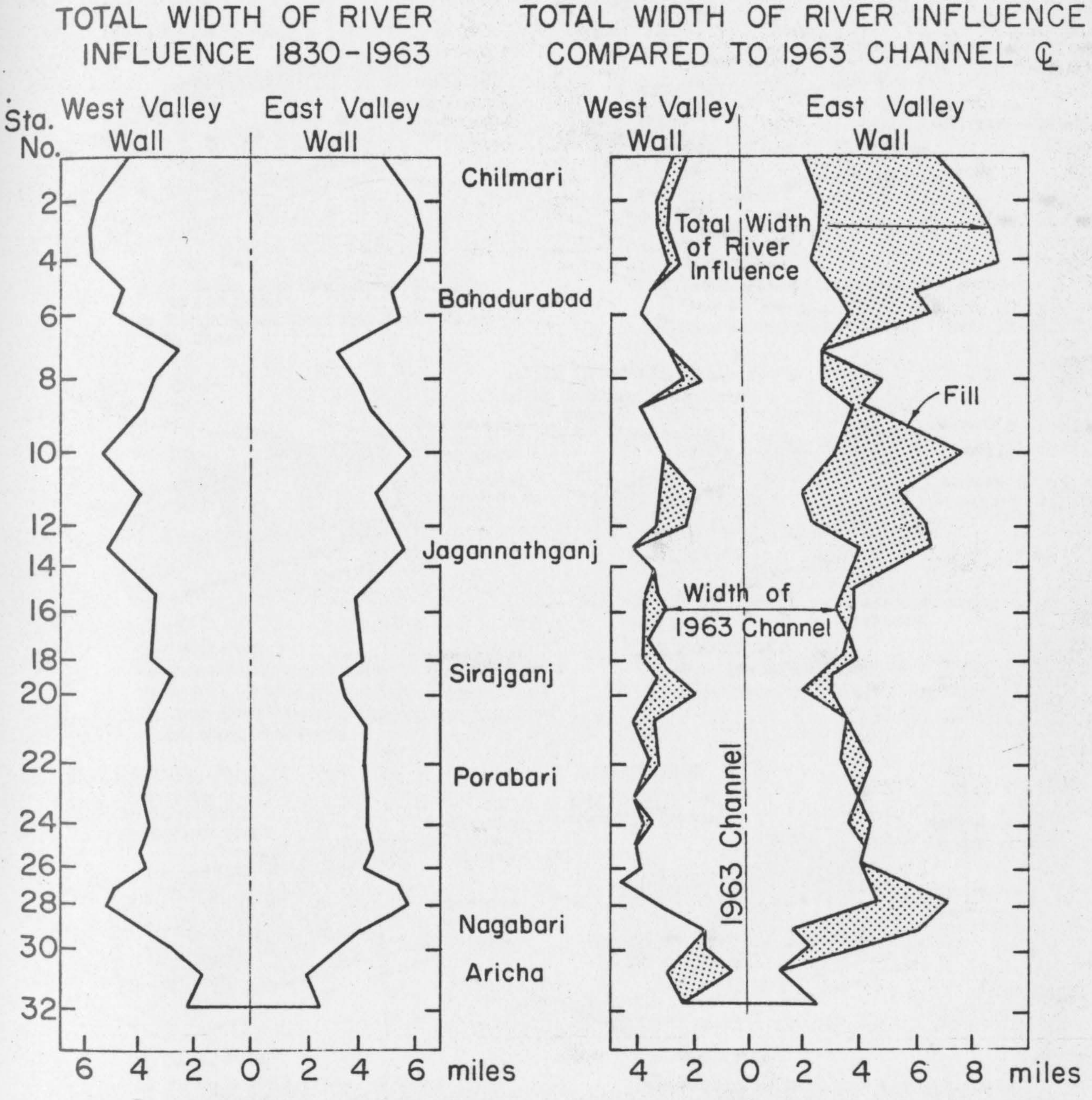


Figure 5 - Total Width of Brahmaputra River Influence During the Period 1830 to 1963. The graph to the right illustrates the total width of the river influence as compared to the banking position of the 1963 river channel. Note that greatest amount of fill has been on the left bank, indicating a dominant channel migration of the river to the west, after Coleman (4)

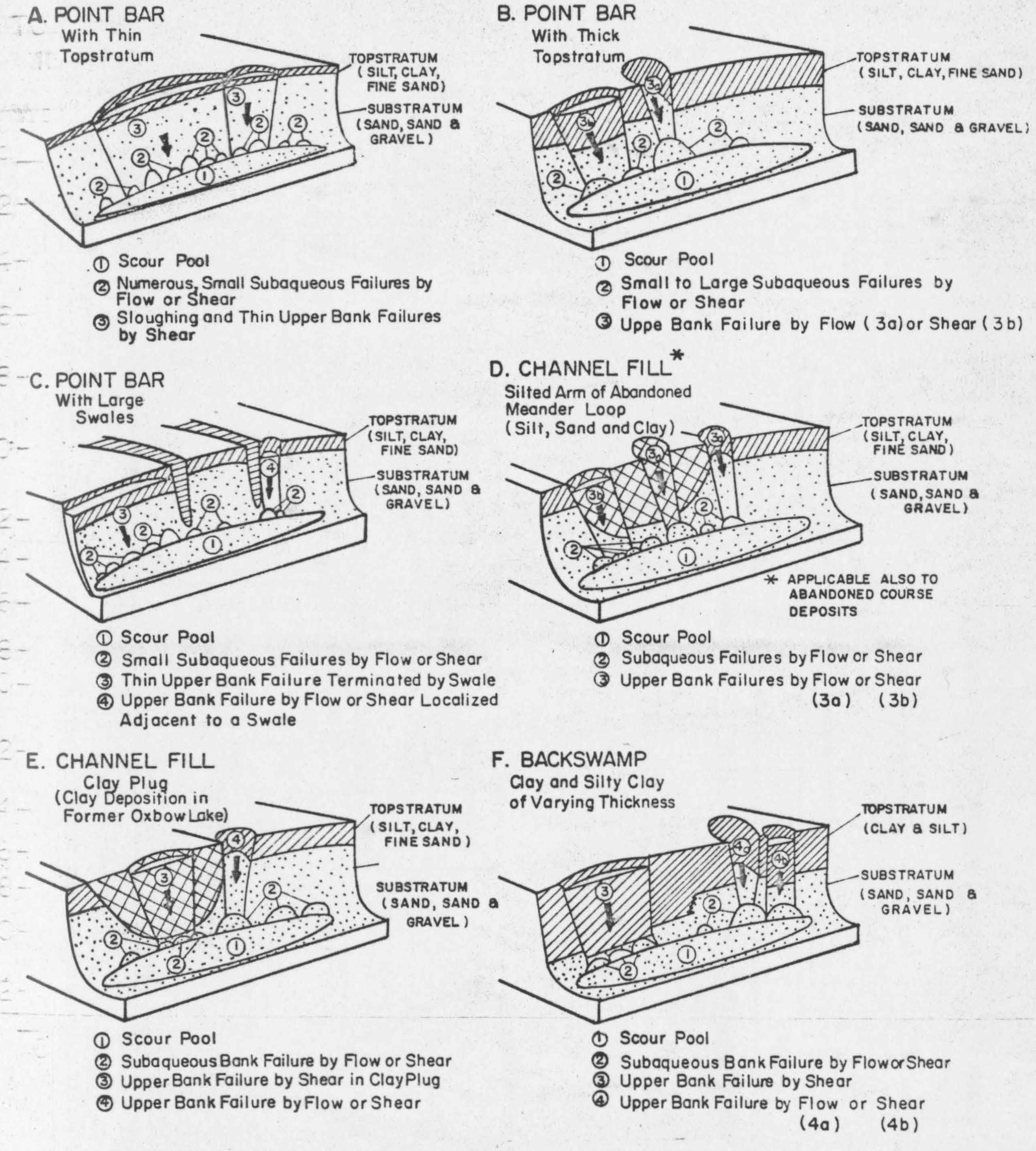


Figure 6 - General Influences of the Geology of Riverbank Soils on the Mechanics of Bank Failure, Potamology Investigations Report 12 - 15

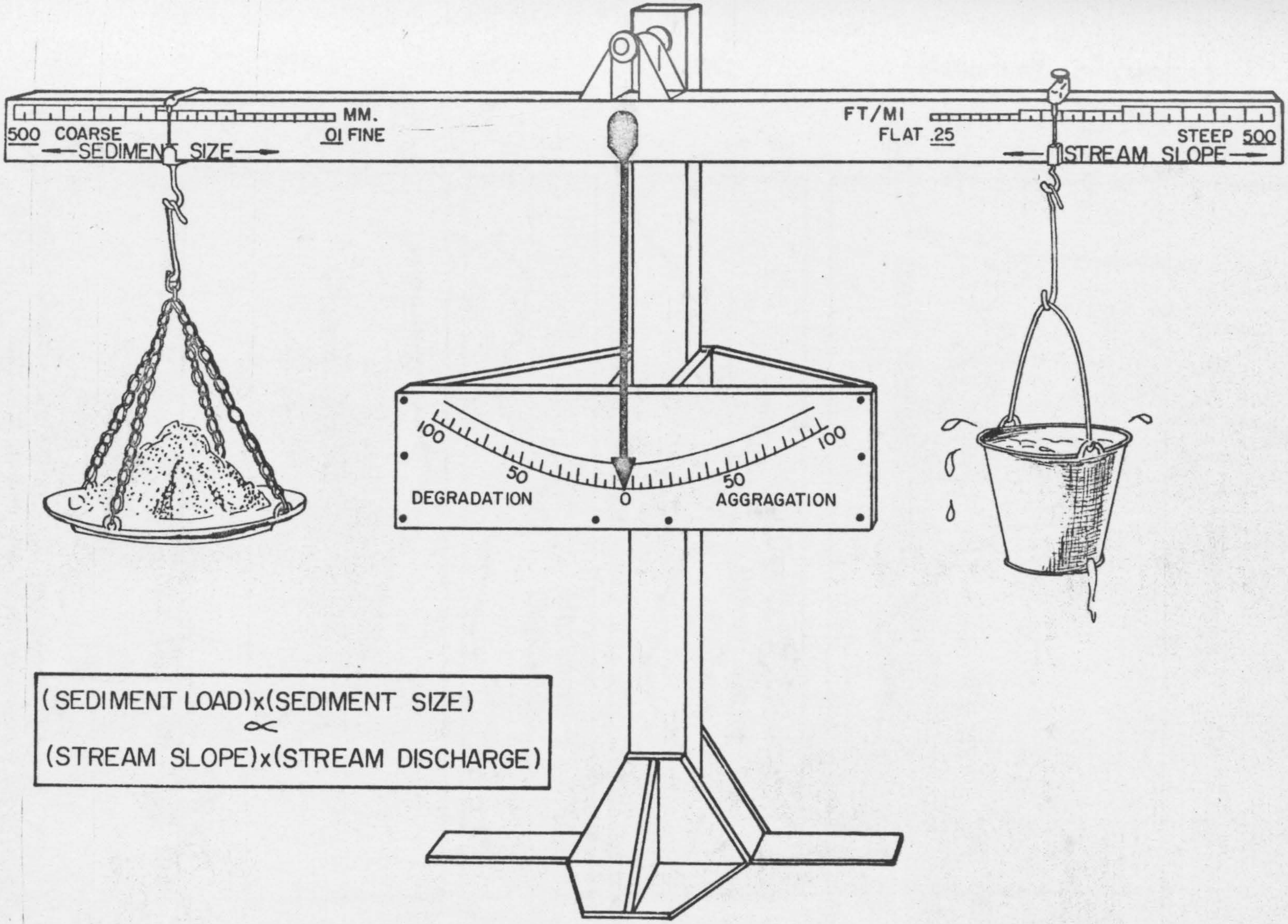


Figure 7 - Channel Response to Development (After W. E. Borland, U.S.B.R.)

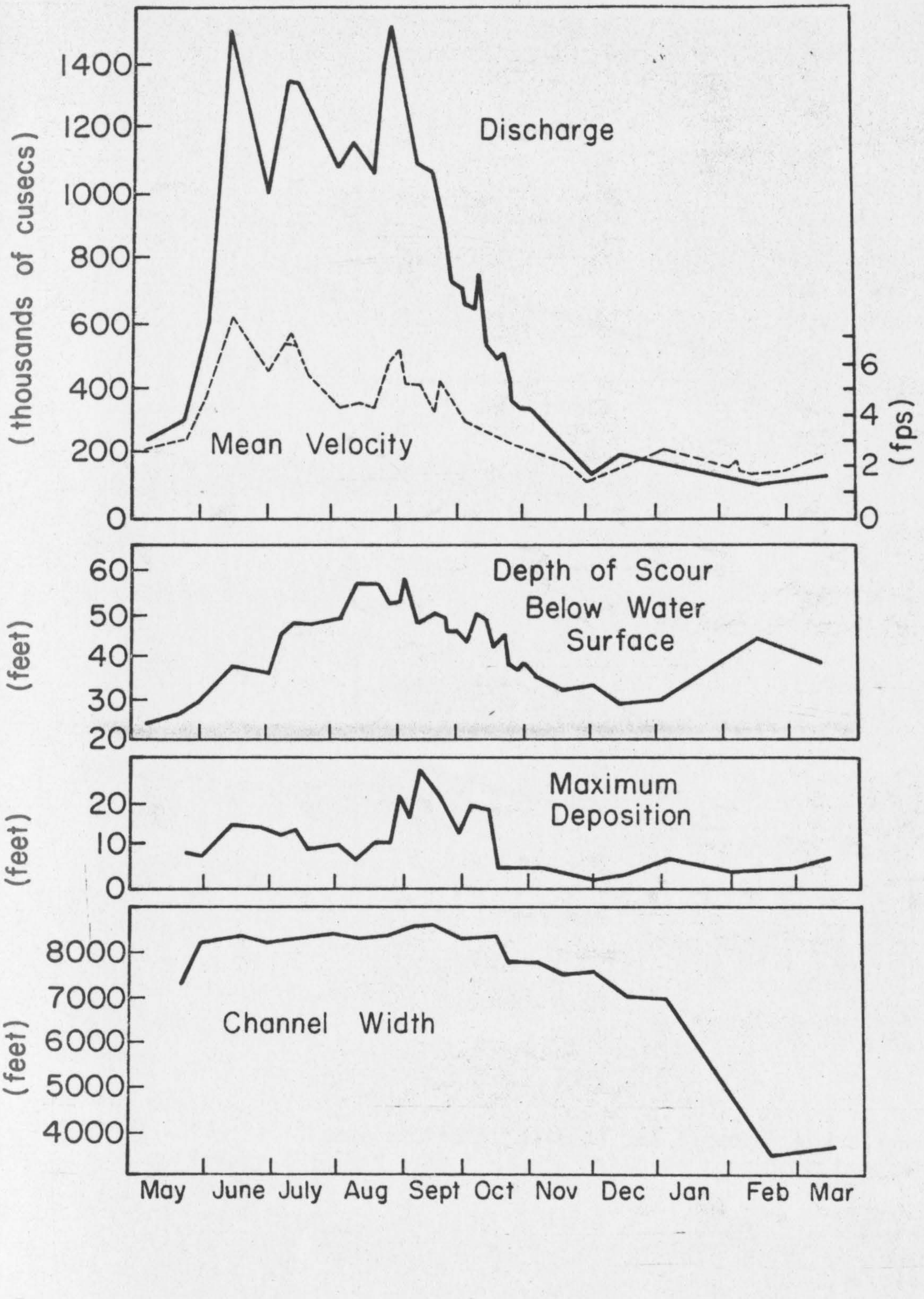


Figure 8 - Graphs Showing Relationships Between Discharge, Mean Current Velocity, Depth of Scour, Maximum Amount of Deposition, and Channel Width During an Entire Flood Cycle on the Brahmaputra River. The graphs represent the 1966-67 flood cycle at Sirajganj, after Coleman (4)

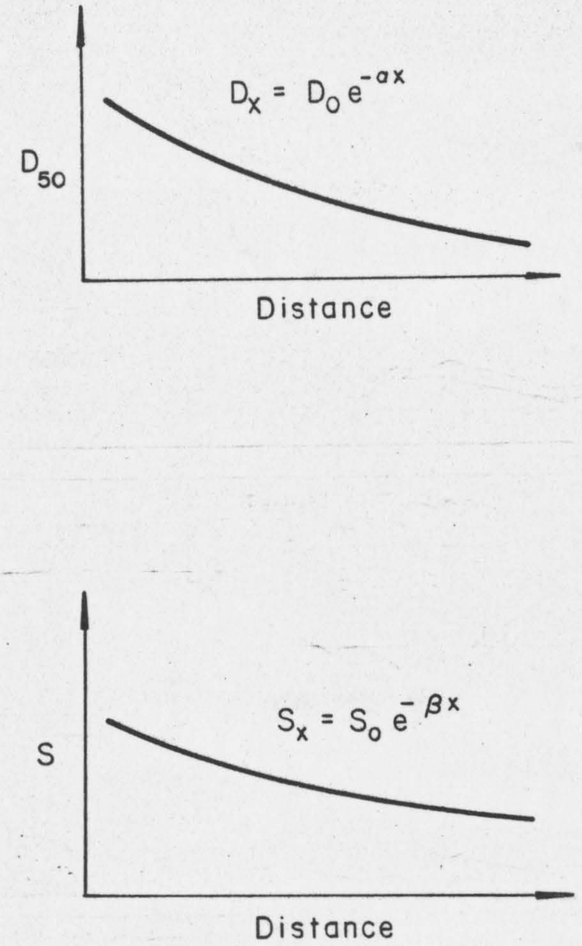


Figure 11 - Typical Change of Median Size of Bed Material and Slope of Energy Gradient with Distance Measured from Some Zero Station Downstream