A Review of Sediment Problems & Possible Solutions

By

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Synopsis

A summary of the science of sedimentation is presented in this paper. Sources of sediment and fundamental laws of sediment transport are discussed. The variety of sediment problems that may exist are described. Methods of measuring and computing sediment loads are given. Possible solutions to the various problems arising from sedimentation are indicated.

Introduction

It should be stressed at the outset that this paper does not present new data, theories or applications. Rather, it is intended as a begins review of the present status of making sediment investigations. It general with a statement of the problems involved, some of the fundamental and methods of observations. Design procedures and methods of alleviating problems follow in the light of basic fluvial dynamics. This paper is oriented to the type of problems that exist in West Pakistan.

It will be well to open this paper with a discussion of the sediment loads of the rivers in Pakistan as compared to sediment loads in other areas of the world. Table I shows the sediment load of a number of selected streams in the United States, divided into problem streams and non-problem streams. From this rather arbitrary division it can be seen that experience in the United States indicates that problems can be expected on river developments in streams where the average annual sediment load exceeds about 1500 parts per million.

Sediment samples collected at irregular intervals during the period July 1960 through June 1961, for various rivers in Pakistan indicated that

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TABLE I

COMPARISON OF SEDIMENT LOAD IN U. S. STREAMS

	Drainage Area (eq. km.)	Annual Discharge $(M^3 \times 10^6)$	Annual Sediment Load $(M^3 \times 10^3)$	Annual Sediment Load $(M^3 \times sqkm)$	Annual Sediment Load (Mg/l)
Problem Streams in U. S.					
Arkansas at Pueblo. Colo. ...	12,200	660	930	76	1,700
Smoky Hill nr. Ellis, Kan ...	13,000	94	330	25	3,650
Middle Loup nr. Dunning, Neb. ...	200	340	380	1,900	1,500
S. Loup at St. Michael, Neb. ...	4,300	355	2,200	510	7,000
N. Loup at St. Paul, Neb. ...	3,400	890	2,300	680	2,900
Powder at Morehead, N. D. ...	21,000	440	10,000	480	24,700
Niobrara at Cody, Neb ...	1,000±	410	500	500	1,300
Moreau at Bixby, S. D. ...	4,100	154	1,300	320	9,000
Cheyenne at Angostura, S. D. ...	23,500	960	9,300	400	10,300
Grand at Wakpala, S. D. ...	14,100	278	1,280	91	4,900
Heart at Mandan, N. D. ...	8,700	253	2,160	250	10,200

Big Horn at Thermopolisi Wyo	...	21,000	1,660	6,900	340	4,400
N. Fk. Red at Altus, Okla	...	6,600	160	1,310	200	9,200
Pecos at Artesia, N. M.	...	25,000	350	1,640	78	6,400
Rio Puerco at Rio Puerco, N. M.	...	15,000	59	14,400	950	244,000
Rio Jemez nr. Jemez, N. M.	...	2,600	62	3,760	1,440	61,000
Rio Chama nr. Chamita, N. M.	...	8,300	540	7,300	880	13,500
Rio Grande at Bernardo, N. M.	...	43,000	1,230	7,400	170	6,000
San Juan at Bluff, Utah	...	60,000	2,700	34,400	570	14,200
Colorado at Lees Ferry, Ariz.	...	280,000	16,800	145,000	540	9,600
Paria at Lees Ferry, Ariz.	...	3,900±	27	5,700	1,500	218,000
Moenkapi Wash at Tuba, Ariz.	...	3,500±	18	1,410	400	80,000
Non-problem streams in U. S. A.						
Story Cr.-Stony Gorge Res., Cal.	...	505	220	48	95	225
Boise River-Arrowrock Res., Ida.	...	5,300	1,000	295	58	300
Osage at Eldon, Missouri	...	36,000	9,000	7,900	220	860
Holston at Cherokee Dam (TVA)	...	8,700	3,800	1,010	115	240
French Broad at Douglas Dam (TVA)	...	6,700	5,900	3,000	450	495
Clinch at Norris Dam (TVA)	...	7,300	3,300	1,300	180	352
L. Tennessee at Fontana Dam (TVA)	...	4,000	3,700	730	180	175

portation remains to be given, and the shortcomings of existing theories probably stem from the lack of adequate knowledge of the physical aspects of the phenomenon,

The main indeterminate factors lies in the conditions prevailing at the boundaries, principally at the bottom of the alluvial channels. The flow of water at the boundaries exerts stresses which transmit forces on to the materials that form the bed of the stream. These forces are generally decomposed into tangential forces and lifting forces.

Bed Load and Suspended Load

The total sediment load in a stream is traditionally divided into two parts : the bed load, which comprises the particles moving essentially in contact with, or in the immediate vicinity of, a movable boundary ; and the suspended load, made of particles entirely surrounded by the water and moving at practically the same velocity, Under normal conditions, the bed load is generally a relatively small proportion of the total load. The mechanics of bed load transportation are,, however, important because they influence suspended sediment transportation.

Interchange

Some of the particles suspended in the flowing water may remain in suspension uuder the action of turbulance and secondary vortices. However, some of them will reach the stream bed after some distance because of their weight, and also because of turbulent mixing action. Every suspended particle which returns to the bottom is then removed from the bed and reinjected into the flow. The sediment suspension within the field of flow is thus maintained in an average steady state.

On the bed, the particles are submitted to normal forces which lift them upwards and to tangential drag forces which move them in a downstream direction. The smaller particles, whieh are sufficiently light to be bronght back into the field of flow, are brought back into suspension. The larger particles, too heavy to be lifted outside of the boundary layer, or to be lifted to all, are dragged along the bed by rolling and sliding as pure bed load.

The existence of the lifting forces presumably caused by turbulence has been demonstrated in the laboratory[2]. Experiments were conducted in a channel with a sand bed covered with a layer of coarse gravel. The flow of water caused the sand to leach through the gravel layer. Unlimited quantities of sand were thus put in suspension, and the gravel layer dropped as the sand was being removed.

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3. *Experimental Studies of Gravel Stabilization Blanket for Stream Bed, Arkanas River Project, by L. G. Straub, St. Anthony Falis Hydraulic Laborotory. 1960.*

Although these experiments have demonstrated the existence of lifting forces, their magnitude cannot, at the present time, be estimated theoretically.

Bed Load Proper

In a river carrying sediments, if the lifting forces at the neighbourhood of the bed are not large enough to put in suspension the coarser fraction of the particles, this fraction will have to be transported by the flow on or near the bed as bed load. A stream which has achieved regime conditions has a bed load carrying capacity—competence—sufficient to move this material downstream, However, this competence, which is a function of the hydraulic characteristics of the river, is limited. In an alluvial river which is in stable regime, the hydraulic elements would have adjusted themselves naturally so that the hydraulic competence of the river be sufficient to move the coarsest fraction of sediments brought to the river by its minor tributaries as a result of watershed erosion.

The number, the size, and the velocity of the partilces in motion determine the rate of bed load transportation. Their mode of movement is one of rolling and sliding over other stationary particles although, because of the roughness of the boundary surface, the moving particles could briefly lose contact with it.

Boundary Shear Stress in a Prismatic Channel.

The magnitude of the tangential boundary stress was first estimated by du Boys. This well known expression of the shear intensity has been found in laboratory experiments to be reasonably correct for a straight prismatic channel with uniform flow. However, it is not applicable to a curved channel.

Experiment studies were started recently[4] and are still under progress to determine the intensity of local boundary shear stresses in bends. These studies are performed on rigid bed models of prismatic trapezoidal channels with various degrees of curvature. The variations of the shear stresses across the section, and along the bends are studied with respect to the average boundary shear stress in a straight reach.

Boundary Shear Stresses in a Natural Alluvial Channel.

Because of the variation of depth in a natural channel, du Boy's formula is not applicable, except under those conditions where average hydraulic elements are considered. However, the irregularity of bed configuration, combined with other hydraulic changes, are likely to result in a relative uniformity of boundary shear, thus maintaining regime conditions.

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[4] *The Distribution of Boundary Shear Stresses in Curved Trapezoidal Channels, Technical reports Nos. 43 & 43S, Massachusetts Institute of Technology, Hydrodynamics Laboratory, October 1960.*

less than ten per cent. No reliable simple method of sampling or measuring the quantity of bed load has been developed, and consequently bed load is not measured except in very special cases. Consequently, in most cases, where sediment load is believed to be a relatively small portion of the total load, the bed load is simply estimated as a percentage of suspended load. In very special cases where the bed load is believed to be quite high, computation procedures may be used to estimate the bed load component.

One method of arriving at a reliable estimate of bed load consists of measuring the suspended load at section of the stream where the hydraulic conditions (turbulence, boundary shear) are such that all sediment load is put in suspension in the field of flow. This can be done immediately downstream from a fall, where the turbulence is sufficient to insure complete mixing of water and sediments. This can also be done at a contracted section of the river. Such suitable contracted sections are generally not available on most streams. However, it is not impossible to artificially create a contracted section on a stream or channel where measurement of the total load is of importance. Measurement by means of conventional sediment samplers can then be made at the contracted section.

Such a procedure was used for obtaining total load measurements in the Loup and Snake Rivers in Nebraska. In the Snake River, a location was found where the river passed through a severely contracted section such that all load in transport was lifted into suspension. By measuring the load in the contracted section and also at a normal section upstream, where both suspended load and bed load existed, a determination of bed load could be obtained from comparison of the two values obtained. Similar measurements were made on the Loup River where a contracted section was constructed. It may be desirable to investigate the possibility of constructing such a contracted section for similar purposes on Pakistan canals where a check or a regulator are not available.

Another method of measuring the total load of a stream over a given period of time is by periodic reservoir surveys. In major reservoirs, the proportion of reservoir sediment inflow that is trapped in the reservoir is very high. Generally, it is above 95 per cent, and in most cases, can be assumed to be 100 per cent. Therefore, if the remaining reservoir volume is periodically measured by accurate surveys, the accumulation of sediment over a given period of time can be measured. From this, the average annual sediment inflow can be computed.

Another method which has been proposed consists of using supersonic sounding equipment to make an accurate detailed maping of the river bed. Analysis of such surveys repeated at short intervals of time would provide an estimate of the volume of sediment movement where the bed configuration is characterized by dunes. However, at the present time, this method has not been used in actual practice to demonstrate its practicability.

Laboratory Analysis.

Laboratory analysis of suspendded sediment samples are required to determine concentration and particle size. The determination of concentration is relatively simple, and is generally carried out by a process of evaporation to dryness, and weighing of the residual. This determination is generally desirable on all sediment samples. The determination of particle size of a suspended sediment sample is usually rather difficult and therefore is accomplished ordinarily on a relatively few samples of suspended sediment. For the larger sizes of sediment, the laboratory analysis for particle size determination can be carried out by sieves. However, this is not satisfactory for most samples, which fall into the smaller size range, and these must be analysed by other methods. Generally, this involves some application of known laws of the fall velocity of given size of sediments in water. A variety of methods have been developed, each of which has its particular application for different size and concentrations of sediment.

III COMPUTATION OF SEDIMENT LOAD

Many sediment problems require the computation of sediment load. One of the most recurring requirements is for determination of the average annual sediment load to assure that adequate space is satisfied within a reservoir for storage of sediment during the economic life of the project. Generally, this is accomplished by analytical determination of the total suspendended load with an arbitrary percentage increase to estimate the total load.

Suspended Load.

In those rare cases where daily records of sediment load have been obtained over many years, the average annual load may be determined simply by taking the average of the total annual load, determined from the daily loads. However, the availability of such data is rare, and other methods are ordinarily required.

The most useful method is that developed by the United States Bureau of Reclamation. This method is usually referred to as ths "Flow Duration—Sediment Rating Curve." The first step is to prepare a sediment rating curve, in which water discharge is plotted against sediment discharge, for all samples of suspended sediment discharge, for all samples of suspended sediment that have been obtained. This requires that sediment concentration (measured in parts per million) be converted to sediment load, in terms of such an equivalent as tons per day. The correlation between water discharge and sediment discharge is rarely good, because of the varying influence of intensity of rainfall, condition of vegetation, season of the year, source of sediment within the drainage basin, and many other factors. However, in most cases a fairly definite general pattern can be established. In some cases, division between different periods of the year is justified. Since the end result is to obtain an average figure, considerable spread in the plotted points can be tolerated.

been shown,[7], [8] that boundary shear stress is not a good parameter to use to describe the bed configuration or to determine the flow and transport parameters : for a given shear, it is possible to have more than one equilibrium bed form, velocity, and transport rate.

Kalinske's and Einstein's Formulae

Two equations for computing the rate of bed load transportation, proposed comparatively recently by Kalinske and H.A. Einstein have a theoretical background. Both were derived logically from explicit but different sets of assumptions.

Both, however, have been legitimately criticized on a number of counts, especially as to the implications of some of the assumptions which were necessary for developing the mathematical treatments. For example, Kalinske at an intermediate step in his presentation made an assumption which would imply that the number of particles in motion is independent of the rate of transport. This simplification is a short-coming of Kalinske's formula. Likewise, major objections have been made to Einstein's developments, that are equally damaging to the confidence that could be placed in his equation.

Einstein developed and published in 1950 a complex procedure for computing the quantity of bed material transported by an alluvial stream in an equilibrium state. His approach was based on the probability of movement of a particle of a particular diameter in the "bed layer." Movement in this layer was considered to occur by rolling and sliding on the bed or by making a series of short hops. The thickness of the bed layer was postulated to be twice the grain diameter. The movement of particles was considered to be governed by statistical laws of probability and was so related to the flow. The average distance traveled by a particle between periods of deposition was assumed to be 100 diameters. The concentration of particles having a particular diameter at the top of the bed layer was assumed to be equal to the concetration of suspended particles of the same diameter at this same beundary. This concentration was then related to the concentration of similar particles at any elevation in the vertical. By integration, the total sediment load of this diameter, per unit width, can be determined at a representative vertical in the stream cross-section for a given discharge. The load is calculated for a number of grain size classes on the basis of sample of bed material. However, the Einstein procedure does not compute the suspended-sediment discharge of particles too small to be in the stream bed in appreciable quantities. Therefore, the discharge of the finer particles must be measured if total sediment discharge of a stream is to be computed. In some manner the measured discharge of sediment of the finer sizes must be combined with the computed discharges of the coarser sediments.

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8. Further Studies (on same subject) by J.F. Kennedy, Report No. KH-R-3, W. M. Keck Lab. of Hydraulics and Water Resources, California Institute of Technology, 1961.

Field verifications have demonstrated that the Einstein formulas do not accurately represent actual sediment transportation. In addition to this, the amount of data necessary for their application make the Einstein procedure most complex to use in practice. For these reasons, the Einstein procedure was modified and improved.

The Modified-Einstein Procedure.

This procedure was developed by B.R. Colby and C.H. Hembree within the scope of studies for the development of the Missouri River Basin in an attempt to permit the computation, with reasonable accuracy, of the total sediment discharge, rather than just one part of the discharge and especially not an indefinite part. In addition, the modified-Einstein procedure is reasonably simple to use.

It is based on Einstein's formulas and consists of computing the sediment discharge for several ranges of particle sizes by applying different methods of computation for the ranges of small particle sizes and for the ranges of large particle sizes. In each range of the small particle sizes, the sediment discharge is computed from the sampling of suspended-sediment discharge by a specified procedure. In the size ranges of the larger particles, the total sediment discharge is determined about as proposed by Einstein with a few changes.

Admittedly, the principal disadvantages of the modified-Einstein procedure are :

(*a*) the inaccuracies and uncertainties with respect to vertical velocity distribution and other variables and relationships of the Einstein procedure :

(*b*) the need for obtaining streamflow measurements and accurate size distributions of suspended sediment and bed material ;

(*c*) and the amount of time required for the computations.

However, its main advantages are :

(*a*) it makes effective use of the usually available basic data to increase the accuracy and dependability of the computations ;

(*b*) it requires no point-integrated samples and no water-surface slopes or energy gradients ;

(*c*) it can be applied to a single defined cross-section even though this section may not be uniform or representative ;

(*d*) it provides a reasonably correct size distribution of the computed sediment discharge ;

(*e*) and it computes the sediment discharge of all sizes of particles that are present.

Because the modified procedure is closely tied to measured streamflow and suspended sediment, it probably leads to relatively accurate values of total sediment discharge for an alluvial section where adequate sampling can be made.

Because of its superiority over other methods presently available, the modified—Einstein procedure is recommended for use where practicable.

IV. FLUVIAL DYNAMICS

Fluvial dynamics are the study of the deformations of riverbeds, and of the causes of these phenomena. The principal aspects of the dynamics of natural rivers are summarized here, and their fundemental principles applied to the behaviour of man-made canals.

Regime of a River

The following discussion applies to alluvial rivers. An alluvial river is defined as a water course confined in a channel kept open by the flow of water in a flood plain made of materials deposited by the river itself at an earlier period of its history. Most rivers of the world are flowing in alluvial flood plains as soon as they are far enough from their headwaters. This is generally the case of West Pakistan rivers.

It has long been established that alluvial rivers ultimately reach a profile of equilibrium, which is more or less parabolic from their headwaters to their estuary. With the exception of reaches constrained by rock bed and banks, and some younger streams, most rivers have achieved their profile of equilibrium.

It is also know that the other physical characters of an alluvial river, width and depth, correspond to a stable equilibrium, generally referred to as its "regime." This concept of regime means that a watercourse with established conditions of flow and sediment load tends toward the establishment of one-and only one-set of geometric features which characterize a state of stable equilibrium.

The formation of an alluvial valley is conditioned by a number of factors. Most important among the factors of the regime is the flow characteristics of the river. Average flow and its seasonal variations, maxmum flow, play an important role in the establishment of the geometric characterisitics of the channel.

However, the sediment transport characteristics of a river constitute another major factor of its character, just as important as precipitation over the watershed, topography of the basin, etc. The formation of the valley depends upon the size and the quantity of sediment transported by the flow. The hydraulic characteristics of the river, such as slope, width, depth, friction coefficient, etc., are determined in a large measure by the sediment load.

In addition to the influence, on the average, of the annual sediment load on the regime of a river, the variations of solid transportation as well as variations of flow rate result in corresponding variations of river forms. Although the functional relationships between these phenomena are not well known, their existence has been demonstrated.

A given watershed seems to yield sediment transport by run-off according to certain relationships. At a given point of a river, the total sediment discharge can generally be related to the water discharge.

Factors of Sediment Transport

The rate of sediment carried by a river generally depends mainly upon the following factors :

(*a*) Nature of rocks and soil cover in the watershed. The hardness of rocks, or their resistance to erosion, has an effect on the sediment rate of the tributaries in the watershed. The thickness of the soil cover, the density of vegetation, and agricultural practices are also factors of the rate of sediment that will reach the main stem of the river.

(*b*) Topography of the watershed. The power of erosion of overland runoff in the upper watershed is greater as the slope of the land is steeper. The amounts of sediment brought into the rivers are larger in such conditions.

(*c*) Intensity of precipitation. Violent storms result in more severe soil erosion than precipitations of moderate intensity. This factor probably causes the apparent lack of consistency of the relationship between sediment rate and flow rate.

(*d*) Washload. This is the sediment load which originates in the stream beds themselves. It generally consists of material eroded from the banks, as the rivers change their course in plan.

Variations of Sediment Load

The solid charge of a stream as observed at a given point varies. It is generally possible to establish a correlation between the water discharge and the total load. However, the flow rate and the sediment rate can be considered as independent variables. The interdependence between these two parameters, valid at the headwaters, is reduced to a functional relationship in the river itself. This concept, advanced by Brooks[9] and supported by others, permits to explain how the dependent variables, such as velocity and friction factor. adjust themselves to the independent variables of flow rate and sediment transport rate.

Dynamism of a River

Even after having reached its profile of equilibrium, an alluvial river remains a dynamic phenomenon. Its bed and its banks are in constant

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[9] *Norman H. Brooks, "Mechanics af Streams with Movable Beds of Fine Sand," Proceedings, ASCE, April 1955, Vol. 81, Separate No. 668.*

movement. The bed material moves downstream at a variable rate. The banks are constantly eroded and filled to form new meanders.

The concept of a river having achieved "regime conditions" implies that on the average, the totality of sediments brought to the river are carried downstream and ultimately discharged into the ocean at its estuary.

The size of sediments transported by a river decreases as they are moved downstream by the flow. While relatively large stones may be present in the upper reaches, their sizes are reduced by abrasion and other processes as they progress downstream. A travel of forty to fifty miles is often sufficient to reduce cobbles to fine silt. This size reduction permits a decrease of the boundary stresses required to transport bed sediments, such as that caused by the flattening of the river slope in the downstream reaches.

However, the occasional sediment rate changes cause corresponding morphologic changes which reflect an adjustment of the hydraulic characteristics to the sediment conditions. These bed changes generally occur in cycles. so as to result in an overall stability of the regime.

1. *Short Duration Changes.* Spectacular changes may occur in a small number of days, or even hours during floods. Less impressive, but not less consequential, are systematic changes that occur practically constantly in the beds of alluvial rivers.

(*a*) Dunes movement. The configuration of the bed of alluvial rivers generally corresponds to an irregular dune pattern. Depending on the hydraulic conditions, these dunes may become ripples, or disappear to be replaced by a somewhat plane surface. Sand waves occur generally on the bed of a river in a regular pattern, and they vary in a systematic manner with discharge changes, becoming larger as the flow increases, and smaller as the flow decreases. These dunes constantly move in a downstream direction because of the movement of the individual particles that form the dunes just as desert sand dunes move under the influence of the wind. There generally is a lag in the rate of change of sand waves ; for the same flow, the dunes are smaller on a rising river than on a falling river.

Although much work has been done recently in hydraulic laboratories on the characteristics of bed configuration, this subject still remains to be fully investigated, as much by field observations in large rivers as by theoretical research.

(*b*) Crossings between bends. The existence of bars between bends of a river, oblique to the channel centerline, is well known to navigators. The height of these crossing bars varies with the discharge ; they rise and fall in a manner rapidly related to the flow. When a period of high flow is succeeded by a fairly rapid fall, these built-up crossings may cause the formation in the river of a series of pools with steep crossing slopes. A more gradual fall of the river stage would scour the crossings and result in a lowering of the pools to normal low water. This process may be explained by a scouring of the bends during high stages and deposition at the crossings.

This phenomenon is, of course, related to the sand waves.

(*c*) Changes caused by unusual floods. A river temporarily supplied with large amounts of sediments that may be extremely large in size may deposit cobbles, stones, and even rocks for considerable distances, thus resulting in the need for extensive dredging at bridge crossings and other locations.

Where flood flows have a transporting power in excess of the quantity of sediments available, severe degradation, either vertical or lateral, or both, may occur, generally resulting in deposition in lower reaches.

2. *Long Term Changes.*

These are morphological changes which continue in the same direction for an extended period of time, generally followed by changes in the reverse direction so as to result in a long-term cyclical evolution.

(*a*) Aggradation and degradation. Generally, riverbeds may be degraded by one to three feet for a number of years, then will aggrade, with or without secondary fluctuations, in the reverse direction· The exceptions to such a regularity are due to special causes, such as a radical change of the sediment load of a river. For example, release of clear water from a newly constructed reservoir will start a non-return degradation process downstream. The absence of bedload supply will prevent the replacement of the material dragged by the flow in a downstream direction. Bed material will thus be removed until flatting of the slope to a value corresponding to the non-transport condition. Such degradation has been observed to reach up to ten feet. If the material in place is too large to be removed, especially when the regulated flow has been decreased, lateral erosion may occur if finer materials are present in the banks.

This degradation which follows an artificial change in the regime of a river has been attributed to the fact that "clear water is more erosive than turbid water." The truth of the matter, as was explained above. is that the regime of a river depends not only on flow conditions, but also on sediment transport conditions. When the total load, and particularly the bedload of a river is changed, the moving boundary is also affected.

(*b*) *Bank Erosing and Deposition.* In rivers which follow a relatively straight course, the banks are generally eroded in a sinusoidal form, with deeps and crossings. The crossings move downstream either regularly or in a disorderly manner. This is due in part to secondary helicoidal currents, not mentioned previously, but which play an important role. Another factor is probably the fact that low flows and the corresponding variable sediment rates require different longitudinal slopes.

However, wandering channels generally hold the respective location of the deeps and the bars. Their movement downstream occurs by the same action as that of meanders migration.

c. Mechanics of Meanders.

Meanders of alluvial rivers are direct consequence of lateral erosion, already mentioned above. Meanders are generally contained within relatively high banks with respect to flood stages. This confinement may have been caused either by berming up of the banks, or by deepening of the bed. Bank erosion being the primary cause of meanders, their creation implies the existence of currents with a sufficient erosive power. However, this erosive power must be more active on the banks on the bed. The formation of meanders for a given erosive power of the flow depends on the resistance of the banks and bed material, as expressed by the size of materials, their cohesion and their gradation. In particular, the relative resistance of bed material with respect to bank resistance is an important factor. However, if the banks are made of very soft materials, meanders may not develop and the bed will merely widen without becoming braided.

These various factors and several others, combine in each particular case to cause meanders on rivers which may, on a cursory examination, appear to be quite different. However, a common character is the dynamism of meanders. Although their evolution if quite complex, it follows general laws which are here mentioned qualitatively.

As the meanders are formed. their curvature and amplitude increase up to certain dimensions, unless meander-cutting prevents this evolution to reach its term. These ultimate dimensions are related to the erosive power at which lateral erosion stops. Geometrical characteristics of meander have been studied with some success by various authors, and some relationships were found between curvature, width, wave length, and amplitude.

Meanders migrate in a downstream direction. The lower Mississippi meanders, for instance, would migrate at a velocity of about 1000 feet, or more per year.

The increase of length of the oxbows may result in a suicide of meanders by cut-off. A rapid regressive degradation upstream from the cut-off point aggradation downstream from it will follow this suicide of the meander and the phenomenon will duplicate itself again and again. Cut-offs may also occur by erosive action of flood waters that spill over the banks. The area occupied by the old meander may be filled, or remain as a small lake until regeneration of the meander.

3. Influence of River Changes on Hydraulic Characteristics.

The systematic river changes that occur in a river, related to the sediment transport, are a major factor of the hydraulic characteristics of the river such as stage-discharge relationship, frictional resistance to flow, depth-width ratio, slope, etc.

The rating curve of a given section is a loop rather than a curve. This may be due to the fact that on the rising stage the sediment load, usually high, requires an adjustment of the stream to increase its transport capability. The bed is then smoothed out and the velocity increased. The sediment load being usually smaller on the falling stage than on the rising stage, the stream can transport the load with a lower velocity and larger depth. The stream then adjusts to this condition by forming rougher dunes than it did on the rising stage.

The configuration of the bed and the size of the dunes which depend upon the flow conditions and upon the size of bed load material, have a strong influence on the resistance to the flow. This fact has been borne out by a number of laboratory experiments and field observations.

The resistance to flow is also dependent upon the grain size of the bed material, and upon the suspended sediment load. These factors, as well as bed configuration, are not recognized by flow formulas of the Manning type. This explains the wide variations observed in the apparent roughness coefficient exhibited by channels which would otherwise look similar. In consequence, roughness, or resistance to flow, is not an attribute of the soil formations through which the river flows, but is rather a property, or condition, of the riverbed, controlled by a combination of flow rate and sediment rate in the river.

The laws that govern the depth-width ratio in a river are not well known, although a number of correlations were studied by several investigators, in particular by L. B. Leopold, Th. Maddock, Jr., and M.G. Wolman. However, it is suspected that a river must adjust its depth and width so as to carry the water flow in such conditions that the corresponding boundary shear stresses are just sufficient to transport the sediment load imposed by watershed erosion.

Alluvial Canals

Alluvial canals are man-made courses generally excavated in natural deposits. Their function is to convey water that may be charged with sediment load imposed by the parent river from which the water is diverted. They may be artificially lined, or not.

Because of the generally lower cost of unlined canals, they have been an important part of hydraulic structure. However, engineers have been faced with the difficulty of constructing a canal which would keep its original hydraulic characteristics throughout its period of operating. Many canals, shortly after having been put in operation, showed signs of severe erosion, whereas others were being filled by sediment deposits. The same method of design led to success in some cases and failure in many others.

A canal is a water course subject to the same fundamental laws of fluvial dynamics as natural rivers. The concept of regime having been accepted for natural alluvial streams, one must recognize that any artificial channel, under given conditions of flow rate and sediment rate, will tend to achieve a slope, a depth, and a width that conform with the laws of fluvial dynamics.

The ability to accurately predict these ultimate geometrical characters would enable the engineer to construct channels which would not erode nor silt, except for minor cyclical variations reflecting seasonal variations of flow and sediment load. Since such complete knowledge is not available at the present time, the best that can be accomplished consists of identifying the dominant factors in each particular case and anticipating their action in the light of fundamental mechanics of rivers. Design procedures can then be devised to systematize the analysis of these factors and simplify investigations.

The roughness factor of alluvial canals is affected by the following factors in the same manner as for natural rivers : bed configuration, size of bed material, and total sediment load.

V—METHODS OF ALLEVIATING PROBLEMS

The following is but a brief review of the possible solutions to sedimentation problems as they may present themselves to the engineer engaged in river control. The planning stage, the detailed design stage, and the operation stage will be considered in succession.

A. Planning.

In the planning of reservoirs for water storage, erosion in the watershed must be accepted as inevitable in certain respects. Total average annual sediment load which will reach the reservoir must be estimated. A portion of the reservoir capacity will be reserved as "dead storage" for the accumulation of sediment. Only that storage capacity in excess of dead storage will be usable for active purposes such as irrigation, flood control, or power. The dead storage should be sufficiently large to contain all the sediments incoming during a reasonable part of the useful life of the project. However, provision of dead storage for sediment storge may be costly where the sediment load is large. Estimates at the volume required should, therefore, be realistic.

In the planning stage of a river project, the incidence of proposed structures upon the existing river system must be evaluated as well as possible. The pattern of flows released from new storage structures may become drastically different from these presently prevailing in the system. Rivers and canals which have reached regime conditions may be seriously affected. This situation may be complicated by the fact that sediments presently supplied to the rivers and canals will be entrapped in the reservoirs.

It is not impossible to predict the extent of such an impact on the existing system. Predictions of degradation below reservoirs have been made with a surprising degree of accuracy. A method was developed for the Middle Rio Grande by the U. S. Bureau of Reclamation in cooperation with the Corps of Engineers.[10] In this procedure, the river is divided into convenient reaches which can be treated as units with similar characteristics within the reach, such as, slope, width and river bed mat erial. From the suspended sediment sampling and flow records, the suspended load is determined. Bed load or the load not measured by sampling and the total load is then determined by use of the modified Einstein procedure. This is the basic condition without dam.

Utilizing the same reaches but with modified conditions of rate of flow and sediment inflow due to the dam, the capacity of the reach to transport sediment is determined by application of the Lane-Kalinske formula for suspended sediment load : and the average of the Kalinske and Schoklitsch formulae for the unmeasured load. The results are then adjusted to conform to the results obtained by the application of the modified Einstein procedure.

From the samples of stream-bed material which have been obtained at the river ranges, composition of the river bed material in each reach is estimated for several divisions of grain sizes, each of which is subject to transport at different rates of flow. The amounts of sediment entering the reach are subdivided in the same fashion. "Educated" assumptions are made as to depths of turnover of streambed material. With the ability of the stream to transport the various sizes and the total amount of the various sizes in the river bed and entering the reach available for transport known, solid outflow for the reach can be determined. This process is repeated for each successive year and the net differences in inflow and outflow of sediment yields the amount of aggradation of degradation for the reach.

Although prediction of the effect of a proposed reservoir on the downstream reaches of a single river may be quite difficult, the problem becomes almost inextricable if a large system of canals presently in operation downstream from the site of the future structure. The canal may have reached regime conditions, but these will most likely be disturbed. Experience in other rivers where such changes have occurred shows that they are seldom beneficial. Rehabilitation works may be required to prevent these changes from taking major proportion.

The importance of adequate planning points toward the need for basic investigations. Their purpose is to acquire an adequate knowledge

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[10] "*An Estimate of the Magnitude of the Degradation which will rssult in the Middle Rio Grande Channel from the Construction of the proposed Sediment Storage Basin and Contraction Works,* "*Hydraulic Laboratory Report No. Hyd. 290, U.S Bureau of Reclamation, July* 15, 1948.

of the sediment characteristics in the river basin where large projects are contemplated, and eventually to arrive at a better understanding of the role of sedimentation in the stability of rivers and canals.

Such investigations have been proposed, and are presently under way in the Indus Basin. They include a programme of data collection intended to give a good indication of the changes that may occur in the future.

Throughout the entire Punjab area, staff gages will be located in the rivers at intervals of five to ten miles. They will serve as integrators of the aggradation or degradation in the steams. Aerial photographs will be obtained about every three years at bank-full stage on the recession stage of the hydrographs to indentify areas where a change in the limits of the river channel may occur.

Additional data to be connected on existing canals as well as rivers include actual discharge from measurements, cross-sections, water surface profiles, vertical velocity profiles, water temperatures, samples of bed material, depth and point-integrated suspended sediment sampling.

These data will constitute the largest amount of information systematically collected on a river and canal system. and should enable a better planning of future development of the Indus Basin, and possibly other plans.

B. **Design.**

1. *River Control Works.*

An important phase of river control projects is the prevention of migration of existing channels from their present location. This may be accomplished in various manners.

The banks of a channel, and sometimes its bed, may require riprap protection. Empirical rules, rather than rational design, are presently used for such cases. Flood control channels, or other high velocity channels may be concrete lined. In the cases where transport of large size bed load occurs, the lining may be subjected to a severe abrasion. Settling basins located at the upstream end will generally provide good protection when they are adequately dimensioned, and dredged at regular intervals.

When the boundary shear stresses in an unlined canal are not excessive (up to 0. 2 pounds per square foot) and the problem is one of protecting fine sand or cohesionless silt against erosion by water with little or no bed load, a thin layer of fine gravel, two to three grain diameter thick, will be most effective.

Meander cutting is a measure frequently taken, although seldom successful. It should be kept in mind that meanders are part of the regime of a stream. Unless measures are taken to give the stream rigid boundaries (revetments), or to act on the causes of the meander formation, they will almost certainly reappear.

Another interesting and often successful method of reclaiming land from a wide river channel consists of constructing groins that extend from the banks toward the channel centerline. When judiciously spaced and oriented, these groins create zones of low velocity where sediment is deposited. However, unless the newly created berms are protected by vegetation and other means, they will ultimately be washed away by flood flows.

It is worth mentioning the deceiving case of low velocity concrete-lined channels that are not protected against the admission of excessive sediment loads. Bed load transport may then occur, and the channel behave as an alluvial channel with moving boundary. Its resistance to flow may then be similar to that of an unlined canal, thus resulting in a great reduction of its discharge capacity.

Finally, a few words may be said about channel improvement programs. During large floods, floating and other debris are accumulated in natural channels near bridges or at other locations. Waterways are then obstructed. Measures may be taken to clear the streams, and heavy constrnction equipment used for this purpose. It is often decided to improve the channel, and large size stones may be scraped away from the bed. The natural armor of the stream is thus removed, and soon thereafter erosion starts, and bridge piers may be severely undermined. Before natural return to regime conditions and formation of a new armor, repairs are often required.

2. Canal Intakes and Desilting Works.

Much work has been done in West Pakistan to develop intakes which would prevent excessive quantities of sediments from entering a canal. A large number of imprortant structures have been constructed and a valuable experience thus gained. Therefore, little will be mentioned here on this subject.

The location of head regulators with respect to bends in the parent river is one of the most important factors to be considered. Helicoidal currents in straight channels have been mentioned previously. Their deformation in a bend has a strong effect on the amount of sediment that might be drawn from the river by a canal intake.

A considerable amount of hydraulic studies were made in laboratories to develop standard types of "silt excluders" and "silt ejectors." Silt excluders located at head regulators can be made to work satisfactorily provided that periodic sluicing is successful in moving deposited materials downstream from the control structures. Silt ejectors located on canals

The admission in the canal of larger quantites of materials to be transported on the bed permits larger tractive forces, therefore larges velocities. This results in smaller cross-sectional areas and generally lower construction costs. However, the frictional resistance will be correspondingly larger.

(*d*) **Variable Sediment Load and Water Flow**. The variations of sediment concentrations in the parent river and the variations of water demand in the canal complicate the problem, but to an extent that could be handled by a suitable computational procedure. The problem is essentially the same as that of degradation predictions. However, reliable methods of estimating bed load must be available. The lack of accuracy of existing procedures could be compensated by means of a controllable silt excluder located at the headworks. Such a device would also permit to adjust sediment load to water demand so as to maintain regime conditions.

C. Reservoir Sluicing

Sluicing from large capacity reservoirs for the purpose of releasing entrapped sediments through low level outlets is generally not effective. However, it can be done successfully on low head barrages. Periodic sluicing generally washes sediments away from the approaches of canal intakes and from the settling basins of silt excluders.

However, when the barrage is used as a diversion structure, a relatively low regulated flow will be left in the channel downstream. Large quantities of sediments being released in this channel periodically, and the transport capacity of the channel being greatly reduced, the channel may undergo drastic changes which should be expected.

D. Watershed Management

Silt—soil carried from land into streams—can wreck man's activities and works. Silt begins with erosion, which oftentime strips farm lands of their best top-soil, or cuts ugly, damaging gullies. Future generations might be presented with the incongruous picture of a dam, structurally safe for many more years of use, rendered useless because its storage-capacity is gone.

Sound watershed management can minimize the ill-effects of sedimentation. Public agencies can work on erosion control through maintenance of forests and other vegetal cover, by land management, the use of good farming methods, and possibly installation of small erosion-control structures. Individual farmers, through their own initiative, can contribute much toward the prevention of erosion.