KEYNOTE SPEECHES

PRACTICAL SEDIMENT MANAGEMENT TECHNIQUES UTILIZED IN THE UNITED STATES

by
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Introduction

Sediment processes impose numerous significant impacts on all aspects of water resources planning, development, utilization and maintenance. However, the sediment transport concepts and relations presently utilized have serious limitations for many applications. The following paragraphs introduce my understanding of the status of present knowledge of sediment technology, and more importantly, identify the myriad of practical problems and the inadequacies of concepts and theories in the development and utilization of both simple and complex water resources developments.

The history of the development of sedimentation concepts and theories dates back to antiquity as reported by Simons & Sentürk (1977). Most early sedimentation problems were related to flood control, channel stabilization, diversions for irrigation, water supply and navigation. The rate of expansion of knowledge of sediment transport processes has been slow. In fact, we have far to go and much to learn.

In general, the transport of sediment in channels is subdivided into five classifications: bed load, suspended bed material, wash load, saltation load, and total load. There are numerous other related terms widely referenced in the literature dealing with the transport and deposition of sediment.

The multitude of sediment transport equations for alluvial channels that have evolved have restricted applicability because of limitations imposed by the concepts upon which they are based and the data utilized to develop and verify the applicability of these relations. Important limitations that the engineer and scientist must be aware of include the following.

- Most sediment transport relations have only been tested and developed for sand-bed flumes and channels.

- These transport relations are often based upon data resulting from studies conducted in small sand-bed flumes. In general, the range of sediment sizes investigated was small; discharge was small; slope was varied over a significant range; and the flow conditions were usually steady and uniform. Additionally, normal variations in magnitude of measured variables have been treated as errors in measurement. This adds to the confusion and possibly the lack of confidence in sediment transport relations.

Analysis of concepts and relations related to steep rivers and streams verifies that very few transport relations are applicable and that only limited data have been collected and analyzed. Work by Shields relating to initiation of sediment motion is a basic reference and has been used to analyze beginning of particle motion for the full-range of sizes of bed material encountered. Regarding Shields' work, recent studies have confirmed that for determining initiation of motion for a wide range of sizes, the often assumed constant k in the Shields relation $\tau/\Delta\gamma D = k$ varies between relatively wide limits. For example,

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the dimensionless shear varies between 0.02 and 0.10 depending upon the size and gradation of the material, the characteristics of the channel within which the material moves, the discharge and its characteristics, and other factors. However, many individuals have assumed the value of k to be constant. This is basically true for a limited range of particle sizes.

The supply of sediment to a system is controlled to varying degrees by: climatic conditions, both past and present; the geology of the basin; the physiography of the basin, i.e., gradients, etc.; the soil mantle; the vegetation; the geomorphology, past and present with consideration of the future; the characteristics of the bed and bank material forming the perimeter of the channel; the presence of natural and man-made controls; and the stability of both the watershed, including consideration of how stability is defined, and the channel, including the origin, magnitude and duration of discharge, and the impact of past episodic events, i.e., debris flows, mud flows, glacial outburst floods, etc. The analysis and design required to meet selected objectives must as a minimum consider the following.

- The plan form of the river, i.e., whether it is meandering, straight or braided; the past history of occurrence of river forms and the propensity for changes in river form. Rivers can be extremely dynamic and to some degree treacherous to the uninformed.

- The existence of thresholds which if crossed can result in a significant change in the plan form of the river, forms of bed roughness, resistance to flow, velocity, channel stability, etc.

- The profile of the river and the occurrence of controls such as rock outcrops; boulder fields; and man-made structures such as weirs, dams and, in some cases, bridges.

- Slope instabilities, i.e., aggrading, degrading, nick points, head cuts, etc.

- Presence of alluvial fans and the dynamics of the fans in recent time.

- Man's impacts on the system including such important items as: dams (all types), diversions, hydropower development, pumping plants, irrigation systems, municipal supply, industrial supply, environmental demands, bridges, channel protection works, sand and gravel extraction, mining, navigation, fisheries, water quality, failure of dams and other structures, flood plain development, pipeline crossings, waste disposal of material from tunnel construction, etc.

In summary, numerous special problems plague those of us involved in erosion and sedimentation problems associated with watershed and river analysis. Our often referred to theories and concepts are mostly a crutch supported by experimental and statistical information and conclusions resulting from studies that are largely based upon:

- laboratory experiments often conducted by staff with limited geomorphic, engineering and field experience,

- limited field data that rarely includes data for large hydrologic and significant hydraulic events, particularly episodic events, and for steep river systems with unstable watersheds,

- the assumption that the characteristics of the bed material forming the bed of the river do not change with time nor with flow conditions, which is an erroneous assumption (that is, mathematical models often make the assumption that the characteristics of the bed material is static and this will introduce a significant error in the computations having ignored the dynamic changes that will occur in the characteristics of the bed material),

- lack of knowledge of sediment supply-limited conditions in many settings, and

- lack of detailed knowledge regarding sediment transport in complex systems when considering nonuniform, unsteady flow, particularly rapidly varying nonuniform and unsteady flow (for these conditions, experience may be more important than results obtained from the use of very questionable relationships and models).

Consideration of the preceding concepts and facts points out the need for expanded research and field studies in the identified areas regarding sediment transport where there is limited knowledge and experience. Such studies would be relatively expensive and time consuming. However, the alternatives are not attractive as we deal with increasingly complex situations and constraints involving the environment, economics, policies, geology, geomorphology, geotechnical factors, watershed management, etc. In development work, the engineer is often handcuffed and gagged by policy and by environmental and economic constraints imposed by a staff with a frightening lack of technical knowledge but with strong opinions based more on emotional response rather than on logic and understanding. The system becomes even more confused as hearings and litigation evolve, largely conducted and judged by individuals who do not know that they do not know. Too often the approach adopted is "why complicate a simple, legal, environmental issue by giving consideration to technical facts when one's mind is made up?"

Sediment Transport Equations

As indicated in the introduction, the subject of sediment transport has been studied by engineers and geomorphologists for many decades. Knowledge of sediment transport is very important to watershed analysis, river hydraulics and the dynamic adjustments of river systems resulting from natural causes, the implementation of various water resources development activities and responses to environmental concerns. Sediment transport involves a complex interaction between numerous interrelated variables. However, theoretical approaches in the study of sediment transport are based upon simplified and idealized assumptions. It has been common practice to assume that the rate of sediment transport or the magnitude of sediment concentration can largely be determined by certain dominant variables such as water discharge, velocity, the energy gradient, shear stress, stream power, unit stream power, relative roughness, the Froude number, etc. The variable emphasized depends upon the research work reviewed. In some cases, only two or three major variables are utilized. This usually results in an over-simplification of the problem. When different equations are applied to a specific river, the results may vary drastically from one another. Such differences raise questions regarding the accuracy and validity of the various equations.

Transport methods are based upon varying theoretical considerations, statistical interpretations of basic data, and limited verification of the relations with field data. In fact, in some cases there has not been any verification of transport equations for field conditions. The majority of these relationships have been developed to apply to sand-bed channels. The exceptions are the Meyer-Peter, Müller method which is widely used for sand-, gravel- and cobble-bed streams, the Milhous and Parker methods which are strongly related to gravel-bed streams, and the Yang and Molinas method which is applicable to streams with bed materials ranging in size from fine sand to small gravel.

To illustrate the accuracy, or lack thereof, by applying various relations to specific sites, Stevens and Yang (1989) developed several comparative plots utilizing different equations as illustrated in Fig 1. The graphical results speak for themselves.

The transport of sediment from watersheds and in natural river systems depends upon numerous interrelated variables. It is concluded that there is no universal equation that is applicable to all conditions. Based upon extensive field experience, the following recommendations are presented for consideration by individuals involved in sediment transport analyses.

1. Study the geomorphology of the system to become better acquainted with the physical processes and with changes in the system that have occurred and may occur over time. Similarly, it is important to assess future impacts and changes that may affect the system.

2. Investigate the characteristics of the watershed and the channel system to obtain a realistic evaluation of sediment supply to the reach in question.

3. Examine the available transport equations and determine which ones are best suited to this particular environment.

4. Calculate the rates of transport using the selected relationships and compare the results with field data.

5. Select that relationship which best agrees with field observations, and if sufficient data are available, refine this relationship so that it is site specific.

In general, it is possible to use various forms of streampower or unit streampower relationships if calibrated to the particular system in question. However, it is strongly recommended that for field applications the energy gradient term should be replaced with an appropriate velocity term. The principal reason for this suggestion relates to the difficulties involved in accurately measuring stream gradient, the simplicity and accuracy with which velocity and velocity distribution can be measured and/or estimated and the close correlation between energy gradient and velocity.

To estimate the transport capacity of steeper streams with coarse bed material, the Meyer-Peter, Müller bed-load transport relation is often cited and relied upon in engineering and environmental analyses. For steep river systems, best results can be obtained by development of site-specific relationships based upon the collection of adequate field data. However, the collection of such data can be time consuming and costly. The lack of acceptable relationships describing sediment transport in coarse bed material streams is not the result of lack of importance to the involved professionals, but relates more specifically to the difficulty of collecting meaningful laboratory and field data. Another severe limitation of present relationships, both theoretical and statistical in form, is that these relations have, in general, been developed for estimating the bed-material transport capacity of channels. When dealing with coarse bed-material channels, the governing factor may be sediment supply. In steep mountain streams, the transport capacity for a range of sizes of bed material may exceed the supply by a factor of 100, and in some cases even 1,000. Failure to accept and investigate this fact can lead to improper conclusions and an inadequate project design.

In the application of transport equations, it is not uncommon to utilize two equations in unison to solve a particular problem. For example, one might utilize the Meyer-Peter, Müller relationship to estimate bed load and the Einstein bed-load function to estimate

NIOBRARA RIVER NEAR CODY, NEBRASKA

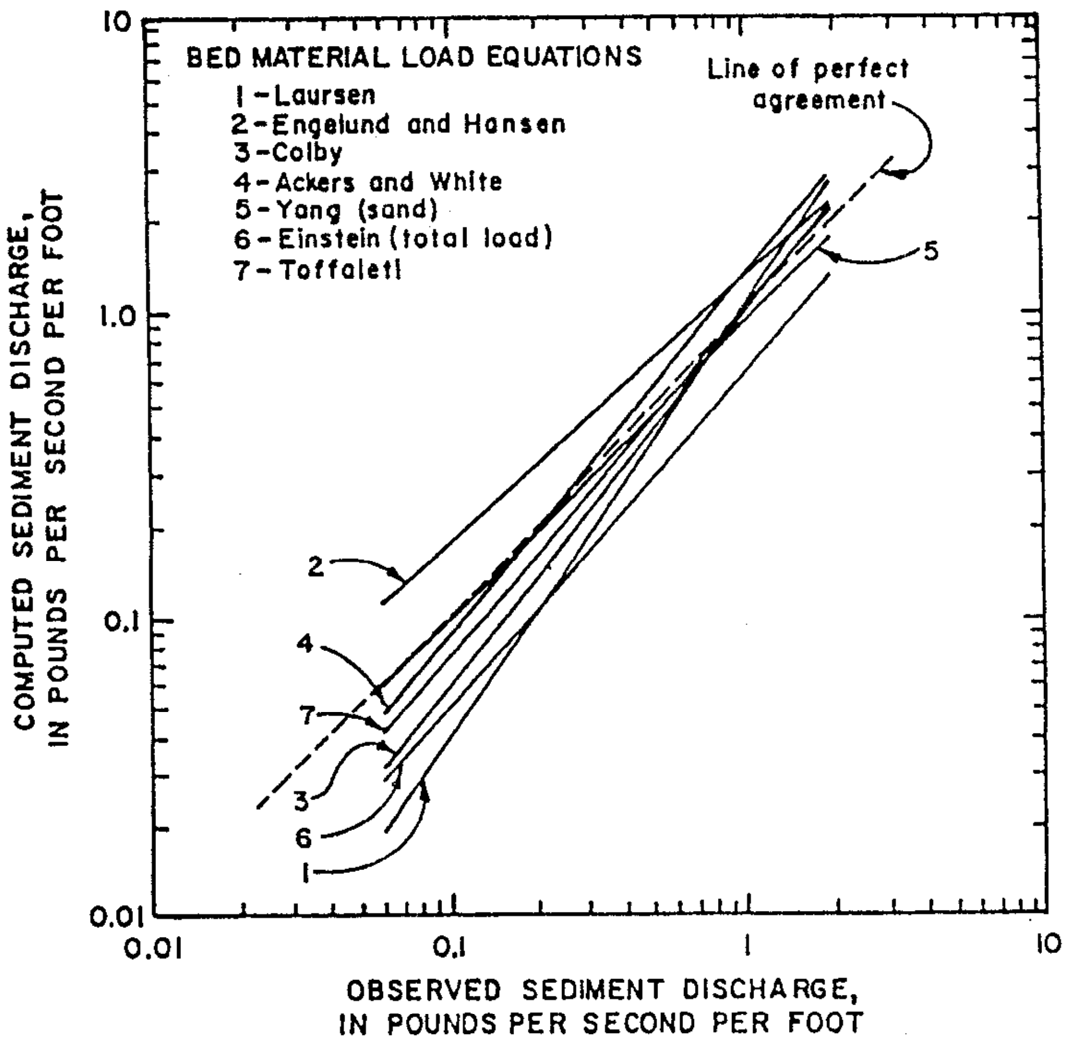

Fig. 1 Comparison between computed and measured bed material discharges from the Niobrara River near Cody, Nebraska (Stevens and Yang, 1989).

suspended load. The results of both calculations are often combined into a single relationship verified by field data. Thereafter one can fit an empirical relationship to the transport curve describing total bed-material transport to utilize in water and sediment routing. Such a procedure does not sacrifice accuracy and can significantly reduce computer time.

Alluvial Fans

Typical problems encountered on alluvial fans include the following.

- Rapid flattening of the channel gradient as one moves from the apex to the toe of the fan. This results in a fan-shaped accumulation of sediment which, in general, has developed over geologic time.

- A geomorphic feature that experiences high velocity flow at the apex of the fan with rapidly reducing velocities and loss of ability to transport sediment in the downstream direction due to the flattening of the gradient and the development of numerous dynamic subchannels. These channels rapidly change with time during a flood event and changes are more pronounced over large time periods involving numerous floods.

- The occurrence of channel avulsions due to local sediment deposition causing the formation of new channels and the abandonment of old channels.

- A significantly unstable system where, over time, the floods of water and sediment work randomly back and forth over the fan's surface in a highly unpredictable manner except for perhaps the upper one-fourth to one-third of the fan where the channel may be more or less entrenched in the fan.

- Changes in the watershed upstream of the fan such as may be imposed by climatic conditions, fire, earthquakes, overgrazing, land use changes, development of upstream water resources, agricultural uses, etc.

- Cases where fans are relatively dormant. Fans can be artifacts of ancient hydrology and hydraulic events that basically flushed most of the available sediment supply from the upstream watershed.

All of the above factors contribute to the complexity of natural fan geometry and fan dynamics. The hydrologic and hydraulic conditions which occur on a fan are often further complicated by real estate development and road construction which ultimately leads to the use of debris basins and channelization on the fans. There are examples where debris basins have been designed and constructed to control a nonexistent sediment supply, and conversely, debris basins have not been constructed where the ability to produce large volumes of sediments exist on the upstream watershed. Even with development and use of control measures, flow conditions on the fan can be unpredictable and adverse to the safety of occupants and the developed real estate thereon.

Analysis of Steep Mountain Streams and Rivers

The engineer is often required to develop water resources in mountainous areas for a variety of purposes, i.e., hydropower, irrigation, industrial and municipal supply to satisfy environmental concerns, etc. To properly evaluate the role of sediment in these steep mountain streams and to identify and evaluate potential impacts downstream in flatter reaches of the system, it is necessary to study and analyze the following.

- Climatic conditions.
- Hydrologic conditions.
- Physiographic conditions.
- The hydraulics of the system, which requires knowledge of runoff of water and sediment from the contributing watershed; the characteristics of the sediment supplied from the watershed; the geometry of the channel system, i.e., gradient and cross sections; a detailed record of discharges involving actual data and possibly synthesized data; methods of estimating resistance to flow; measured and computed velocities; the characteristics of the present bed and bank material considering size, size distribution, armoring potential, and impacts of past episodic events that have contributed to the characteristics of the bed material; and conditions associated with initiation of motion and, in this regard, consideration of the appropriate value of the dimensionless Shields shear stress, measured bedload, measured suspended load, washload, and estimates of the total bed-material load based upon available field data supplemented by calculations. In general, it is necessary to develop specific relationships applicable to the site in question. Existing relationships should not be used without modification and verification. Sadly, existing relationships that may not apply are often utilized.
- Environmental, economic and political constraints.

Sediment Supply Versus Computed Sediment Transport Capacity

Perhaps the more complex problem arises when working with steep river systems in which the bed material is relatively coarse. For such rivers, there are reasons why much greater differences between supply of sediment and transport capacity exists. Typical conditions that must be recognized and analyzed in these steep systems include:

- relatively stable watersheds that produce very little sediment,
- a hydrology moderated or aggravated by snowmelt and/or precipitation on a melting snowpack,
- river and tributary channel beds more related to past geological and climatological conditions that consist of very coarse material containing artifacts of past floods and mud and debris flows, and possibly even post-glacial activity,
- lack of any definable relationship between the material forming the bed of the stream and the sizes of the material delivered to a point of analysis from the upstream watershed and channels,
- the significant occurrence of an armored bed,
- the impact of rockfalls, boulder fields, rock outcroppings, waterfalls, beaver dams, alluvial fans, etc., and

- the potential in some environments for glacial lake outburst floods.

To illustrate the great differences that can exist between supply of sediment and transport capacity for the same sizes of sediment, refer to Fig. 2.

Summarizing the pertinent issues, the danger of not recognizing the preceding identified complexities may lead to adopting sediment transport rates that are too large. This leads to incorrect conclusions regarding rate of loss of live storage in downstream reservoirs, erroneous identification of aggradation that, if in fact it occurred, could reduce channel capacity and increase flood hazards and creation of an environment for rapid encroachment of vegetation resulting in increased resistance to flow, increased deposition and accelerated loss of channel capacity.

Impacts of Variations in Resistance to Flow on Hydraulic Conditions

In both sand-bed and gravel- and cobble-bed rivers, the assumption of constant resistance to flow can lead to significant errors in determination of velocity, velocity distribution, river stage, bank stability, design of stabilization works, and, of course, the rate of bed-material transport. To bring the bed-material transport into proper perspective, resistance to flow in sand-bed rivers can experience reductions in resistance to flow on the order of 200 to 300 percent as flow ranges from small, normal flows to flood stage.

Resistance to Flow in Man-Made and Natural Channels

Resistance to flow data from all types of alluvial streams, ranging from steep mountain streams with coarse bed material to very large flat gradient streams with fine sand beds, exhibit large variations in resistance to flow with discharge. Generally, although not always, as discharge increases resistance to flow decreases. However, this assumption does not necessarily hold for steep mountain streams during periods of major floods with overbank flow. There is a tendency to select resistance coefficients that over-estimate velocities for such cases. In order to accurately model open-channel hydraulic conditions over a range of discharges, the variability in resistance to flow and velocity must be evaluated.

Dams, Reservoirs and Associated Problems

Dams and reservoirs interrupt and alter the natural flow of water and sediment through the drainage system. The reservoir is a sink resulting in hydraulic conditions that reduce the velocity of flow often to near zero within the reservoir. The change in velocity is usually sufficiently rapid as the water enters the reservoir that the least mobile sediment particles settle out first and the finest sediment particles travel farthest into the reservoir before settling out. In fact, depending upon the characteristics of the discharge into the reservoir, the physical properties of the sediment, and the geometry of the reservoir, density currents may develop capable of carrying fine sediment particles all the way to the dam where some particles will deposit and the remainder will pass on through the outlet works of the dam. The sediment deposition within the reservoir depletes live storage and develops a deltaic-shaped deposit in the upper reaches of the reservoir. Such deposits may or may not be transported toward the dam at a faster rate when reservoir storage is small and flood flows enter the reservoir. However, in general, when reservoirs are subjected to wide fluctuations in water surface elevation, the resulting hydraulics can propel large volumes of sediment from the delta toward the dam, often

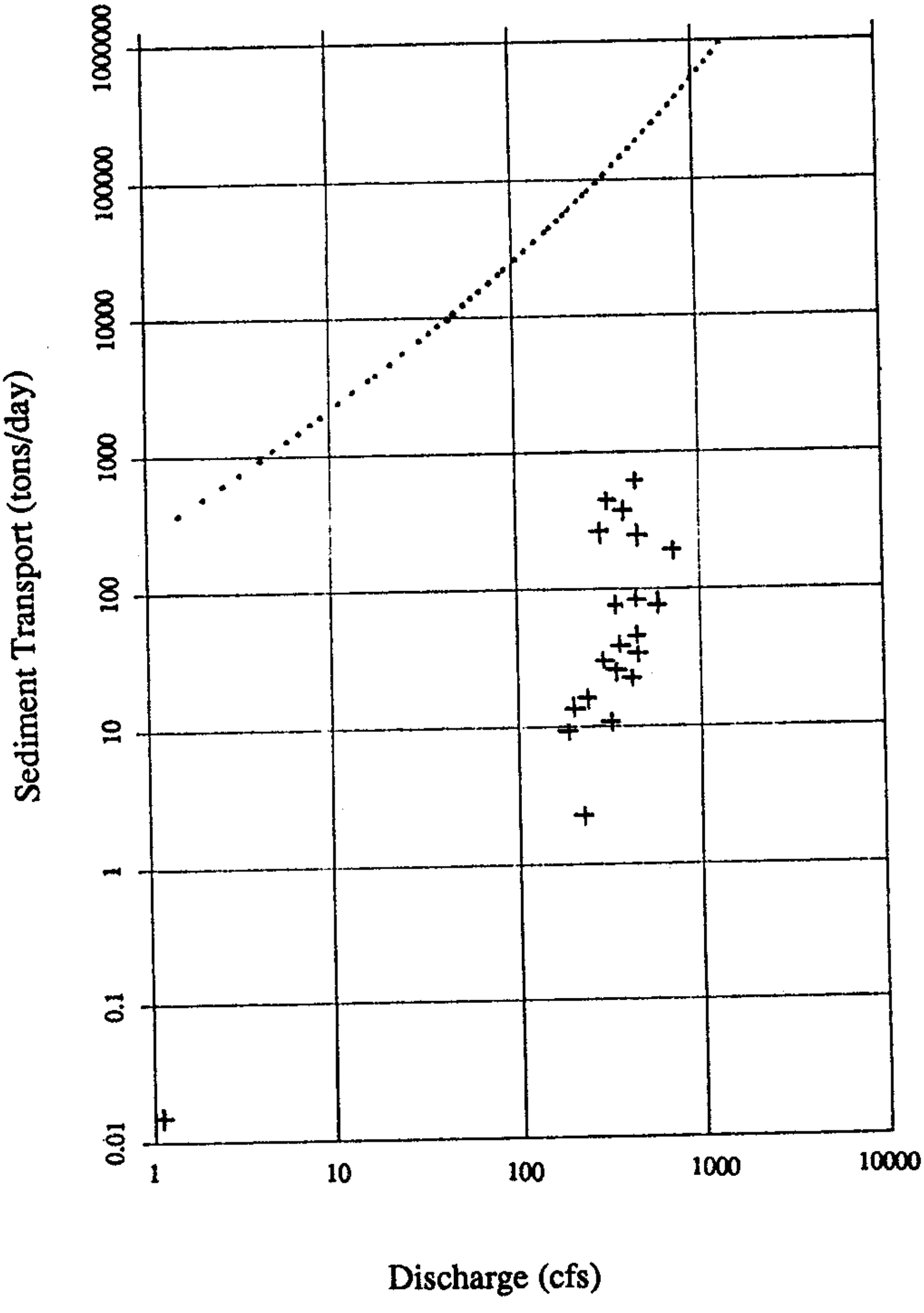

Fig. 2 Sediment transport verses discharge - SP3.

endangering its ability to function satisfactorily. For example, advancement of the sediment wave to the dam can result in blockage of intakes to the turbines, sluices and canals.

Degradation, the opposite of aggradation, usually develops downstream of the dam. Degradation may be induced by the introduction of clear water from the reservoir to the downstream channel. It follows that the natural gradient of the channel will be reduced from that value that the channel had developed historically to convey both water and sediment to imposed conditions. The resulting degradation can steepen the gradient of the tributary streams and can induce channel instability. The destabilized tributary streams produce an increased volume of sediment that is conveyed to the main stream. The introduction of this sediment tends to correct the degradation in the main channel. Hence, construction and operation of reservoirs requires that the engineer and the scientist develop functional transport relationships capable of coping with all facets of such problems. How is this done?

- Often, attempts are made to obtain satisfactory answers using the typical, steady, uniform transport equations based upon data collected in small flumes. There are severe limitations and considerable risk when adopting this procedure.

- Physical models may be designed and constructed to study critical problems of a three-dimensional nature produced by the method of reservoir operation. Usually such models are developed utilizing the Froude modeling law, but ignoring the complexities of sediment transport and deposition. The numerous limitations imposed by conventional physical modeling concepts has been documented by Einstein and Chien (1953). This is a very important document. Physical models usually require some degree of vertical distortion and/or the use of light-weight materials to properly simulate the size, gradation and transport of the natural sediment. The use of physical models does result in the development of a better physical understanding of the three-dimensional nature of complex problems, but unless properly designed and interpreted the results may be more qualitative than quantitative. Experience is a necessary ingredient to the proper design, operation and interpretation of data from physical model studies of fluvial systems.

- Mathematical models are often used to analyze complex reservoir problems. A review of such models reveals the adoption of assumptions that may be so far removed from the three-dimensional nonuniform unsteady flow situation that the modeling effort, in many cases, is more of a game for modelers to play with than a meaningful means of obtaining quantifiable results. The less the prototype experience the modeler has, the greater the risk of coming up with a nonapplicable solution. Unfortunately the utilization of results of such studies applied in ignorance by both the designers and the clients may result in disastrous failures.

Problems of Special Concern at Hydropower Sites

From the preceding examples, it is apparent that sediment-related problems encountered at hydropower sites are numerous, challenging and require practical and effective solutions. This is particularly true for sites involving steep, flashy rivers; unstable watersheds; large and variable sediment loads; and the potential for episodic events of major magnitudes resulting from such random variables as extreme climatic events, earthquakes, fire - often encompassing fragile components of the environment. To begin with, a detailed analysis of climatic and hydrologic conditions imposed upon the watershed and river is essential in estimating the yield of sediment; the characteristics of the sediment, i.e., size and gradation; the flow duration curve; the geometry of the reservoir and the details of the dam and spillway, as dictated by the operational rules imposed to achieve the objectives of the project. Assuming the preceding knowledge has been quantified, the handling of the water and sediment at the intakes to a power tunnel requires careful consideration. Usually, it is necessary to design the gates and sluices to minimize the introduction of adverse sizes and concentrations of sediment into the power intakes. The sluiceway must be designed to mitigate sediment problems adverse to power production and unfavorable to the longevity of the live storage in the reservoir. Furthermore, the system must be able to function intermittently as needed without danger of being plugged by sediment and debris. Also, the system must be designed to accommodate any future required maintenance at minimum expense with the least possible interruption of power production. The power intakes must be designed considering the magnitude of sediment load entering them and methods of reducing suspended sediment concentrations and sizes that could be harmful to the system. After the water and unavoidable sediment enters the power intakes, it is necessary to determine whether or not flushable traps designed to intercept coarse sediment are required. With this task accomplished, the remaining sediment may still be too coarse and concentrations may be too large requiring the design and installation of desanders to remove all of the remaining sediment particles larger than about 0.1 to 0.2 mm. The requirements on removal of sand is dependent upon the type of turbines and the head under which these turbines are designed to operate. The desanders are a continuing problem. They must be designed to accommodate efficient and periodic flushing of the accumulated sediments. Such designs can be rather sophisticated and usually require detailed physical, and possibly mathematical, modeling and testing. The design of each of these intricate features is dependent upon our ability to properly analyze and control the sediment. More specifically, excessive concentrations of sand particles in the flow arriving at the turbines can result in significant damage to the turbine runners and buckets and adversely effecting the economics of the project.

Conclusions

It is concluded that:

- There is a significant need to teach and utilize the knowledge of physical processes more effectively in order to cope with the myriad of sediment problems that are encountered in water resources development projects.

- The sediment transport problems encountered involve much more than applying selected transport relationships to estimate the rate of bed-material transport in a reach of river.

- Sediment transport relations are generally based upon theoretical concepts that assume steady, uniform flow conditions.

- Most transport relationships that are widely used have been developed for sand-bed rivers with few exceptions.

- The use of sediment transport relationships that involve velocity as a variable often have been used without consideration of the variation in channel geometry, distribution of flow, distribution of velocity and distribution of transport in the cross section.

- Presently it is assumed that most experienced engineers do consider the variations in cross section, velocity and transport within a study reach and/or system.

- When applying mathematical modeling concepts to alluvial rivers, the changes that occur in the characteristics of the bed material with time and with transport and the potential for the development of a significant armoring of the bed have often been ignored. Presently these deficiencies in analysis, for the most part, are being corrected.

- In applying sediment transport equations to fluvial systems, it is not uncommon to utilize more than one relationship to develop a sediment discharge relation which can be described by empirical curve fitting for use in mathematical models. Such a procedure simplifies modeling efforts.

- There is a continuing need to develop improved transport relationships more specifically oriented to field conditions. For example, improved methods must consider unsteady uniform flow, the changing characteristics of the bed material with time and discharge, the great variation in resistance to flow, the significant variations in velocity and the accompanying significant changes in sediment transport.

- Individuals that are not acquainted with the physical processes related to transport sediment are unlikely to produce the quality of results required for successful analysis and design of water resources projects.

Bibliography

Einstein, H.A., 1944. "The Bed-Load Function for Sand Transport in Open Channel Flows," U.S. Department of Agriculture Technical Bulletin 1026.

Einstein, H.A. and N. Chien, 1953. "Second Approximation to the Solution of the Suspended-Load Theory," University of Clifornia Institute of Research, No. 3.

Meyer-Peter, E. and R. Müller, 1948. "Formulas for Bedload Transport," Proceedings of the Third Meeting of International Association for Hydraulic Research, Stockholm.

Simons, D.B. and F. Sentürk, 1976. Sediment Transport Technology, Water Resources Publications, Littleton, Colorado.

Stevens, H.H., Jr., and C.T. Yang, 1989. "Summary and Use of Selected Fluvial Sediment-Discharge Formulas," U.S. Geological Survey Water Resources Investigation Report 89-4026, Denver, Colorado.

Yang, C.T., 1973. "Incipient Motion and Sediment Transport," ASCE Journal of the Hydraulics Division, Vol. 99, No. HY10.

Yang, C.T., 1984. "Unit Stream Power Equation for Gravel," ASCE Journal of the Hydraulics Division, Vol. 110, No. HY12.

PRACTICAL SEDIMENT MANAGEMENT IN CHINA

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ABSTRACT

Sediment management is guided by both technology and local socioeconomic conditions. Upstream management in China emphasizes gully control. Warping of land is practiced wherever conditions permit. Both make use of sediment as an asset. Sediment is also used to enlarge Yellow River levees to 50 to 70 m wide.
Useful storage capacity of a large reservoir may be preserved permanently by a scheme of operation summed up as "discharging the turbid and impounding the claer".

INTRODUCTION

Sediment management is of vital importance to China, as many of her rivers carry heavy sediment loads and good management can often reduce the detrimental effects of sediment and in some instances even turn sediment into an asset. Although the basic principles of management may be the same everywhere, the specific methods adopted in the management varies with the local socioeconomic conditions.

In upstream areas, the goal of sediment management is to reduce erosion and sediment output from the watershed in order to improve its ecological system as well as to provide a better environment downstream. To achieve this, one must enlist the support of the local people by adopting a strategy of conservation that will help raise their standard of living.

When a large project is constructed on the main stem of a sediment-laden river, sediment management often aims at preserving a large capacity of storage for permanent use with least adverse impacts on the up- and downstream reaches. This becomes imperative, when there are important riparian cities, industries or agricultural centers to be protected or when the river is a main artery of shipping.

In North China and, especially in the basin of the Yellow River, warping or colmatage is widely practiced as a means to reduce the amount of sediment delivered downstream or to increase the productivity of a farm. It is now also a practice to enhance the safety of a levee by dredging sediment from the river to build a large berm in the back of the levee. These usages have relieved rivers of billion tons of sediment.

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UPSTREAM MANAGEMENT

In planning the upstream management or control of sediment, one should keep on mind the time element and the local socio economic conditions. Although biological measures are very desirable for the improvement of the ecosystem, it takes time for the vegetation to grow and therefore cannot solve the urgent problems at hand. These measures despite being advocated by many people would also have little chance to succeed in China today because they do not fit the socioeconomic conditions of the local communities where raising of grain and fuel production is of chief concern. Without the incentive of the local peoples, it is simply impossible to carry out a large-scale conservation program over a vast area. In the light of these remarks, it should be understandable why engineering measures are playing the top role in the present upstream management of sediment in China, although the importance of biological measures are never overlooked and have been applied wherever feasible.

The areas of highest modulus of erosion in China lie in the arid and semiarid gallied-hilly regions of the loess plateau in the northwestern part of China. The average modulus of annual erosion is 10,000 to 30,000 tons per sq km. The key problem in this region used to be lack of adequate food production. In striving to produce enough food to sustain life, local farmers used to cultivate extensively on the slope at low unitary yield. In so doing, man power was practically all tied up in the inefficient farming and, moreover, erosion of the watershed was increased because the ground vegetation was damaged. Degraded ecosystem resulted in decreasing unitary produce which in turn prompted the farmers to enlarge their cultivation on the slope, disregarding conservation requirements. To break this vicious circle, one must first solve the problem of food production for the farmers. For watersheds smaller than about 30 sq km, the answer is to construct sediment barriers on gully floors. Because of the high erosion rates of the watershed, the space behind a small sediment barrier built in spring may be silted up in one flood season, creating a piece of good land (herinafter referred to as silted land) ready for cultivation in the following spring. Another piece of silted land may then be created in the same manner by building another sediment barrier upstream, until a series of silted land is formed covering the floor of the entire gully. A long series of silted land may be separated by a number of small storage dams to protect and to supply water for the land downstream. As the silted land is composed of the topsoil eroded from the upper parts of the watershed, it is more fertile than a piece of land on the slope. Properly farmed, a piece of silted land can produce several times more grains than an equal piece of land on the slope. For instance, at Wangmaugou Gully of the Wudinghe River system, the watershed area is 5.97 sq km and the produce per ha of its silted land is about 4 metric tons or about 5 times the average produce from the slope including the terraced field [Zhang, Y. X.,1982]. With more than enough food produced by farming the productive silted land, the farmers no longer insisted on cultivation on the slopes. In fact, for an increase of 1 ha of silted land in the gully, 1.95 ha of cultivated land on the slope has been actually given up by the farmers to be placed under the control of soil-conservation measures. More efficient farming also allows more manpower to be diverted to the conservation of the hill slopes. Thus the creation of fertile land by building sediment barriers solves the problem of increasing grain production vital to the local farmers and is in line with their incentive to raise their living standard. It is therefore not surprising that the construction of sediment barriers has flourished. According to Hua, S. Z.[1990], in the riparian region along the middle course of the Yellow River alone, 40,000 such barriers have been built.

The so-called sediment barriers are actually low earth dams built by a highly efficient hydraulic sluice method developed in north China in the sixties. The height of the dams depends mainly on the topography. An investigation of 50 such dams in the western part of the province of Shanxi shows that, varying with the cross section of a gully, a dam may be 5 to 20 m high [Yang, S. W. et al, 1985]. At Wangmaugou, a dam is generally 15 m or higher. Flood control and sediment trapping dams are designed for 2% and 5% floods respectively. In the 28 years from 1953 to 1981, thanks to the conservation measures applied to the gully and the slope, practically all floods and eroded sediment have been kept within the watershed of this gully.

The hydraulic sluice method of dam construction is so efficient and fits the local conditions so well that of more than 10,000 dams built on the Wudinghe River system up to 1985 about half were built by this method. The investment per cu m of storage capcity created by these dams ranges from 3 to 5 cents (RMB) only [Yan, W. Z.,1985]. Hydraulic sluice dams are also being advocated for use to trap the huge amount of coal mine tailings and the material dumped from road construction within gullies. Dams of this type have been built in many parts of China [

In western Shanxi [Yang, S. W. et al, 1985], it has been observed that, although gullies occupy only 44% of a drainage area, about 83.5% of the erosion takes place in the gullies and that terracing, afforestation and grass planting altogether can control not more than half of the erosion. The balance of sediment eroded has to be trapped by dams built on the floor of the gully. Construction of sediment barriers in this region dates more than 500 years back. In addition to yielding good farm land, sediment barriers also stop erosion of the gully floor and make it easier to control the advance of the gully head and erosion from the gully walls. About 5,000 cu m upwards of sediment are trapped under one mu (equal to 1/15 ha) of silted land. If 50 mu of silted land are to be created per sq km in western Shanxi, then in this part alone about 6 billion cu m of sediment can be prevented from getting into the Yellow River.

Between 1980 and 1986, 32 gullies draining into tributaries emptying into the middle course of the Yellow River were selected as the first group of experimental watersheds to be placed under a program of strict soil conservation control [Middle Course Training Bureau, YRCC]. The watersheds of the gullies add up to be 648 sq km. The tributaries concerned are the Huanfuchuan in Inner Mongolia Autonomous Region, the Wudinghe in Shaanxi and the Shanchuanhe in Shanxi. Annual precipitations range from 300 to 500 mm. Population is 45,785. The same general strategy of giving grain production the top priority as explained above was also adopted. In six years, by replacing many of the inferior farms on slopes with the fertile silted farms on the gully floors, the farm area has been reduced from 189.86 sq km to 160.42 sq km, but the grain produce was up from 11.5 million kg in 1979 to 18.5 million kg in 1986. Significant changes in land use of these experimental watersheds brought about by the implementation of this program are indicated below.

	Total land sq km	Farm sq km	Forest sq km	Meadow sq km	Noncultivated sq km	Waste sq km
1979	647.59	189.86	74.86	14.67	273.38	94.82
1986	647.59	160.42	194.28	24.89	176.36	91.64

In south China, there is a large region of weathered granitic hills with steep slopes subjected to very heavy sheet and gully erosion. An important form of gully erosion is the so-called slope disintegration caused by the combined action of gravity and water finding its way into the cracks of a steep slope. In Deqing County of Guangdong Province, 10,000 cases of slope disintegration have occurred, averaging 10 occurrences per sq km. The average modulus of annual erosion is greater than 10,000 tons per sq km. In Xingguo County of Jianxi Province, the situation is even worse and the corresponding modulus is 13,500 tons per sq km [Guo, T.F., 1990]. Slope integration may be controlled by excavating intercepting ditches round the rim of the slope to be protect- ed, stabilizing the floor of the gully with sediment barrier and planting trees on berms cut on the surface of the slope. Erosion in Deqing County used to affect agricultural production so much that in the Qing dynasty there was a mass exodus of people from the county. Even today the population of Deqing County is still below its old peak.

Under favorable topographical conditions, warping or colmatage may also be used as a means of sediment control in the upstream areas. The Yongding River in north China is also known for its heavy sediment load. The gullied part of its basin has an erosion modulus of 10,000 t/sq km/year and the remaining part has a modulus of 2,500 t/sq km/year. A part of the river flows through rather wide valley. Warping is practiced here to enhance the productivity of the land and to reduce the sediment load of the river. Statistics covering the period of 1951-80 indicates that soil conservation had reduced the sediment input to the river by 44.5% of which 20% were due to warping, 17.5% due to depostion in reservoirs and 7% due to conservation measures carried out on hillside [Mu, J. Z. and Y. T. Gao, 1985]. Deposition in the Guanting Reservoir in the downstream part of the Yongding River has already led to many environmental problems [Zhang, Q. S. et al, 1986]. Warping is being considered as a means to mitigate the adverse effects due to the rise of ground water on farms on the flood plains of the reach at the north entrance of the reservoir. The application of warping will be revisited afterwards.

RESERVOIR ON A MAIN STEM

A reservoir on the main stem of a river is usually required to maintain a permenent storage capacity in order to serve a certain purpose, such as flood control, power generation and navigation. For a reservoir on a river carrying large sediment load, heavy deposition in the reservoir may also raise the back-water and lead to a series of problems on the upstream area. Therefore, management of sediment in this case is to limit the depostion in a reservoir. The method employed in China to achieve this is summed up as "discharging the turbid and impounding the clear". This method has been expounded by many authors[e.g., SIHR and Tsinghua University, 1978; Zhou, W. T., 1984; Ding, L. Y., 1985; Lin B. N. et al, 1989]. The main idea is to draw down the reservoir to an appropriate level during the flood season and let whatever flood flows permissible by the levee system downstream pass through the reservoir. The stage of the reservoir will be raised only long enough to store the peaks of floods exceeding these permissible discharges. As the major part of the sediment load of a river is found in the flood season, operating the reservoir in this manner will allow much of this sediment load to be discharged from the reservoir. Storing the peaks of the floods will indeed augment deposition in the reservoir. But the probability for large floods to occur is usually small, say, once in 40 years or longer and the duration of the peaks is usually short, say, 15 to 20 days, so that in long term operation the average duration of peaks per year is small and over the years the consequences of additional deposition caused by temporary impoundment of the reservoir will not be appreciable. This method of reservoir operation is particularly desirable when the reservoir is narrow and when there is a large difference between the natural surface gradient of the river and the equilibrium slope of an alluvial channel corresponding to the same water and sediment discharges. In the case of the planned Three Gorges Project, calculation shows that in 80 to 100 years the deposition in the reservoir will reach equilibrium and sediment input to the river downstream of the project will return to its original value prior to its construction. Thus this way of reservoir operation will eventually remove its impacts on the river downstream. Calculation also indicates that all sediments finer than 0.01 mm in diameter will be discharged from the said reservoir at the very beginning, so that construction of the said project should have little effect on either the geomorphologic process of the estuary and its neighboring coastal regions or the nutrients carried by the flow of the river. Operating a reservoir in this manner can of course be justified only when reservoir deposition must be limited.

WARPING AND DREDGING

Warping has been practiced extensively in north China where the rivers generally carry very heavy loads of sediment. In addition to its application in upstream areas as a means to reduce the sediment input into a river, as stated previously, it has been applied to consolidate the levees along the downstream course of the Yellow River. Over 240 simplified dredgers have been built by the Yellow River Conservancy Commission (YRCC). Instead of the conventional cutters, these dredgers are equipped with jets at the slurry intakes that may be used to stir up the fine sediment on the river bed to attain a local concentration of several hundred kg per cu m. The slurry so formed is pumped to the regions in the back of the levees to build up a berm 50 to 100 m wide, reaching a height of 7 to 9 m above the original ground level and 2 to 4 m below the top of the levee. Up to 1987, the use of dredgers, siphons, pumps and culverts together have enabled one to obtain enough sediment to strenthen about 630 km of the levees along the Yellow River in Shandong and Henan Provinces. Safety of the levees is thus greatly enhansed. Considerable economic return has been realized by utilizing a part of the berm to plant trees as well as to grow orchards and grains [Liu, D. L. & X. N. Li, 1988; Zhao, T., 1989; Jiang, S. T., 1987].

Warping as means to improve the quality of land has a long history in China. The Record of Canals and Rivers of the Han dynasty (206 BC to 220 AD) stated:

"In ten parts of water from the Jing River*, there are several parts of sediment by volume. It irrigates and fertilizes the land, so that crops can be grown to feed and clothe the millions in the capital area".

Another example of ancient warping recorded is what took place in 1069 to 1085 AD with the approval of premier Wang Anshi during North Song dynasty. Altogether 60,000 ha of marsh near to the then capital Kaifen were converted to good farm by warping with flow diverted from the Yellow River.

In modern time, warping has been applied to improve the bad lands along the downstream course of the Yellow River. These lands include (1) salt marsh resulted from seepage from the river which is higher than the riparian ground, (2) large holes over 10 m deep left by over pouring currents at spots of levee breaching in the old days and (3) ancient river bed with high ground water table and covered with coarse material. Warping has been effected mainly by diverting the muddy water from the Yellow River in flood season. Since the sixties, over 81,300 ha in Henan Province have thus been converted into highly productive farms [Zhao, T. Y., 1989]. This part of the province used to grow little rice

* A tributary of the Yellow River in Shaanxi Province.

although it is highly valued by the local people as a staple. Now with the new land much rice is grown. Additional rice paddies are still being created by warping in three riparian counties in Henan. Warping can make good use of a large quantity of sediment. For instance, in the last thirty some years, Shandong Province alone has used up to 1 billion tons of sediment in warping of land, irrigation with turbid water and consolidation of the Yellow River levees [Li, Z. M. et al, 1989]. Another example to be cited concerns the relatively small Luohui irrigation district in Shaanxi Province on the right bank of the Middle Course of the Yellow River where warping was applied to ameliorate 3,720 ha out of a total of 6,735 ha of the district. Between 1969 and 1985, 106 million tons of sediment were diverted from the North Luohe River and spread on the land [Xu, Y. A. et al].

Perhaps one of the ideal sites for the application of warping is the watershed of the Hunhe River which is a tributary of the Sanggan River emptying into the Yongding River [Ling, L. W. & Z. G. Guo,1985]. Beijing is located on the alluvial fan formed joitly by the Yongding and Caobai Rivers after the former e-merges from the mountains. The watershed of the Hunhe River is 2,077 sq km of which 461 sq km is the gullied-hilly area on loess plateau. The annual precipitation is 466.9 mm of which 60 to 80% take place in the flood season from June to September. Annual sediment yield is 7.35 million tons of which 81% come in the months of July and August. Concentration of sediment in the river during the flood season can reach 837 kg/ cu m. It is to be noted that July and August happen to coincide with the busy season of irrigation. The area to be irrigated is 28,200 ha. The design discharge of the canal discharge is 427.3 cu m/s. Sediment eroded from the watershed carries much nutrient and is of a size that will help reduce upward filtration of ground water. Under all these favorable conditions, the improvements brought about by every warping will last for three years. Sediment diverted for warping is as much as 2.28 million tons/year which is 31% of the incoming sediment load.

In the past, an irrigation system will be closed down when the concentration at the intake exceeds 15% by weight or 166 kg/cu m. Warping and better understanding of the properties of hypercon-centrated flow enable one now to divert flows at concentrations up to 60% by weight or 957 kg/cu m [SIHR and Tsinghua University, 1979]. Thus in a sense warping amounts to an augmentation of water available for irrigation.

CONCLUSIONS

As sediment management will affect a large area and a large population, in mapping the strategy of its implementaion one must take into account the social-economic conditions prevailing in the region concerned in order to enlist the support of the local people. Thus for upstream sediment management in regions of intensive erosion, the key to success is to raise food production by building up good farm lands through rapid siltation behind sediment barriers on a gully floor. High yield of grain from the silted land makes it easy to persuade the farmers to stop tilling the slope. Efficient farming also releases the manpower needed for slope conservation, including terracing and planting of trees and grasses. A strategy in line with the local farmers' incentive to raise their living standard is also the basis for the success of farm warping.

Sediment management in large projects including the construction of large reservoirs and the upgrading of the long levees along the Yellow River is mainly a technical matter.

REFERENCE

Abbreviation: YR = Yellow River, a periodical in Chinese published by the Yellow River Conservancy Commission, Zhengzhou, China and distributed by China International Book Trading Company, P. O. Box 3820, Beijing , China.

Ding, L. Y., Sanmenxia Reservoir and its operation. YR, 5, pp 66-70, 1985.

Guo, T. F., Soil and water conservation in China. Pt.IX, Lecture Notes, Regional Training Course on soil erosion and its control, Vol. 3, IRTCES, Beijing, 1990 (in English).

Hua, S. Z., Guiding thouhgts and fundamental measures for the regulation and development of the source area of coarse sediment in the Yellow River Basin. YR, 1, pp60-63, 54, 1990.

Jiang, S. T., Stability analysis of the Yellow River levee. YR, 3, pp 26-30, 1987.

Li, Z. M., L. H. Zhan and Ma R. F., Utilization of the Yellow River sediment for soil improvement and levee strenthening. Proc. 4th ISRS, Beijing, pp 1571-78, 1989 (in English).

Lin B. N. et al, On some key sedimentation problems of Three Gorges Project (TGP). International Jouranal of Sediment Research (in English), Edited by IRTCES, 1, pp 57-74, 1989.

Liu, D. L. and X. N. Li, Administration and development of the berms in the bak regions of Yellow River levees. YR, 6, pp 23-26, 1988.

Middle Course Training Bureau, YRCC, Preliminary analysis of the comprehensive regulation of the first group of small watersheds under soil conservation control. YR, 3, pp 44-50, 1987.

Mu, J. Z. and Y. T. Gao, Measures of sdiment retention in the drainage basins and the reduction of the sediment loads in the Wudinghe and Yongding Rivers. YR, 3, pp 17-21, 1985.

SIHR (Shanxi Institue of Hydrotechnical Research) and Tsinghua University, Reservoir Sedimentation, 372 pp, 1979, Water Resources and Electric Power Press, Beijing (in Chinese).

Yan, W. Z. To speed up the regulation of gullies in regions of high modulus of coarse material erosion with hydraulic sluice dams. YR, 3, pp 32-35, 1985.

Yang, S. W. et al, Possibility of building sediment-trapping dams of large and medium sizes. YR, 3, pp 36-39, 1985.

Zhang, Q. S. et al, Environmental Problems associated with sediment deposition in Guanting Reservoir. International J. of Sediment Research (in English), edited by IRTCES, 1, pp 67-68, 1986.

Zhang, Y. X., Hints from the practice of development of sediment basins at Wanmaugou watershed. YR, 5, pp 25-28, 1982.

Zhao, T. Y., The comprehensive utiliztion of water and sediment resources on the reach of the Yellow River in Henan Province. Proc. 4th ISRS, Beijing, pp 1634-41, 1989 (in English).

Zhou, W. T., Experience in reducing the deposition in Ximalin Reservoir by rational operation. YR 2, pp 34-37, 1984.

APPLICATION OF RESEARCH TO SEDIMENT MANAGEMENT[1]

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INTRODUCTION

Albert Einstein once told von Karman that turbulent flow was too complicated for him to investigate. Since sediment movements are caused directly from the interaction between turbulent flow and complex sediment characteristics, sediment motions can be even more difficult to understand than turbulent flows. Fortunately, Hans Albert Einstein, a son of Albert Einstein, had provided us with several significant approaches to sediment problems in his classic publication (see Einstein, 1950). This bulletin has served as the first and most important link between research and practical application.

More than two decades ago, there was a great need to transfer knowledge between the research community and practicing engineers, due to complexity of applying sound judgement in order to solve sediment problems. This information transfer was accomplished through a combination of the following approaches: (1) in-house research by various Federal and State Agencies, (2) participation in technical conferences such as this, (3) employing consultants and graduate students by governmental agencies and consulting firms, (4) offering short term training institutes such as those offered by Dr. Simons and myself at Colorado State University, and (5) by other means. The transfer of knowledge in sedimentation from research to sediment management has been rather successful. University professors, governmental personnel and consulting engineers now work together as true partners. With these above statements as introduction, sediment issues are discussed.

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[1]A keynote speech delivered to the Fifth Federal-Interagency Sedimentation Conference at Las Vegas, Nevada, March 18, 1991.

CURRENT ISSUES

In a recent report edited by Fan (1990), the following four major issues were stressed by various Federal Agencies: Watershed sediment yields and management; sediment and river behavior near the dams; channel stability and bank protection; water quality, contaminants movements, and ecological impacts. Certain other important issues were dredging, recreation, instrumentation, scour near structures and legal issues. Some of these issues can be illustrated by the following examples.

A. Watershed Sediment Management

Watershed sediment yield is, perhaps, the most difficult problem facing us in the field of sedimentation because it involves climatic changes, variability of rainfall, growth and decay of ground covers, heterogeneous soil conditions (including cohesive soil components), formation of rills and gulleys, and other complex issues. In the past decades, significant progress has been made in understanding the various processes involved and numerous models have been developed (see Walling et al. 1985), but the most reliable current approach to estimate watershed sediment yield is still through field data collection to establish the sediment rating curve and comparing with sediment yield from similar basins. I have discussed with UNESCO about the possibility of compiling the available watershed data in a special manner to facilitate the comparisons. Watershed sediment yields are derived from sheet erosion, channel bank erosion, landslides and debris flow. For instance, the stream bank erosion contributed more than half of the total erosion from Eel River, California. Earth movements may affect sediment yields in certain locations. Current research knowledge on various phases of erosion and transport processes do provide extremely useful information on the method to group these available sediment yield data and also developing guides to use these available information.

Soil conservation and debris dams are the two major approaches to control watershed erosion. Massive efforts have taken place in China to employ these efforts. Important information could be derived if the Universal Soil Loss Equation (or certain variations of it) is used to check the reduction of sediment yields results. The required height, strength, and spacing of debris dams are subjects of research, particularly for the cases of debris flows. The question of designing these structures for certain return periods or through risk damage analysis is still debatable.

B. Sediment Problems Near Dams

Sediment deposition in the reservoir reduces the water storage volume and may decrease the useful function of the dam. When dam sites are abundant, another dam can be constructed. However, after the recognition of the environmental impacts of dams, desirable dam sites are either extremely limited or non-existent. Thus several major dam designs include the possibility to preserve reservoir capacity. IRTCES (1985) and Fan (in Bruk, 1985) presented valuable Chinese experiences and data in this regard. These are briefly summarized below:

1). Reduce sediment inflows by soil conservation as well as warping, vegetation screen, and bypassing heavy sediment laden flows. In some case more than half of the normal sediment inflows were reduced by watershed treatments. Vegetation screen to trap sediment particles can cause severe environmental problems and thus should be used with great caution. Bypassing heavy sediment inflows is a desirable approach if a bypass channel can be constructed.

2). Increase sediment outflows from reservoir by density currents, releasing heavy sediment concentrations during floods, and drawdown flushing. The necessary conditions for the occurrence of density currents have been established but these are not sufficient conditions. It is generally believed that at best 10% of the sediment inflows can be carried out of the reservoir by density currents. The pool level can be lowered during the flood season to sluice out flow containing heavy outflow from reservoir and this practice has been applied successfully in several Chinese reservoirs.

3). Recover reservoir water storage volume by flushing, dredging, and siphoning. Flushing sediment deposition from the reservoir can be properly designed and operated in a dam constructed in a relatively narrow canyon. Both numerical and physical model studies for the famous Chinese Three Gorge Dam have verified this possibility. Some critical hydraulic issues to be resolved are: (a) no objectionable amounts of sediment will enter or even block flow passages of the turbines and navigation locks and (b) the equilibrium profile of the sediment deposits in the reservoir can be maintained. In other words, sediment deposit in the reservoir will not exceed the designed volume. After the establishment of the equilibrium sediment deposition profile, coarse sediment may still be able to deposit in the reservoir but an equal amount of sediment must be removed by the flow to maintain this equilibrium profile. This is particularly difficult to estimate for branched flows. Dredging is rather costly and usually is applied only when no other means are available. Fan (in Bruk, 1985) discussed some successful operations of using siphon dredging to remove sediment deposits in France and China.

C. Channel Stability

Each researcher has his or her favorite basic transport equations and following is my list:

1) Bed Load

Bed load relationships are difficult to establish because of the lack of reliable data from streams. Thus many bed load relationships were developed based on flume data. As shown by Chien and Wan (1983), many bed load relationships provide similar results for certain flow conditions. The procedure developed by Einstein (1950) is still the most comprehensive one available today. In general, Einstein's relationship provides as good solution as any other relationship. For transport of coarse sand, pebbles and small gravel, many specialists elect to use Meyer-Peter's equation (1948) because this relationship was developed based on this type of data. For high sediment rate where intergranular forces are important, Bagnold's (1973) relationship is used. Ackers and White's (1973) equation has received increasing attention and should always be checked as a reference. It is difficult to use relationships presented by Wiberg and Smith (1989) due to the lack of knowledge of the variation of the representative bed form dimensions. Parker (1990) and his co-workers have presented extremely valuable knowledge on the movements of gravel particles but the constants in their relationships should be calibrated with more data. Similarly, the relationships presented by Misri, Garde and Ranga Raju (1980) should also be tested further by data.

For low transport rates, bed load rate varies with the 15th power of shear stress, and for high transport rates, bed load rate varies with the shear stress to the 1.5 power. Most of the investigators correctly related bed load rate to the grain shear stress, rather than the total shear stress because shear stress related to form roughness does not transport sediment bed load particles downstream.

For the transport of non-uniform sediment size, readers are referred to Einstein (1950), Ackers and White (1973), Samaga (1984), and Parker (1990). More research is needed to obtain data for the transport of non-uniform sediment size in order to develop a generally acceptable equation. Perhaps the use of Einstein's equation with a modified hiding factor as introduced by Shen and Lu (1983) would provide an answer as well as any other method.

2) Total Loads

Einstein (1950) presented the most comprehensive analysis on total sediment load. Unfortunately, the results from this final relationships were never verified by measurements and therefore will not be described here. Readers, especially researchers, should refer to Einstein's article for detailed understanding on sediment transport.

(a) Large Rivers (flow depth greater than 10 feet or 3 meters)

Many American engineers prefer to use the total sediment load relationship as described by Toffaleti (1969) for large rivers because this relationship was developed by data collected from large rivers in the United States. This data was taken over a 20-year period covering a range of discharges of 20,000 cfs to 500,000 cfs. (The above information was obtained by private communication with Toffaleti).

(b) Small Rivers (flow depth less than 10 ft or 3 meters)

Colby (1964) investigated the variations of sediment transport load as a function of the mean flow velocity, depth, viscosity, water temperature, and concentration of the fine sediment discharge of sand per foot of channel width. In spite of many inaccuracies in the available data and uncertainties in the graphs, Colby found that "..about 75 percent of the sand discharges that were used to define the relationships were less than twice or more than half of the discharges that were computed from the graphs of average relationships. The agreement of computed and observed discharge of sands for sediment stations whose records were not used to define the graphs seemed to be about as good as that for stations whose records were used." Note that all curves of 100 ft depth, most curves of 10 ft depth and part of the curves of 1.0 and .1 ft were not based on available data and were extrapolated.

(c) For sediment load studies in laboratory flumes, either Shen and Hung (1972) or Young (1973) curves can be used. These curves produce similar results.

3). Channel alignments: Meandering streams are usually much more stable than braided streams. Great effort have been made to stabilize large meandering rivers such as that for the Mississippi River. Renewed efforts should be made to understand the following items for stream at the upstream watershed: (a). conditions for the formation of braided streams to avoid the occurrence of such unstable stream patterns. (Contrary to early research findings, braided pattern can occur at a lower channel slope than that for meandering pattern for the same total flow discharge on a given stream.), (b). behavior and migration of meandering bends should be analyzed from modeling the flow velocity and shear stress distributions in the bends (see Elliot, 1984 and Ikeda and Parker, 1989), and (c). the ranges of meandering length, width, and curvature that can be tolerated for a given sequence of flow and sediment conditions on a particular stream. The applicability and limitation of using the 85 percentile flow discharge as the channel forming flow should be thoroughly investigated. Engineers and geomorphologists should combine their efforts to analyze stable streams when necessary.

4). Types of channel modification listed in ascending order of impact on fish and wildlife resources according to U.S. Soil Conservation Service, Tech. Release No. 25, Department of Agriculture, Washington D.C., 1977, are given in the following Table 1.

Table 1
TYPES OF CHANNEL MODIFICATIONS LISTED IN ASCENDING ORDER OF IMPACT ON FISH AND WILDLIFE RESOURCES

1. Riprapping (placement of rock as bank protection)
2. Selective snagging (selective removal of objects such as fallen trees
3. Clearing and snagging (removal of debris such as shoals and vegetation)
4. Widening (enlargement of channel by widening)
5. Deepening (enlargement of channel by deepening)
6. Realignment (construction of a new channel)
7. Lining (placement of nonvegetative, smooth lining)

5). Aesthetically pleasing bank protection by vegetation: Using vegetation for bank protection has been in practice for centuries, but only recently has a more scientific approach been instigated. Vegetation can divert high velocity flow away from the bank and can also increase the bank resistance. Different types of vegetation with varying degrees of submergence can be planted in certain climatic locations for effective bank protection under some specific flow conditions.

6). Rock structures: Natural rocks for bank protection and drop structure are much more aesthetically pleasing than concrete structures, although the limiting flow conditions for the stability of these rock structures must not be exceeded.

D. Ecological Requirements

Stream ecologists are extremely active in investigating the various biological and water quality criteria in dealing with ecological concern in sediment management. Only flushing flow requirements and floodplain management are selected for discussion here.

1). Flushing Flows: Flushing flows have been used for at least two purposes: (a) for channel maintenance and (b) for the removal of objectionable fine sediment particles from the stream bed for fishery survival. Since the flow requirements for these two different purposes are usually not the same, there is little chance that a single criterion can be found for both purposes. In order to identify a flushing flow requirement, one should specify its magnitude, duration and timing. The origin of flushing flow is not clear, but we did specify the needs of flushing flow to maintain channel integrity in our analysis of Niobrara River, Nebraska for impacts on whooping cranes during the late 1970's for the U.S. Bureau of Reclamation. At that time we were not aware of any earlier usage of this term, "flushing flows." If flushing flow should be defined as the flow to maintain channel integrity as was used by us, this flow is rather similar to the dominant channel forming flow. As stated in the channel stability section, this magnitude should be investigated thoroughly. The duration of applying this flushing flow should be at least long enough to recreate the desirable dominant bed features and channel patterns. Thus the time requirement to apply flushing flow can be shorter for a braided channel than for a meandering channel. Since the channel flushing flow is usually a high flow, it would be more efficient to apply this flow immediately after high flows.

If the flushing flow is defined as the flow to remove fine sediment from the stream bed, then this flow should be determined by sediment transport analysis. If these fines had not been deposited for a long period of time, flow above incipient motion may be needed. If these fines had been deposited for a long duration, a flow much greater than that indicated by Shields' criteria would be needed.

2). Floodplain management: Due to the requirement of not depleting wetland in the floodplain, certain amounts of flooding in the floodplain may be desirable. This can be illustrated by a project at the Kissimmee River Basin in Florida. A year after the completion of flood canal C-38, there is a strong movement to backfilling this flood canal and return the flow to the original river system. This project, if completed, will be the largest ecological restoration project in the United States.

CONCLUSIONS

Some of the current sediment issues clearly indicated the need to investigate and solve these problems by personnel from different disciplines as we must manage sediment from different aspects.

REFERENCES

Ackers, P. and W.R. White. 1973. "Sediment Transport: New Approach and Analysis." JHD, Proc. ASCE, Vol. 99, No. HY-11, Nov.

Bagnold, R.A. 1973. "The Nature of Saltation and of Bed Load Transport in Water," *Proc., Royal Soc. London,* Ser.A, Vol. 332, pp. 473-504.

Bruk, S. 1985. "Methods of Computing Sedimentation in Lakes and Reservoirs" UNESCO International Hydrological Programme, Paris.

Chien, Nien, and S.W. Wan, 1983. *Mechanics of Sediment Transport,* Science Press, Beijing, China (in Chinese).

Colby, B.R. 1964. "Practical Computations of Bed Material Discharge," J. of Hyd. Div. ASCE, Vol 90, HY 2, March.

Einstein, H.A. 1950. The bed load function for sediment transportation in open channel flows; U.S. Dept. of Agriculture Tech. Bull. 1026, 70 pp.

Elliot, C. (Ed) 1984. *River Meandering,* Am Society of Civil Engineers. pp. 384.

Fan, S.S. 1990. "Major Sedimentation Issues and Activities at the Selected Federal Agencies", Federal Energy Regulatory Commission.

Ikeda, S and G. Parker, 1989. *River Meandering,* Am Geophysical Union Water Resources Monograph No. 12. pp. 485.

IRTCES, 1985. "Lecture Notes of the Training Course on Reservoir Sedimentation," International Research and Training Center on Erosion and Sedimentation, P.O.Box 366 Beijing, China.

Mirsi, R.L., Gardi, R.J. and K.G. Ranga Raju, 1984. "Bed Load Transport of Coarse Non-Uniform Sediment," J. of Hyd. Eng. ASCE, Vol. 110, No. 3, March.

Meyer-Peter, E. and R. Muller, 1948. "Formula for Bed Load Transport," Proc., 2nd Meeting, Intern. Assoc. Hyd. Res., Vol. 6.

Parker, G. 1990. "Surface based bed load transport relative to gravel rivers." J. of Hydraulic Research IAHR, Vol. 4, pp 417-436.

Samago, B.R. 1984. "Total Load Transportation of Sediment Mixtures," Ph.D. Thesis, U. of Roorkee, India.

Shen, H.W. and C. Hung, 1972. "An Engineering Approach to Total Bed Material Load by Regression Analysis," *Sedimentation*, Ed. by H.W. Shen, Water Resources Publication.

Shen, H.W., and Lu, J.Y., 1983. "Development and prediction of bed armoring," *J. of Hyd. Eng. ASCE,* Vol. 109, No. 4, April.

Toffaleti, F.B. 1969. "Definite Computations of Sand Discharges in Rivers," J. of Hyd. Division ASCE., Vol. 95, HY 1. Jan.

Walling, D.E., Hadley, R.F., Lah, R., Onstad, C.A., and A. Yain 1985. "Recent Developments in Erosion and Sediment Yield Studies," UNESCO International Hydrological Programme, Paris.

Wiberg, P.L. and Smith, J. Dungan. 1989. "Calculations of the critical shear stress for motion of uniform and heterogeneous sediments," Water Resources Research, Vol. 23, No. 8, August.

Yang, C.T. 1973. "Incipient Motion and Sediment Transport," J. of Hyd. Div., ASCE, Vol. 99, HY 10.