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RESERVOIR SEDIMENTATION AND OPTIONS FOR ITS REGULATION, AN OVERVIEW

BY

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1. INTRODUCTION

Reservoir Sedimentation is one of the most important factors in the planning of a storage-dam. So much so that the economic life of a storage project is assessed from the estimated time it will take to be filled up with deposited sediments, because in many cases the life of the structures of the dam is longer than the period in which the reservoir is likely to be silted up.

In addition, the sedimentation process can have major environmental impacts during the operation of the project.

Inspite of such basic importance of the sedimentation aspect the tools for accurately determining the effects of this phenomenon are still not developed to a degree compatible with other facets of dam engineering. The main reason has been the lack of essential data required to sufficiently define the complex process of reservoir sedimentation.

However, a lot of advancement has been made in the sediment data collection techniques in the last few decades, and the enormous amount of information thus collected, world-wide, has been analyzed systematically to help in research efforts on this subject.

Lead has been taken by countries like China and USA where reservoir sedimentation problems have been faced on many dams and attempts have been made to mitigate their effects. Pakistan is also situated in a region in which sedimentation problems are highly serious. Whereas, a great deal of work was done here in the past on the study of sediment problems in channels, its implications on dams and reservoirs have not so far attracted much attention in this country.

If proceedings of the Pakistan Engineering Congress can be taken as an indicator of the creative work in engineering fields we find that only two papers have been presented in the past on this subject, one in 1957 and the other in 1959. This was before the time the major dam building phase started with the construction of Warsak dam.

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The second paper mentioned above, is an excellent presentation by Mr. S. S. Kirmani which candidly brings out the seriousness of the reservoir sedimentation factor, posing unusual difficulties in designing storage reservoirs on the Indus and its tributaries. It also summarizes the results of the few years of sediment data which was collected till that time.

Based on the state of the art perceptions at that stage his suggestion to solve the sedimentation problem on future dams was to explore the feasibility of off-channel storages, rather than to examine the possibility of removing the sediments from the reservoirs.

In the present paper it is attempted to give an overview of developments which have taken place in recent decades in the assessment of sediment yield estimates; application of sediment transport mechanics on submerged deposits; options for regulating sediment deposition and sluicing it out from the reservoir. These techniques have been successfully applied on many prototype examples around the world and are now becoming essential tools for design of storage dams on catchments having high sediment inflow.

2. SIGNIFICANCE OF THE PROBLEM :

It is widely realized that all storage reservoirs are destined to be filled up sooner or later by the sediment brought by the stream on which it is built. However, the quantitative significance of this problem is seldom appreciated. Magnitude of the problem can be assessed from the following calculations :

Total volume of storage in 36,500 large dams, world wide, is estimated to be 4,880 Km^3 (3,958 MAF).

- Assuming 100 years average life,
- Annual loss of reservoir capacity = 49 Km^3 /yr.
- Assuming a modest average cost of storage as $ 120 million per Km^3
- The annual loss is roughly $ 120 x 49 = 5,880 million dollars per year
- or $ 16 million per day.
- Cost wise this compares roughly with the cost of something like a Tarbela dam each year.

In addition to the enormous penalty in terms of money there are other important considerations which make the loss of storage capacity very critical.

- Good storage sites are limited, implying that the loss of a reservoir due to sedimentation would require much greater cost and disruption of accrued benefits to replace it.

- From all run-off from land surface only one third is recorded as the base flow in rivers which is available as run-of-the-river flow for diversion without storage; and two third is the run-off in floods. Flood flows are flashy and unpredictable, therefore, to utilize the flood flows for increasing demand of water for growing population more and more storage dams are unavoidable. Thus, the loss of existing capacity by sedimentation is a serious loss.

2.1 Main Problems Resulting from Reservoir Sedimentation

The main adverse effects which can be faced due to reservoir sedimentation are listed under the following heads :

a) Depletion of reservoir capacity

b) Aggradation in the backwater area

c) Degradation in the downstream reach of the channel

d) Abrasion of structural components of the dam, waterways, metallic parts like gates, valves, liners, etc, and machinery parts if the project has hydro-power or pumping provisions.

e) Clogging of narrow water passages like tunnels and conduits and small openings, if the deposited material in the reservoir is liquefied due to heavy seismic shaking, and a flow slide takes place.

Environmental, technical, and economic impacts of these effects have to be carefully examined in the design stage of the project where serious sediment problems are faced.

3. SEDIMENTATION PROCESS :

As a global phenomenon sedimentation is a geological process which is responsible for the formation of sedimentary rocks. Sedimentary rocks cover two-thirds of the land surface of the earth, showing the preponderance of the outcome of sedimeatation process. This phenomenon is well illustrated in reservoir sedimentation on a small scale.

Basic stages of sedimentation process consist of :

- Erosion ; by weathering or chemical action, aided by gravity forces.
- Transportation ; of eroded material, mainly by water or air.
- Deposition ; temporary or final (in the ocean).

The process is schematically shown in Fig. 1.

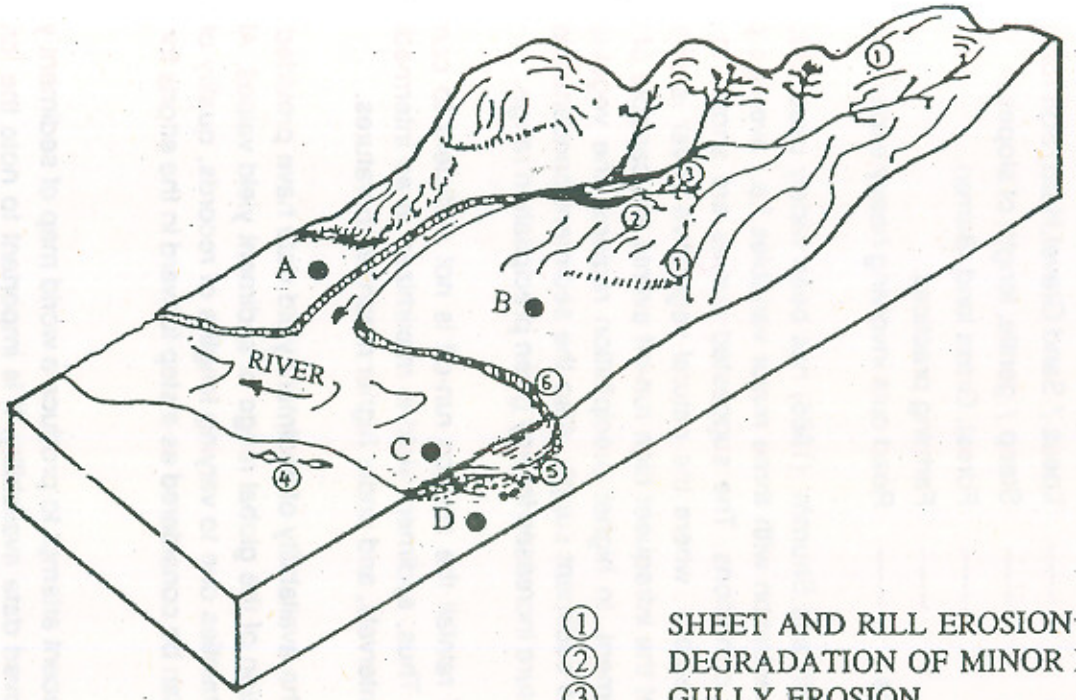
The three phases consisting of sediment production, transport, and deposition are not continuous in most cases, but are intermittent and may take conturies before a sediment particle reaches the place of final deposition. In each phase different forces of nature act on the sediment particle in many different ways during the course of its travel.

Sediment production is highly influenced by weathering effects caused by climatic factors like temperature variation, action of rain and snow; and chemical action from elements contained in the soil and water. Gravitational force acting according to the steepness of relief is another important agent in disintegration of parent material through rock falls or land slides. The effect of such atmospheric agents vary on different types of formations according to their hardness and other geological characteristics.

Similarly the transportation and depositional patterns greatly vary in relation to topographical and morphological conditions. Velocity of the transporting medium, water or air, being the main controlling factor.

The combination of such a large number of independent variables creates very complex transient conditions which make it extremely difficult to discover scientific relationships or evolve empirical formulas for predicting sedimentation patterns over a wide range of spatial or temporal conditions.

FIG. 1



① SHEET AND RILL EROSION
② DEGRADATION OF MINOR DRAINAGE WAYS
③ GULLY EROSION
④ FLOODPLAIN SCOUR
⑤ STREAMBED DEGRADATION
⑥ STREAMBANK SCOUR

A● DEPOSITION AT BASE OF STEEP SLOPES (COLLUVIUM)
B● VALLEY DEPOSITS
C● POINTBAR DEPOSITION
D● STREAMBED AGGRADATION

TYPICAL EROSION AND DEPOSITION OCCURRENCES

4. SEDIMENT YIELD ESTIMATION :

As stated above it is not possible to develop a universally applicable approach for estimating sediment yield of a catchment. However, numerous attempts have been made to propose empirical formulas based on local observations. In recent studies large amount of measured data collected world-wide has been analyzed, with the help of electronic computers, to develop co-relations of sediment yield with physical factors like :

- Climatic conditions ------- Arid /Humid, Temperature regime, etc.
- Type of Soil / Rocks ------- Loess / Sand Gravel,Hard/Soft rocks.
- Topography ------- Steep / gentle, length of slopes .
- Soil cover ------- Forest, Grass land, Barren.
- Cultivation ------- Farming practices.
- Construction Activities ------- Road cuts involving heavy excavations.

The study by Longbien and Shumm (1965) has been widely used which co-relates the range of sediment concentration with three major variables i.e., average precipitation, temperature and soil cover conditions. The suggested curves are shown in Fig. 2. This figure indicates that in dry regions, where the natural vegetative cover is sparse and the sediment supply is abundant the infrequent high run-off events are capable of transporting high concentrations of sediment. In higher precipitation regions, the vegetative cover is generally good and limits the sediment supply. Also the sediment concentration increases as the mean annual temperature increases for any given precipitation range.

At very low range of rainfall the surface run-off is not sufficient to carry away the available sediment material. Thus, sediment yield is maximized at an intermediate amount of rainfall, occurring at long intervals, and under higher mean temperatures.

Recent increases in the availability of sediment yield data have provided a welcome extension to the documentation of the global range of sediment yield values. Although this data also suffers from uncertainties due to varying lengths of records, quality of measuring techniques etc, but still this can be considered as a step forward in the efforts for refining the sediment yield estimation.

Figure 3 presents a recent attempt to produce a world map of sediment yields which takes into account the improved data availability. It is important to note the large areas of highest yield rates in North Central China, northern part of South Asian Sub-continent, and some other zones in Middle East and Central Asia.

FIG. 2

SEDIMENT CONCENTRATION

As Affected by Temperature and Rainfall
(Schumm 1965)

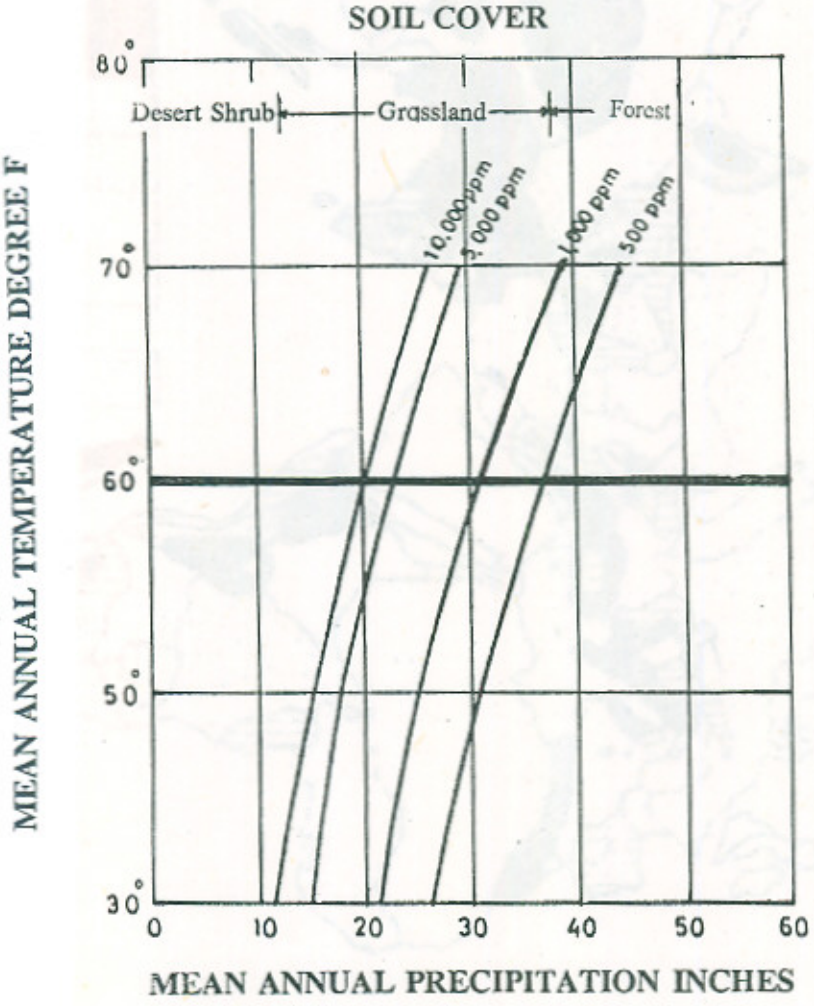
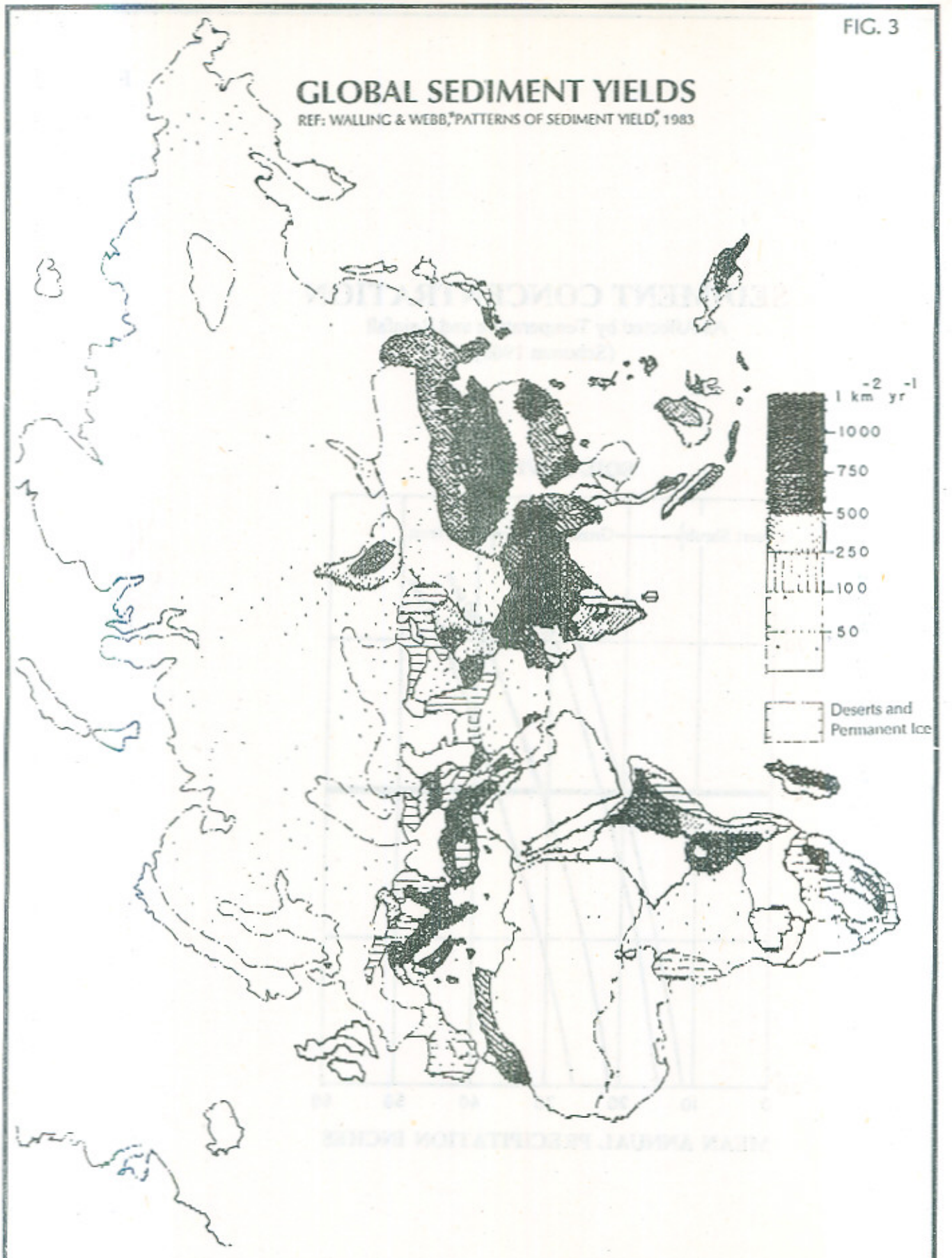


FIG. 3

GLOBAL SEDIMENT YIELDS

REF: WALLING & WEBB,"PATTERNS OF SEDIMENT YIELD", 1983



Of particular significance is the fact that the upper catchment of river Indus and its major tributaries fall in the highest sediment yield zone, explaining the abnormally high sedimentation problem faced on the reservoirs constructed on these rivers. It is therefore obvious that special measures are required in the design of dams in these areas.

4.1 Sediment Data Collection and Analysis :

As apparent from the foregoing discussion the impact of sedimentation problem varies in a wide range of severity at each dam. This is primarily related to the yield of sediment influenced by the regional characteristics, as well as specific conditions of the catchment, at each location.

Due to this situation the need for compiling a reliable data base related to the subject is a pre-requisite of highest importance. Great deal of improvement has been achieved in sediment measuring techniques and equipment, and it is essential that in all such areas where sedimentation is likely to be of significance a net work of measuring stations should be installed and carefully operated for collecting the requisite data. The main type of information to be collected are :

- Suspended Sediment Concentration
- Bed load sampling at selected stations
- Grain size analysis of sediment samples
- Seasonal and short period variations in sediment flow

The observed data is analyzed in detail to provide necessary information for design studies.

5. SEDIMENTATION IN RESERVOIRS :

When a reservoir is constructed on a stream the velocity of flow entering the pool will be reduced, or practically brought to zero, causing most of the coarse sediment transported by the stream to get deposited in the upper reach of the pond. Subsequently when the water level of the reservoir is lowered to the drawdown level the previously deposited sediment gets re-exposed to the erosive action of the stream, which picks it up again and re-deposits this sediment nearer to the lowest reservoir level. In this process sorting of the material by particle size takes place, the finest sizes being carried the farthest downstream.

In case compulsory drawdown to the lowest level is not practiced, these deposits can extend into the backwater zone to cause aggradation in the upstream area.

On the other hand degradation can be caused downstream of the dam by the silt free water released from the dam outlets, if trap efficiency of the reservoir is high.

The successive layers of sediments deposited near the entrance of the reservoir continue to build up and from a delta across the valley. The typical shape of deposited sediments are shown in Fig. 4.

The sediment delta proceeds gradually towards the dam, and as a result the storage capacity gets depleted and the functional use of the reservoir in regulating the flow is diminished. With the passage of time the delta can reach the body of the dam. If there is no provision for sluicing or flushing of the delta deposits, then the reservoir will permanently lose its storage capacity. If provisions are made in the dam by way of low level outlets sediment can be passed through the reservoir and the economic life of the project can be extended. This subject is discussed later on.

5.1 Sedimentation Index :

The estimation of total sediment quantity which is likely to flow into the reservoir annually is the most important factor which determines the degree of importance this problem will have on the overall project planning and design of the reservoir structures. For this purpose the Sediment Index for the dam will be a useful indicator as shown below :

If V_r is the volume of the reservoir and
S_r is the average annual sediment yield (volumetric)

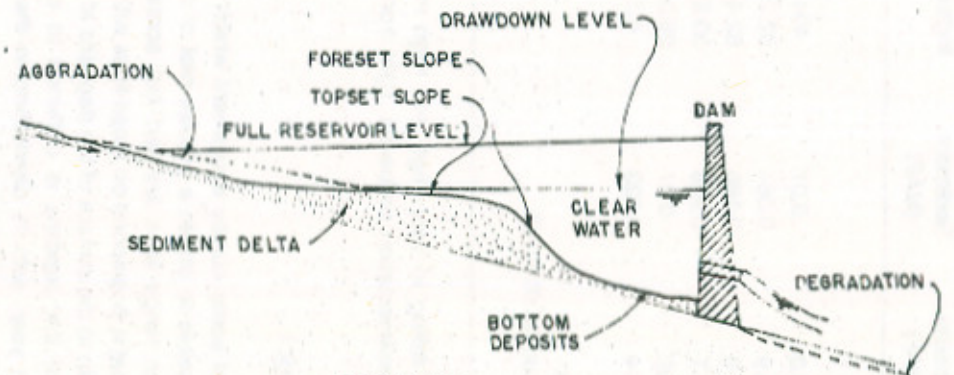
Then V/S is the 'Sedimentation Index', placing the project in following Intensity range classification.

Intensity Range of sediment yield at Reservoirs,

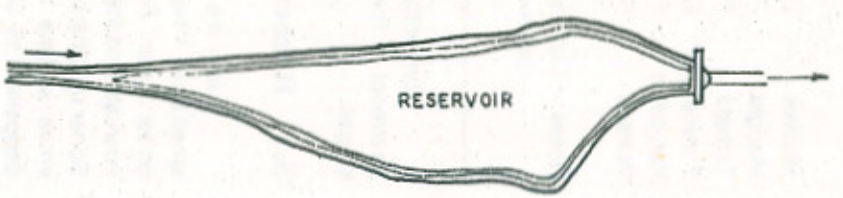
Sedimentation Index, V/S	Intensity Range
< 50	Very High
50 - 150	High
150 - 300	Moderate
> 300	Low

Data from a few projects to show the wide range of variation in the impact of sediment problems is presented in Table -1 below :

FIG: 4



SECTION



PLAN

PROFILE OF SEDIMENT DEPOSITS
IN A STORAGE RESERVOIR

TABLE - 1

CAPACITY - SEDIMENT INFLOW RATIO FOR SELECTED DAMS

Dam	Country	Storage Capacity (MAF)	Annual Sediment (MAF)	Sediment Index	Intensity Class
Hoover	USA	28.3	0.07	404	Low
Mangla	Pakistan	5.9	0.064	92.2	High
Tarbela	Pakistan	11.6	0.186	62.4	High
Sanmenxia	China	28.7	0.928	30.9	V. High
Kalabagh	Pakistan	7.90	0.27	29.3	V. High
Warsak	Pakistan	0.14	0.033	4.2	V. High

Notes :- Data is indicative only
- Sediment density assumed 80 lb/cft

Evidently, the projects falling in Very High and High intensity class need careful treatment of the anticipated sedimentation problems, right from the planning and design stages.

5.2 Reservoir Survey :

With the introduction of sonar survey equipment which could be operated from a small boat it has become possible to obtain a precise plot of sediment deposition profile under water. For this purpose range lines are laid out across the reservoir at regular intervals and the measuring boat is positioned on these lines with the help of survey control. Sonar reading pick up the depth to the surface of the deposits at each point. By this method entire surface configuration of the deposits is obtained to compute the rate of fresh deposition of sediments each year, and its distribution in the reservoir; also giving the movement patterns occurring in the deposits.

At Tarbela dam this survey is carried out every year, after the monsoon season during which heavy load of fresh sediments are brought into the reservoir. The profile of sediment delta in Tarbela reservoir as well as its plan showing the range lines are given in

Fig 5. The sediment delta is advancing gradually towards the dam and it is expected that the toe can reach the dam in about 15 to 20 years. The possible problems likely to be faced at that time are discussed subsequently.

5.3 Density Currents :

Another characteristic feature related with reservoir sedimentation is the formation of density currents. The incoming turbid flow heavily charged with suspended particles behaves like a denser layer of fluid entering into the clear, thus, lighter fluid of the stagnant pool. If the entering jet is also colder than the pond temperature the difference in the density of the two layers is accentuated and the denser layer dips to the bottom of the reservoir bed and continues to flow as a stratified current along the bed for considerable distances. This is termed as 'underflow' current.

In case where the temperature gradient is reversed and the entering jet is warmer than the pool water the incoming current can float on the surface of the pond as 'overflow'. And in conditions where the pool water is near freezing in the bottom and warmer at the surface, the incoming current can form a density current at an intermediate depth termed as 'interflow'. The phenomenon is illustrated in Fig. 6.

Realizing the capacity of density currents to carry high concentrations of fine sediments from its entry to the dam, provision for selective withdrawal from the reservoirs have been made on many projects, by means of outlets at suitable levels, from which the density current can be discharged. This method is used to reduce the rate of silting and extend the life of the reservoir. At Lake Mead (USA), concentratons of 20,000 ppm are noted in the density currents.

At Khanpur Dam, Hazara, formation of density current is observed regularly after occurrence of flash floods which bring in highly charged turbid flows into the lake. It is believed that this phenomenon is particularly strong at this dam because the flood flows are generated by freezing rain and hail storms on the Nithiagali and Murree slopes and the cold turbid currents enter the warmed up reservoir within a few hours time. Since the sediment consists largely of fine silts and clays, derived from the shaly strata which predominates in the catchment, the density currents contain high percentage of colloidal material. This material remains in suspension for a long time so that the seepage flow from the relief wells also becomes turbid. This happening created a false alarm about the safety of the dam at the time of the first occurrence of density current formation.

If proper monitoring and documentation is carried out the possibility of utilizing density currents for discharging a substantial part of the sediment, and thereby prolonging the life of the reservoir can be examined.

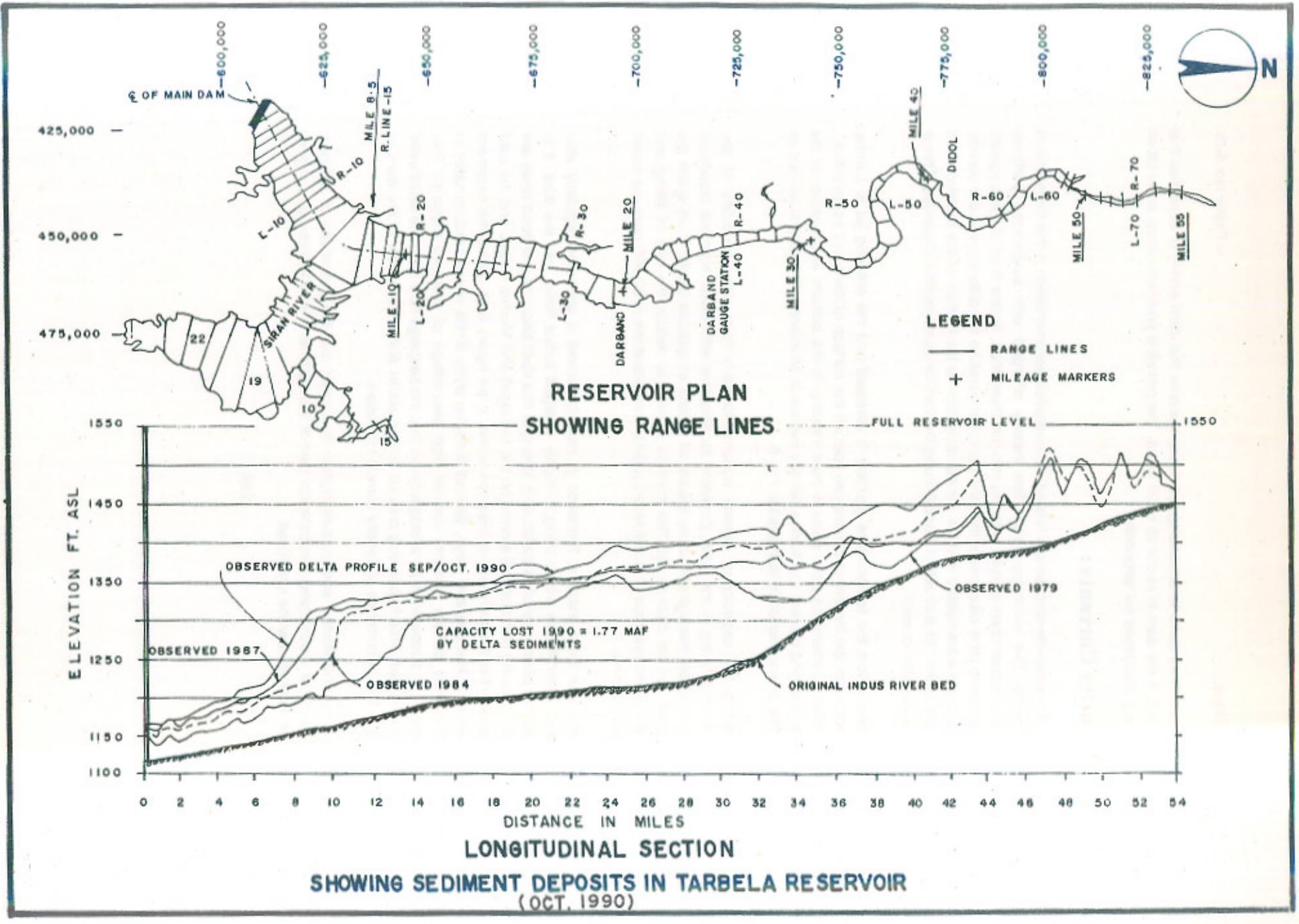
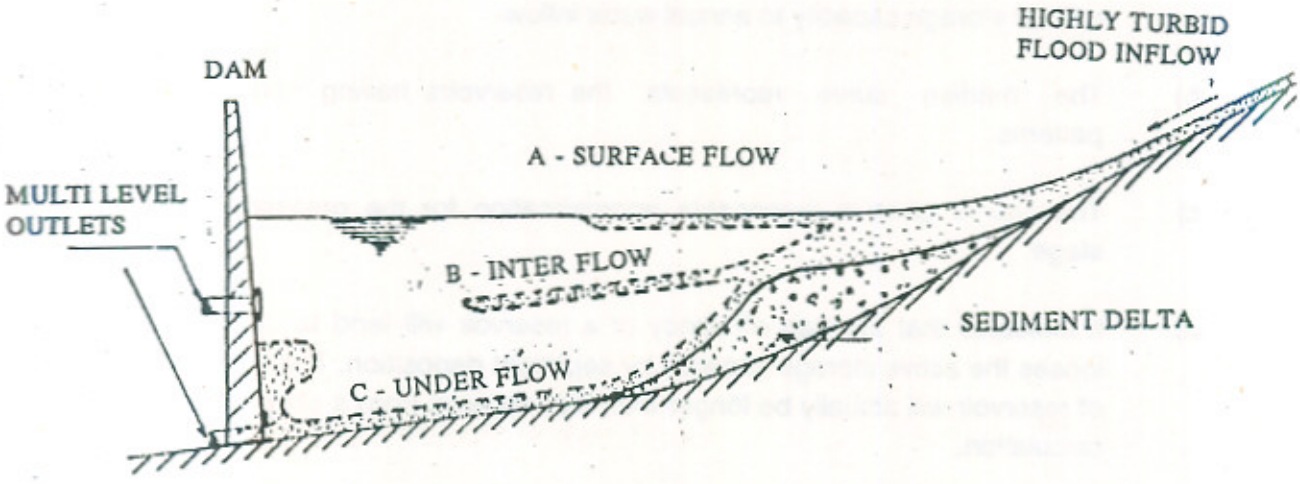

600,000
625,000
650,000
675,000
700,000
725,000
750,000
775,000
800,000
825,000
425,000
450,000
475,000
℄ OF MAIN DAM
MILE 8·5
R. LINE-15
R-10
L-10
R-20
L-20
MILE-10
R-30
L-30
MILE 20
DARBAND
R-40
L-40
DARBAND GAUGE STATION
MILE 30
R-50
L-50
MILE 40
DIDOL
R-60
L-60
MILE 50
R-70
L-70
MILE 55
SIRAN RIVER
22
19
10
15
N
LEGEND
RANGE LINES
MILEAGE MARKERS
RESERVOIR PLAN
SHOWING RANGE LINES
FULL RESERVOIR LEVEL
1550
1450
1350
1250
1150
1100
ELEVATION FT. ASL
OBSERVED DELTA PROFILE SEP/OCT. 1990
OBSERVED 1979
CAPACITY LOST 1990 = 1.77 MAF
BY DELTA SEDIMENTS
OBSERVED 1967
OBSERVED 1984
ORIGINAL INDUS RIVER BED
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54
DISTANCE IN MILES
LONGITUDINAL SECTION
SHOWING SEDIMENT DEPOSITS IN TARBELA RESERVOIR
(OCT. 1990)

FIG. 6

DENSITY CURRENT FORMATION



POSITION OF DENSITY CURRENT:

A. IF RESERVOIR WATER COLDER THAN INCOMING FLOW

B. IF BOTTOM PART OF RESERVOIR COLDER AND UPPER PART WARMED UP

C. IF ENTIRE RESERVOIR WARMED UP THAN INFLOW

5.4 Predicting Rate of Sediment Deposition :

In early 1950's a significant contribution was made in estimating the rate of silt accumulation by analyzing the data from a large number of existing reservoirs. It was observed that the proportion of total sediment entering the reservoir, which will be deposited therein, depends on the ratio of the storage capacity to the total water inflow. In large reservoirs with capacity equal to or more than the annual water inflow the entire incoming sediment will get deposited. In other words the trap efficiency will be near about 100 percent. Smaller reservoirs which can not store a large proportion of annual inflow of water will release a part of it as surplus flow. This will also carry a part of the suspended load, thus reducing the trap efficiency to an amount less than 100 percent. Brune, presented a set of curves based on the above approach, shown in Fig. 7. The salient points of these curves are as follows:

a) The percentage of sediment trapped in the reservoir is plotted against the ratio of storage capacity to annual water inflow.

b) The median curve represents the reservoirs having normal release patterns.

c) The curve gives a reasonable approximation for the preliminary design stage.

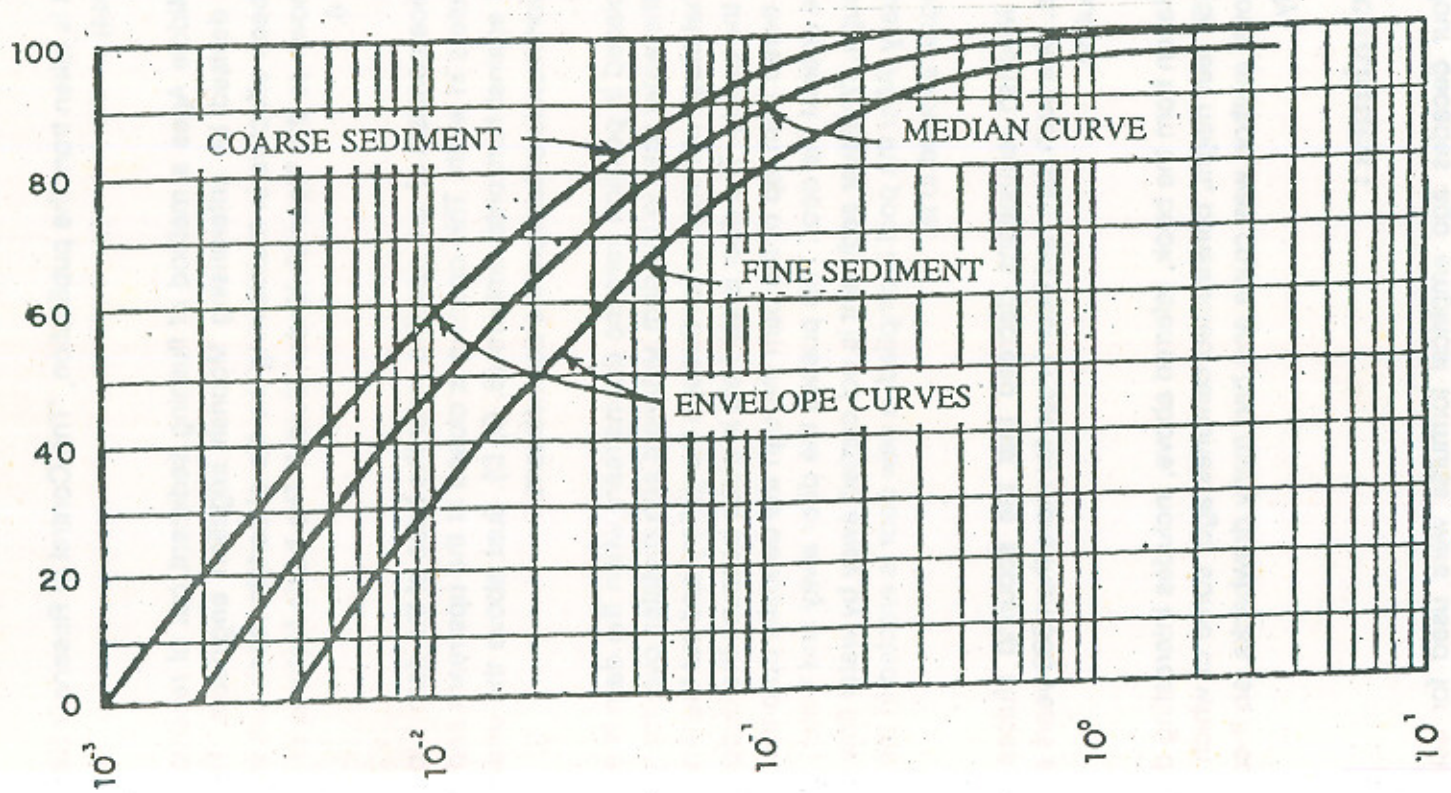
d) It indicates that the trap efficiency of a reservoir will tend to diminish as it looses the active storage capacity by sediment deposition. Therefore, the life of reservoir will actually be longer than that appears from a simple arithmetic calculation.

6. OPTIONS FOR REGULATION OF RESERVOIR SEDIMENTATION :

Due to serious implications of reservoir sedimentation, efforts have always been made by dam designers to adopt methods for regulating the phenomenon so as to mitigate the losses that accrue to the costly storage projects. Due to highly complex nature of the problem, methods of general applicability could not be developed until recent decades. However, examples of desilting the reservoirs are reported in literature which were followed locally, since centuries ago. One such method was practiced in Spain which is highly educative.

FIG 7

BRUNE'S CURVE FOR RESERVOIR TRAP EFFICIENCY



6.1 Example from History :

(The account is taken from the publication, "The Control of Reservoir Silting" by Carl B. Brown, USDA, 1944)

During the Middle Ages a method of flushing sediment out of reservoirs in South Eastern Spain was devised by enterprising Moorish irrigation engineers. Their method though crude, had been effective in maintaining the life of certain reservoirs for centuries. This method was known as the 'Spanish Under Sluice'. The basic features of this method are illustrated in Fig. 8.

The undersluice consists of an opening near the base of the dam 1 to 3 meters in height and 1 to 3 meters in width. This opening is closed at the upstream end by wooden door (A), supported against horizontal timbers (B, C, D). Just above the undersluice is a gallery to allow the workmen to enter from the downstream.

The door is placed in position from the downstream when the dam is empty and is well caulked. When the water rises in the dam sediment accumulates over the years upto a specified depth. At that stage workmen enter through the gallery and cut the timbers B, C, D and escape through the gallery. The door is still held in place because the deposited mud is solid. A hole is then bored from top of the dam through the deposits upto the door, which exerts water pressure against the door. This pushes the door away and water, carrying the sediment bursts through. Whatever sediment is not carried away by water flow is shovelled into the stream manually. After the pool is emptied, a new door is erected in the undersluice and the reservoir is again allowed to fill.

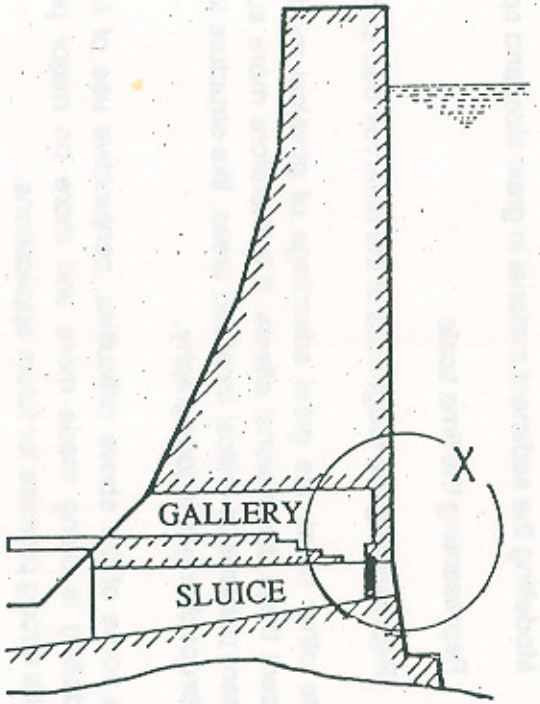
The ancient Moorish regulations decreed that the scouring sluices should be opened every 4 years. One such dam had been in use for more than 300 years as a result of the above sluicing routine.

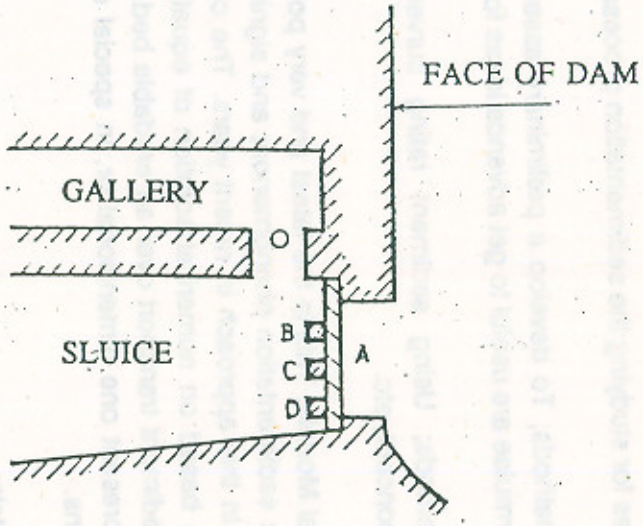
The account taken from the book, referred above, includes interesting details about several dams upto 156 feet height, constructed centuries ago, some of which were still in service. The silt removal method was crude and had many drawbacks, so it could not get universal acceptability.

6.2 Study Techniques :

Until about four decades ago empirical formulas were used for estimating the sedimentation rates. These formulae were developed mostly on the basis of local

FIG. 8





DETAIL AT-X

A. HEAVY TIMBER BULK HEAD

B.C.D. STRONG TIMBER BEAMS

SCHEMATIC DIAGRAM OF THE OLD SPANISH SYSTEM FOR UNDERSLUICING
(AFTER D'ROHAN)

experience. Considerable progress has been achieved since, and advanced techniques are now available to analyse the reservoir sedimentation problem and to develop options for regulating it.

The main techniques for studying the sedimentation process are :

a) Empirical methods; To develop a preliminary assessment of the problems empirical formulae are useful to get advance ideas for design.

b) Analytic methods; Using sediment rating curves, transport equations, probability concept, etc.

c) Mathematical Models; This is the latest and very powerful tool for analysing the complex sedimentation phenomenon; and significant advancement has been made in this approach in recent years. The concept of mathematical modelling is based on numerical solution of equation of the continuity of water and sediment transport over an erodable bed. The available software generally represent one dimensional or, in special cases, two dimensional flow conditions.

d) Physical Models;

Physical model studies of sediment mechanics in reservoirs pose far more difficulties than, for example, for low head river models. Some of these are :

- Large distortion in model scale necessary to represent the whole reservoir.
- Modelling the sediment material in grain size, and specific gravity.
- Representing the time scale
- Representing the roughness of the reservoir bed surface.

On the other hand, the great advantage of physical models is that it can represent three dimensional effects. It is therefore more suited to study the sediment patterns at critical localised areas, like structure locations, intakes, and abrupt changes in topography.

To overcome some of the above difficulties, conjunctive use of Mathematical and Physical modelling is being made more and more on major projects, and this approach holds strong promise for future applications.

6.3 Sediment Regulation Methods :

The methods for regulating reservoir sedimentation can be divided into three categories :

6.3.1 Preventive methods to reduce sediment inflow :

a) Reduction in sediment production through watershed management. Such a scheme would involve afforestation, land use change , and construction of small structures to control gully erosion and to trap sediment. These measures are time consuming and beneficial effects in control of sediment can only be noticeable after a length of time.

b) Trapping sediment before entering the reservoir

These consist of either constructing small debris dams or to bypass the sediment to suitable adjoining areas. The cost of debris dams have to be weighed against the provision of an equivalent storage in the main dam.The later is generally much cheaper, therefore debris dams do not provide an economic solution.

By-passing the sediment before entering the reservoir is only possible where suitable conditions exist, which are found in very rare cases.

c) A variant of by-passing is the off-channel storage reservoirs. In these cases flows with high concentration is passed in the main river and relatively clear water is diverted into the off-channel storage. Such schemes will be successful only on those projects where hydrological regime suits the water regulation requirements and will generally need high costs in diversion facilities.

6.3.2 Methods that use Hydraulics of Flow to Transport Sediment Through the Reservoir.

In this category the following methods are included :

a) Flushing
b) Venting Density Currents
c) Sluicing

a) Flushing

Sediment flushing from dams primarily depends on pushing the deposits through low level outlets under high hydraulic gradient and abruptly releasing the stored water. The deposits are progressively removed by retrogressive erosion and transported by high velocity water jet.

Almost complete emptying of the pond is involved which may be practiced once in a year or even less frequently, as permitted by the operational constraints.

In this method due to sudden release of large sediment slugs, channel blockage may take place downstream of dam and create problem of flooding and channel deterioration. There are other problems related to flushing such as, abraison caused by high sediment concentrations to the outlet gates and water passages.

b) Venting Density Currents :

The mechanism of the formation of density currents have been explained earlier (Section 5.3). If the occurrence of these currents are monitored carefully and allowed to flow out of the reservoir through outlets situated at appropriate levels, sizeable portion of incoming sediments can be discharged. Regular monitoring of density currents are done at many dams around the world and are used in venting out of fine sediments. In some cases 20 to 40 percent of incoming sediments are passed out by this means.

c) Sluicing Operation :

Sediment sluicing is an operational regime in which main sediment load entering the reservoir is transported through it, largely without getting deposited. This is achieved by a combinations of two main operations :

- First, by maintaining a suitably low drawdown level in the reservoir to generate a flow velocity which can transport most of the sediment over the topset surface of old deposits.

Second, by providing sufficient outlet capacity to discharge the flow needed to maintain the low reservoir level, as required for the first condition.

In this procedure well defined reservoir operation rules are to be observed. This may entail some additional release of water over and above the regulation requirements and loss of some power generation due to lower reservoir levels. The benefits from an extended reservoir life will however, outweigh the penalty in adopting this option.

From the above discussion it is evident that sediment sluicing is the most effective solution for regulating the sediment deposition. It is successfully tried in China, of which a case history is presented below.

6.3.3 Sediment Dredging :

Removal of sediments by dredging is a very costly proposition and has not been widely used in large reservoirs. In some known examples this option is utilized where the dredged material has commercial value, for example, as concrete aggregate.

However, as the demand for combating reservoir sedimentation grows, technological innovations will most likely evolve hydraulic dredging methods to make it economically viable in large reservoir.

7. SOME CASE HISTORIES

Brief case histories of a few dams are presented to illustrate the impacts of reservoir sedimentation problems.

7.1 Warsak Dam on River Kabul, Pakistan

This project has the lowest ratio of storage capacity to rate of sediment inflow as shown in Table-1. It is known that the entire storage volume of the reservoir was filled up within 5 years of its commissioning. As no provision for any of the option for sediment removal was made in the design and no major rehabilitation measures could be undertaken, the project has turned into a run-of-the-river scheme.

Practically no regulation capacity is available for either irrigation or hydro energy generation. Large quantities of sand enter into the turbines causing extensive damage to the runners and other machinery parts. The result is that energy output of the station remains significantly below the rated capacity.

7.2 Sanmenxia Dam (China) :

Sanmenxia dam on Yellow river in China is another example of very high sedimentation rate (Ref. Table 1).

It is a major project constructed in 1961 with flood control and power generation as its main objectives. After commissioning, the reservoir lost its capacity at a rapid rate and serious environmental problems were noted within two years of its operation, due to exceedingly high rate of sediment deposition.

In view of the serious problems, reservoir operation scheme was changed and impoundment was restricted at a lower level.

Reconstruction work was carried out to provide sluicing facility in the dam on following lines (Ref. Fig. 9).

a) Opening up of low level sluices, which were initially provided for river diversion during construction of the concrete dam and had been plugged.

b) Excavating two new tunnels from the downstream, opening into the reservoir at a suitably low level.

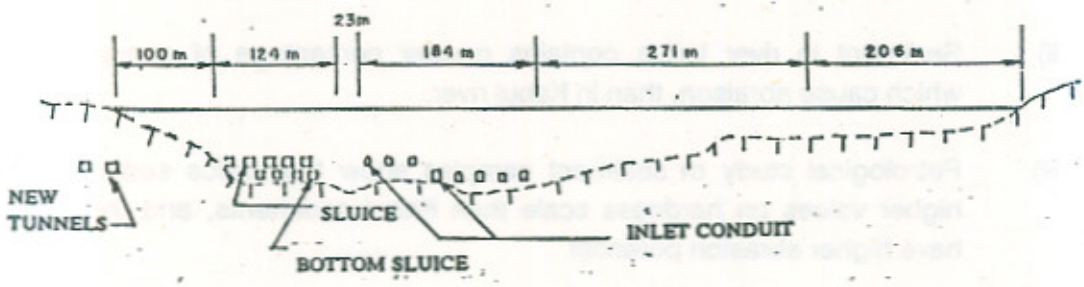
These facilities provided a satisfactory arrangement to exercise sluicing operations every year. This also resulted in partial recovery of the storage volume lost to sedimentation earlier. Operation of the project on this pattern, since 1974, shows more or less an equilibrium in sediment inflow and outflow. The functional objectives are, of course, modified slightly to suit the revised operational regime.

7.3 Tarbela Dam : River Indus, Pakistan :

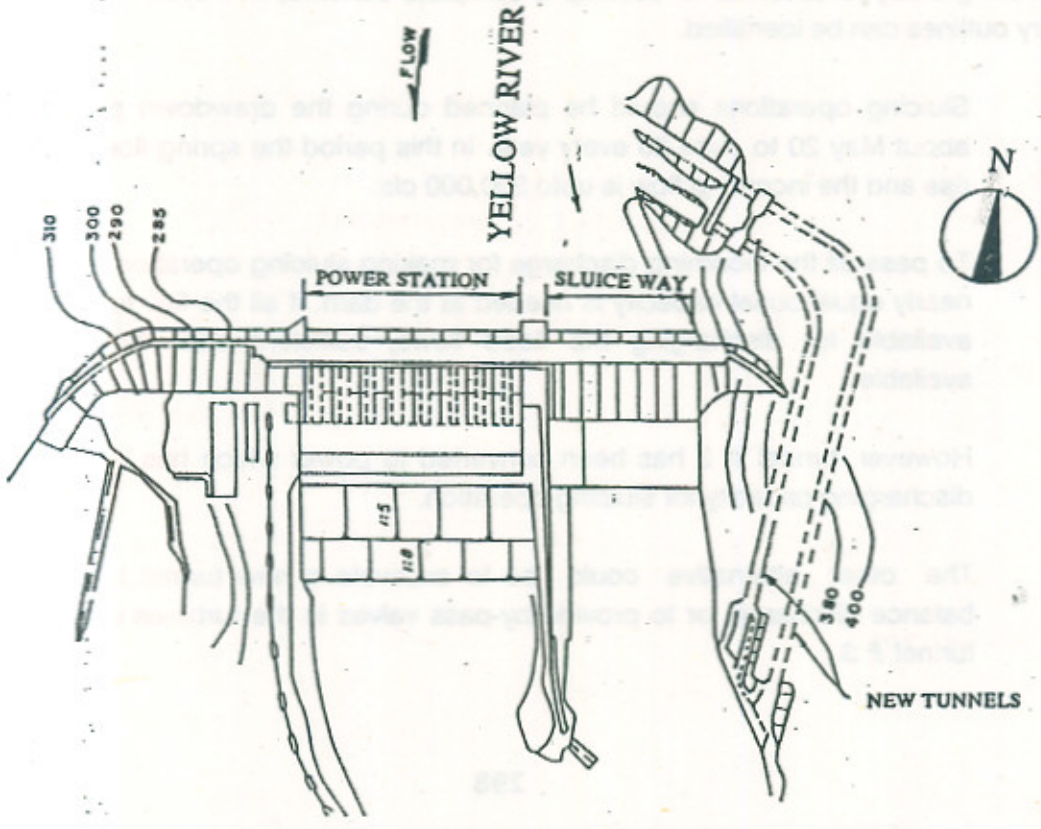
Tarbela dam constructed in 1975, on the river Indus has a storage capacity of 11.6 MAF. Average annual run-off is 64 MAF and annual sediment inflow is estimated as 0.186 MAF. The sedimentation index comes to 62.4 which places the dam in High intensity class of reservoir sedimentation (Ref. Table 1).

FIG. 9

SANMENXIA DAM
(YELLOW RIVER-CHINA)



UPSTREAM ELEVATION



GENERAL PLAN AFTER RECONSTRUCTION

In the original design of the dam no special provision for sediment removal was incorporated in the project scheme. The sediment delta is steadily proceeding towards the dam as explained in para 5.2 and shown on Fig. 5. It can be visualized that when the delta reaches the dam a situation somewhat similar to Warsak can develop, with the difference that the magnitude of the problems would be many times greater because,

i) Size of machines at Tarbela are much bigger, being 432 MW as against 40 MW at Warsak, thus making repairs that much more difficult.

ii) Sediment in river Indus contains greater percentage of coarse fractions which cause abraison, than in Kabul river.

and iii) Petrological study of sediment samples show that Indus sediments have higher values on hardness scale than Kabul sediments, and therefore will have higher abrasion potential.

This situation presents an alarming prospect in near future at Tarbela dam, if appropriate preventive measures are not taken in time.

From the possible options the sluicing method would perhaps be most effective. A full engineering study is essential to develop a complete scheme, however, the following preliminary outlines can be identified.

a) Sluicing operations should be planned during the drawdown period from about May 20 to June 20 every year. In this period the spring floods start to rise and the incoming flow is upto 200,000 cfs.

b) To pass all the incoming discharge for making sluicing operation successful nearly equal outlet capacity is needed at the dam. If all the five tunnels were available for discharging the flood flows, sufficient capacity would be available.

However, tunnel # 3 has been converted to power which has reduced the discharging capacity for sluicing operation.

c) The other alternative could be to excavate a new tunnel to pass the balance discharge, or to provide by-pass valves in the turbines installed on tunnel # 3.

7.4 Kalabagh Dam : River Indus (Pakistan)

The proposed Kalabagh dam will be located 120 miles downstream of Tarbela on the main Indus river and will control a catchment area nearly 70 percent larger. Consequently the estimated annual sediment yield is also considerably higher, being 0.27 MAF as compared to 0.186 MAF. The gross storage capacity of Kalabagh will be 7.9 MAF and sedimentation index will come to 29.26.

From Table 1 we can see that Kalabagh dam will fall in Very High range of sedimentation intensity. If this project is designed without any mitigation device its life will be very short and it will not be economically viable.

Due to this reason sediment sluicing option has been incorporated in the project design. Detailed analysis of this option was made with the help of HEC-6 computer programme which confirmed that a large proportion of incoming sediment will be passed out of the reservoir. The design features will tend to achieve an equilibrium in the inflow and outflow of sediment after 50 years. Fig. 10 shows the reservoir depletion curve for the first 50 years. With the sluicing provision reservoir capacity will reduce from 7.9 MAF to 5.2 MAF and the rate of depletion will diminish rapidly later on. Against this the depletion would reduce the capacity to 2.3 MAF without sluicing.

To achieve full sluicing results a specified reservoir operation sequence will have to be followed under which the reservoir will be kept at the minimum drawdown level every year from June 20 to July 20 and the flood flows occurring during this period will be discharged without major impounding. For this purpose adequate discharge capacity is provided by two low level outlet conduits of 36 ft dia plus the orifice spillway.

The operation pattern of the reservoir is shown on Table II.

8. CONCLUSIONS :

1. Sedimentation is a major problem in storage reservoirs constructed in high yield catchments. Pakistan is situated among the high yield regions of the World.

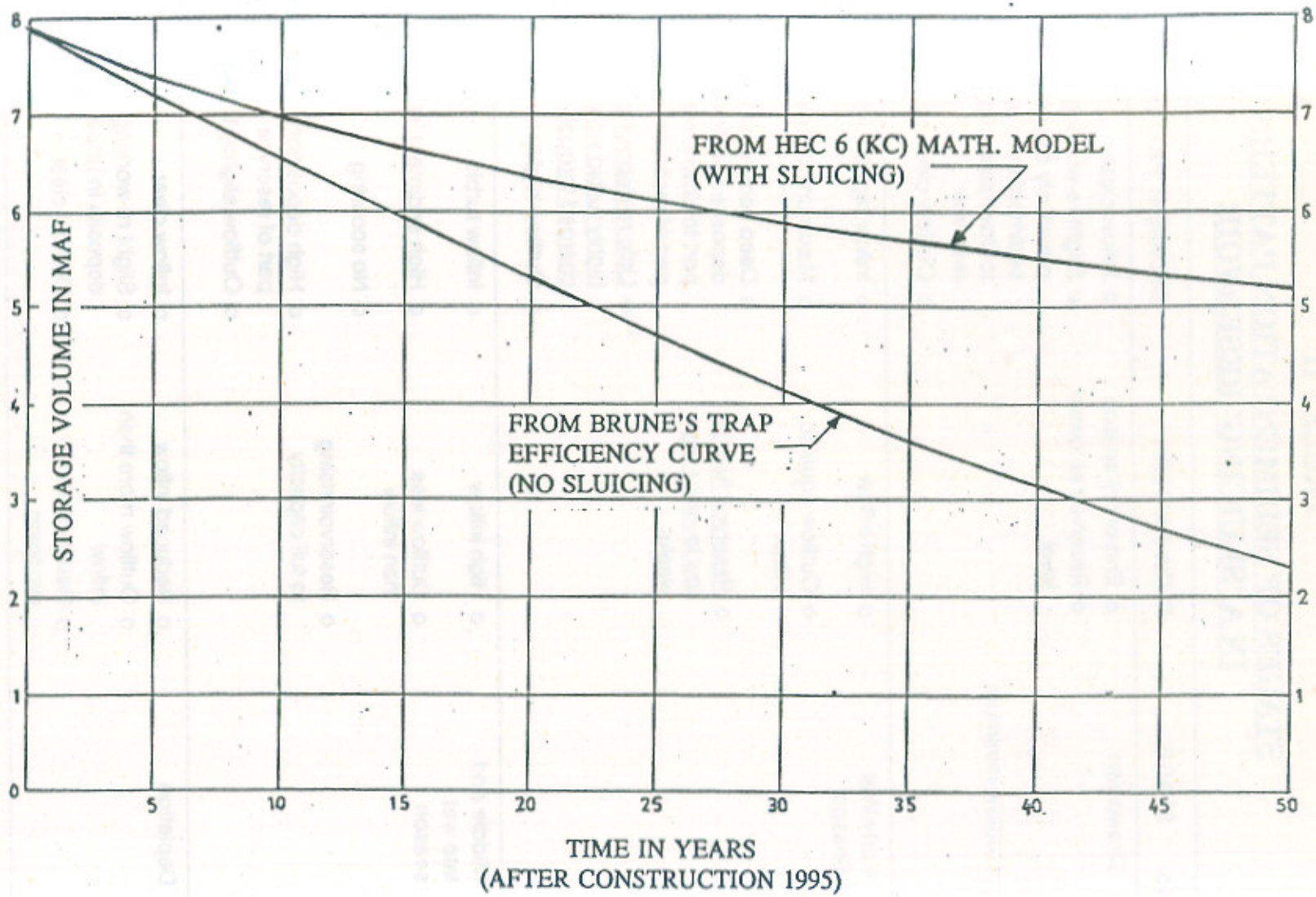
2. Reservoir sedimentation is a very complex phenomenon and it is essential that adequate arrangements should be made to collect the sediment data on all rivers of the country.

3. Sedimentation research facilities should be developed to study and analyse the problems associated with the process. This is very essential in view of an ambitious programme of construction of major dams for regulating the flood flows of Indus Basin.

4. Options for regulating the sediment deposition in reservoirs are available and these should always be examined carefully during the planning and design stage of future dams.

5. The sluicing option is the most effective one and suits the hydrologic regime of our country.

FIG. 10



STORAGE DEPLETION CURVE FOR KALABAGH DAM

TABLE - II

STAGES OF SEDIMENTATION PATTERN IN A "SLUICING" RESERVOIR

S.No.	STAGE	FLOW PATTERN	SEDIMENT PATTERN
1	Drawdown o Outflow minimum	o End of dry season o Reservoir at lowest level	o Inflow clear o Slight re-working of previously deposited sediment from upstream to downstream part of reservoir o Outflow clear
2	Early Wet Season	o High inflow o Outflow equal to inflow o Reservoir held at low level for few weeks	o Inflow highly turbid o Maximum sediment inflow o Deep scouring in previously deposited sediment - Transport to downstream / deeper part of reservoir o Little re-deposition and highly turbid water discharged through low outlets o Outflow highly turbid
3	Middle and late wet season	o High inflow o Outflow less than inflow o Reservoir rising to full capacity	o Inflow turbid o High sediment inflow o No scouring o High deposition in upstream part of reservoir o Outflow slightly turbid
4	Depletion	o Reduced inflow o Outflow more than inflow o Reservoir level dropping	o Inflow clear o Slight re-working of deposits in upper part o Outflow clear

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