The Sediment Problem on the Indus at Tarbela

By

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ABSTRACT

Deposits of sediment in a reservoir on the Indus at Tarbela would be very large, because the annual volume of inflow which would pass through the reservoir and drop its load of sediment would be several times the capacity of the reservoir. Sediment samplings have been made on the Indus and studies have been carried out in order to estimate the probable rate of accumulation of sediment in a reservoir. The Indus at Tarbela drains an area of 70,000 square miles, most of which is barren, is undergoing heavy weathering, and appears to provide an inexhaustible source of sediment to be picked up and transported by the flood-season discharge resulting from melting snow and monsoon storms. Samplings of the suspended sediment carried by the river, show it to be nearly two-third sand, more than one-quarter silt, and a small fraction of clay. The concentration and the daily load of sediment increase rapidly with the discharge, the total annual load averaging 360 million tons, most of which is transported during about 2-1/2 months of the year. Although no samplings of bed load have been made, the river bed and valley floor material is mostly gravel and cobbles and it appears that the bed load is small.

Project planning studies of a reservoir at Tarbela have considered three sizes of project. The reservoir would extend some 45 miles up the Indus and 12 miles up the Siran. The maximum depth would be of the order of 400 feet.

Sediment deposits in the reservoir would form a delta at the upstream end of the reservoir, which would be re-worked and re-deposited further down stream every year as the reservoir level fell and the incoming river eroded the recently deposited material. Initially, and for many years, it is expected that all of the suspended sediment would be deposited in the reservoir. The proposed layout of the dam and outlet works, governed largely by the topography at the dam site, places the outlets about 100 feet above the bottom of the reservoir, so there is little likelihood of any sediment being transported through the reservoir and

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discharged by the outlets. After many years, and when the sediment deposits had nearly filled the reservoir, the shorter detention time and the higher flow velocities in the reservior would result in some through-flow of sediment and it is probable that operation of the spillway crest gates could be scheduled so as to pass large quantities of sediment and perhaps sluice out recent deposits. Eventually, this process would serve to maintain a small residual reservoir capacity. Together with the capacity in the Siran arm of the reservoir, would deplete very slowly, the residual capacity in the Indus arm would give a total of about 1 MAF which would persist for a very long time.

Estimates of the probable time required to deplete a reservoir to the residual 1 MAF capacity range from 35 or 40 upto 55 or 60 years for the three sizes of project studied, namely, gross capacities of 6.0, 7.8 and 9.8 MAF.

No appreciable growth of the delta upstream of the head of the reservoir would be expected; at least until the reservoir had been depleted and the deposits within the reservoir had reached a stable condition. At that time it is possible that the coarse gravel and cobbles of the valley floor might accumulate in such a fashion as to start a very slow, almost imperceptible, long-term aggradation of the valley floor.

Downstream of a reservoir at Tarbela the river would have a tendency to degrade, as the clear water from the reservoir picked up a new load of sediment from the banks and bed of the river. The river bed material is largely a coarse cobble-gravel with a relatively small fraction of sand. After some lowering of the river bed, the coarse material would tend to form a protective armor to prevent further degradation. Alluvial deposits of fine material along the banks would probably be attacked, however, unless preventive measures were taken.

Means to reduce the rate of depletion of the reservoir storage have not been studied in detail. A reduction of the supply of sediment, or any method of removal would appear to involve such a vast undertaking that it could hardly be practical.

The development of an off-channel reservoir to receive water diverted from the main river would greatly reduce the volume of sediment-laden water flowing into the reservoir, and would extend its period of depletion correspondingly. The possibility off-channel storage exists, at Tarbela, and may ultimately provide a reasonable solution to the sediment problem at that site.

INTRODUCTION

The heavy burden of sediment carried by the rivers in Pakistan has posed many problems for the Engineer. The threat of unwanted deposits is everpresent. In the irrigation canals, the problem has been to keep them clear of sediment accumulations which would reduce their capacity. The solution to this problem has been threefold : to exclude as much sediment as possible from the canal head, to extract sediment from the canal at some point below the head, and finally to keep the remaining sediment in motion within the canal and deliver it to the farmer. The creation of large reservoirs on the main rivers of Pakistan will pose the problem of how to preserve the essential storage capacity in the face of sediment deposits in the reservoirs. The "exclude and extract" solution is hardly applicable to large reservoirs, although it may offer some clues. In general, an immediate solution to the reservoir problem is not at hand, although there is some prospect of a partial solution over the long term.

The problem at Tarbela would be more acute than on most rivers, because of the relatively small size of the proposed reservoir compared with the annual volume of flow which would pass through the reservoir. The reservoir would act as a sedimentation basin to trap the sediment from the entire flow of the river. Much of the flow water is surplus and would pass to sea unused, but free of the sediment load which it had left behind at Tarbela. The high degree of exposure to sedimentation of the Tarbela reservoir is illustrated in the following table which compares the ratio of average annual inflow to reservoir capacity for several reservoirs.

Reservoir	River.	Average Annual Inflow, MAF	Gross Reservoir Capacity, MAF	Ratio of inflow to Capacity.
Tarbela	Indus	61.0	7.8*	7.8
Garrison	Missouri	17.6	23.0	0.77
Mangla	Jhelum	22.6	8.0*	2.8
Elephent Butte	Rio Grande	1.1	2.6	0.42
Rockland	Neches	1.7	6.8	0.25
Fort Peck	Missouri	4.2	19.4	0.22
Dennison	Red River	4.14	5.5	0.75

*Assumed capacity.

Measurements have been made of the sediment load in the Indus, and studies carried on to estimate how rapidly the storage space in the proposed Tarbela reservoir would be depleted by accumulations of sediment. The work has included sediment sampling and determination of sediment in the river at all discharges, carried out originally by the Irrigation Department and currently by the Water and Soil Investigation Division (WASID) of WAPDA, as well as office analysis, research and computation. A careful study has been made of pertinent literature (see reference list) and informal discussion held with personnel having long experience on reservoirs in the central and western United States.

This paper will describe briefly the field measurements carried out, and the findings of the office studies of sedimentation of the reservoir, and will offer some random thoughts which, it is hoped, will promote discussion or speculation.

The River.

The Indus basin above Tarbela is about 700 miles long and only about 100 miles wide, with a total area of 70,000 square mile, most of which is in high mountainous country (Fig. 1). The annual rainfall in the upper valley areas is only a few inches, and the heavier precipitation intercepted by the high mountains occurs as snow. Most of the run-off is from melting snow, except that an area of about 4,000 square miles lying just upstream of the dam site receives some 18 inches of monsoon rainfall annually, much of which runs off rapidly in flash floods.

A long-term discharge record at Tarbela has been developed. The data used were (1) six years of gauge and discharge record at Darband, just upstream of Tarbela, and (2) discharges derived from a gauge record since 1868 at Attock, downstream of Tarbela and downstream of the mouth of the Kabul river (Fig. 2). The average run-off at Tarbela works out at about 61 million acre-feet. The discharge ranges from less than 20,000 c. f. s. to nearly 700,000 c. f. s.

The flow at Tarbela follows a typical pattern-low flows during the winter, some increase in discharge during the spring months as snow melting begins, a rapid increase in flow in the early summer, followed by flood peaks during the summer as snow melting continues and monsoon storms bring large amounts of rainfall to the area just above Tarbela. In September, with the cessation of summer rains and the end of the snow melting, the river falls rapidly. The flow diminishes further during October to the low winter flows (Fig. 3).

The river slope is steep in the reach above, through and below the reservoir area. The average slope is about 8 feet per mile, but varies, over short reaches, from 6 to 11 feet per mile.

The sources of sediment in the Indus basin above Tarbela have not been localized. The mountainous, lightly forested or barren areas of the upper Indus basin appear to be undergoing heavy weathering under the severe climatic conditions of freezing and thawing, exposure to heavy snowfall, and the action of glaciers. Sand and gravel deposits occur along the river banks. Many of these deposits are alluvial, some may be deposits dropped by local nallahs, and many have their source in the steep barren hillsides along the river which appear to be standing at the angle of repose. No information is available about the relative amounts of sediment contributed by the various tributaries.

The Sediment Load

An estimate of the annual load of sediment transported by the Indus was derived from measurements of sediment concentrations, and from river discharges. River samplings taken over a wide range of discharges were analyzed for sediment concentration, from which the daily sediment load was computed. The relationship of daily load to river discharge, derived from these determinations was then combined with the long-term record of daily flow to yield the total sediment transported over the 92-year period of record from 1868.

Some sampling of sediment in the Indus near Darband was carried out in 1954 and 1955. While these early measurements provided helpful data on the concentrations of suspended sediment and the proportions of sand, silt and clay forming the sediment, the equipment was not suited to the conditions, especially during the flood periods of great depths and high current velocities, and the samplings were not wholly adequate. A new series of measurements started in mid-1960 was made with improved equipment and methods, but not until 1961 was the combination of equipment, method and freqnency of observation such as to yield properly representative data.

The improved samplings during 1961 were made daily from mid-May through October, with only a few brief interruptions, and with less intensive during the low-flow period after October. The observations were made at 3 depths at each section, namely 2 feet below the surface, mid-depth, and 2 feet above the bottom. The 3 samples at each depth were combined and then analyzed to determine concentrations in parts per million, and to give the grain size distribution of the suspended sediment. The measurements are continuing in order to confirm the data obtained, to extend the range of discharges sampled, and to reveal any long-term changes in sediment transport.

The samplings have been made from a cableway across the river at Darband, some 20 miles above the dam site at Tarbela. At Darband, the river is confined in a single deep channel, with no overbank flow except in the highest floods. The flow velocities are quite high, reaching 15 feet per second during high flows. Sampling is more difficult, and probably less accurate, at these high velocities. In spite of a very heavy weight on the equipment, the cable carrying the equipment is deflected downstream at a large angle from the vertical, and accurate location of the sampling bottle, especially at the deeper depths, is difficult if not impossible. At high discharges, the river depth at Darband approaches 100 feet. The high velocities do have an advantage which tends to offset some of the difficulties: a maximum of sediment is in suspension, and the great turbulence must keep the sediment well distributed in depth, so that inaccuracies of positioning of the sampling equipment are perhaps less serious than they would otherwise be.

The suspended load observed at Darband consists of clay, silt and sand, the particle sizes being defined by WASID as: less than 0.0055 mm ;

from 0.0055 mm to 0.044 mm ; and from 0.044 mm to about 1.0 mm ; respectively. The clay portion is small, about 8% of the total, the silt portion is about 29%, and the remainder, 63%, is sand. Figure 4 shows a typical size distribution curve. The samplings taken at Darband show that both concentration and size distribution are fairly constant with depth. Occasional samplings, unsually those with higher sediment concentration, show a greater fraction of sand in the samples taken close to the stream bed.

The sediment rating curve, or relationship between discharge and daily sediment load, as determined from the 1961 data, is shown on the log-log plot of Figure 5. Each plotted point shows how much sediment was actually being carried by the river at the time of observation. It does not show how much could have been carried, but reflects only the amount of sediment that was supplied to the river and was carried by it. The horizontal spread among the plotted points on Figure 5 shows that at times the load was much less than usual, at other times, perhaps because of some local upriver cloudburst or the rapid collapse of a heavily undercut river bank, the sediment load was much greater than usual, the spread being of the order of 4 to 1. The plotted curve is not an envelope but has been located to give weight to all of the points.

It may be inferred from the range of loads transported at any given discharge that in general if more sediment were supplied, the river could transport much heavier loads than it usually does. Expressed differently, the river has excess transporting power — it is not "saturated" — and presumably could transport the same load of sediment at a flatter river slope and slower flow velocity. The significance of this fact will be seen in the subsequent discussion of how the sediment will deposit in the reservoir and how the delta at the head of the reservoir will develop.

The total transport of sediment in any period can be obtained by converting the daily discharges of the period to daily sediment loads by means of the sediment rating curve. This was done for 92-year period 1868 to 1960, using the discharge records at Attock converted to Darband, and the sediment rating curve of Figure 5. Over the 92-year period the average annual suspended sediment load was found to be 360 million tons per year.

It is also of interest to determine what fraction of the total average sediment load is carried by each range of discharge. This was done by combining a flow-duration curve and the sediment rating curve. Figure 6 shows the amount of sediment carried by the flows in each discharge range in an average year. Figure 7 is based on the same data and shows the total amount of sediment, expressed as a per cent of the average annual load, which is transported by all the daily discharges smaller than a specified discharge. It will be seen, for example, that all of the daily discharges below 150,000 c. f. s., i, e., the discharges occurring for some 80% of the time, transport only about 9% of the total load of sediment.

Thus, 91% of the sediment is carried during about 20% of the year, or a period of less than 2-1/2 months.

Some samplings have been made of Siran river at Thapla. This tributary enters the Indus within the proposed reservoir area and downstream of the sampling station on the Indus near Darband. The Siran observations do not yield a relationship as well-defined as that for the Indus, largely because of the more rapid fluctuations in discharge of the Siran. The annual sediment load of the Siran works out at about 1% that of the Indus, roughly the same ratio as the annual discharges of the two rivers and in any event an almost negligible amount.

No measurements or estimates of the bed load in the Indus nor any samplings of the moving bed material have been made at any time. Indications are that the amount of bed load is small, and it was not considered necessary at this time to undertake the elaborate program which has been necessary to carry out actual measurements.

Samples of river bed and valley floor material taken in the area near the Bara Axis dam site show about 75—80% cobbles and gravel having particle sizes above 10 mm. and 15—20% fine sand having particle sizes smaller than 1.0 mm. There is very little coarse sand and fine gravel in the size range 10.0 to 1.0 mm. Typical size distribution curves are shown in Figure 8.

The Reservoir

The planning studies for a reservoir at Tarbela have investigated three sizes of project. The following description pertains to the intermediate size, a reservoir which would have a gross storage capacity of 7.8 million acre-feet, and a dead storage of 1.8 million acre-feet. The reservoir would extend more than 45 miles up the Indus, and its upper reaches would be very narrow (Fig. 9). The maximum reservoir depth, at the dam, would be nearlly 400 feet. Pertinent elevations would be as follows :

Top of gates	elev. 1490
Spillway crest	elev. 1440
Proposed minimum drawdownlevel	elev. 1300
Irrigation outlets	elev. 1200
River bed at dam, approximately	elev. 1100

The reservoir would have two arms, the main one in the Indus valley and a smaller arm running some 12 miles up the valley of the Siran. The live storage capacity in the Siran arm would be about 15% of the total live storage.

The reservoir would be operated for the benefit of irrigation. It would fill rapidly during the early part of the flood season, usually in late June or early July, and there would ordinarily be surplus water discharging over the spillway in July, August and early September. The reservoir would usually start to empty in late September. In most years, the draft on storage would be through the winter, and the heaviest draft, and the most rapid drop in reservoir level would occur in April and May, and perhaps into June.

There would be a limited choice possible in the schedule of reservoir filling. The reservoir could be filled at the start of the flood season, and kept full thereafter, or it could be kept at an intermediate level for a while and topped out toward the end of the season. The program of filling might have an influence on the sedimentation in the reservoir. This will be discussed later.

Deposition in the Reservoir

Deposition of sediment in the Tarbela reservoir would take place in the form of a conventional underwater delta, starting at the upstream end of the reservoir where the velocity and transporting power of the incoming stream would begin to decrease. As the coarser particles settled out and the delta started to form, the stream would carry the finer material over the top of the newly formed delta and drop it at the front of the delta, where the velocity would be less. In the case of a river entering a narrow reservoir, such as Tarbela at its upstream end, the delta would spread and generally occupy the entire width of the valley. Seasonally, as the reservoir was drawn down, the top surface of the delta would be eroded slightly but, in general, the stream would cut its way into a single channel through the delta. When the reservoir was again full, and large quantities of sediment were being brought into the reservoir, the channel through the delta would tend to refill, and the delta building would proceed. The top of the delta would generally remain below the maximum reservoir level. New material brought in would be carried over the top of the delta and dropped over the front of the delta into the deeper water. Channel cutting during drawdown periods would re-deposit the delta material farther into the reservoir and would discourage any accumulation of material upstream of the original head of the reservoir.

The finer particles, silt and clay, would be carried farther into the reservoir. Density currents may be expected to carry some clay into the deeper parts of the reservoir and down to the dam. In asmuchas the outlets would be in the spillway which would be located in a valley around the left abutment of the main dam, and would have to be some 100 feet above the river bed, there is little likelihood that the density currents would retain their integrity to rise and flow out of the outlets, at least until the river bed above the dam had filled to the general level of the outlets. These currents would probably dissipate in the depths of the reservoir, and the suspended clay would be deposited in the deeper portions of the dead storage space.

After the delta had advanced and filled the narrow upstream end of the reservoir, above Kirpalian, the delta growth would be less predictable. As the incoming stream entered a wider reservoir, the delta might grow for some time as a narrow finger along one side of the reservoir. Sooner or later an avulsion would occur — breakthrough of the stream into the quiet reservoir alongside the delta finger — and the growth would take place in a new direction. This random growth of the delta might temporarily create isolated pools, but, over a period of time, as a result of avulsions and the active re-working which would take place when the reservoir level was lowered, these pools would be filled, and the deposits would work inexorably toward the dam.

In the case of the Tarbela reservoir, about 15 per cent of the total storage capacity would be located in the Siran valley. This portion of the reservoir would be the last to fill with sediment. It is probable that at such time as the Indus valley section of the reservoir became nearly filled with sediment, most of the incoming sand would be transported to the dam and through the outlets or over the spillway, and only fine materials, some silt and clay, would slowly intrude into the Siran area. Thus, the last portion of the reservoir to be depleted, about 1 MAF on the Siran, would be depleted much more slowly than the main body of the reservoir located on the Indus.

The usable storage in this branch of the reservoir might be partially lost, however, when the delta in the Indus valley had advanced past the mouth of the Siran, except as the annual drawdown would serve to erode and maintain an effective channel from the Siran area down to the spillway and outlets.

The possibility that delta growth at the head of the reservoir might extend upstream as well as downstream and thereby reduce the quantity of sediment deposited within the reservoir has been investigated. There is no basis on which to expect this type of deposition. It appears that for a combination of reasons only a negligible deposit would occur upstream of the reservoir. The stream is not "saturated", that is, it can carry more sediment than it ordinarily does and, hence, it would not drop its load of sediment immediately when the slope and velocity were reduced at the head of the reservoir. Rather, the material would be carried along into the reservoir area. More importantly, the annual reservoir drawdown would create steep slopes and high velocities over or through the newly formed delta area and the deposits would be heavily eroded and redeposited in the deeper portions of the reservoir.

On a very long-term basis, in terms of almost geologic time, it is likely that there would be upstream aggradation above the Tarbela reservoir. The reason for this is as follows : The material of the valley floor is a mixture of sand and cobble-gravel with many large particles up to boulder size. These large particles probably do not move a great deal, or perhaps move only during rare floods. Thus, from time to time, but infrequently, some of this coarse material would be brought into the reservoir area and deposited on or in the delta at the head of the reservoir. During succeeding periods of drawdown, however, this very coarse material would be undermined, and would gradually work its way into the delta formation, and down toward the deeper part of the reservoir. After many years, and after the deposits of sediment in the reservoir had reached a more-or-less steady state, with a small residual reservoir capacity maintained just above the dam, the possibility of further re-working of the coarse material would diminish, and the rocks and boulders would start to accumulate. As they accumulated, at some point in the reservoir, and spread over the width of the reservoir as the drawdown channel worked back and forth over the delta-like deposits of sediment, they would tend to form a fixed point in the river profile, with little motion of coarse material passing this point. Thenceforth, the infrequent contributions of coarse material brought down by the occasional floods would accumulate above this fixed point, and gradually the slope of the river bed would tend to return to its present slope, working upstream from the ill-defind "fixed point" in the reservoir. The valley floor, just as at present, would contain some sand and fine material in addition to the coarser cobble-gravel. To the extent that material was deposited in this slowly-rising valley floor, it would not be transported into and through the reservoir. But the whole process would undoubtedly proceed so very slowly that the change would be imperceptible.

The percentage of the incoming sediment which remains in the reservoir is characterized as the trap efficiency.

Previous studies of the trap efficiency of many reservoirs have related this factor to the ratio of annual inflow volume to reservoir storage capacity (Reference 3). On the basis of this ratio alone, Tarbela reservoir might be expected to have an initial trap efficiency of 85 to 90%, decreasing during the life of the reservoir until, with depletion of the reservoir capacity to about 1 MAF, a trap efficiency of about 60% could be expected.

In view of the large physical size of the proposed Tarbela reservoir, it is expected that initial trap efficiencies would be higher than the above-mentioned values which were, in general, derived for reservoirs of much smaller size. The Tarbela reservoir, initially, would be some 47 miles long and nearly 400 feet deep in its deepest portions. The detention time in the reservoir, even for the summer flood discharges, would be measured in days (for example, 6 MAF corresponds to 2,00,000 c.f.s. flowing for 15 days). The entrance to the outlets would be about 100 feet above the river bed, and the spillway crest would be nearly 400 feet above the river bed. Thus, there would be no possibility of sluicing the deep-lying sediment past the dam. At the most, some of the clay fraction of the suspended sediment might be carried through the reservoir by a density current. The clay fraction is about 8% of the suspended load, and only a small portion of this, at best, could be expected to reach the lower end of the reservoir and rise from the river bed to be discharged through the outlets or over the spillway. The large percentage of sand in the suspended load would reduce the through-flow of sediment and increase trap efficiency. Thus, it appears that initially the trap efficiency would be substantially 100%.

As the useable live storage capacity decreased and the detention time shortened and the through-flow velocity increased, an increasing amount of suspended load would be carried through the reservoir. After some time, the deposits would advance down to and past the mouth of the Siran. The Siran basin is isolated from the main reservoir (Fig. 9), and the only silt deposited there would be that left by the small amount of Indus water, less than 1 MAF, which would flow into and fill that basin. The Siran arm of the reservoir would thus show a very slow rate of depletion.

The spillway gates would be 50 feet high. It would feasible, in the later life of the reservoir, to operate briefly each year with the gates all open and large discharges through the outlets and over the spillway, with a view to sluicing out as much sediment as possible and maintaining some undepleted storage at the lower end of the reservoir, generally above the spillway crest elevation.

If this mode of operation could be followed successfully, the trap efficiency of the reservoir would have decreased to a very small value when there was still some usable storage remaining—perhaps 1 MAF or more—and this capacity should remain for a very long time.

For the studies of reservoir depletion which are described below, the trap efficiency was assumed to be 100% until the gross capacity decreased to 4.5 MAF, thereafter to diminish gradually to 60% at the time the reservoir had about 1.5 MAF of remaining capacity, and then to diminish rapidly to zero.

An estimate of the likely rate of depletion of the reservoir capacity as a consequence of sediment deposition was made. The study was based largely on the method described by Borland and Miller (Reference 1). The basic data used for the study were :—

(1) the computed sediment load derived from the sediment rating curve (Fig. 5) and the 92-year hydrograph derived from the Attock record ;

(2) assumed values of the trap efficiency of the seservoir ;

(3) the area and capacity curves for the undepleted reservoir ; and

(4) an assumed density for deposited sediments. The study was made for three sizes of reservoir having initial gross capacities of 6.7, 7.8 and 9.8 MAF, each with a minimum pool level at Elevation 1300. An area-capacity curve is given on Figure 9.

The density of the consolidated sediment deposits was estimated to be 85 pounds per cubic foot on the basis of analyses of the samples. It is possible that the finer silts clays will make an initially very light deposit which, over the years, would consolidate to a higher value. Little evidence could be found in the literature to justify an assumed density greater than 85 pounds.

Depletion studies were made for the three sizes of reservoir investigated, assuming a sediment inflow computed from the flow record. The studies assumed that the initial sediment inflows were those of September 1878 and the subsequent sequence of inflows followed the chronological record after that date.

Curves showing the estimated progress of depletion are shown on Figure 10. The lines indicating decrease of live storage in the early years are not well - defined and are shown dashed. The proportion of sediment which would settle into the dead storage volume depends, among other things, upon the occurrence of submerged density currents and upon the erosin and re-deposit during periods of drawdown of sediment originally deposited in the upper zones of the reservoir. These factors can be estimated only in any approximate way.

The shape of the depletion curves in the final stages of filling is largely indeterminate. The problems of estimating the minimum trap efficiency and the expected slow rate of depletion of the tributary channel storage in the Siran basin have already been discussed. It is probable that a complete loss of storage in the Indus arm of the reserveir could be prevented by annual sluicing through the spillway gates and the outlets. It is reasonable to assume that at least 1 MAF of storage would be available for a long period of years. This is reflected in the curves of fiigure 10, which show the estimated depletion for three sizes of reservoir. The rates of depletion become less well-fined as the reservoir approaches its long-term condition, and the lower ends of the depletion curves of Figure 10 have been shown as dashed lines approaching a storage capacity of 1 MAF. The approximate periods of time which would be required to reach 1 MAF can be stated as 35-40 years, 45-50 years, and 55-60 years, for the 3 sizes of reservoir.

In deriving the rate of depletion of the proposed reservoir, it has been assumed that each cubic foot of sediment, measured in place in the reservoir, would reduce the capacity of the reservoir by one cubic foot. But the density in place of this sediment has been taken as 85 pounds per cubic foot, while the particle density of the sediment is of the order of 166 pounds per cubic foot. Thus, each cubic foot of sediment includes nearly one-half of a cubic foot of pore space, which is potential storage capacity. Whether or not the deposits would retain or give up the pore water is a function of many variables, notably the gradient, the permeability, the distance of travel, and the time available. In estimating the life of the proposed reservoir, no allowance has been made for this possible pore-water or ground-water storage. If such storage were in fact realized, it would tend to make the actual rate of depletion less than estimated and thereby slightly extend the estimated life of the reservoir.

the river would be carrying the sediment brought in by the Kabul, its total load would generally be so much less than heretofore that it would still have erosive power. There are no significant opportunities for sediment replenishment, however, until the river leaves its narrow valley just above Kalabagh. Some erosion could be expected at this and downstream points, diminishing as the successive entering tributaries brought in their sediment loads and thereby increased the total load being carried by the main river.

Long Term Considerations.

The major reason for the rapid depletion of the proposed Tarbela reservoir is the fact that it would retain the sediment from the entire annual flow of the Indus, averaging 61 MAF, instead of from the few MAF needed to fill the reservoir.

If it were possible to bypass the reservoir so that most of the sediment-laden water would pass downstream, and only enough water were diverted to fill the reservoir each year, then the life of the reservoir would be extended by a large factor. A reservoir of 6 MAF live storage capacity would last at least 10 times as long, if it received only as much water as was needed to fill it.

Bypassing a river as large as the Indus cannot be done readily. The same purpose can be accomplished, however, if storage capacity located away from the river can be developed, that is, off-channel storage, and the water to be stored diverted into it. The prospective short life of any storage located directly on the Indus makes it imperative that any project *on* the Indus should be carefully examined to see whether it can be replaced by or become part of a project located *off* the Indus.

Interestingly enough, the development of off-channel storage is an adaptation of one well-tested solution to the canal sediment problem. Just as with the canals, sediment would be *excluded* from the off-channel storage reservoir, except as it must be accepted with the water used to fill the storage.

Fortunately, it appears that the Tarbela project may perhaps provide the first phase of a long-range project providing almost sediment-free storage in one or other of the adjoining valleys tributary to the Indus near Tarbela. While this off-channel storage will have tremendous significance in preserving the value of the Tarbela project, it does not remove any of the urgency from continuing studies of the sediment problem at Tarbela, or from consideration of any and all means to extent the life of Tarbela itself.

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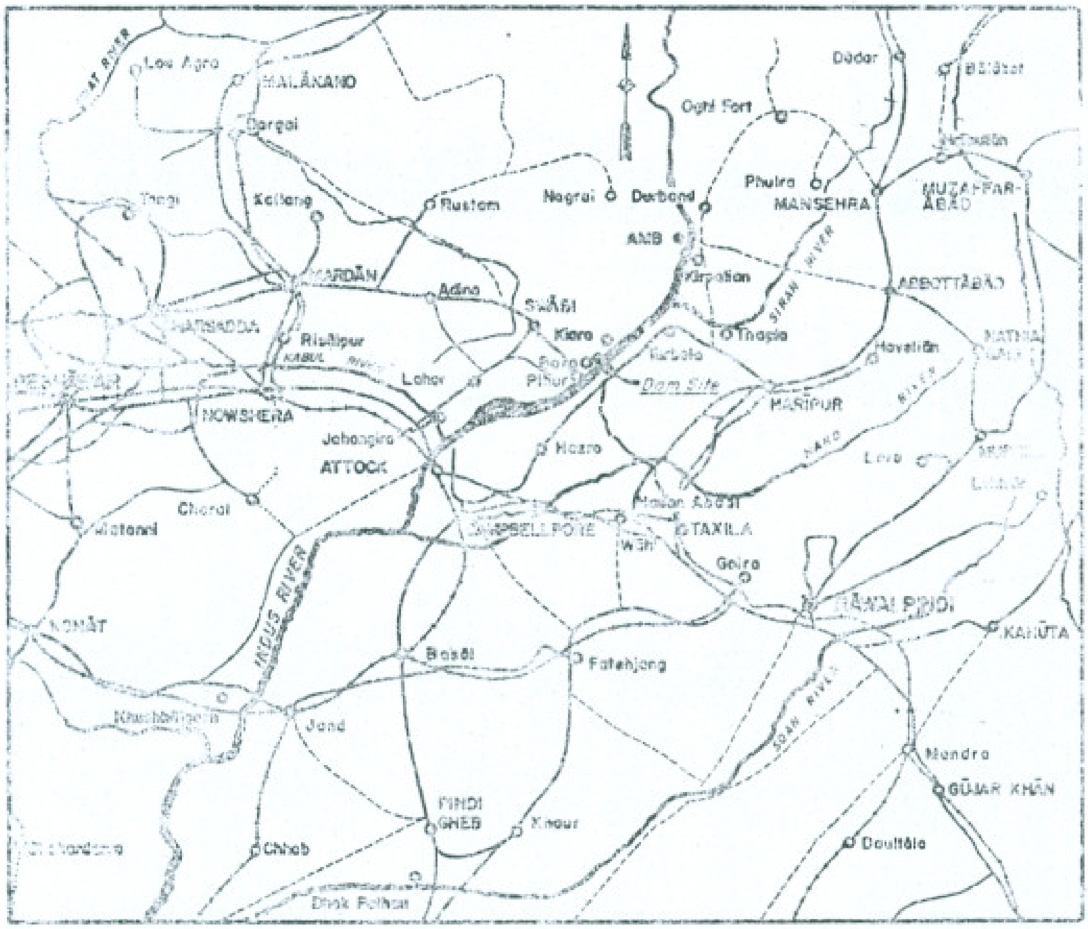
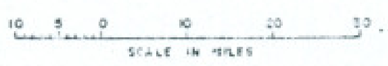
FIG I
THE INDUS BASIN



MALĀKAND
Dargai
Rustam
Nagrai
Darband
Oghi Fort
Dādar
Phulra
MANSEHRA
MUZAFFAR-ĀBĀD
AMB
Kirpalian
ABBOTTĀBĀD
MARDĀN
Adina
SWĀBI
Kiara
Thapla
Havelian
Risālpur
KABUL RIVER
SIRAN RIVER
Dam Site
HARIPUR
NOWSHERA
Jahangira
ATTOCK
Hazro
Cherat
TAXILA
Gaira
RAWALPINDI
KAHŪTA
INDUS RIVER
Basāl
Fatehjang
Jand
SOAN RIVER
Mandra
GŪJAR KHĀN
PINDI GHEB
Chhab
Doultāla
Dhok Pathan



10 5 0 10 20 30
SCALE IN MILES

FIG 3

TYPICAL HYDROGRAPHS — INDUS RIVER AT TARBELA

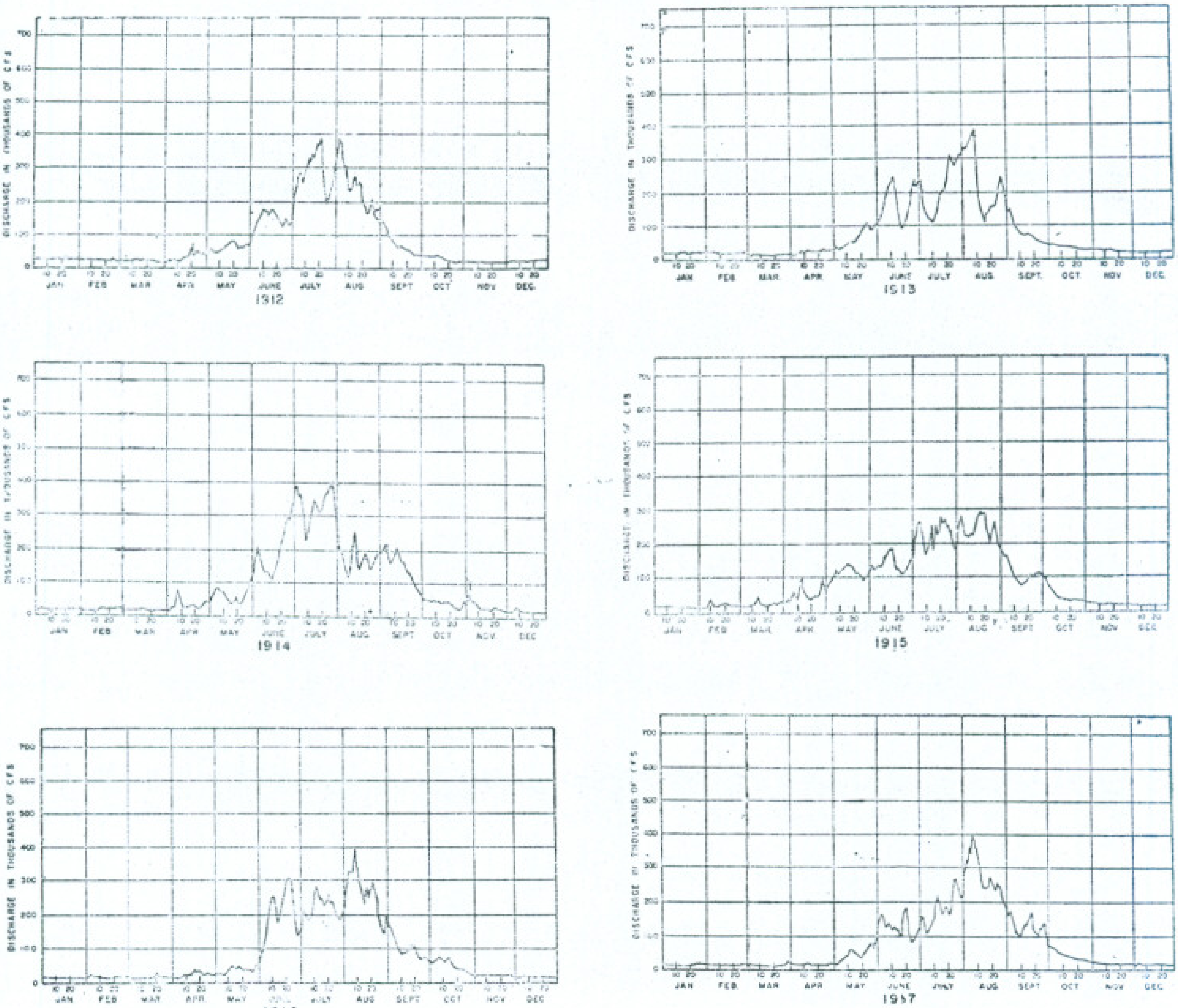


FIG 3

TYPICAL HYDROGRAPHS —
INDUS RIVER AT TARBELA

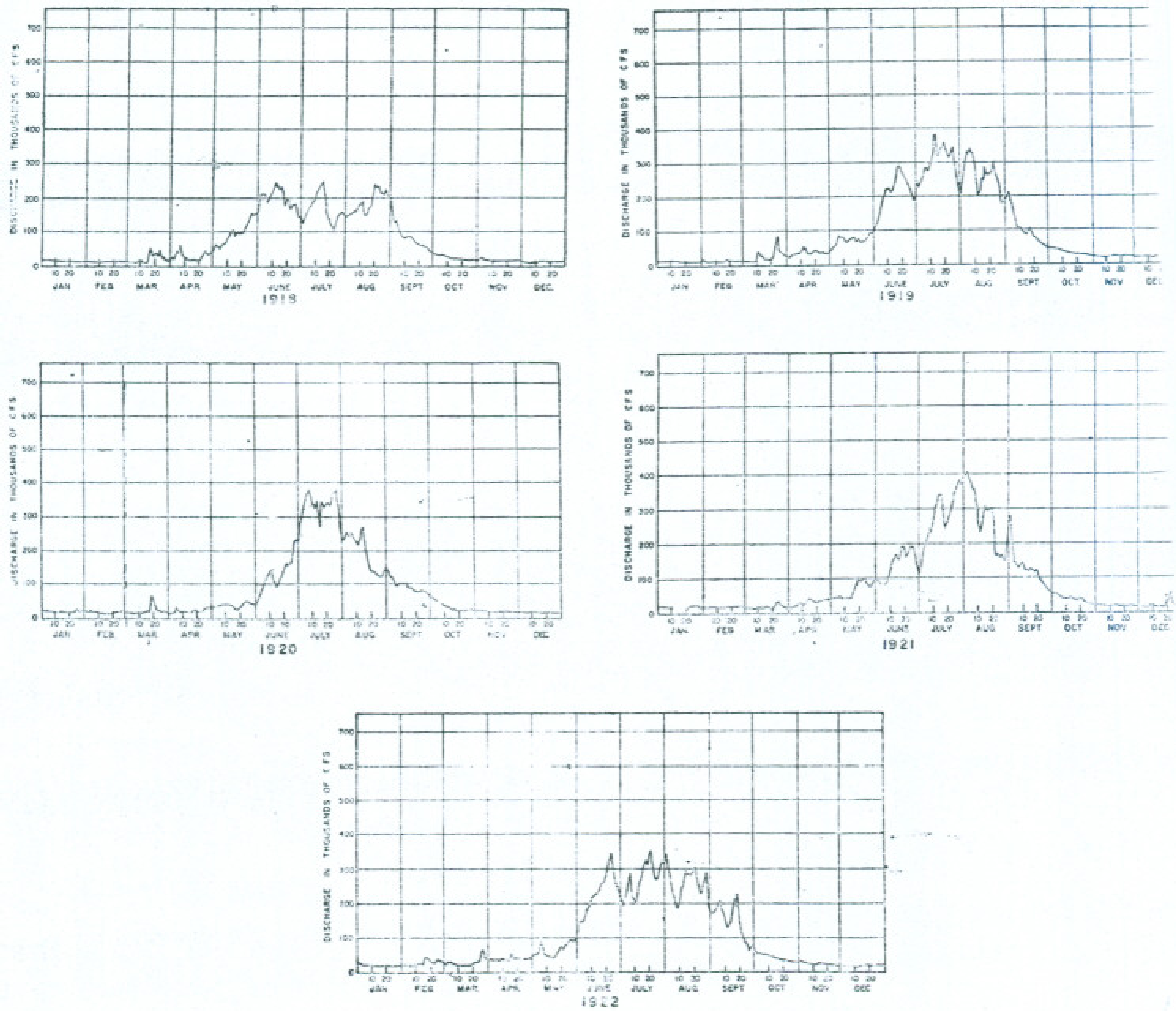
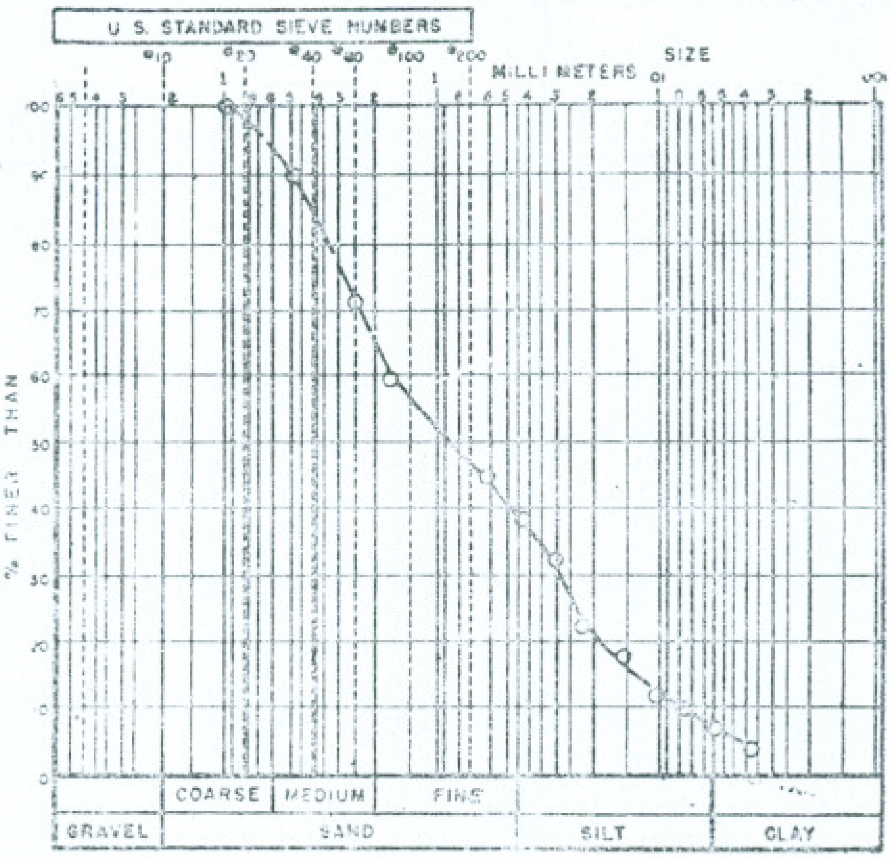


FIG 4

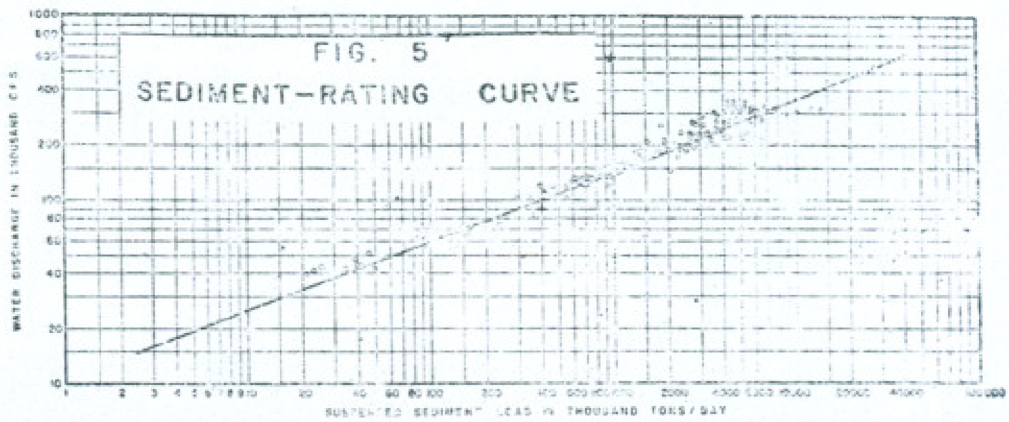
TYPICAL GRAIN SIZE DISTRIBUTION

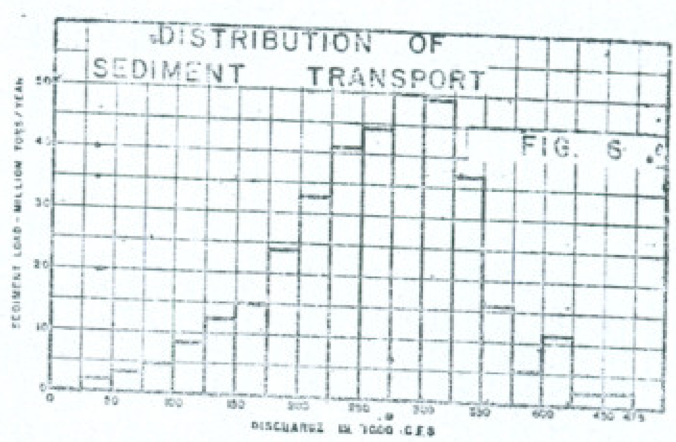
SUSPENDED SEDIMENT - INDUS NEAR DAR BAND

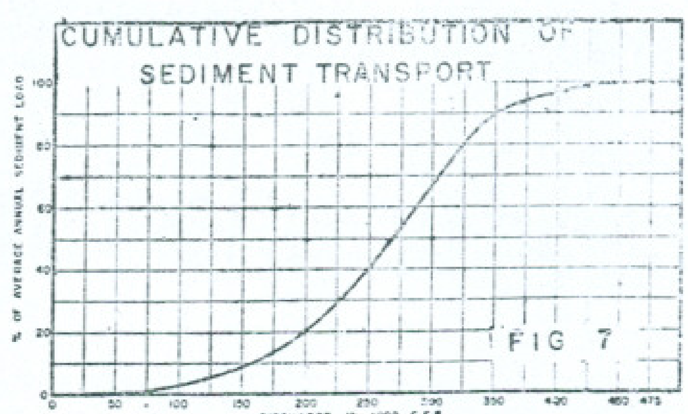


REMARKS

Composite of three samples taken at mid-depth on 14 July 1961
Indus River near Darband
Discharge 270,000 cfs







SEDIMENTATION OF MANGLA RESERVOIR I

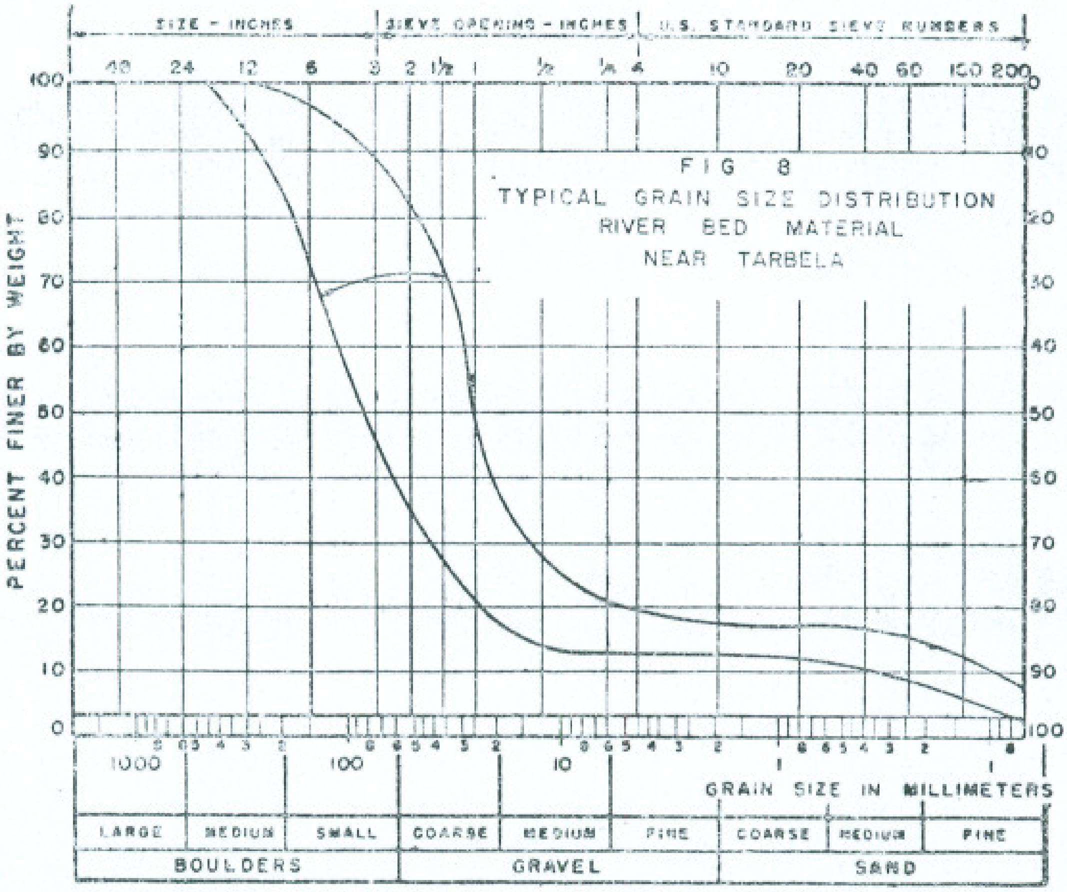


FIG 8
TYPICAL GRAIN SIZE DISTRIBUTION
RIVER BED MATERIAL
NEAR TARBELA

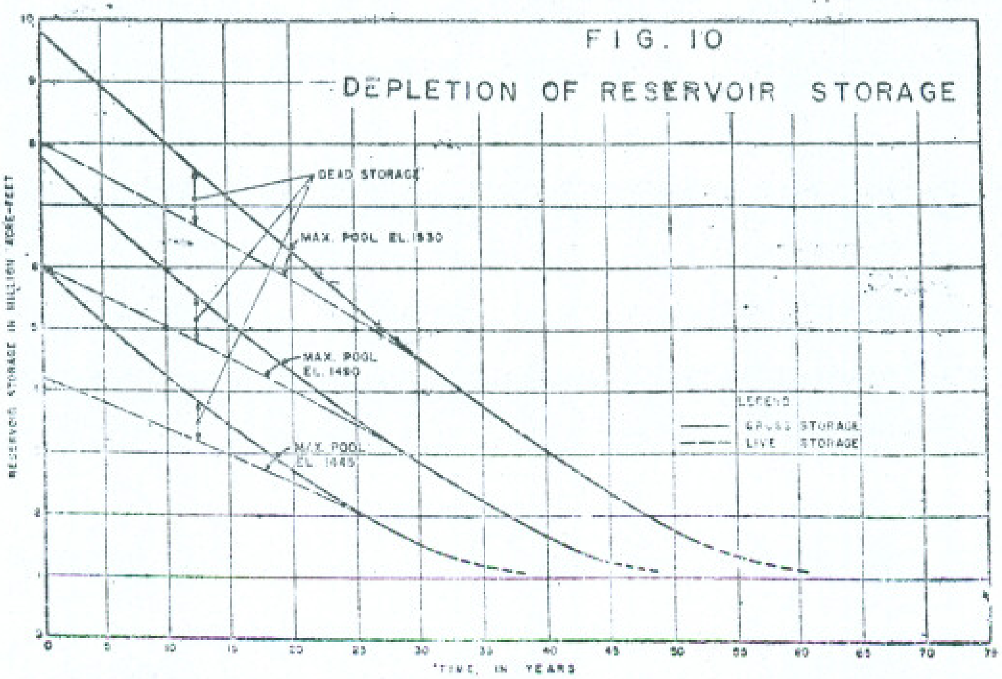


FIG. 10
DEPLETION OF RESERVOIR STORAGE

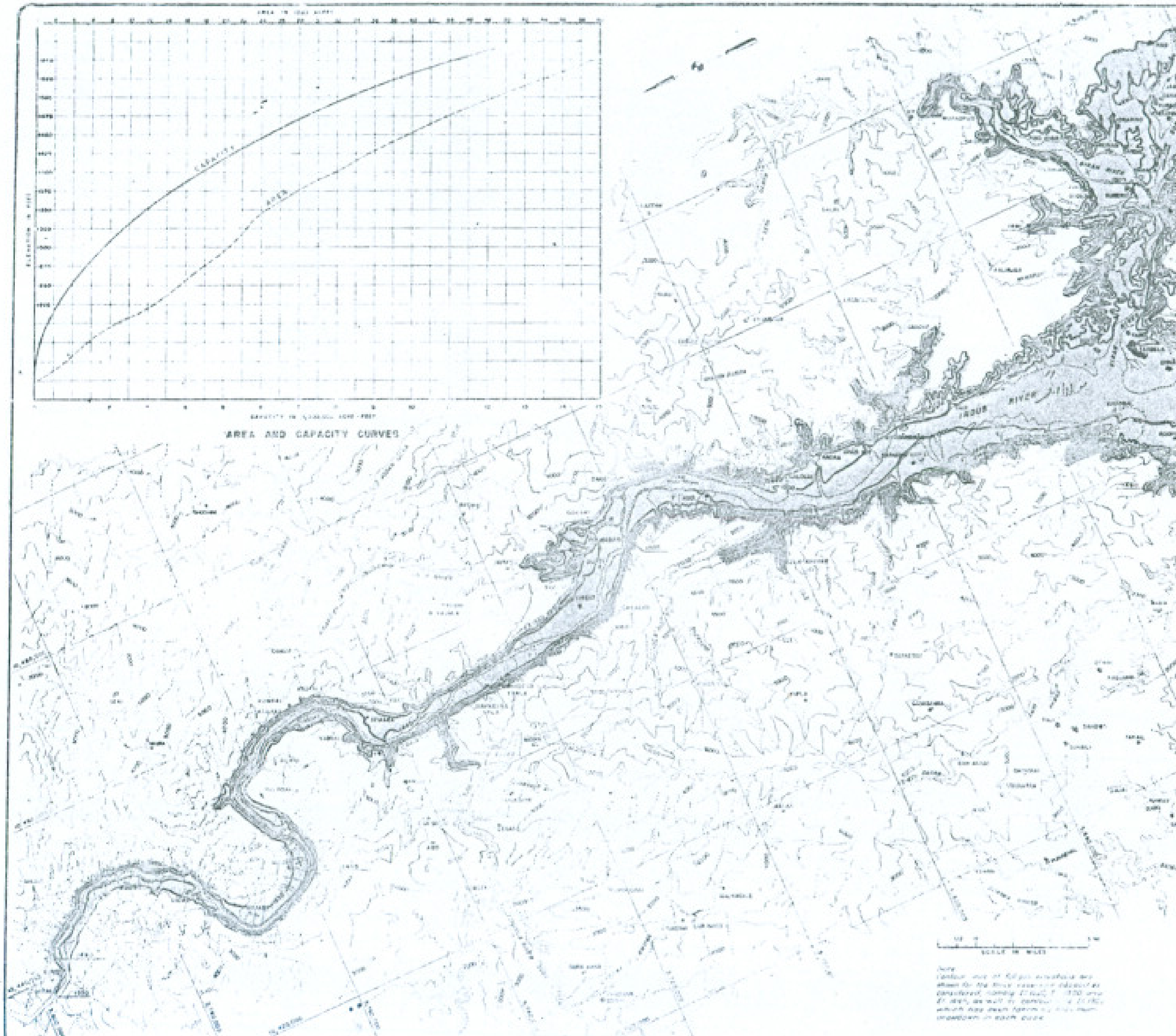


FIG 9

RESERVOIR MAP