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SILTING OF RESERVOIRS

BY

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FOREWORD

The subject " Silting of Reservoirs " has been on the agenda of the Central Board of Irrigation and Power since 1939 and has been discussed in the Annual Meetings of the Research Committee and the Board. It has assumed greater importance now due to the large number of storage schemes under construction and contemplation in India, as it is linked with the life of the reservoirs. Shri A. N. Khosla has given particular attention to this subject and published two papers in 1940 and 1941. Since then, some work on the subject has been done in the Irrigation Research Stations, and some data has been collected from Indian rivers and Reservoirs.

In view of the importance of the subject in the successful development of river valley schemes and the wealth of information contained in Shri Khosla's papers and the data since collected, the Executive Committee of the Board requested Shri Khosla to prepare a publication of the Central Board of Irrigation & Power on the subject.

Shri Khosla has compiled the information available on the subject in the form of this publication and it is hoped that besides being of value to the profession, it will help in further work on the subject at the various Stations.

The Central Board of Irrigation & Power is grateful to Shri A. N. Khosla and others who have collected the data on the subject and are helping in advancement of this important subject further. It is hoped the information contained in this publication will be useful to those interested in the study of the subject and will supply the need of the Indian Engineers employed on construction of river valley schemes. The author has stated that the treatment of the subject in the publication is by no means exhaustive and up-to-date. It is however, hoped that in view of the vigorous research in hand on the subject in various research and field stations in India, it will in the near future be possible to bring out a more comprehensive and upto-date edition of this publication.

S. L. MALHOTRA,

Secretary,

Central Board of Irrigation and Power,

PREFACE

As Superintending Engineer, High Dams Circle in the Punjab, in 1939, the author was faced with the problem of "Siltling of Reservoirs" in dealing with the designs of Bhakra, Balehu and other storage dams in the Punjab. During his visit to the United States of America from April to October 1939, he made a special study of the problem in its relation to storage reservoirs in that country. On return to India, he initiated sediment studies on several streams in the Punjab. Many of these studies are still continuing. In 1945, soon after assuming charge as Consulting Engineer and Chairman, Central Waterways, Irrigation and Navigation Commission—now Central Water and Power Commission—the author initiated similar sediment studies on the Kosi and Mahanadi rivers and later on the Tapi and other rivers.

The author submitted two papers on the subject of Siltling of Reservoirs to the Central Board of Irrigation, one in 1940 and the other in 1941. This subject has since been widely discussed in the Central Board of Irrigation and elsewhere. This was one of the subjects discussed at the fourth plenary session of the International Commission on Large Dams held in Delhi in January 1951.

There has been a very considerable and insistent demand in India for authentic information on the subject, particularly that relating to Indian rivers. This paper has been written primarily to satisfy this demand and in the hope that it will facilitate and encourage further exhaustive and scientific study of the subject.

In recent years, considerable amount of work has been done on sediment studies of various rivers in India and abroad and much useful data has become available in different parts of the world. Not all of this data has, however, been available to the author; nor had the author sufficient time to make an exhaustive study of what was available.

An attempt has been made in this paper to present the problem of 'Siltling of Reservoirs' in its fundamental aspects and to draw attention to certain salient features as well as some current misconceptions. One conclusion appears to stand out and that is that the silt yield of a catchment is essentially a function of its area and geological formation.

The treatment of the subject in this paper is by no means exhaustive, nor quite upto date. The only justification for its publication at this stage is, therefore, to meet the persistent demand of irrigation engineers for the maximum available information on the

subject and for conclusions, though tentative, based on an analysis of this information. The study of the subject is being vigorously pursued in many research centres and field stations in India and abroad and it is hoped that based on these a more comprehensive and upto date publication will be brought out by the Central Board of Irrigation in the not distant future.

The literature in U.S.A. has been obtained through the courtesy of the Bureau of Reclamation, Geological Survey, Soil Conservation Service, Forest Service, Corps of Engineers and other organisations. Acknowledgments are due to all of these organisations. In particular, the author owes a debt of gratitude to Mr. Michael W. Straus, Commissioner and the Bureau of Reclamation for their generous help in supplying literature and providing facilities for establishing contacts with the research and field workers.

Acknowledgments are due to the Irrigation Research Division Poona, Bombay State, for the information on reservoirs in that State mentioned in Chapter 2, Part A, and Shri B. P. Saxsena, I.S.E., for his contribution in respect of storage reservoirs in Uttar Pradesh reproduced in Chapter 2, Part B.

The author is particularly indebted to Dr. R. C. Hoon who has done very considerable original work in connection with the silt problems of the Mahanadi and Kosi rivers, the data in respect of which, as given in the text, are mainly derived from his work. He has given many original and useful ideas on the technique of observations, field equipment and method of analysis. He has also assisted the author in preparing and editing the text.

The author is equally indebted to Shri N. D. Gulhati, I.S.E., Chief of Natural Resources, Planning Commission, Government of India and formerly Secretary of the Central Board of Irrigation, for the immense pains he took in compiling the original text from the various papers and discussions contributed at the meetings of the Central Board of Irrigation; and to Shri M. L. Madan for his general assistance. Acknowledgments are also due to Shri S. L. Malhotra, I.S.E., the present Secretary of the Central Board of Irrigation and Power for his valuable assistance in finalising the text and its printing.

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INTRODUCTION

The problem of silt, as far as it related to canals, has been investigated on an extensive scale throughout India and more particularly in the Punjab ever since the days of Kennedy but that relating to the silting of reservoirs does not seem to have received much attention in this country. It is satisfactory to note, however, that the Central Board of Irrigation and Power (India) has included this problem as one of the subjects for investigation. A sub-committee was appointed by the Board to draw up a note on the factors to be considered for a systematic study of the silting of reservoirs.

In compliance with a resolution passed on the subject of Silting of Reservoirs by the Central Board of Irrigation in 1939, Appendix (Para 1), and the instructions issued by it, *vide* Appendix (Para 2), information about silting of reservoirs has been collected by the Poona and United Provinces (now Uttar Pradesh) Research Divisions regarding the old reservoirs in their states. The data collected for the existing storage reservoirs in the Bombay and Uttar Pradesh States as abstracted from the Annual Reports of the Poona Irrigation Research Division and from the note of silting on reservoirs by Shri B. P. Saxena, I.S.E. are given in Chapter 2. The data for some of the reservoirs in the Central Provinces and Berar (now Madhya Pradesh), Hyderabad and Baroda is also contained in that Chapter.

The problem has been subjected to a good deal of sustained scientific study in other parts of the world, notably, the United States of America. The Bureau of Reclamation hydrologists with the help of Geological Survey and Navy department are using the Navy techniques, which comprise under-water Photography, "supersonic soundings and coring *etc.*, developed during war time to locate submarines and sunken ships and to chart the ocean floor, to probe the bottom of reservoirs. Some very valuable work has been done in Egypt in connection with the Aswan Reservoir, and in South Africa in connection with four reservoirs on the Sundays and Great Fish rivers. In the Punjab also, silt sampling has been done on the River Sutlej at Bhakra in connection with the Bhakra Dam since 1916 and on the Beas at Balehu dam site during the summer of 1939.

An extensive programme of silt investigations has been undertaken since 1946 by the Central Waterpower, Irrigation and Navigation Commission (now Central Water and Power Commission) in connection with the Hirakud and other proposed dams on the Mahanadi River in Orissa and the proposed dam on the Kosi river in Bihar and Nepal and later on some other rivers also.

A correct knowledge of the probable rate of silting of reservoirs is of vital importance to any undertaking requiring the construction of a storage dam. The height of the dam is determined by a consideration of the necessary useful storage and the additional capacity required for silt reserve. If a reservoir is constructed for purposes of irrigation, the silting, if not adequately provided for, may start depleting the useful capacity of the reservoir just when the areas dependent on it, approach their maximum development. This may, not only impair the financial prospects of the scheme, but may spell disaster to the colonies and communities which owe their existence and subsequent prosperity

to such undertakings. In the case of reservoirs for flood control, the depletion due to silting will progressively reduce their flood absorption capacity and to that extent, expose the country-side to increasing flood damage. In the case of those for hydro-electric development, this depletion will interfere with the equalisation of supplies which enables the generation of the maximum of power for any given stream flow.

In view of the stakes involved, the subject of silting of reservoirs assumes great importance and justifies amply a programme of systematic and thorough investigation. Silt experiments should be undertaken and continued for a number of years at all the likely storage sites in India. Information should, at the same time, be collected from all existing reservoirs in India and other countries and carefully analysed.

A large number of dams have been visited by the Author since 1939 in the United States of America, Canada, Europe and Africa. The information gathered locally as well as that from published and un-published literature with regard to the silting of reservoirs in those countries has been included in this book.

The results of silt investigations carried out on the Sutlej, the Mahanadi and the Kosi rivers for the Bhakra, Hirakud and Kosi dams respectively, have also been included.

The literature referred to in the Bibliography has been freely drawn upon and referred to in the text.

CHAPTER I

Catchment, Stream Flow and Silt

THE ORIGIN OF SILT

The term silt, as used in this book, is stream-born material derived from the disintegration of rocks. The main factors causing disintegration are the diurnal and seasonal variations in temperature, wind and rainfall and the chemical agencies in air and water. Disintegration, erosion, transportation and sedimentation are the various stages leading to silting.

Generally speaking, sedimentary rocks such as sand-stones, clays, and shales are subjected to much greater disintegration than igneous rocks. Forest and other vegetable cover hold the soil in place effectively against ordinary rains but are relatively ineffective in preventing erosion by intense rainfall.

The processes of disintegration and its extent in relation to geology of the catchments concerned have been well described by Herman Stabler ⁽³⁵⁾. According to him, two processes, viz. weathering (disintegration in place) and corrosion (the tearing away or placing in motion of disintegrated material), are involved in the origin of silt and the speed of the first of these processes is materially affected by the nature of the country rock. Igneous rocks, in general, are hard, dense, and crystalline and they weather slowly. The older sedimentary rocks are likewise relatively dense and offer resistance to weathering. The younger sedimentary deposits, particularly recently laid alluvium, are especially susceptible to rapid weathering. Consequently, other things being equal, regions of igneous and precarboniferous rocks are regions of clear water streams and regions of recent sedimentaries and valleys filled with alluvial deposits are most likely to give rise to streams heavily laden with silt.

Among the younger sedimentary rocks, difference of texture and cementation are reflected by differences in speed of weathering. Loosely cemented sand-stones and friable sandy shales are readily susceptible to weathering and corrosion and are prolific producers of silt. For instance, Holecek ⁽¹⁴⁾ has described that the tributaries to the right of the Slevakian Carpathian mountain carry lot of sediment since they come from the outer fly-ash zone and the tributaries from the left bring almost clear water since they travel through dolomite and limestone regions.

The chemical composition of rock material is a factor in the silt problem. Rocks, that contain high percentages of aluminium silicate, weather into clay with fine flaky particles readily susceptible to corrosion and water transportation. Regions of such rocks are likely to be regions of cloudy, although, not necessarily heavily silt-laden streams.

Vegetation and incidence of climate are other important factors in the weathering of rocks and in the availability of weathered material for water transportation. By disruptive action of roots and chemical action of organic solvents, vegetation aids weathering and adds to the volume of material suitable for transportation as silt and to the dissolved load of streams. By protection of the land surface from action of wind and water it retards or

prevents silting material from corrosion and thus tends to avoid the overloading of streams with suspended matter.

Rainfall, if it comes in a series of erratic cloud bursts, will accelerate erosion and transportation of silt. If, however, it is gentle and spread evenly over the catchment area and over the seasons, weathering, erosion and transportation of silt will be reduced owing to the sustained vegetal cover made possible by such distribution and the stream supplies will be less heavily silt laden.

An arid climate will cause excessive weathering and torrential rainfall will carry this excessive weathered material and result in heavy though sporadic flows of silt in streams.

Snow-fed supplies do not appreciably add to the silt load of a stream but supplies derived from rainfall do, more or less, in proportion to such supplies. Glacial supplies are silt laden.

Steep hill sides will part with debris much more quickly than gently sloping ones.

The above factors are a general guide to the relative degree of weathering and corrosion in various types of catchments. For determining the rate of silting of any particular reservoir, a number of other factors have to be considered. These are the areas of the catchment basin, the annual run-off, storage capacity, the period of storage in relation to silt load of the stream, the location of sluices and outlet works and the method and purpose of release of supplies through the dam.

SILT LOAD OF STREAMS

The detritus carried by streams is of two kinds (a) suspended load, *i.e.*, silt carried in suspension by water in a stream and (b) bed load, *i.e.*, the material which rolls along the bottom of the stream by the action of flowing water. The relative proportion of these has been the subject of much controversy but no satisfactory figures are yet forth-coming. In most cases, the bed load is considered to be small.

Suspended Load.—The magnitude of suspended load is capable of fairly accurate measurement by standard methods of sampling and analysis. From a large number of experiments carried out in the United States of America (12) it has been found that (a) a sample taken from six-tenth depth gives the mean percentage of silt in the vertical within the limits of permissible error: and (b) that the mean of the results obtained from three tests made at the centre of the section and at distances of one sixth the width from each edge of the stream, affords mean percentages for the cross section.

Similar experiments carried out in Egypt (27) on the Nile at Halfa, Dakka, Aswan and Gaafra have indicated that (a) the clay and silt are fairly constant throughout a vertical, the variation being almost entirely in the coarser sand portion of the suspended solids, (b) the mean concentration at half depth bears a constant ratio to the mean concentration in the water passing the whole cross section of the river. This ratio comes to 0.984 with an average departure of 0.026.

Bed Load.—No practical means of measuring bed load have been devised. Fortier and Blaney (12) estimated the bed load of the Colorado River at Yuma as 20 per cent. of the suspended load. * Humphreys and Abbot put it at 11 per cent, for the mouth of the Mississippi. Follett from a study of the Rio Grande

believed it to be 25 per cent. Davis, as a result of studies of San Carlos River at Costa Rica arrived at percentages between 1.7 and 7.1. Maddock and Borland (18) consider that the material transported along the bed may vary between 2 to 50 per cent. of the total silt transported. They are of the opinion that transport along the bed increases when the material is fine in composition, the material in suspension is less, the average grain-size of the suspended material approximates to that of bed material and when the bed either increases or decreases in depth; any change of any of these factors in the opposite direction tend to decrease the transport along the bed.

Stevens (29) analysed certain data and worked out as a very rough approximation that in the Coeur d' Alene River at Rose Lake Idaho, the bed load and suspended matter were equal but that a ten per cent. error one way would account for the entire silt deposit as bed load and a ten per cent. error in the reverse direction would account for the entire silt deposit as suspended load only. According to him the bed load may be any where from 0 to 100 per cent. of the total load.

R. C. Hemphill (27) is inclined to believe from investigations in Texas Streams that the quantity of silt transported as a true bed load comprised a much smaller percentage of the total load than is generally assumed.

Simanka (27) from a study of the distribution of silt in a vertical (Figure 1)

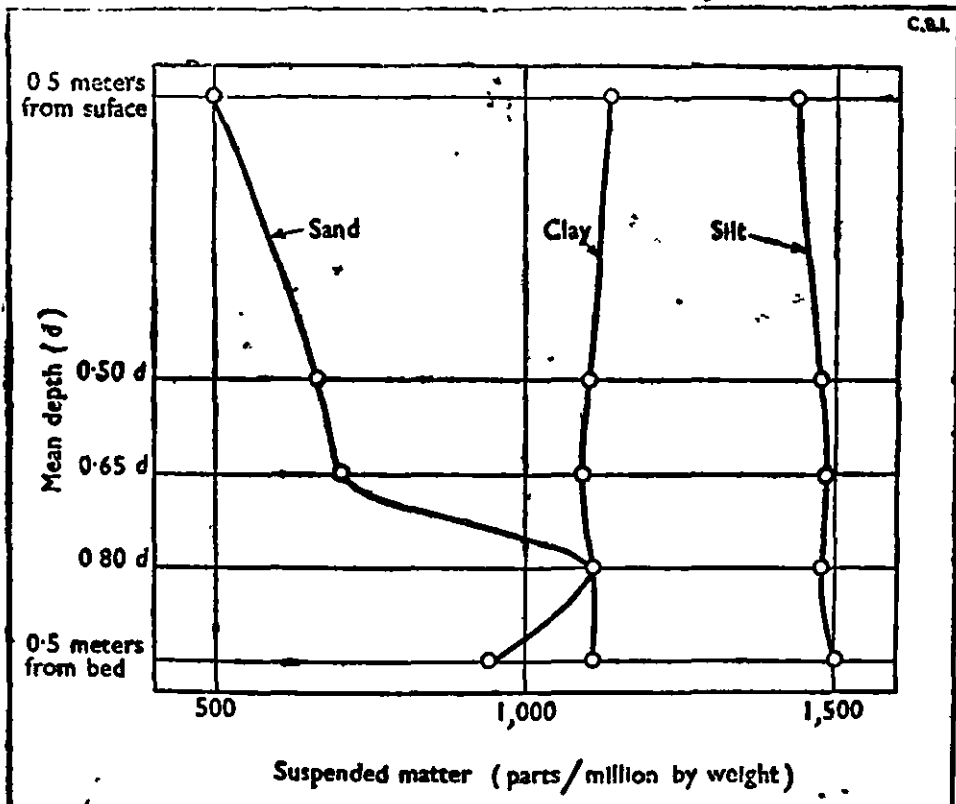


Figure 1:—Mean distribution of total suspended matter in the vertical (Halpa 1931).

concludes that the bed load cannot be heavy. If the bed load were considerable and not all carried through the sluices of the Aswan Dam, one would expect a continual rise of the bed upstream of the solid part of the Aswan Dam, for which there is no evidence.

It will thus be seen that information about the relative proportion of bed load and suspended silt is meagre and very conflicting. As far as is known, no successful attempt has been made to measure the material transported as bed load. It appears, as stated by Simaika and Hemphill that the bed load is not really so important a factor as it is sometimes made out to be.

Of late, great activity has been shown in the United States of America in the study of bed silts as apart from suspended silts and in that of the mechanics of sediment transportation. Various types of samplers have been tried both for suspended and bed silts. A complete description of these is given in two reports of the Hydraulic Laboratory of the University of Iowa. These studies were planned and conducted jointly by the Tennessee Valley Authority, Corps of Engineers, Department of Agriculture, Geological Survey, Bureau of Reclamation, Indian Services and Iowa Institute of Hydraulic Research.

The Central Board of Irrigation (India) has also had this subject under examination and investigation for a number of years and is shortly issuing a separate publication giving detailed instructions regarding the measurement and analysis of detritus load in rivers and canals.

SILT DISTRIBUTION AND VELOCITIES IN A VERTICAL SECTION

From the silt graphs reproduced in Figure 2, Faris⁽¹²⁾ concludes that there is no evidence of any direct relationship between suspended load and the velocity of water at the river stations under consideration. It is true, he says, that the higher the velocity, the greater the carrying capacity but since the capacity load is not even approximately reached, the magnitude of silt charge carried must be a function of loading and not of capacity to carry.

Hoon⁽¹⁵⁾ gives a comparative investigation of solid transport in the Mahanadi and Kosi Rivers, in India, in which he shows that the solid discharge of Kosi is 4 to 5 times greater than that of Mahanadi, this difference being attributed to the availability of silt in the Kosi catchment and the steepness of the gradient of that river and consequently of higher velocities. He indicates that in the Mahanadi River, the coarse and medium silt concentrations vary along the vertical depth of the river and increase from surface downwards. The average concentration points for the coarse and medium silts in the majority of cases lie near 0.55 or 0.6 depth, that for coarse silt being relatively at lower depths than for medium silt: the variation in discharge seems to affect silt concentration at all points along the depth, being low for small discharges and high for larger discharges.

From his experiments Venoni⁽³³⁾ concludes that the addition of sediment to a clear flow causes the velocity to increase, the increase apparently depending on the size and amount of sediment in the flow. This effect reduces the apparent resistance or roughness co-efficient of a channel. The increase in the velocity, however, does not give rise to an increased sediment transporting capacity, since it is accompanied by a shear or drag at the boundaries.

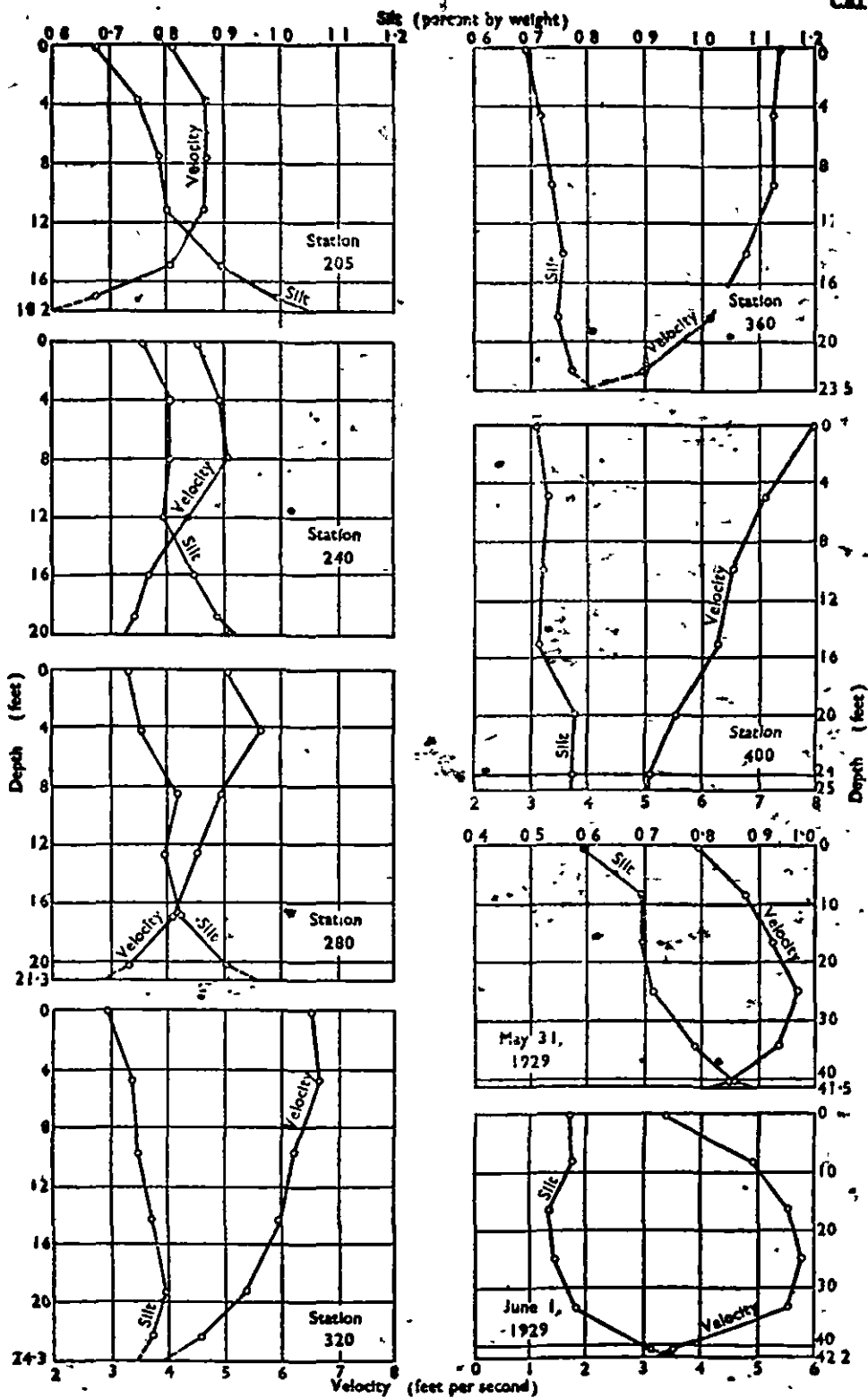


Figure 2-Velocities and silt percentage curves at different stations on the Brazos river at Rosenberg on April 16, May 31, and June 1, 1929.

SILT PERCENTAGE AND DISCHARGE

The greater part of the silt load of a stream is made up in advance by the process of weathering after a dry period, the first water that runs off picks up the weathered material and carries it into the stream. After the first flushing, the amount of detritus available for transportation must depend on erosion which can only be light, in view of the fact that regions of excessive erosion

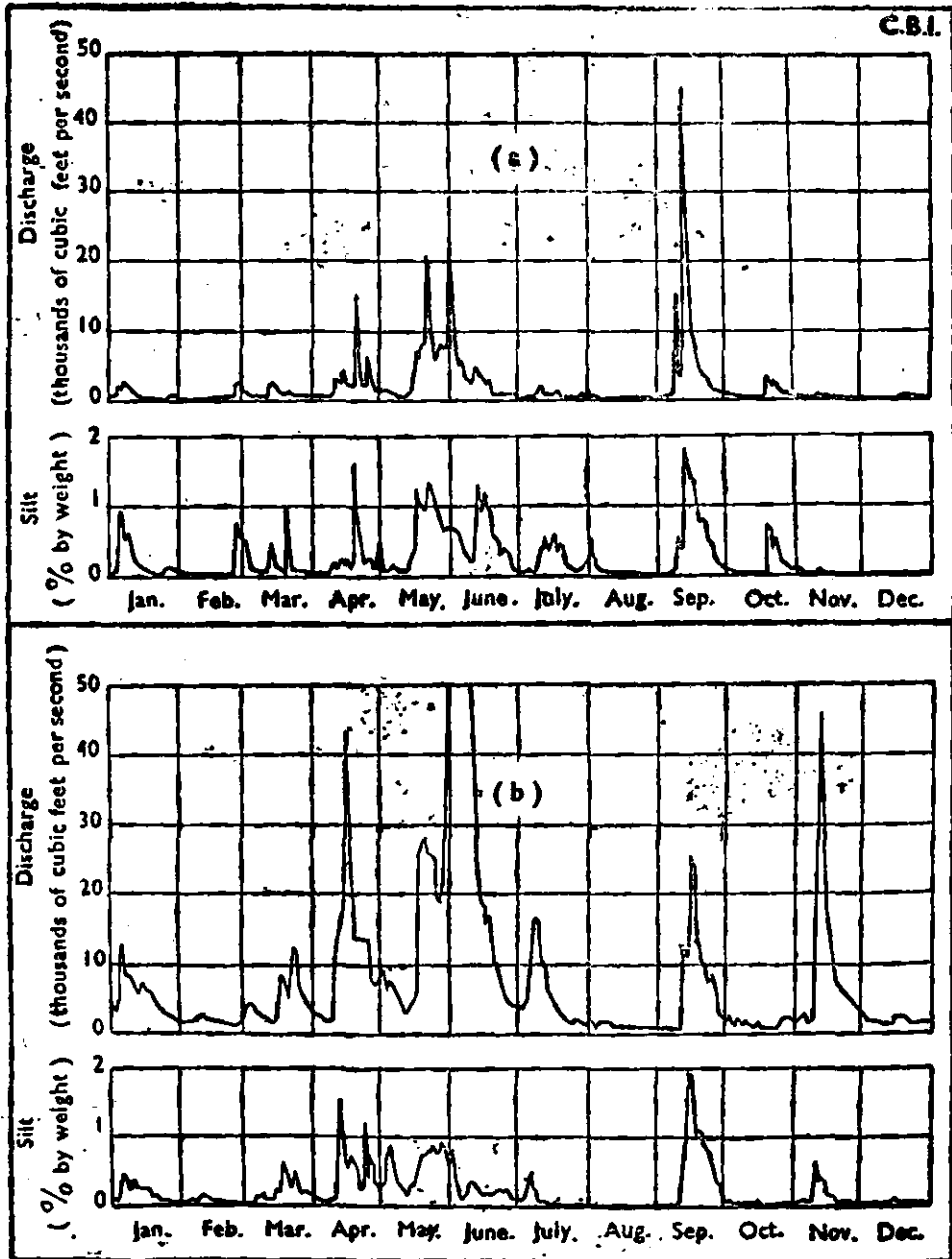


Figure 3 :—Discharge in feet second and percentage of silt by weight, Brazos river during 1929 (a) at Waco (b) at Rosenberg.

form but a small part of a large drainage basin. This explains why in a rainfed stream the maximum concentration of suspended load occurs earlier than the maximum height of flood.

In the early flood months, when the river is steadily rising, the concentration is higher for the same discharge than for subsequent months when the river is steadily falling. The same opinion is expressed by Faris (12). According to him the maximum silt percentage by weight usually occurs prior to the maximum stream discharge Figure 3 (a) and (b). When samples are taken throughout a rise and fall in a stream, an increase is noticeable in silt percentage up to a certain discharge. A further increase in discharge is associated with a decrease in percentage of silt due to dilution. As the water surface recedes during the falling stage, the silt percentage is again increased.

Silt and discharge curves at Halfa on the Nile in Egypt (Figure 4) and at Bhakra on the Sutlej in India (Figure 5) show similar characteristics.

The river Nile in Egypt is fed by rains during the monsoon months as are the rivers in India, as may be seen from the following extract. (35)

“ The concomitant variations of the gauge readings at Aswan and Bombay rainfall found by Sir William Wilcocks and Sir John Elliot are explained because conditions favourable for an abundant Abyssinian rainfall are found in those that favour a strong Bombay monsoon ”.

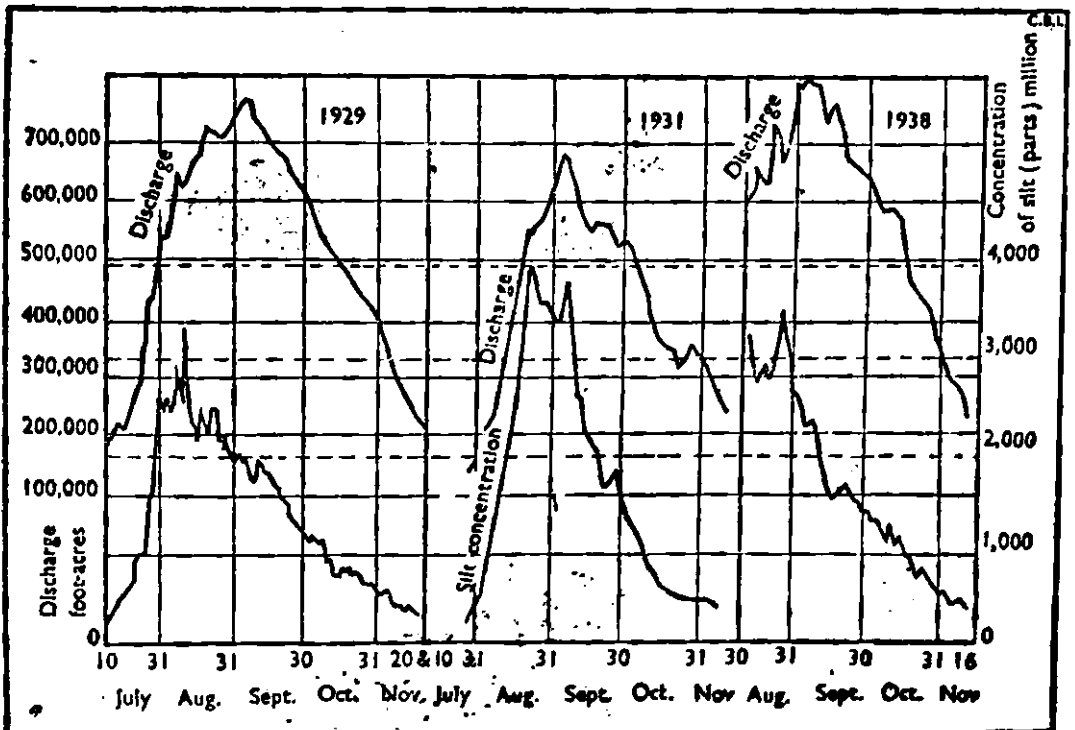


Figure 4 :— Discharge and silt concentrations at Halfa on the Nile in Egypt.

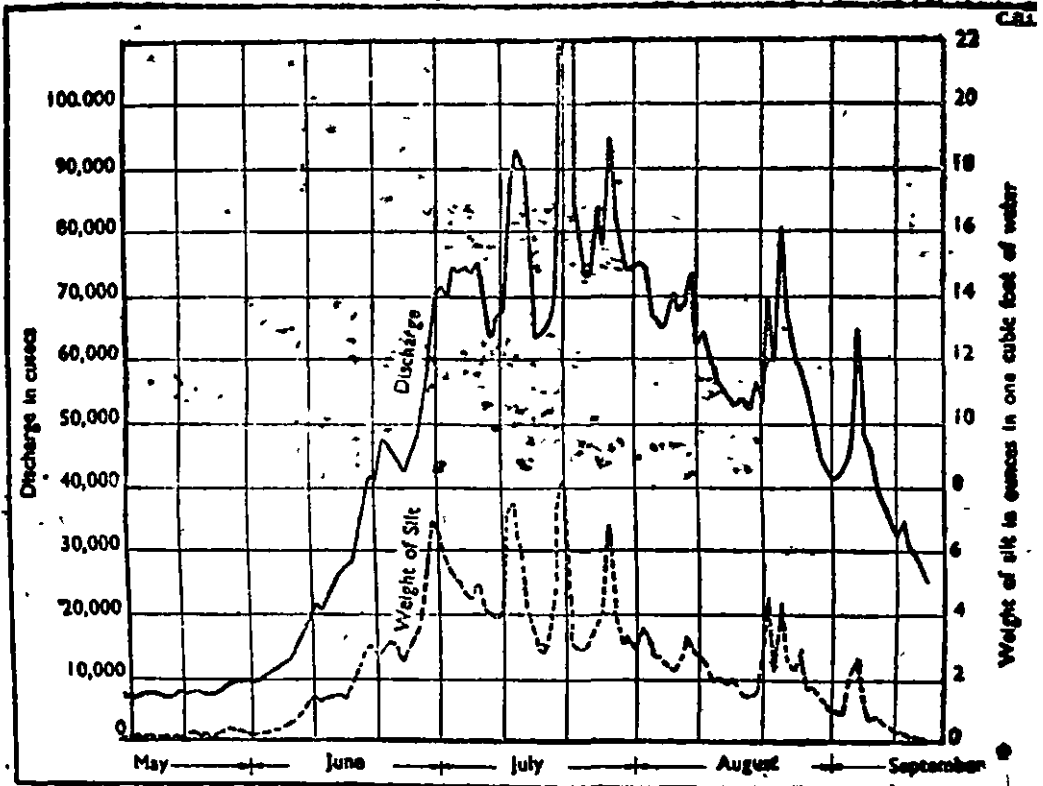


Figure 5 :— River Sutlej at Bhakra—Discharge Silt graph from actual observations, 1925

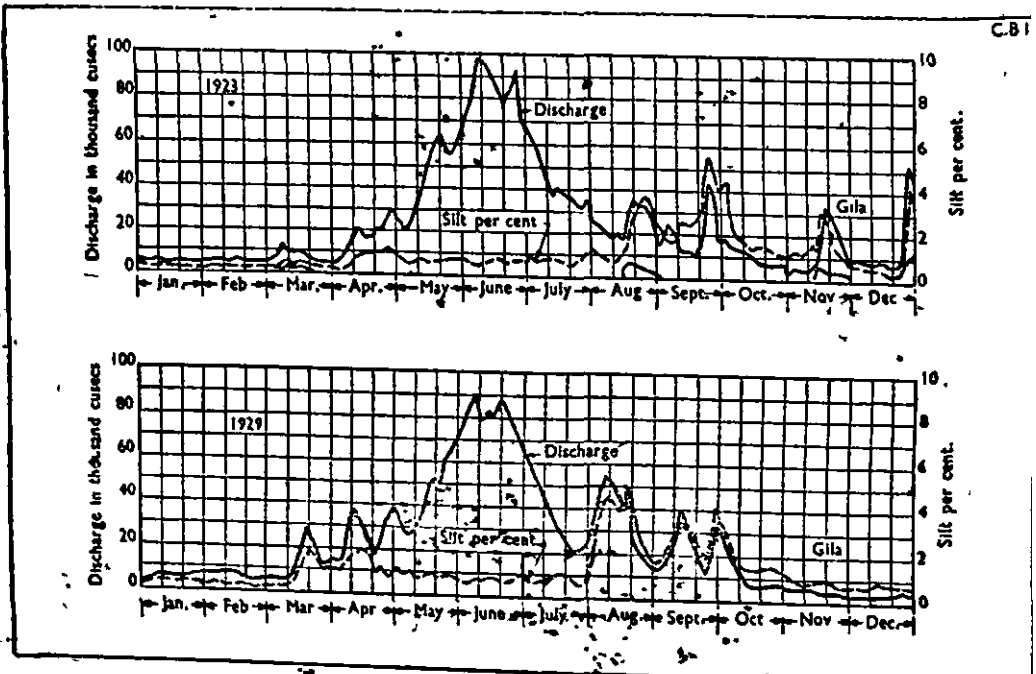


Figure 6 :—Silt discharge graphs of the Colorado River.

In his report on the Silting of Reservoirs, Edgecombe ⁽¹⁹⁾ remarks that there is lack of any relationship between percentage of silt and river discharges. Typical silt discharge graphs of the Colorado River for 1923 and 1929 are given in Figure 6 which supports the above statement. But in connection with the Colorado, it has to be remembered, as pointed out by Edgecombe, that this river is snow-fed during the months of May, June and July while cloud bursts are liable to occur in August, September and October.

According to Maddock and Borland ⁽²⁰⁾ a correlation between discharge and sediment load is difficult when much of the discharge comes from ground-water in-flow or when part of the stream flow comes from run-off from melting snow and part from rainfall. Figure 6 is a very good illustration of the fact that in the case of snow-fed waters the silt concentration not only does not increase with discharge but may actually go down due to dilution. The snow water will wash down the silt in the river section occupied by the flood discharge but no higher. Rainfall on the other hand will wash down weathered material from all hill faces in the area of rainfall. The rise and fall of silt graph with that of discharge in the rainy months of August, September and October in Figure 6 illustrates the fact that the silt concentration of the rain fed streams generally varies with the discharge.

Vetter ⁽²⁴⁾ reports that from the results of total load of Colorado river it appeared that in the coarser grades there was a fairly well defined relationship between total load and discharge; but as the material became finer the points scattered more and more and no relationship appeared to exist between the discharge and material finer than 0.01 mm. Vetter describing the suspended load of Colorado at Imperial Dam and Laguna Dam sites arrived at a conclusion that the suspended load constituted by far the major portion of the load carried by the river. The following reasoning was given to support that: "As a result of turbulence the water particles and with them the suspended solid matter are constantly mixed. In the course of this mixing a certain number of silt particles will strike the bottom of the stream and at the same time a certain number of particles will be torn loose from the bed by the boundary layer and thrown into the stream. If the silt-laden stream is in equilibrium, the intensity of the turbulence in the boundary layer must be sufficient to maintain a certain silt concentration in the layers adjacent to the bed. If this concentration is known it is possible to calculate the concentration of any other depth."

The quantity of suspended matter carried by a river usually varies considerably from year to year. The annual suspended load in small flashy streams is carried only during a small number of days out of the year and silt content of the water may vary considerably, within a short time, on the rising or falling stage of the stream. Figure 7 shows discharge plotted against concentration of suspended matter for a particular flood on Coon Creek at Coon Valley. The importance of careful and frequent sampling during floods is obvious from an examination of this curve; that is, if only a single sample were taken to examine the daily stream load, a sample taken at 5:40 a. m. applied to the mean daily discharge would give a load of 64 tons per day and a sample taken at 8:00 a.m.

would give a load of 22,700 tons per day, but by planimetering Figure 7, which is plotted from 21 samples, the true load is found to be close to 7,660 tons per day. Thus, it is seen that the reliability of the results is dependent largely on obtaining samples at the right time.

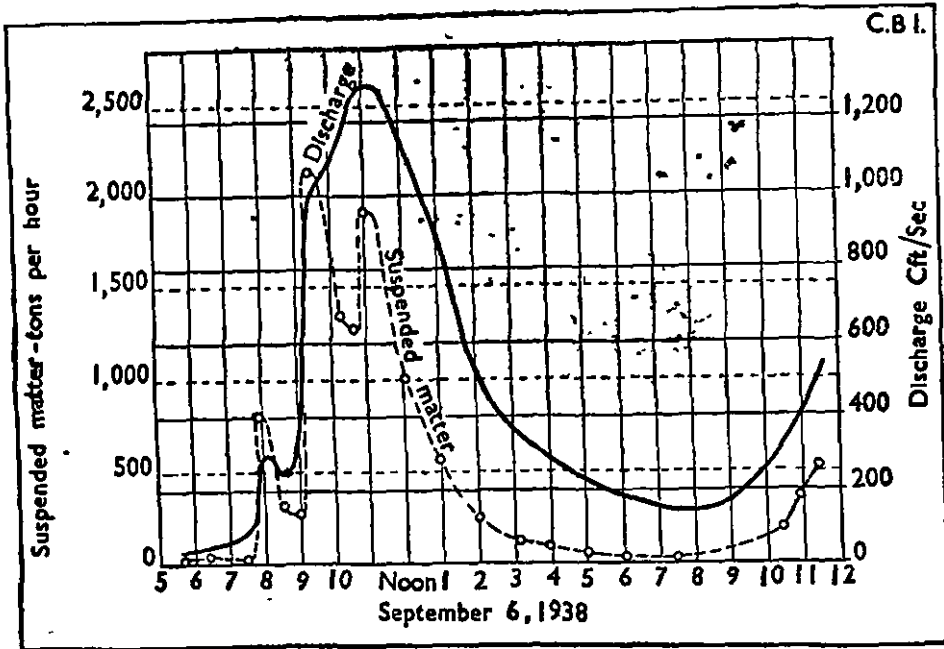


Figure 7:—Discharge and suspended matter relationship for Coon Creek at Coon Valley.

SOME HEAVY SILT CONCENTRATIONS

On the Elephant Butte Reservoir the flashy summer flood waters usually carry 4.0 to 10.0 per cent. and occasionally as high as 12 to 15 per cent. by weight of silt which is characterised by a high percentage of colloidal argillaceous matter. On the other hand the spring floods coming from the head-waters of the Rio Grande from the mountainous drainage area are supplied largely by melting snows, springs and normal run-off, and normally carrying the greater part of the total annual inflow, contain only 0.5 to 1.0 per cent. of silt. The difference between the silt concentrations of rain-fed and snow-fed supplies is again emphasized.

Similar heavy concentrations have been observed in the Roosevelt Reservoir where it is believed that the silt deposited in times other than floods is negligible.

The extent of weathering in a particular catchment is, other factors being normal, a function of time. A certain quantity of weathered material is made available for transportation during the year. If the rainfall is more or less evenly distributed over the period, this weathered material will be transported gradually and the silt concentration will be low. If the rainfall is torrential and erratic, the entire run-off will be in the form of a few freshets and the silt concentration will be very heavy. This explains the heavy concentration at the

Elephant Butte and Roosevelt Reservoirs. But this heavy silt concentration during flashy floods should not be interpreted as an indication of abnormal silting. The rate of silting will be governed by the area of the catchment.

Silt concentrations of 30 per cent. to 51 per cent. by weight have been recorded from some of the rivers in China.⁽²⁹⁾ For instance at Shenh sien on Yellow River the maximum concentration of silt was 46 per cent. by weight⁽²⁸⁾.

RATE OF FALL OF PARTICLES

The process of silting up in a reservoir depends upon the rate of fall of the different particles. Considering the sedimentation process Lane⁽¹⁷⁾ suggests that the particles as they are subjected to less turbulence in a reservoir, would have medium settling rates which are slower than that of sand particles. According to him the settling rates of the sediment particles carried by any given stream covers a wide range, the ratio of the diameter of the largest particles to the smallest may, in some cases, reach an order of magnitude of 1,000,000. Sediments having a high settling rate act very differently from those of medium settling rate and those of low settling rate. In this connection a reference to the ultra-mechanical analysis of silt reported by Hoon⁽¹⁵⁾ are of special interest.

THIXOTROPY AND DENSITY CURRENTS

The phenomenon of thixotropy plays an important part in transport of materials, since this can turn a mixture of water and solid material into a heavy viscous jelly like liquid mud (which if undisturbed, behaves as a solid) in which even very coarse materials float. This phenomenon may provide a partial explanation to the surprising power of transportation shown by certain torrents, causing what is called "Lave" in French. Importance may sometimes be attached to this in the upper portion of catchments where affluents are torrential in character. Mention has been made by Fox⁽¹³⁾ as to how by the phenomenon of thixotropy huge boulders and blocks of granite were transported in streams of Cherraponji (Assam), which observation was made by a geologist.

According to Lane⁽¹⁷⁾ the density currents occur along the sloping bottom of a lake and are due to the fact that the density of the sediment-laden water is greater than that of the clear water. These currents may flow scores of miles along the bottom of a reservoir, underneath the clear water without mixing appreciably. The material in these density currents will be composed mainly of the clay-sized particles with possibly some of the smaller of the silt sizes. Duquesnois⁽⁸⁾ and Raynaud⁽²²⁾ have conducted experiments to study the utilization of underflow for the outflow through discharge walls and also to determine the laws governing the flow of currents of muddy water through reservoirs. A trial has been made to make a comparison between underflows and free surface-flows. Drouhin, Mallet and Pacquant⁽⁷⁾ have examined this matter thoroughly and from their observations of the process of sedimentation, they have pointed out a number of factors which influence the rate of sedimentation of basins and the possibility of washing away of the gravel.

SETTLING OF SILT IN RESERVOIR

What happens to the various grades of material carried by a river when it enters a reservoir which is full? Reminieras and Braudeau (24) have shown that the coarser materials moving along the bottom or deposited on reaching calm water are later picked-up again by the movement so as to form a sort of delta with a sheer front downstream, in cross-section straight and horizontal, in longitudinal section concave and extending upto well above the highest water level of the lake. The finer materials are carried further into the lake, either by natural gravitation or by density currents or by under flows.

Maddock and Borland (25) have reported a combination of factors leading to sediment deposition either in the upstream or downstream of reservoir. The factors which favour upstream deposition are (a) reservoir storage being at high elevation *i.e.*, full, (b) heavy sediment concentration with a large portion of load being coarse-grained, (c) large outlets at low elevation, (d) much vegetation at the head of the reservoir, and (e) constrictions in the reservoir between the head of the reservoir and the dam. Factors leading to sediments deposition in the downstream are (i) reservoir storage usually at low elevations particularly during floods, (ii) sediment concentration low with fine-grained particles (iii) a type of reservoir having a short length and having a steep slope to the original valley floor, (iv) no vegetation at head of reservoir and (v) small outlets at a high elevation.

Lane suggests six possible types of action depending principally on the particle size of the sediment involved in sedimentation of reservoirs (17). These are the action of coarse sediment, ordinary deposition of suspended sediment, action of density currents produced by the settlement of suspended sediment, action of common form of density currents, the sloughing of deposited sediment and colloidal suspension.

Rao and Raghavachari (21) have attempted to study the problem of silting up of the reservoirs formed across rivers, assuming a sedimentation theory. According to them the silting up of a reservoir takes place in three stages *viz.*, (i) silt is formed completely upto the sill level of surplussing sluices or spillway, (ii) the river forms a regular channel, the width and depth of which will be so regular that there will be neither scouring nor silting up of the course, and (iii) the rate of deposition of silt is very slow and hence the reservoir will have longer life.

The Japanese Hydrologists (26) lay stress on the "relief energy"—which is defined as the difference between the highest and lowest altitude in a specific area—which bears a greater significance as a factor to the configuration of the mountain land which in turn is a factor of sedimentation. Accordingly as a cause to create sedimentation, the factors relative to configuration has a more marked effect than the nature of rocks and their kind and composition in the catchment areas.

VOLUME-WEIGHT RELATIONSHIP

In considering the life of a reservoir we are concerned not so much with the weight of silt deposit as with its volume. The probable rate of silting of proposed reservoirs can be estimated in two ways. One is by taking representative samples of water from the stream concerned during the period it carries

silt, determining the concentration by weight and converting it to volume in foot acres. The other is on the analogy of similar existing reservoirs which have had their silt deposits surveyed over a sufficiently long period. The second method, though the more direct of the two, is subject to limitations, as each stream has its own catchment characteristics. Estimates have, therefore, to be based on the silt concentration by weight as obtained from sampling. It is, thus, essential to know the relationship between weight and volume of silt so sampled. According to Maddock and Borland (18) the weight of a cubic foot of sediment appears to be definitely related to the size of the sediment particles modified by the method of reservoir operation and the age of deposit.

The best known experimental work on this subject has been done by the Department of Agriculture, United States of America, as reported in their Technical Bulletin No. 382 (12) on the Silt Load of Texas Streams, by Orville A. Faris. Of all samples tested in this connection the leanest containing 18.7 pounds of dry material per cubic foot of deposit, possessed prominent colloidal characteristics. This sample was taken immediately above Lake Worth Dam on the West Fork of Trinity River. The densest sample was the cobble like formation containing 106.1 pounds of dry material per cubic foot of deposit taken from the Medina Reservoir. Between these two extremes, all intermediate values have been met with at one place or the other. The general remarks of Faris, may be quoted as follows :

“ In a reservoir used for flood control only, the water is stored temporarily and the deposited material, subjected to shrinkage during long periods of time, has an average ultimate weight of dry materials per cubic foot of deposits approximating 90 pounds ; in the average reservoir for storage of water for future use, dry periods and increased demand for water result in lowering of the water surface and exposure of the silt deposit for periods of time, resulting in an average ultimate weight of dry material per cubic foot of deposit approximately 70 pounds ; and in a power reservoir where the head is maintained practically constant, exposure and the resulting shrinkage does not take place and the average ultimate weight of dry material per cubic foot of deposit approximates 30 pounds ”. Faris recommends 70 pounds for the average ultimate weight of dry material per cubic foot deposit. For weights of some of the individual samples studied by Faris see Tables III and VI (Chapter 2).

For the Boulder Reservoir on the Colorado, the weight of dry material per cubic foot of deposit has been accepted as 85.9 lbs. While discussing the rate of silting-up of the Vaal Dam, McCrae (19) gives a useful account of the method adopted in his calculation. He states “ The mud which settles in dams has a specific gravity which depends mainly on the consistency of the mud which is conditioned by the amount of water in it. Specific gravities as low as 1.3 have been recorded for such deposits but usually higher values have been obtained. As a rough approximation a specific gravity of 1.5 might be taken and if it be assumed that the true specific gravity of the solid matter (clay and sand) of the mud is 2.6 then the mud would be a mixture of 54 % of solid and 46 % of water and on this basis one ton of the dry solids would make 40 cubic feet of deposited mud. It has been shown that the weight of the dry solids deposited in the dam in 8 years is approximately 20.76 m. short tons and this would produce about 830 m. c. ft. of mud which is equivalent to about 19,000 acre feet.

RATE OF SILTING AND CATCHMENT AREA

The most important single factor in determining the silt yield of any catchment is its area. The silt characteristics of catchments vary within very wide limits. The Columbia River above the Grand Coulee Dam, with a catchment area of 74 thousand square miles and mean annual run-off of 80 million foot-acres is believed to run practically silt free. The River Nile above the Aswan Dam carries approximately 100 million tons of silt per year but the silting in the reservoir above the Aswan Dam is negligible owing to the large sluicing capacity at bed level and to storage capacity being only 6-7 per cent. of the mean annual runoff which enables the requisite storage to be obtained during the period of low silt concentration. These are extreme cases but the rate of silting in the other major reservoirs, dealt with later on, is, more or less, of the same order, expressed in foot-acres per 100 square miles of catchment area, in spite of a variety of combinations of geology, topography, vegetation and rainfall, (Table XXXVII).

In large catchments, rock formations may vary within wide limits but these factors seem to balance up to give similar annual silt yield per 100 square miles. Wide divergencies in rates of silting can generally be explained by artificial interference with the normal characteristics of the catchment such as construction of check dams in tributaries, large scale afforestation, denudation; etc. Thus on the Elephant Butte Reservoir with a catchment of 26,312 square miles and the Roosevelt Reservoir with a catchment of 5,760 square miles, the annual rates of silting work out to 61 and 79 foot-acres per 100 square miles of catchment respectively. In both cases, the storage capacity is more than the annual run-off, so that all the silt brought down the catchment is retained in the reservoirs except small quantities which may find their way down through the outlet works. These two appear to set the upper limit. The annual rate of silting per 100 square miles of catchment in the other reservoirs is materially very less except in a few abnormal cases.

The volume of material eroded, transported and deposited varies greatly in accordance with local conditions. Cassidy (2) notes that during a single flood some 405 foot-acres were torn away from an area of 7.7 sq. miles. In the same catchment the volumes involved vary from 1-20 foot-acres per year per square mile of catchment with peaks reaching 3-4 times as much. The figures for transportation given by Hoon (15) for the Mahanadi and Sapt Kosi are 92 foot-acres per 100 sq. miles and 518 foot acres per 100 sq. miles respectively indicating that the Kosi brings with it, about six times as much silt as the Mahanadi. For the Yellow River, in China the silt yield is about 445 foot-acres per 100 sq. miles of catchment.

METHODS AVAILABLE TO COMBAT SILTING UP OF RESERVOIRS

No suitable method of combating the silting has been evolved except, to provide a larger capacity than what is required or by increasing the capacity of the reservoir by additional structures.

One of the most effective operational techniques where it is applicable, consists in so conducting operations as to disturb the natural movement of solid materials along the valley as little as possible. This presupposes that relatively small proportion of the river discharge is to be utilised. Such techniques have been responsible for the negligible silting of Aswan Dam.

The control of erosion in the catchments as a measure to combat silting up, is effective in large catchments.

Duquesnois (8) and Raynaud (22) suggest the most economical and effective way of reducing sedimentation, consisting of the utilization of underflow for the outflow through discharge valves of the silt which usually gathers in the bottom of reservoirs. The problem is still to be studied.

Dredging or suction dredging though an expensive method has been studied in detail by Drouhin, Mallet and Pacquant (7) with the idea of making use of the filled land for cultivation at a later stage. Holecek (14) stressing upon the careful operation and regulation of gates, shows that by suction dredging the deposition of silt will not occur. Nizery and Rousselier (20) also refer to the value of such dredgings. For the protection of lateral accumulations along the rivers heavily loaded with alluvia, reference may be made to the methods reported by Holecek (14) and Ehrmann (11). Ehrmann suggests flushing by the dam, designing the construction of the dam and to have a guard wall and pit at the foot of the intake racks, which can be connected with the downstream side by a bottom gate.

Cassidy (2) reports the two general types of control structures developed for debris problem of the Los Angeles area (a) for intensely developed debris cones, a debris basin near apex of cone with concrete channel carrying clear water from the basin through developed area, (b) for the cones not intensely developed, a system of groins and levees on the upstream part to confine flow to a fixed channel and funnel it into a concrete channel through the developed area.

CHAPTER 2

Silting of the existing Reservoirs in India

A. STORAGE RESERVOIRS IN BOMBAY STATE

NATURE OF DATA

A few water samples are taken each year in certain selected reservoirs during the flood season to estimate the amount of silt in flood waters prior to its entry into the pond and at its exit via the waste water. These are taken as far as possible, on the lines recommended in the Appendix. The samples could be taken only for one or two floods during each season as several difficulties have to be encountered in the work. The chief difficulty is the high velocity of water, frustrating every attempt to take samples on exact alignments or very near thereto and at the required depths particularly during high floods. Some floods go unobserved as it is not possible to anticipate their intensity or peak.

Thus the samples obtained can give only a very approximate idea of the silt content entering or leaving the reservoirs. Capacity surveys appear to be the only method of watching the rate of silting of existing reservoirs and these are invariably resorted to in the Bombay State wherever there is any doubt that the usable capacity of a reservoir is diminishing rapidly.

Some observations were also made in 1941 to ascertain :—

- (i) weighted mean diameter of silt particles suspended in the flood waters passing over the waste weir, and
- (ii) the profile of deposited silt in the basin of tanks and lakes.

These were not continued later as they did not lead to any useful result. It was found that the silt collected from the waste weir was very fine (of the order of 0.005 mm. dia.) and flocculated during the period of travel of the sample from the lake to the laboratory.

A few observations on the volume weight relationship of silt on Lake Fife and Dhupdal Reservoir were, however, carried out in 1943 and 1944 respectively.

An abstract of the information regarding silt and connected data is given in Table I. Some remarks regarding individual reservoirs are given below.

DHUPDAL RESERVOIR (NEAR GOKAK)

District	Belgaum
River	Ghataprabha
Catchment area	1,080 square miles
Nature of catchment	Cultivated area in transition tract
Rainfall	23 inches
Mean annual runoff	2,754,000 foot-acres
Height of dam	27 feet
Storage capacity	33,705 foot-acres
Years of capacity surveys	1891, 1911, 1924

Silt and connected data of some existing

Ser. No.	Reservoir			Catchment area (sq. miles)	Height of dam (feet)	Storage Capacity			Mean annual rainfall (inches)	Mean Annual runoff (foot-acres)
	District	River	Name			Foot-acres	Percentage of annual runoff	Per sq mile of catchment (ft. acres)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
147	Belgaum ..	Ghata-prabha	Dhupdal ..	1,080	27	33,705	1.2	31.2	23.1	2,754,000
148	Sholapur ..	Man ..	Maswad Tank	480	80	59,742	..	124	20.2	..
149	Poona ..	Mutha	Lake Fife (Khadakwasla Dam)	196	102.5	90,086	8.9	460	40 (dam site) 250 (ghata)	1,009,800
150	Ahmednagar	Hangs	Visapur Tank..	169	84 (maximum)	27,961 (1927) 30,509 (1933)	103	176	20	23,600
151	Sholapur ..	..	Ekrak Tank ..	159	76	72,599	..	457	26.4	..
152	Nasik ..	Darna ..	Lake Beale (Darna Dam)	156	94	178,212	31	1,141	125	568,572
153	Satara ..	Yerla ..	Nehr Tank ..	59.6	74	11,227	..	189	25.3	..
154	Satara ..	..	Mayani Tank	51.7	57.3	4,317	..	835	21.3	..
155	Khandesh ..	Panjara	Mukti Tank ..	34.2	65	7,862	..	230	20.6	..
156	Bijapur ..	..	Muchkundi Tank	26	60	14,791	..	569	23.2	..
157	Ahmednagar	Sina	Pimpalgaon Tank	24	34	4,473	..	186	24	..
158	Poona ..	..	Matoba Tank	20	59	5,258	..	263	16.1	..
159	Satara ..	Man	Pungli Tank ..	20	53.5	4,408	..	220	18.6	..
160	..	..	Koregaon ..	7	..	2,404	..	343	..	..
160a	Nasik ..	..	Chankapur ..	100	101	35,527	..	..	..	..
160b	" ..	..	Waghad Tank	29	96	13,912	..	..	..	..
160c	" ..	..	Paraul Tank ..	17.3	62	2,859	..	..	..	..
160d	Poona ..	..	Shrusuphal Tank	23.5	52.3	9,200	..	..	..	..
160e	" ..	..	Shetphal tall Tank	2.33	66	1,359	..	..	..	..
160f	Sholapur ..	..	Pathri Tank ..	27.5	63.7	9,867	..	..	..	..
160g	" ..	..	Ashti Tank ..	9.25	57.7	32,388	..	..	..	..
160h	Ahmednagar	..	Bhandarsdera..	47	270	278,116	..	..	..	..

* The Serial Nos. are in continuation of those in Table XXXVII.

E I

dams in the Bombay State

Run-off per sq mile of catchment (foot-acres)	Years of Capacity Survey			Silt deposited					Remarks	References
	First	Last	Period in years	Total Foot-acres	Foot-acres per year	Percentage of original capacity	Annual Percentage of annual runoff	Per 100 sq. miles of catchment area		
(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
2,550	1891	1924	33	4,890	148.2	0.44	0.0054	13.7	Cultivated area in transition tract with low rainfall.	
..	1888	1943	55	24,452	444.6	0.74	..	92.3	Catchment in Satara district with good soil.	
5,152	1870	1940	70	19,140	273.4	0.30	0.027	139.3	Hilly terraced fields with good rainfall.	
186	9	1,515	168.3	0.55	0.57	105.7	Catchment consists of black soil and rainfall occurs in occasional heavy torrents.	
..	1870	1923	53	12,536	236.5	0.33	..	148.7	Black soil tract.	
3,645	1910	1941	31	1,565	50.5	0.028	0.0089	32.4	Catchment rocky and hilly.	Report on Irrigation and Allied Research, Poona, 1944.
..	1895	1942	47	1,722	36.6	0.33	..	62.0	Black soil tract.	
..	1873	1942	69	3,582	51.9	1.20	..	100.3	Catchment in Satara district with good soil.	
..	1869	1927	58	514	8.9	0.11	..	26.2	Famine area, Hilly catchment with low rainfall.	
..	1880	1944	64	1,190	18.6	0.12	..	71.2	Famine area. Black soil tract. Tank rarely overflows.	
..	1912	1941	29	283	9.7	0.22	..	40.2	Famine area. Tank rarely overflows.	
..	1884	1941	57	1,042	18.3	0.35	..	91.5	Mostly supplied by Lake Fife water.	
..	1878	1942	64	1,997	31.2	0.71	..	166.8	Black soil. Tank rarely overflows.	
..	1891-92	1925	33	487	14.8	0.61	..	211.4	..	
..	..	..	..	1,918	..	..	..	..	Hilly catchment
..	..	..	..	1,974	..	..	..	..	"
..	..	..	..	134	..	..	..	..	"
..	..	..	..	1,013	..	..	..	..	"
..	"	
..	..	..	..	506	..	..	..	..	Hilly catchment
..	..	..	..	10,745	..	..	..	..	Soily and Murumy catchment
..	..	..	..	21,252	..	..	..	..	Rocky catchment

C.B.I. Publication, 1941.

During 1941, samples from three sites—ten miles upstream, five miles upstream and near the dam—were taken on two days in August. The variation in the silt content was from 0.14 to 0.40 parts per 1,000 parts of water by weight. The results of the first flood appeared to be inconsistent, while the second flood showed that the amount of silt deposited in the lake was 0.02 parts per thousand.

In 1942, the variation was 0.10 to 0.80 and two out of the three floods showed a tendency of the dam to silt up (average 0.035 parts per thousand).

Four sets of samples were taken in 1943. The first of July flood was heavy and apparently the silt deposited in the reservoir previously was scoured out by the flood. The subsequent three floods, which were ordinary, showed little silting. The average silt content was 0.088—variation being from 0.05 to 0.21 (1.7 recorded on one day near dam being exceptional). The observations show that conditions during floods of various intensities are different. During the same year silt may be scouring or be depositing and the present method of determining silt content during various floods does not give any correct idea of the rate of silting.

River Cross Sections

Cross section taken near the weir showed that between the years 1890 to 1940, the original straight course of the river near the right flank has altered. The river has shifted to the left bank, with the result that silt is being scoured from the left bank and deposited on the inner side or the right bank.

The cross section at entry and in the ponding limit did not show much change, except a slight deposit of silt on both sides.

Rate of Silting

Table II gives the results of silt surveys carried out in the years 1891, 1911 and 1924.

TABLE II

Period of record	Silt deposited in foot-acres				Catchment area (square miles)	Silt deposited in foot-acres per 100 square miles of catchment area
	Years	During period	Per annum	Cumulative total		
1891-1911 ..	20	3,972	198.6	3,972	..	18.4
1911-1924 ..	13	918	70.6	4,890	..	6.5
1891-1924 ..	33	4,890	148.2	..	1,080	13.7

Volume-Weight Relationship of Silt

Samples of silt of two categories were taken from the Dhupdal Reservoir in 1944. Six samples were taken one foot under water from both the banks and as many corresponding samples 10 to 15 feet above the water edge. The densities of the samples are given in Table III.

TABLE III

Volume-Weight Relationship of Silt Samples taken from Dhupdal Reservoir

Sample No.	Inside water	10 to 15 feet above water edge		
	Dry weight/ volume	Sample No.	Dry weight/ volume	Wet weight/ volume
	(Pounds per cubic foot).		(Pounds per	cubic foot)
1	78.9	1A ..	75.8	109.1
2	64.2	2A ..	68.4	99.6
3	62.2	3A ..	64.2	98.9
4	67.8	4A ..	62.5	92.0
5	61.4	5A ..	48.3	80.1
6	67.3	6A ..	58.6	82.6
Mean	67.0	Mean ..	63.0	93.7

The mean density of these samples is 67.0 lbs. per cubic foot for those under water and 63.0 lbs. per cubic foot for those above it. This may be compared with the dry weight of silt reported in the case of Lake Fife, viz., 52.7 (under water) and 63.4 (outside it).

Remarks

The catchment is in the transition tract as in the case of Lake Fife but it has a low rainfall. The rate of silting per 100 square miles of catchment is therefore, low.

LAKE FIFE (KHADAKWASLA DAM)

District .. ..	.. ..	Poona
River .. ..	.. ..	Mutha
Catchment area .. ..	.. ..	196 square miles
Nature of catchment .. ..	.. ..	Hilly terraced fields
Height of dam .. ..	.. ..	102.5 feet
Storage capacity .. ..	.. ..	90,086 foot-acres
Rainfall .. ..	.. ..	250 inches (ghats)—40 inches (Dam site)
Mean temperature .. ..	.. ..	75°F
Mean annual runoff .. ..	.. ..	1,009,800 foot-acres
Type of flood .. ..	.. ..	Concentrated
Years of capacity surveys .. ..	.. ..	1870, 1904, 1940

Suspended Silt Samples

The results of silt samples taken during floods are given in Table IV.

TABLE IV

Year (1)	Silt in parts per thousand by weight		Difference of Columns (2) and (3) (4)	Remarks (5)
	Entering lake (2)	Leaving lake (3)		
1941 ..	0.209 (Range 0.09—0.43)	0.103	0.106	Average of seven readings.
1942 ..	0.197 (0.06—0.33)	0.075	0.122	Average of two readings.
1943 ..	Samples not taken			
1944 ..	0.500	0.230	0.270	One reading.

This gives an approximate idea of the intensity of silt entering and leaving the lake during floods and it would not be correct to work out the quantity of silt deposited in the lake from this.

An examination of the diameter of the silt leaving the waste weir in 1941 showed that only colloidal silt was carried over, while most of the suspended silt was deposited in the lake.

Rate of Silting

The Silt surveys were carried out in 1870, 1904 and 1940 and the results are set down in Table V :—

TABLE V

Period of record	Years	Silt deposited in foot-acres			Catchment area (square-miles)	Silt deposited in foot-acres per 100 square miles of catchment area
		During period	Per annum	Cumula- tive total		
1870-1904 ..	34	16,432	483	16,432	..	246.4
1904-1940 ..	36	2,708	75	19,140	..	38.3
1870-1940 ..	70	19,140	273	..	196	139.3

Volume-Weight Relationship of Silt

Samples to determine the density of silt under water and outside it were taken in 1943. The results are given in Table VI.

TABLE VI

Volume Weight Relationship of Silt Samples taken from Lake Fife in 1943

Malkhed Village	Wet weight/ volume (Lbs. per cubic foot)	Dry weight/ volume (Lbs. per cubic foot.)	Difference of Columns (2) and (3)	Moisture percentage
(1)	(2)	(3)	(4)	(5)
A. Silt exposed for a long time 300 feet away from the water edge in the lake	82.1	63.4	18.7	22.8
B. Silt newly exposed on the edge of water ..	83.8	61.1	22.7	27.0
C. Silt under water .. .	97.4	52.7	44.7	45.9

It is seen that under water a cubic foot of silt weighed about 97 lbs. and the weight of moisture contained in it was 45 lbs.

Remarks

The catchment is in the transition tract consisting of cultivated lands with good rainfall. Silting is, therefore, more than in the ghat storage (Darna Dam).

LAKE BEALE (DARNA DAM)

District	Nasik
River	Darna
Catchment area	156 square miles
Nature of catchment	Rocky and hilly
Rainfall	125 inches
Temperature	88.8°F. (maximum), 66.7°F. (minimum).
Mean annual runoff	56,3572 foot-acres
Type of flood	Distributed
Height of dam	94 feet
Storage capacity	178,212 foot-acres
Years of capacity surveys	1910, 1941

Suspended Silt Samples

In 1941; only one sample was taken in August. This showed that the silt content near the dam was 0.1 part per 1,000 parts of water by weight. No samples were taken in 1942.

The flood in July 1943 was heavy and the silt content in the Darna was also exceptionally high, (9.84 parts per thousand at 6/10 depth, near Ghoti).

The average silt content, exclusive of this heavy flood (2 samples taken in August) was as below and showed a silting tendency:—

(Silt content in parts per 1,000 parts of water)

	Surface	6/10 depth
Near Ghoti (at entry)	0.654	3.66
Near Dam	0.081	0.065

During 1944, monsoon samples were collected twice in August and September, the former flood being the bigger of the two. The average silt content varied from 0.052 parts per thousand parts near the dam to 0.066 about two miles above it. The silt content at entry varied between 0.024 to 0.061 parts per thousand parts. The silt content was low with little tendency to deposit.

Silt Surveys

Silt surveys were carried out in 1910 (at the time of construction) and in 1941. The silt deposited during the 31 years works out to 1565.4 foot-acres, i.e., 50.5 foot-acres per annum. That works out to 32.4 foot-acres per 100 square miles of catchment area or 0.028 per cent of original capacity per year.

Remarks

The Darna is a ghat-fed reservoir bringing low amount of silt from its rocky and hilly catchment. The rate of silting is, therefore, low. Some silting that has occurred is in the lowest reaches of the lake.

NANDUR MADHMESHWAR WEIR

Catchment area 1,650 square miles

This is a pick-up-weir built lower down across river Darna on which Darna Dam is constructed. The silt contents at entry and near the weir in different years were as under:—

(Silt content in parts per 1,000 parts of water)

	At entry	Near weir	Remarks
1941 .. .. .	..	0.290	Average of 2 samples
1942	0.240	0.127	One sample
1943	0.131	0.111	One sample
1944	0.391	0.236	Average of 2 samples

The average silt content in this basin is more than that in the Lake Beale above Darna Dam which forms the storage of this pick-up-weir. This is due to the fact that this drains, in addition, areas in the plains, with level, cultivated black soil.

There is a heavy silt deposit in the ponding limits of the basin.

VISAPUR TANK

District	Ahmednagar
River	Hanga
Catchment area	159 square miles
Nature of catchment	Black soil
Mean annual rainfall	20 inches
Mean annual temperature	83.5° F.
Mean annual runoff	29,600 foot-acres
Type of flood	Concentrated
Storage capacity	27,961 foot-acres (in 1927) 30,509 foot-acres (in 1933)

Suspended Silt Samples

Silt content of flood waters in different years was as under :—

TABLE VII

Year	Silt in parts per thousand by weight		Difference of Columns (2) and (3)	Remarks
	Entry	Head-works		
1	2	3	4	5
1941	1.700	1.760	0.060	One observation.
1942	0.783	0.688	0.115	Average of two observations.
1943	0.395	0.084	0.311	One observation—maximum flood.
1944	0.766	0.213	0.553	One observation—no discharge over the waste weir.

The silt content in the Hanga river which is in the heart of black cotton soil is much higher than that of the hilly Darna river. The catchment has an average rainfall of 20 inches but this occurs in torrents and the floods are concentrated. The result is that erosion is heavy and silt content in the flood waters very high.

Rate of Silting

The results of silt surveys show that the rate of silting per year is 168 foot-acres. This works to 105.7 foot-acres per 100 square miles of catchment or 0.55 per cent. of original capacity per year.

Remarks

Silting in tanks is generally rapid as they rarely overflow and practically the whole of the silt brought down by the rain is deposited. The catchment consists of deep black soil and rainfall is occasionally heavy.

PIMPALGAON TANK

District .. .. .	..	..	..	..	..	..	..	Ahmednagar
River .. .. .	..	..	..	..	..	..	..	Sina
Catchment area .. .. .	..	..	..	..	..	..	..	24 square miles
Nature of catchment .. .. .	..	..	..	..	..	..	..	<i>Muramy</i> (decayed trap)
Height of dam .. .. .	..	..	..	..	..	..	..	34 feet
Storage capacity .. .. .	..	..	..	..	..	..	..	4,473 foot-acres
Rainfall .. .. .	..	..	..	..	..	..	..	24 inches

Description of the Tank

The Pimpalgaon tank is situated on the river Sina, along the Shundi Wambori road north-east of Ahmednagar, and is used for water supply of the Ahmednagar town. The catchment is *muramy* (decayed trap) about 24 square miles in extent. Rainfall is limited to 24 inches and the tank rarely overflows. The length of the earthen dam is a little over a mile and its height in the valley 34 feet.

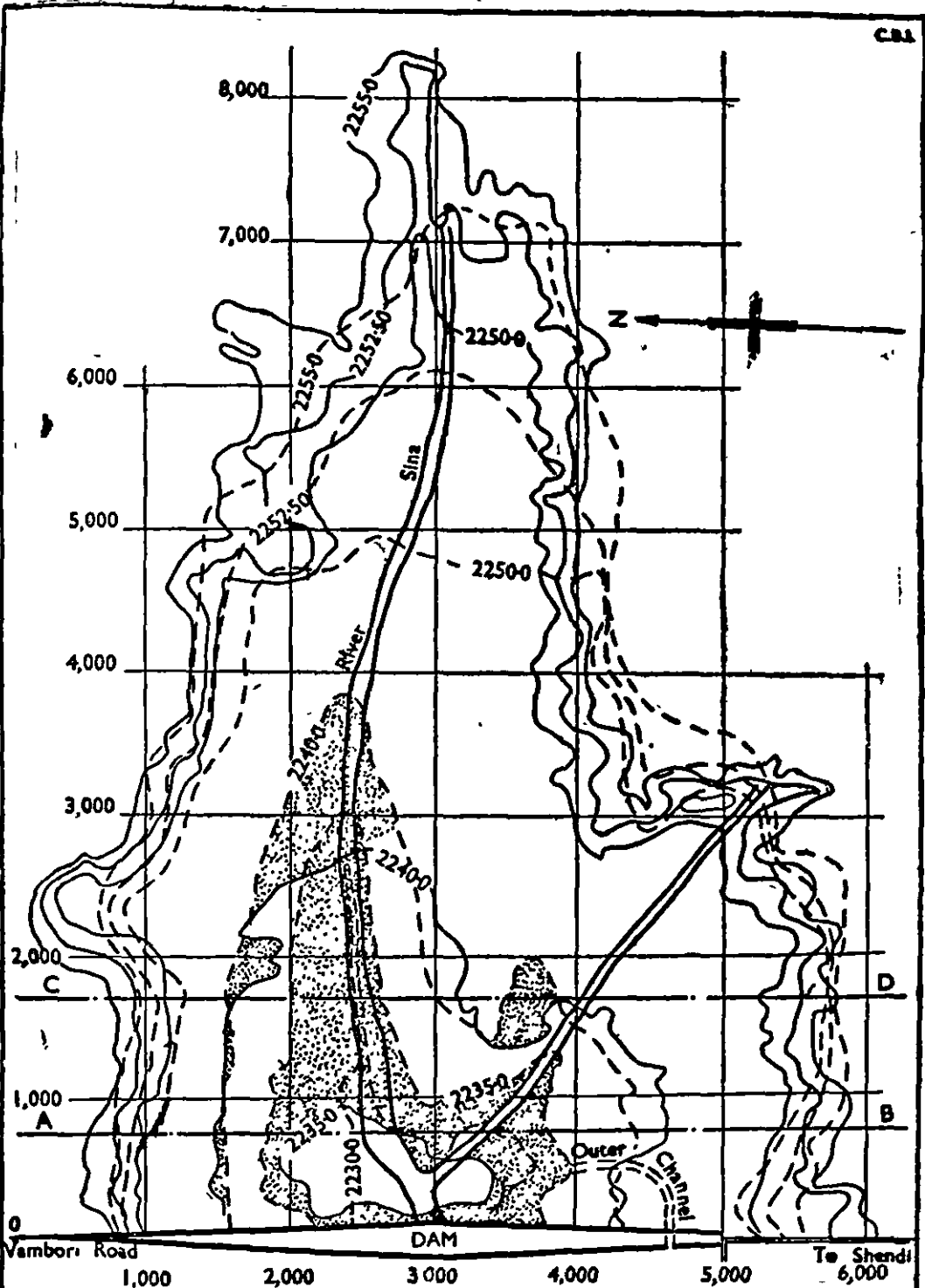
Capacity Surveys

The original capacity when the tank was constructed in 1922 was 4,473 foot-acres and as surveyed in 1941 it was 4,190 foot-acres, giving a total silt deposit of 283 foot-acres during 29 years. This gives a rate of silting per year of 9.7 foot-acres or 0.215 per cent of original capacity or 40.2 foot-acres per 100 square miles of catchment area.

The silting has been compensated by raising the full supply level by a foot.

Mode of Silting

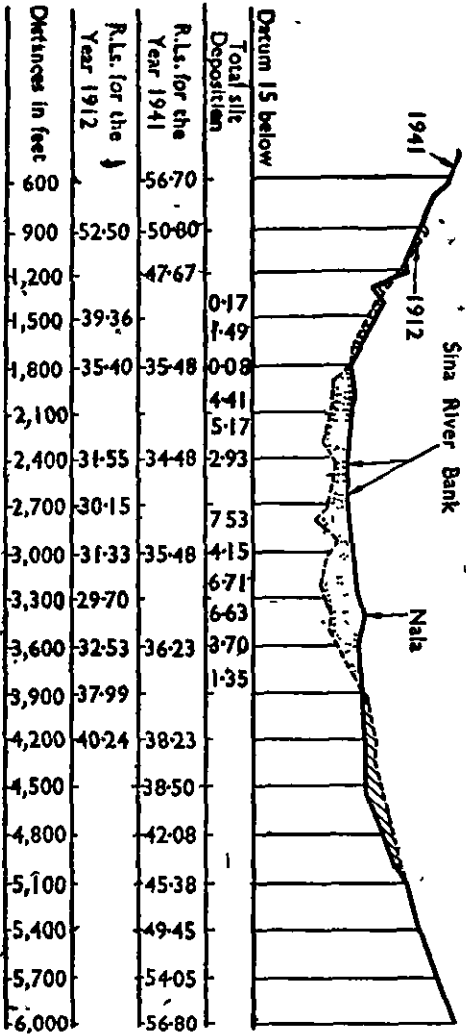
Detailed data about the capacity surveys carried out in 1912 and 1941 is also available for this tank. Figure 8 is a plan showing contours for 1912 and 1942, and Figure 9 gives cross sections along lines AB and CD. These show that the main valley has completely silted up in the lower portion (cross section AB) upto sill level, *viz.*, R. L. 2234.0. Silting has extended backwards along the main gorge (valley) up to R. L. 2240 and a thin layer of silt must have been deposited even upwards. But there was little silt deposited on the sides of the valley and there was on the contrary a tendency to scour as can be seen from the (1941) dotted contours of 1912 receding above the full line contours of 1941. In contrast to the silting up of the main gorge in the lower reach, the upper reach—broad to start with—appears to have been eroded sharply into a narrower gorge. The channel to the right changed its old circuitous course and took a straight run. The old bed was naturally silted up. These statements are better understood by a reference to the longitudinal section of the channel (Figure 9). It has silted up in a horizontal layer upto R. L. 2235, *i.e.*, just above the minimum water level in hot weather controlled by sill level. Silting extended upwards to R. L. 2244 with a slope of 1 in 317, which is fairly steep. R. L. 2235 and 2245 represent the limits of variation, the minimum water level before the monsoon and the normal water level thereafter. Silt brought down by the first storm is evenly dropped within the permanent hot weather ponding limits. It is subsequently dropped at different levels as the water level rises in the monsoon.



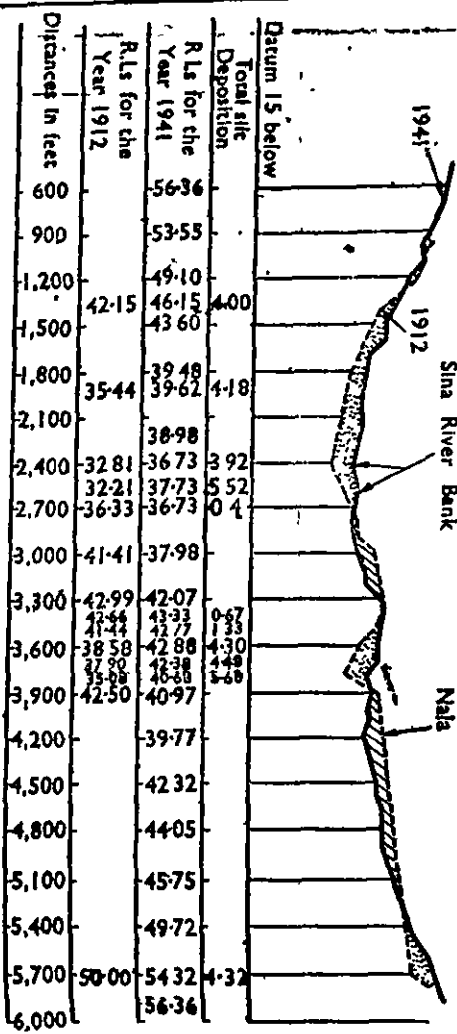
Note:-
Dotted Contours for 1912.
Full Contours for 1941.

FIGURE 8 :- PIMPALGAON TANK-PLAN SHOWING
CONTOURS FOR 1912 & 1941

CROSS SECTION A.B.



CROSS SECTION C.D.



ROUGH LONGITUDINAL SECTION ALONG VALLEY

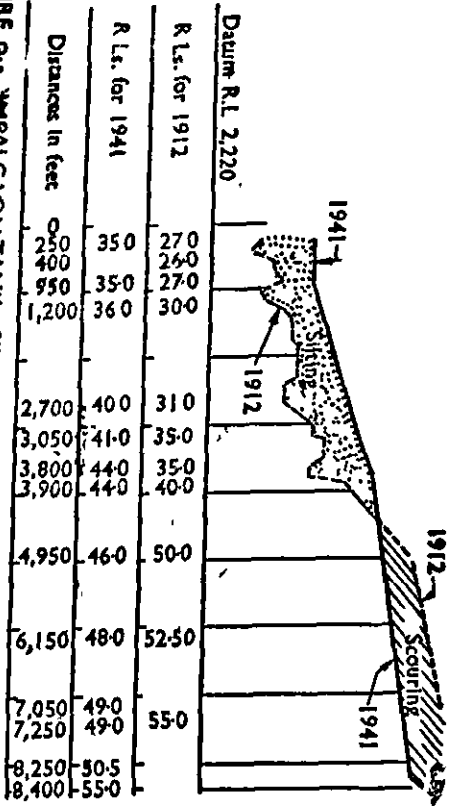


FIGURE 9.- WAPALGAON TANK - SILTING SURVEYS DURING 1912 & 1941

Figure 10 shows the area in square feet of each contour determined at the time of capacity surveys in 1912 and 1941. It is seen that the area of contours upto R. L. 2244 has decreased due to silting, beyond this, the area has increased due to scouring.

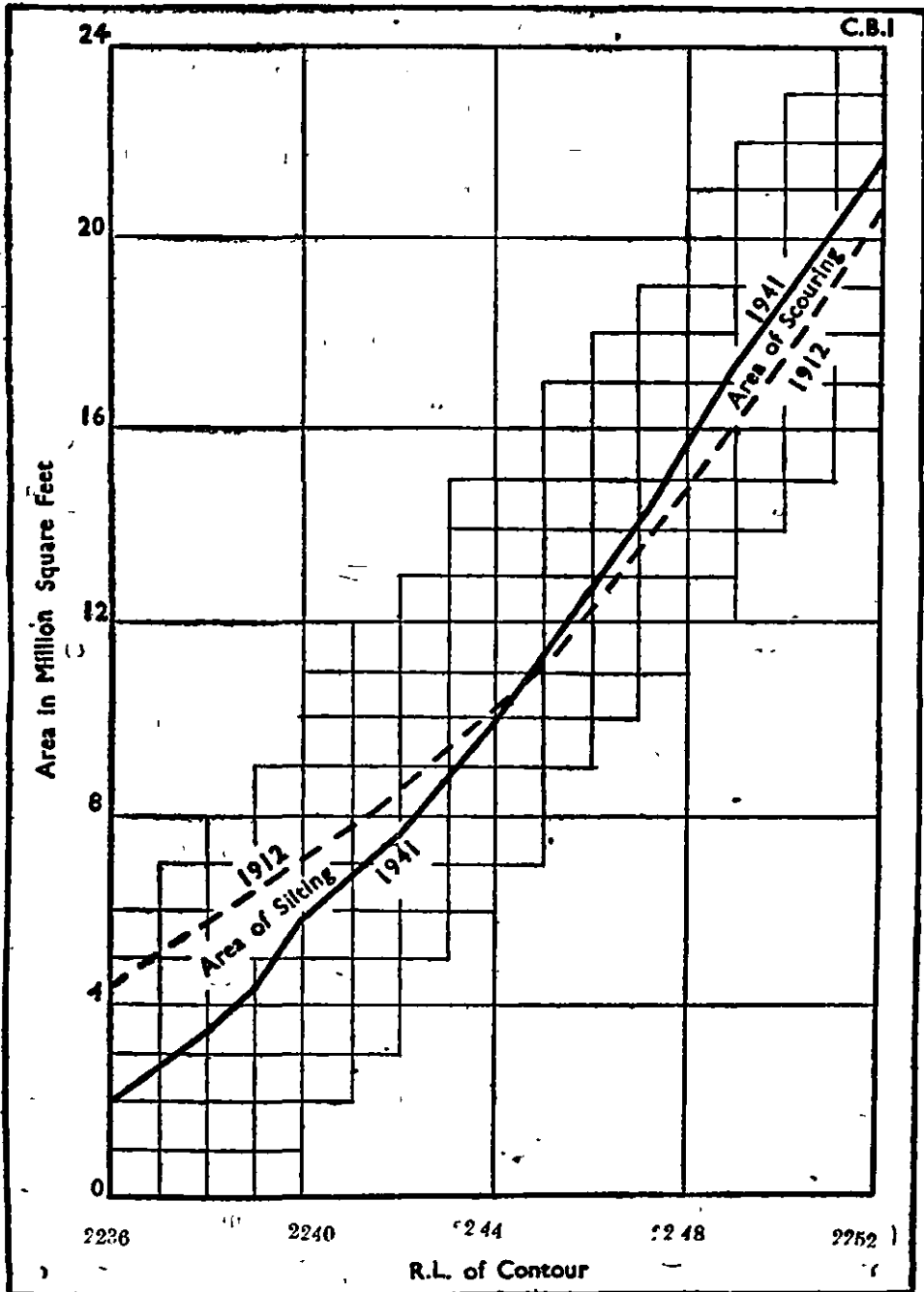


Figure 10 :—Pempalgaon Tank—Graph showing silting surveys, during 1912 & 1941

Remarks

The silting has occurred in the dead water zone below the sill level and has not affected the useful capacity appreciably.

GENERAL OBSERVATIONS

The catchment area of Lake Beale (Darna Dam) is in rocky tract and there is very little erosion. The rate of silting is, therefore, low.

Dhupdal and Lake Fife are both in the transition tract with terraced fields but the latter has much higher rainfall. The result is that Lake Fife has a silt deposit as high as 139 foot-acres per 100 square miles of catchment, while Dhupdal has only 14 foot-acres.

Silting in tanks is generally high as they have enough soil in the catchment area and the tanks rarely overflow. The rainfall is low but there are occasional heavy storms with consequent high erosion. The reduction in capacity of the tanks and reservoirs is generally brought about at the rate given below :—

Particulars	Number of years	Percentage reduction in reservoir capacity
1. Reservoirs	24	9.20
2. Tanks with hilly catchments	48	8.70
3. Tanks in plains with <i>muramy</i> and soil catchments	60	36.00
4. Tail tanks	60	19.00

Depending upon the data of construction and the nature of the catchments the capacities of tanks with soily catchments have been considerably reduced. The tank of Mayni is very nearly filled up. Thus in the soily catchments the tanks are being silted up within 100 to 200 years.

B. STORAGE RESERVOIRS IN UTTAR PRADESH

There are some 65 reservoirs in the Uttar Pradesh situated in Bundelkhand and Mirzapur districts to the south of the Yamuna and the Ganga Rivers. They were constructed as Irrigation Works for protection against famine. The Capital Investment is above Rs. three and a half *crores* and annual irrigated area is over half million acres. The physical characteristics of different catchments and the average runoff are varied; the catchment area ranges from 1 sq. mile to over ten thousand sq. miles; the storage capacity from 230 foot-acres to 81,000 foot-acres and thus a wide field of study for the rate of sedimentation is offered. Observations of the quantitative study of the probable rate of silting have been carried on some of the largest reservoirs over a long period by capacity surveys, which are discussed below. A few typical examples of the smaller reservoirs have also been incorporated.

DHUKWAN RESERVOIR ON BETWA RIVER

Catchment	..	..	..	..	..	..	8,240 sq. miles
Rainfall minimum	..	..	..	..	..	..	18.2 inches (1913)
Rainfall maximum	..	..	..	..	..	..	52.3 inches (1934)
Rainfall average	..	..	..	..	..	..	42 inches
Runoff minimum	..	..	..	..	..	..	1,000,000 ft. acres (1913)
Runoff maximum	..	..	..	..	..	..	10,000,000 ft. acres (1934)
Runoff average	..	..	..	..	..	..	5,660,000 ft. acres (1934)
Height of the dam	..	..	..	..	..	..	50 ft.
Length of the dam	..	..	..	..	..	..	3,916 ft.
Length of Lake	..	..	..	..	..	..	9 miles
Area of Lake	..	..	..	..	..	..	64,000 acres
Capacity at crest	..	..	..	..	..	..	56,252 foot-acres

Catchment characteristics

The catchment is entirely monsoon fed and contains wooded hilly country and cultivated land. The upper parts of the main river and its principal tributaries traverse through Vindhyan ranges and the catchment basin is almost equally interspersed with wooded hills and with scrub *jungle* plains of steep slopes and cultivated plains of medium slopes. The upper Vindhyan vary in height from 1,700 to 2,400 ft. above sea level and consist of massive sand-stones with a bed of conglomerate at its base. The lower Vindhyan principally consist of sand-stone, slate and shale intermixed with poorer conglomerate. Further down in the watershed basin, the ranges vary in height from 700 to 1,400 ft. above sea level and consist of massive rocks, indistinctly foliated and traversed by quartz reefs and numerous basic dykes of dolerite or diabase. These hills combined with well wooded forests occupy one third of the catchment.

A portion of the catchment consists of undulating and plain wasteland with ravine edged river beds covered either with scrub *jungle* or growing long grass. The balance of the area which forms the *doab* of the various tributaries is mostly black cotton soil, generally under some form of cultivation. These areas are liable to sheet and gully erosion and they furnish, in major part, all the silt in the river.

Rate of Silting

Capacity surveys were carried out in 1916, 1930, 1932, 1937 and in 1942. The results of the surveys of 1930 and 1932 were inconsistent and have been discarded. The rate of silting is given in Table VIII and Figure 11.

TABLE VIII

Period of record	Silt deposited in foot-acres				
	Years	During period	Per annum	Cumulative total	Per 100 sq. miles catchment per annum
1907-1916	10	12,924	1,292	12,924	16
1916-1937	20	12,007	603	24,931	7
1937-1942	5	-61	-12	24,870	Nil
1907-1942	35	24,870	701	..	8.5

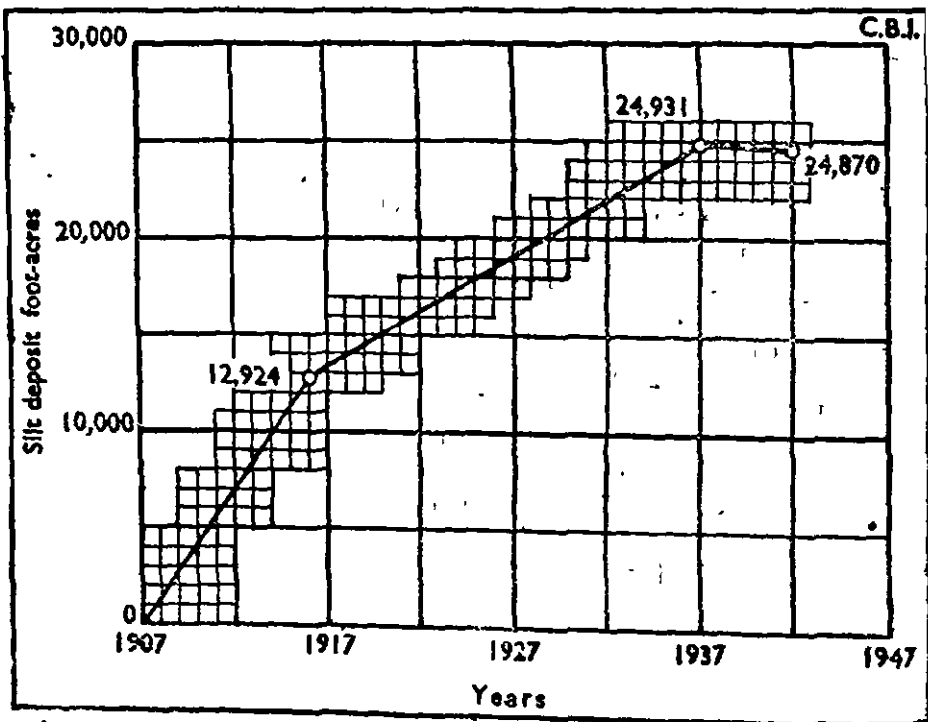


Figure 11 :—Showing silt deposited in Dhukwan Reservoir

Remarks

The rate of silting was high in the first ten years and has been falling rapidly since, which appears to be due to :—

- (1) Settlement and shrinkage of silt deposits due to superimposed load of additional silt and due to exposure.
- (2) Capacity runoff ratio is 1 to 100, and apparently, the reservoir has silted upto section required for normal floods.

(3) The capacity surveys indicate that the lake at the dam has a regular shape and silt deposits are distributed uniformly along the axis. As the distant ends at the flanks have silted up and the river flow is becoming confined within higher banks, resulting in velocities at the various points of the cross-section is less and, therefore, the tendency to silt is falling.

PARICHA RESERVOIR ON THE BETWA RIVER

It is a subsidiary Reservoir on the Betwa river, 30 miles below Dhukwan.

Catchment	10,384 sq. miles
Rainfall	41 inches
Runoff	7,200,000. foot-acres
Maximum Height of the Dam	54.8 ft.
Average Height of the Dam	20 ft.
Length of the Dam	3,853 ft.
Length of lake	17 miles
Area of Lake	2,400 acres
Capacity at crest	50,305 foot-acres

Catchment characteristics

The additional catchment is about 2,000 sq. miles and its features are not different from those of Dhukwan.

Rate of Silting

Paricha Dam was constructed in 1885, some 22 years before the upper reservoir Dhukwan. Its capacity was surveyed in detail in 1912 and again later at different intervals. The surveys indicate that the reservoir has never shown a tendency to silting, but, on the other hand, has been scouring all this time (Table IX).

TABLE IX.

Period of Record	Years	Scour in foot-acres			
		During period	Per. annum	Cumulative total	Per 100 sq. miles catchment per annum.
1912-1923	11	4,362	397	4,362	4
1923-1933	10	616	62	4,978	..
1933-1938	5	280	56	5,258	..
1938-1941	3	2,667	892	7,935	9
1941-1943	2	2,478	1,238	10,411	12
1912-1943	31	10,411	336	..	10

The scour has been plotted in Figure 12 which brings out that the rate of scour in the various periods has been variable.

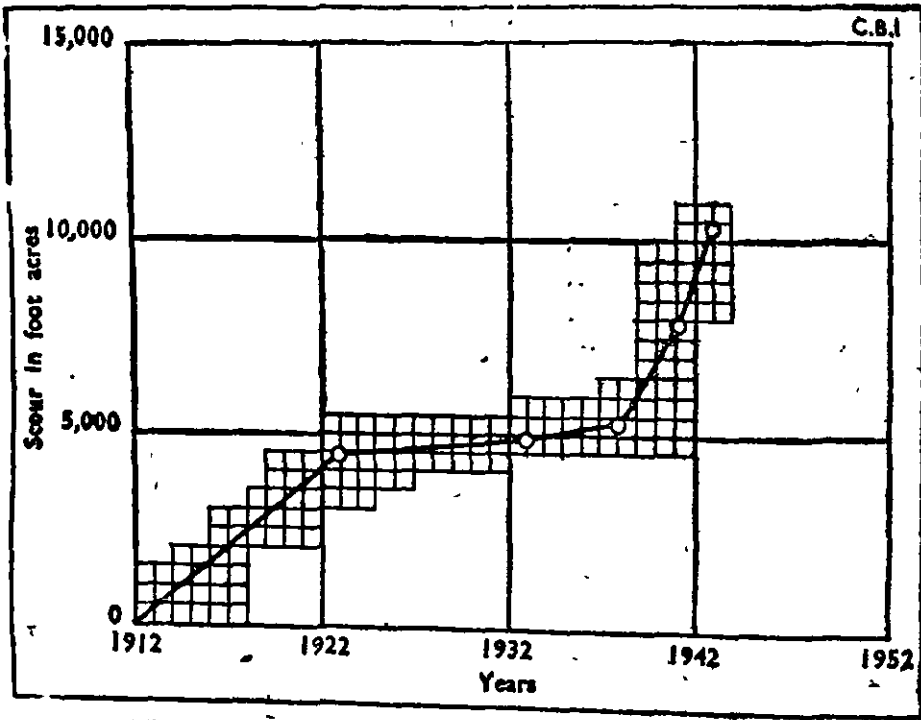


Figure 12 :— Rate of scouring of Paricha Reservoir

Remarks

Paricha is a second major reservoir on Betwa, being 30 miles below Dhukwan and its catchment is 2,000 sq. miles greater than that of Dhukwan. Although, a good part of the silt may be trapped at Dhukwan, some of the suspended load is certainly carried down. Instead of showing any signs of silting, the reservoir has progressively scoured and the circumstances leading to continued scouring appear to be :—

- (1) The reservoir is a sort of raised natural lake.
- (2) The reservoir is situated in a narrow long gorge with high bank on either side and it has small waterspread. The length of the lake at Paricha is 17 miles and its area 2,400 acres as compared to 9 miles length and 6,400 acres area at Dhukwan, whereas the storage capacity is almost similar.
- (3) The flood lift in the river has not been appreciably altered after the construction of the dam. The river has been steadily adjusting its section required for floods by scouring both the bed and its sides and consequently, the capacity of the lake has gradually increased.

Paricha is an unique example of a reservoir which has shown continuous scouring all these years.

PAHARI RESERVOIR ON DHASAN RIVER

Catchment	..	..	..	..	..	3,026 sq. miles
Rainfall	..	..	..	..	..	38 inches
Runoff	..	..	..	..	..	2,760,000 foot-acres
Length of the dam	..	..	..	..	..	1,848 ft.
Height of the dam	..	..	..	..	..	54 ft.
Length of the lake	..	..	..	..	..	8 miles
Area of the lake	..	..	..	..	..	1,700 acres
Capacity at crest	..	..	..	..	..	38,284 foot-acres

Catchment Characteristics

In general, the catchment is similar to that of Dhukwan. The differences are that (1) the scrub and *jungle* portion has lighter growth and is more liable to erosion, and (2) the cultivated area has more of lighter types of Bundelkhand soils which are easily erodible in comparison to heavier soils. In other words, this river carries somewhat heavier silt load.

Rate of Silting

Capacity surveys have been spread out over a long period and the rate of silting is indicated by Table X and Figure 13.

TABLE X

Period of record	Years	Silt deposited in foot-acres			
		During period	Per annum	Cumulative total	Per 100 sq. miles catchment per annum
1911-1916	5	3,047	609	3,047	20
1916-1932	16	18,118	1,132	21,165	37
1932-1939	7	2,289	327	23,454	11
1911-1939	28	23,454	838	..	27.7

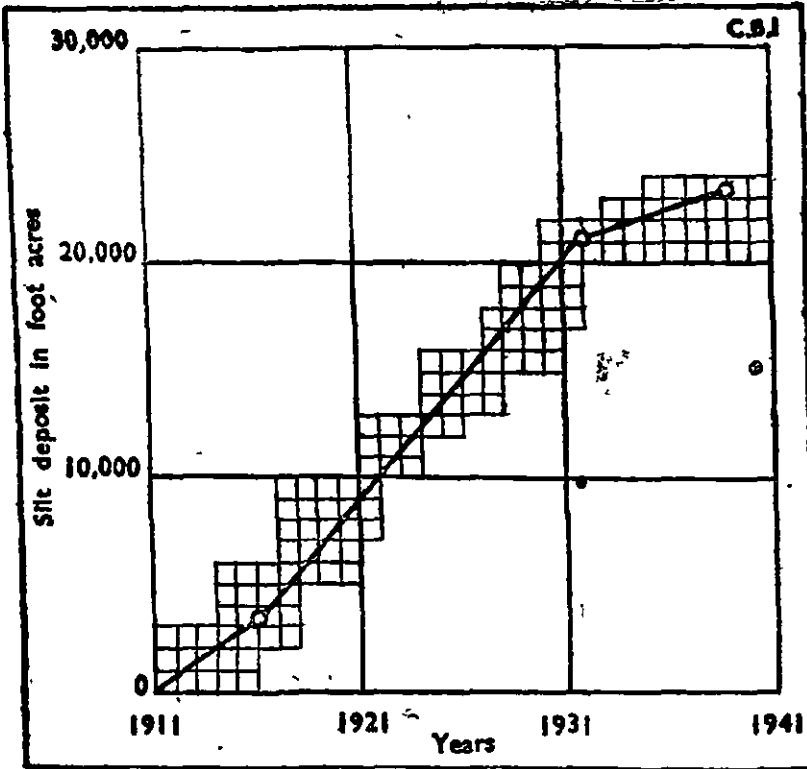


Figure 13 :—Rate of silting of Pahari Reservoir.

Remarks

The rate of silting has been high in the first 20 years but it has been falling subsequently. The higher rate of silting appears to be due to:—

- (1) The cultivated area comprises of lighter soils as against heavier soils in the catchment of Dhukwan and Paricha reservoirs.
- (2) The shape of the lake is irregular in the upper parts of the reservoir where silting has been heavier.
- (3) The deeper portions of the lake have silted most, and the extreme ends at the flanks a little less so that a shallower section required for the floods is maintained.
- (4) The rate of silting rose during the first 20 years of the reservoir and in the meantime the section of the lake stabilised. The rate of silting has been falling for the last 7 years.

LACHURA RESERVOIR ON DHASAN RIVER

This is a subsidiary reservoir on Dhasan river, 6 miles below Pahari. The catchment is only 214 miles greater but has similar characteristics as of the catchment of Pahari.

Catchment	3,240 sq. miles
Rainfall	38 inches
Runoff	2,960,000 foot acres
Length of the dam	1,732 ft.
Height of the dam	57 ft.
Length of the lake	6 miles
Area of the lake	960 acres
Capacity at crest	16,728 foot-acres

Rate of silting, based on capacity surveys is given in Table XI and Figure 14.

TABLE XI.

Period of record	Years	Silt deposited in foot acres			
		During period	Deposit foot-acres per annum	Cumulative total	Per 100 sq. miles catchment per annum
1908-1939	31	3,613	117	3,613	4
1939-1945	6	1,278	213	4,891	7
1908-1945	37	4,891	132	..	4

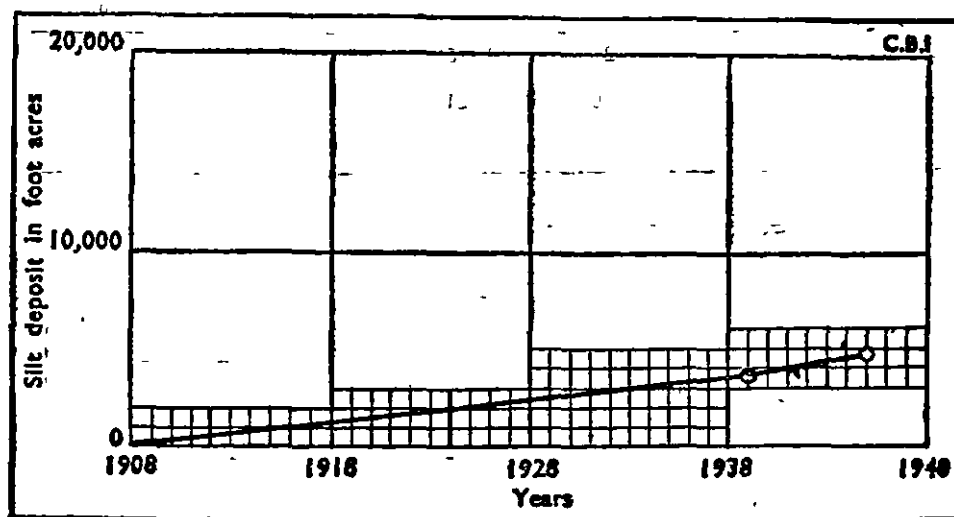


Figure 14 :—Rate of silting of Lachura Reservoir.

Remarks

The rate of silting in Lachura reservoir is small as the entire bed load and a good part of the suspended load is arrested in the upper reservoir. Besides in the case of this lake, the river banks are high and the flow is confined to a narrow section. Except at the approaches of the dam, the river section offers little room for silting.

ANGAO RESERVOIR ON KEN RIVER

Catchment	7,199 sq. miles
Rainfall normal	45 inches
Runoff normal	6,000,000 foot-acres
Length of the dam	2,712 ft.
Height of the dam	53 ft.
Length of the lake	7 miles
Area of the lake	3,600 acres
Capacity at crest	48,645 foot-acres

Catchment Characteristics

Ken, like other rivers of Central India is a monsoon stream. It rises in the Damoh District of the Central Provinces, where the famous Kaimur range is the dividing line of the watershed of the Narbada and Ken rivers. These ranges rise from 1,200 to 2,000 feet and comprise of a group of sandstone, shale and lime stones, sometimes resting directly on gneiss.

The total catchment is 7 199 sq. miles and the greater part is covered with steep wooded hills and thick scrubs. The cultivated plains and the ravines which are liable to sheet and gully erosion form only one-fifth of the catchment whereas well wooded and scrub areas are protected against erosion. The rate of silting based on capacity surveys is given in Table XII and Figure 15.

TABLE XII

Rate of silting in Gangao Reservoir

Period of record	Years	Silt deposited in foot-acres			
		During period	Per annum	Cumulative total	Per 100 sq. miles catchment per annum
1912-1933	21	13,715	654	13,715	9
1933-1939	6	3,521	587	17,236	8
1939-1945	6	2,636	439	19,872	6
1912-1945	33	19,872	602	...	8

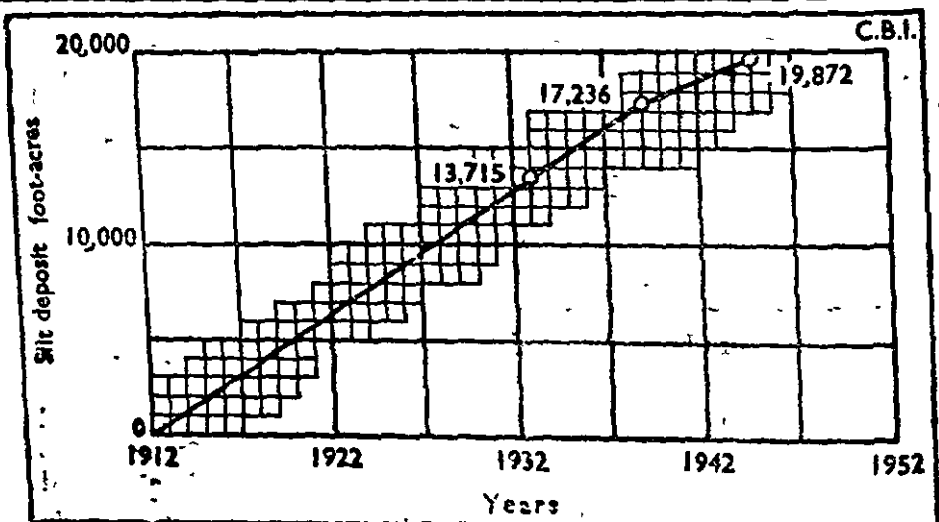


Figure 15 :— Rate of silting of Gangao Reservoir

Remarks

1. The Dam is built obliquely to the flow of water and the flood waters impinge on the right flank at the dam.

2. The lake is irregular in appearance and the river is tortuous for six miles above the dam.

3. Silting has occurred in the deeper portions of the lake and at the far ends of the flanks. The width of the lake has narrowed down considerably in wider sections, and the river is getting confined into a stable channel.

4. The rate of silting is low as greater part of the catchment is not liable to serious erosion.

5. Except for a few miles near the dam, the river flows, through hilly country over a rocky bed with many cascades. The channel is well defined with high banks on the sides.

BARIARPUR RESERVOIR ON KEN RIVER.

Catchment	..	..	..	..	..	7,699 sq. miles
Rainfall normal	..	..	..	..	..	45 inches
Runoff normal	..	..	..	..	..	6,400,000 foot acres
Length of the dam	..	..	..	..	..	1,637 ft.
Height of the dam	..	..	..	..	..	26 ft.
Length of the lake	..	..	..	..	..	3 miles
Area of the lake	..	..	..	..	..	600 acres
Capacity at crest	..	..	..	..	..	4,669 foot acres

Catchment Characteristics

Bariarpur is a second reservoir on Ken river, 25 miles below Gangao reservoir. The catchment is the same as for the upper reservoir. The rate of silting based on capacity surveys is given in Table XIII and Figure 16.

TABLE XIII*Rate of silting in Bariarpur Reservoir*

Period of record	Years	Silt deposited in foot-acres			
		During period	Per annum	Cumulative total	Per 100 sq. miles catchment per annum
1906-1939	33	738	22	738	Insignificant
1939-1945	6	439	73	1,177	1
1906-1945	39	1,177	30	..	Insignificant

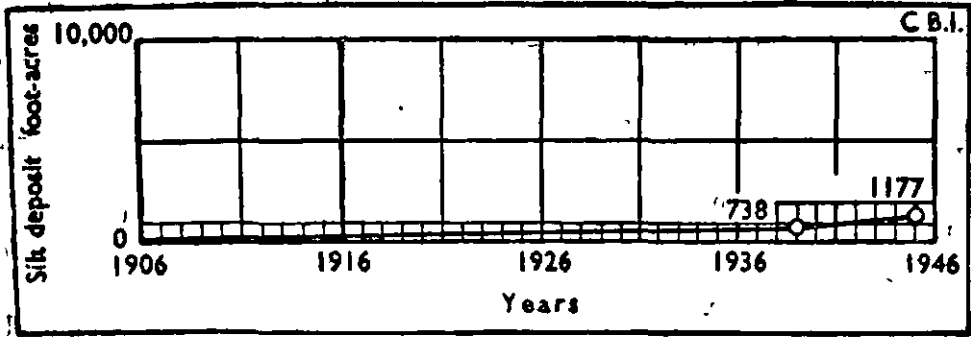


Figure 16 :—Rate of silting of Bariarpur Reservoir.

Remarks

1. Capacity runoff ratio is great, being 1 to 1,400.
2. The main reservoir Gangao is only 25 miles above Bariarpur and traps all the silt.
3. Below Gangao, the river has natural high banks and a rocky bed with steep gradient which keep the river confined in a well set channel.
4. The dam forms a sort of a raised natural lake and the flood lift is not very appreciable, except in the vicinity of the dam.
5. General rate of silting is very low.

PAHUJ RESERVOIR ON PAHUJ RIVER

Catchment	120 sq. miles
Rainfall normal	39 inches
Runoff normal	53,000 foot-acres
Length of the dam	603 ft.
Height of the dam	35 ft.
Length of the lake	2½ miles
Area of the lake	800 acres
Capacity at crest	7,460 foot-acres
Capacity at top of gates	15,640 foot-acres

Catchment Characteristics

About half of the catchment is covered with scrub and thin forest with occasional formations of foliated granitic rocks. The growth of *jungle* and grass offers some protection against erosion. The remaining area is either cultivated land with flat and medium slopes or broken land along streams and is liable to sheet and gully erosion. The soil structure of the cultivated area varies from black cotton soil to light loam, and the shape of the storage basin is irregular. The physical characteristics are such as to encourage erosion. The rate of silting based on capacity survey is given in Table XIV.

TABLE XIV

Rate of silting in Pahuj Reservoir

Period of record	Years	Silt deposited in foot-acres		
		During period	Per annum	Per 100 sq. miles of catchment per annum
1914-1945	31	346	11	9

Remarks

The dam has 6 feet high gates which are kept raised up for most of the year during monsoon in order to ensure full storage. River sluices are provided at bed level with a capacity of 2,400 cusecs. Ordinary spates of 6,000 cusecs, lasting for 4 to 6 hours, are easily cleared by the sluicing capacity with careful regulation. The gates are dropped in high spates only when the flood lift tends to rise above a safe limit.

Storage capacity of the reservoir to the top of gates is one third of the average annual run-off and the spates are of short duration. Although sluicing power is equivalent to low flood discharges, the sluices are often kept open during the monsoon period, and they help to throw out a part of the silt load which may otherwise accumulate above the dam. The contributory causes which lead to silting are :—

- (a) Capacity runoff ratio is 1 : 3.
- (b) Storage basin is very irregular.

BARW SAGAR ON BARWAR RIVER

Catchment	71 sq. miles
Normal rainfall	36 inches
Normal runoff	30,000 foot acres
Length of earthen dam	400 ft.
Height of earthen dam	24 ft.
Length of the lake	1 mile
Area of the lake	900 acres
Capacity	8,300 foot-acres

Catchment area

Half of the catchment is hilly of foliated granitic formation, lightly wooded and the remaining is cultivated area of mixed soils, partly protected with vegetation.

Barwa Sagar is an old *chandela* Tank, constructed or restored in 1705 A.D., as a shallow tank with 5 feet deep storage. It was subsequently taken over by the Irrigation Department in 1890 and raised to store 20 feet water.

The rate of silting is given below :—

Capacity in 1888	..	..	..	..	..	8,300 foot-acres
Capacity in 1909	..	..	..	..	..	7,600 foot-acres
Capacity in 1933	..	..	..	..	..	7,400 foot-acres

Capacity runoff ratio is 1 to 4, silt deposited in 65 years is 900 foot-acres or 14 foot-acres per year, giving a rate of 20 foot-acres per year per hundred square miles catchment.

SMALL TANKS

Bara Tal (Babina)

Catchment area	..	..	..	..	..	2 sq. miles
Normal rainfall	..	..	..	..	..	37 inches
Normal runoff	..	..	..	..	..	900 foot-acres
Capacity in 1906	..	..	..	..	..	1,020 foot-acres
Capacity in 1933	..	..	..	..	..	800 foot-acres
Silt deposited in 27 years	..	..	..	..	..	220 foot-acres
Silt deposited per annum	..	..	..	..	..	8 foot-acres
Silt deposited per annum per 100 sq. miles catchment	..	..	..	..	..	400 foot-acres

Koncha Bhanwar Tank

Catchment area	..	..	..	..	..	2.7 sq. miles
Normal Rainfall	..	..	..	..	..	36 inches
Normal runoff	..	..	..	..	..	1,200 foot-acres
Capacity in 1911	..	..	..	..	..	770 foot-acres
Capacity in 1933	..	..	..	..	..	600 foot-acres
Silt deposited in 22 years	..	..	..	..	..	170 foot-acres
Silt deposited per annum	..	..	..	..	..	8 foot-acres
Silt deposited per annum per 100 sq. miles catchment	..	..	..	..	..	206 foot-acres

Remarks

In small catchments, particularly where capacity-runoff ratio is near about one, entire silt is transported into the lakes and the rate of silting is of a higher order. If the catchments are large, say 50 sq. miles or more, and the capacity-runoff ratio is still about one, the rate of silting is comparatively less as the transported silt load has a much bigger area for dispersal.

OBSERVATIONS OF SUSPENDED LOAD IN RIVERS

Experiments for measuring suspended silt of the rivers were first performed in the Uttar Pradesh State during 1911 and 1912. The method adopted was to take two samples from one point in the centre of the stream, two feet below the water surface, in measured sized bottles. This was allowed to stand for 24 hours until the sediment had settled down, and the top clear water was decanted off leaving a few ounces overlying the sediment. This remaining mixture was passed into a small measuring glass, tapering to a narrow size at the bottom and graded to show drachms and minims, to allow the measuring of the smallest quantities. The mixture was subjected to heat and evaporation, leaving dry residue of which the volume was measured in the measuring glass. The results of experiments made in 1912 are set down in Table XV.

TABLE XV

Name of river	Proportion of dry silt in suspension		Weight in lbs. per cu. ft. well pressed			
	By volume	By weight	Silt		Sand	
			Wet	Dry	Wet	Dry
Khajuri	$\frac{1}{4,800}$	$\frac{1}{3,947}$	111	77	104	90
Karamnasa ..	$\frac{1}{4,700}$	$\frac{1}{3,864}$	105	75	98	86
Ghagar	$\frac{1}{5,000}$	$\frac{1}{4,112}$	105	79	105	91
Garai	$\frac{1}{4,600}$	$\frac{1}{3,783}$	105	75	109	87
Belan	$\frac{1}{3,200}$	$\frac{1}{2,480}$	104	75	Not found	
Gangá at Mirzapur	$\frac{1}{400}$	$\frac{1}{330}$	103	75	106	90

Similar experiments were conducted on Ken and Betwa rivers, and the data for suspended load varied from 1 in 1,500 to 1 in 2,500. The details of the experiments are however not available.

More recently since 1941, the U.P. Irrigation Research Institute has observed the amount of suspended load on the Betwa river above and below Dhukwan Dam. Silt samples are collected in standard bottles of one litre at three points in the section, at 1/6th, at 1/2nd and at 5/6th of the width from either bank, and at 6/10th depth at each of the points. These three samples make up one observation of the silt content over the whole section. The samples are taken during the monsoon period only, when the river carries appreciable quantities of silt. The results are shown in Table XVI.

TABLE XVI.
Quantity of silt deposited at Dhukwan

Year	Runoff (foot- acres)	Total suspended load (foot- acres)	Silt retained in reservoir (foot- acres)	Rainfall in catch- ment (inches)	Percent of total suspended silt retained in reservoir	Proportion of suspended load to run off
1941	1,261,000	795	188	21	24	1 in 1,600
1942	7,075,000	5,427	507	55	9	1 in 1,300
1943	2,544,000	2,173	632	34	29	1 in 1,170
1944	6,601,000	1,897	433	28	23	1 in 3,470
1945	6,670,000	6,511	1,515	34	19	1 in 1,030
1946 .. ..	..	2,722	142	39	5	..

The dry density of the material has been found to vary from year to year. It was taken as 140 lbs. per cft. in 1941, 111.3 lbs. in 1942, 85.37 in 1943, 83.8 in 1944, 70 in 1945 and 77.5 in 1946. Obviously, the moisture content of the samples of the different years has been changing, and the results cannot be considered dependable. It is, therefore, difficult to draw any conclusion until the experiments had been conducted on an uniform basis for several years.

GENERAL OBSERVATIONS

The composition of watershed catchments of Bundelkhand reservoirs is more or less, similar, but the trend of silting is different. An abstract of the results of capacity surveys showing the comparative rate of sedimentation of some of the existing reservoirs in Uttar Pradesh, Madhya Pradesh, Berar, Baroda and Hyderabad is given in Table XVII. The conclusions are :—

(a) Reservoirs like Dhukwan, Pahari and Gangao form one class. There are no reservoirs above them and their sluicing capacity with respect to normal floods is too small for consideration. Rate of sedimentation is comparatively high in the first 15 to 20 years, varying with the nature of the catchment from 9 to 37 foot acres per 100 sq. miles catchment per year. Later, the rate rapidly falls off and may ultimately become negligible. This is easily explained. The runoff capacity ratio is high being roughly 100 to 1, and the river spates require a certain section to maintain the flow. The obstruction by the dam causes the dips and the flanks of the storage basin to fill up with the silt in the early year. A stage comes when the river section is adjusted to carry the normal flood discharge. Under such a condition, the disposal of the suspended load in the area of the lake is harmonised with the conditions of flow as they are in the other parts of the river and silting is greatly reduced. Besides, the progressive development of deltas above reservoir level helps in trapping some

of the silt load, and shrinkage combined with settlement of silt deposits due to weather and due to superimposed load of additional silt reduces the silt volume in the storage basin.

(b) Subsidiary reservoirs like Lachura below Pahari, Bariarpur below Gangao and Pahuj below Garhya and Palanpur show insignificant silt deposits in the first 15 to 20 years, when the upper reservoirs had been picking up the maximum volume of silt. As the lakes above are forming a stable section for the passage of normal floods, more silt is travelling downwards to subsidiary reservoirs where rate of silting is now 6 to 7 foot acres, per year per 100 sq. miles catchment, and is showing a rising tendency.

(c) Bara Tal and Konch Bhanwar tanks are the worst silters. Capacity-runoff ratio is about one and so, the normal runoff along with the entire bed and suspended load is accommodated in the lakes almost every year. In these two cases, silt is being deposited at the rate of 8 foot acres annually; the capacity of the lakes is about 800 foot acres each, and at this rate they are likely to get partially silted up in a period of 100 years. The rate of silting in later years may however rapidly decrease when the reservoir silts up to a section required for normal flood discharge, and the useful life of the lakes may be somewhat prolonged.

SUMMARY AND CONCLUSIONS

In the Bombay State water samples are taken from a few selected reservoirs from flood waters entering a reservoir and leaving the same *via* the waste weir. But the samples have been taken for one or two floods during each season and cannot give any correct idea of the amount of silt deposited in the lake. Capacity surveys are, however, undertaken wherever it is feared that the useful contents of a reservoir are diminishing. A summary of the result is given in Table I.

In Uttar Pradesh the amount of suspended load is being observed on the Betwa river above and below Dhukwan Dam, since 1941. The samples are taken during the monsoon period each year when the river carries appreciable quantities of silt. The results are summarised in Table XV. The great drawback of these observations is the determination of the density of dry silt which has been varying from year to year. The average suspended load retained in the reservoir during the period 1941 to 1946 works out to 519 foot-acres per annum. That may be compared with the average rate of silting, *viz.*, 701 foot-acres as determined by the capacity surveys. The difference is due to the fact that the rate of silting has decreased in later years and the actual rate is now less than in the first 10 years after construction. It is also partly due to the omission of bed load. An abstract of the results of capacity surveys and connected data is given in Table XVII.

The information regarding Madhya Pradesh, Berar, Baroda and Hyderabad State is also contained in Table XVII.

TABLE
Silt and connected data of some existing dams in Uttar Pradesh

Serial No.*	Reservoir		Catchment area in square miles	Height of dam in feet	Storage capacity			Annual rainfall in inches	Annual runoff foot acres	Runoff per square mile of catchment foot acres
	River	Name			Foot acres	Percent of annual runoff	Per square mile of catchment			
1	2	3	4	5	6	7	8	9	10	11
UTTAR PRADESH										
161	Betwa ..	Pericha ..	10,381	55	50,305	0.70	5.0	41	7,200,000	694
162	Betwa ..	Dhukwan ..	8,240	50	56,252	1.00	6.9	42	5,660,000	687
163	Ken ..	Bariarpur ..	7,699	26	4,669	0.07	0.6	45	6,400,000	331
164	Ken ..	Gangao ..	7,109	53	48,645	0.81	6.8	45	6,000,000	833
165	Dhasan ..	Lachura ..	3,240	57	16,728	0.56	5.2	38	2,960,000	913
166	Dhasan ..	Pahari ..	3,026	54	38,284	1.32	12.7	38	2,700,000	912
167	..	Ghaggar ..	310	..	123,684	..	399	..	..	..
168	Pahuj ..	Pahuj ..	120	35	7,400	14.1	62	39	53,000	442
169	Barwar ..	Barwasagar ..	71	24	8,300	27.7	117	36	30,000	422
170	Barwar ..	Kouch Bhanwar	2.7	..	770	64	285	36	1,200	444
171	Barwar ..	Bara Tal ..	2	..	1,020	113	510	37	900	450
MADHYA PRADESH AND BERAR										
172	Tandula and Sukhanalas	Tandula and Sukha ..	319	82	223,957	66	369	52.1	339,000	1,063
173	Maniari ..	Maniari ..	310	95	119,743	51	337	39.3	236,000	763
174	Kharang..	Kharang ..	237	69	155,900	68	658	44.7	231,000	976
175	Suloriyanala	Maramsilli ..	187	84	131,267	65	704	45.8	203,000	1,085
176	Sarathinala	Sarathi ..	37.8	58	13,113	46	348	56.8	28,700	761
177	Charkhamara nala	Charkhamara ..	29.0	61	17,883	84	618	56.7	21,200	731
178	Bagdeonala	Bodalkassa ..	23.5	63	10,010	93	683	38.7	17,240	744
179	Godam nala	Bori ..	20.6	55	8,092	44	391	42.8	18,540	901

*Serial Nos. are in continuation of those in Table I and Table XXXVII.

XVII.

Madhya Pradesh and Berar, Baroda and Hyderabad

Year of capacity surveys			Silt deposited					Remarks Nature of catchment
First	Last	Period in years	Total foot acres	Annual foot-acres	Percent of original capacity per annum	Per thousand of water supply by volume	Per hundred square miles of catchment per annum (foot-acres)	
12	13	14	15	16	17	18	19	20
1912	1943	31	-10,411	-336	Scour	-0.005	-10	Has continuously scoured. Subsidiary reservoir
1907	1942	35	24,870	701	1.24	0.012	8.5	
1906	1945	39	1,117	30	0.64	0.0	Insignificant	Subsidiary reservoir.
1912	1945	33	19,872	602	1.24	0.0100	8	
1908	1945	37	4,891	132	0.80	0.004	4	Subsidiary reservoir.
1911	1939	28	23,454	838	2.19	0.030	27	Has a high percentage of cultivated area in the catchment.
1919	1938	19	..	..	Nil	..	..	Catchment area rocky, no tendency to silt.
1914	1945	31	848	11	0.15	0.021	9	Has two small reservoirs above in the catchment.
1868	1933	65	900	14	0.17	0.047	20	
1911	1933	22	170	8	1.04	0.67	296	
1906	1933	27	220	8	0.80	0.89	400	
1919	1941	22	1,170	53.3	0.024	0.016	16.7	Mostly masari under lain by <i>Moorum</i> and laterite. Hilly with <i>jungle</i> , slopes 1 in 300 to 1 in 1,000.
1930	1941	11	975	88.6	0.074	0.038	28.7	Metamorphic rocks prevalent over the catchment area which lies among forests covered hills with steep slopes.
1926	1941	15	1,490	99.2	0.063	0.043	41.8	Metamorphic rock—Slopes vary. Catchment <i>jungles</i> and hilly.
1922	1941	19	520	27.3	0.021	0.013	14.7	Vindhyan and granites.
1919	1941	23	1,562	71	0.54	0.007	188	Disintegrated crystalline rock. Slopes steep and wooded.
1913	1941	28	407	14.5	0.081	0.069	50.1	Dharwar formation, slopes fairly steep.
1913	1941	28	1,088	38.9	0.242	0.225	165	Dharwar formation, slopes fairly steep.
1927	1941	14	312	22.2	0.275	0.120	108	Steep hills covered with thick <i>jungles</i> ,

TABLE XVII
Silt and connected data of some existing dams in Uttar

Serial No.	Reservoir		Catchment area in square miles	Height of dam in feet	Storage capacity			Annual rainfall in inches	Annual runoff (foot-acres)	Runoff per square mile of catchment (foot acres)
	River	Name			Foot acres	Percent of annual runoff	Foot acres per square mile of catchment			
1	2	3	4	5	6	7	8	9	10	11
180	Budhbura nala.	Khairbanda ..	16.5	60	13,360	58	810	54.9	22,900	1,380
181		Khapri ..	15.4	36	9,472	57	614	44.2	16,600	1,080
182	Dodha nala	Jamunia ..	11.8	50	7,438	77	630	53.0	9,700	821
183	..	Kumhari ..	11.7	39	9,183	75	784	46.6	12,300	1,048
184	Dorki nala	Pindraon ..	9.8	35	8,606	58	882	49.3	14,800	1,517
185	..	Khaira datan	7.5	27	1,919	19	256	45.7	10,000	1,332
186	..	Kumrangl ..	5.9	33	3,611	54	614	47.7	6,710	1,140
187	..	Doritala ..	5.5	36	1,928	33	351	47.4	5,760	1,050
188	..	Moroda-A ..	5.2	29	3,590	68	691	42.9	7,440	1,008
189	..	Wara tank ..	4.4	33	2,273	21	517	55.3	10,900	2,473
190	..	Dhanras ..	4.0	33	1,080	39	270	40.8	3,910	977

—contd.—

Pradesh, Madhya Pradesh and Berar, Baroda and Hyderabad

Years of capacity surveys			Silt deposited					Remarks Nature of catchment
First	Last	Period in years	Total foot acres	Annual foot-acres	Per cent of original capacity per annum	Per thousand of water supply by volume	Per hundred square miles of catchment per annum (foot acres)	
12	13	14	15	16	17	18	19	20
1915	1941	26			No silt			Gneiss rocks, slopes moderately steep.
1908	1941	33	106	3.2	0.034	0.019	20.9	Bare rock <i>moorum</i> , clay etc., light soil underlain at a depth of 3 feet by soft <i>moorum</i> , clay soil underlain at a depth of 3 feet by hard rock. Slopes moderately steep 1 in 200 to 1 in 400.
1916	1941	25	180	7.2	0.097	0.074	61.2	Crystalline rock. Slopes fairly steep and well wooded.
1923	1941	18	828	46.0	0.500	0.374	393	Jungle and cultivated areas in the proportion of 2 to 1. Slope moderate.
1908	1941	33			No silt			Cultivated land and Bhat's moderately steep, slopes 1/200 to 1/400. Clay soil underlain at a depth of 3 ft. by hard rock and partly cultivated.
1908	1941	33	437	13.2	0.689	0.132	176	Kankar, <i>matasi</i> and <i>moorum</i> , flat slopes—1 in 500 to 1 in 2,000. Yellow <i>matasi</i> underlain by soft <i>moorum</i> , <i>moorum</i> underlain at a depth of 1½ feet by hard <i>moorum</i> , hard <i>moorum</i> underlain at a depth of 4 feet by clay with flat black stone. Partly wooded and partly cultivated.
1909	1941	33	414	12.5	0.347	0.187	213	<i>Matasi</i> and <i>kankar</i> moderately steep—1 in 200 to 1 in 400. Light soil underlain at a depth of 4 feet by soft <i>moorum</i> . Porous <i>moorum</i> underlain at a depth of 4 feet by laterite partly wooded and partly cultivated.
1909	1941	33	74.5	2.32	0.120	0.040	42.5	Rock with <i>jungle</i> . Hard silt underlain at a depth of 2 feet by light soil. Slopes steep—1/50 to 1/150 densely wooded.
1908	1941	33	113	3.45	0.096	0.066	65.9	<i>Bhata</i> and <i>matasi</i> . Slopes steep 1/50 to 1/150. Partly wooded and partly cultivated.
1910	1941	31	102	3.24	0.142	0.030	73.6	Rock. Slopes fairly steep.
1909	1941	32	54.3	1.70	0.158	0.043	42.5	<i>Kachar</i> about 1.0 square miles rest rocky. Gradient steep.

TABLE XVII

Silt and connected data of some existing dams in Uttar

Serial No.	Reservoir		Catchment area in square miles	Height of dam in feet	Storage capacity			Annual rainfall in inches	Annual runoff (foot-acres)	Runoff per square mile of catchment (foot-acres)
	River	Name			Foot acres	Per cent. of annual runoff	Foot acres per square mile of catchment			
1	2	3	4	5	6	7	8	9	10	11
101		nikrohi	3.7	29	1,980	2	543	48.2	5,810	1,003
102	..	Borkhera	3.7	30	943	48	256	50.5	1,970	536
103	..	Baloda	3.6	24	1,025	27	284	48.3	3,770	1,050
104	..	Pangri	3.3	39	2,030	43	613	55.6	4,710	1,420
105	Bandha nala	Hargaban	3.2	32	2,521	75	796	43.8	3,330	1,056
106	..	Amachua	3.2	39	1,354	51	429	45.2	2,640	837
107	Dhumna nala	Kirna	2.9	31	2,135	67	735	36.5	3,050	1,048
108	..	Jam Mohgaon	2.5	29	1,394	18	557	53.9	7,922	3,170

—contd.

Pradesh, Madhya Pradesh and Berar, Baroda and Hyderabad

Years of capacity surveys			Silt deposited						Remarks Nature of catchments
First	Last	Period in years	Total foot acres	Annual foot-acres	Per cent. of original capacity per annum	Per thousand of water supply, by volume	Per hundred of square miles of catchment per annum (foot acres)		
12	13	14	15	16	17	18	19	20	
1908	1941	33	322	9.8	0.489	0.256	265	<i>Bhata, matasi and kankar</i> , sloped flat—1/500 to 1/2,000. Partly wooded and partly cultivated. <i>Kankar</i> soil underlain at a depth of 2 feet by yellow soil mixed with <i>moorum</i> underlain at a depth of 3 feet by <i>chhui</i> with boulders.	
1909	1941	31	44.5	1.38	0.145	0.070	37.5	Crystalline rock formation. Slopes fairly steep.	
1908	1941	33	23	7.00	0.681	0.184	194	<i>Bhata, matasi and kankar</i> . Yellow soil underlain at a depth of 1½ feet by soft <i>moorum</i> underlain at a depth of 1½ feet by hard <i>moorum</i> and laterite. Hard <i>moorum</i> and laterite underlain at depth of 3 feet by clay soil. Slopes flat 1/500 to 1/2,000.	
1917	1941	24			No Silt			Rock and ordinary soil covered with dense jungle and entirely bounded by high hills. Slopes generally steep.	
1908	1941	33	74.5	2.27	0.090	0.068	71.0	<i>Kankar</i> soft <i>moorum</i> underlain at a depth of 3 feet by hard <i>moorum</i> . Hard <i>moorum</i> underlain at a depth of 5 feet by soft <i>moorum</i> mixed with yellow clay and soft <i>moorum</i> mixed with yellow clay underlain at a depth of 11 feet by stiff clay. Light soil underlain at a depth of 5 ft. by stiff clay. Slope of catchment is from 1 in 130 to 1 in 200. Partly wooded and partly cultivated.	
1917	1941	24	68.8	2.87	0.212	0.108	91.1	1.5 sq. miles; Kacha earth mixed with sand and the rest rocky. The catchment being hilly, the slopes are steep.	
1906	1941	35	161	4.60	0.216	0.151	158	Light soil underlain at a depth of 4 feet by soft <i>moorum</i> . Clay soil underlain at a depth of 3 feet by hard rock, slope 1 in 60.	
1909	1941	35	220	6.27	0.450	0.079	251	Clay soil overlying porous <i>moorum</i> . Slopes rather flat and only sparsely wooded.	

TABLE XVII

Silt and connected data of some existing dams in Uttar

Serial No.	Reservoir		Catchment area in square miles	Height of dam in feet	Storage capacity			Annual rainfall in inches	Annual runoff (foot-acres)	Runoff per square mile of catchment (foot acres)
	River	Name			Foot acres	Per cent. of annual run-off	Foot acres per square mile of catchment			
1	2	3	4	5	6	7	8	9	10	11
199		Morid	2.5	22	345	14	138	45.1	2,420	970
200	..	Doongar Bari	2.4	33	903	16	369	60.3	5,500	2,245
201	..	Maroda B and C	1.7	B-23 C-20	1,190	72	668	42.9	1,650	970
202	..	Gomdoh	1.6	32	1,080	52	675	52.3	2,070	1,290
203	..	Doril	1.4	25	952	54	680	52.7	1,750	1,250
204	..	Usri	1.4	13	241	25	172	47.5	963	688
205	..	Barpall	1.0	28	644	60	643	50.6	1,067	1,067
206	..	Khortora	1.0	18	322	34	322	45.7	943	..
207	..	Abhanpur	0.8	19	195	23	244	46.6	839	1,047
208	..	Soril	0.7	14	269	39	407	43.4	693	1,048
BARODA STATE.										
209	Surya	Sayaji Sarovar (Ajiva Lake)	36.2 (1891) 78.4 (1931)	40 (at Surya)	59,593	71	760	40	83,600	..
HYDERABAD STATE.										
		Pocharam	240	..	50,906	..	212	..	..	..
		Buyel marchand Tank	168	..	5,840	..	35.8	..	..	..

—concl'd.

Pradesh, Madhya Pradesh, Berar, Baroda and Hyderabad

Years of capacity surveys			Silt deposited					Remarks Nature of catchment
First	Last	Period in years	Total foot acres	Annual foot-acres	Per cent. of original capacity per annum	Per thousand of water supply by volume	Per hundred square miles of catchment per annum (foot acres)	
12	13	14	15	16	17	18	19	20
1906	1941	35	..	..	No Silt	..	..	Light soil underlain at a depth of 3 feet by soft <i>moorum</i> ; clay soil underlain at a depth of 3 feet by soft rock. Slopes steep—1 in 50 to 1 in 150.
1909	1941	32	121	3.78	0.417	0.068	154	Crystalline rocks. Slopes fairly steep well wooded.
1908	1941	33	5.8	0.18	0.015	0.011	10.8	B—Clay soil underlain at a depth of 4 feet by soft <i>moorum</i> . C—Porous <i>moorum</i> underlain at a depth of 4 feet by <i>kankar</i> mixed with the lime, <i>Kankar</i> and <i>matrisi</i> . Slopes steep 1 in 50 to 1 in 150. Partly wooded and partly cultivated.
1913	1941	28	28.2	1.01	0.094	0.049	63.2	<i>Moorum sifar</i> and light soil, flat covered with jungle.
1908	1941	33	40.1	1.22	0.130	0.070	87.4	Generally light soil overlying <i>moorum</i> or laterite. Slopes rather flat.
1908	1941	33	28.3	0.85	0.352	0.088	60.7	Moderately steep country in the crystallinerock formation.
1012	1941	29	44.8	1.54	0.240	0.144	154	0.5 square mile cultivated, the rest fallow or hilly. Slope 1 in 200.
1906	1941	35	92	2.62	0.814	0.278	282	Light soil over hard <i>moorum</i> at a depth of 4 feet. Slopes are moderately steep—1 in 200 to 1 in 400.
1908	1941	33	1.8	0.05	0.023	0.005	5.8	Light soil underlain at a depth of 4 feet by soft <i>moorum</i> . Slope generally flat 1 in 500 to 1 in 2000.
1905	1941	36	62.5	1.72	0.641	0.249	261	Light soil underlain at a depth of 6 feet by soft <i>moorum</i> ; soft <i>moorum</i> underlain at a depth of 5 feet by clay; clay soil underlain at a depth of 2 feet by laterite. Slopes steep 1 in 50 to 1 in 150. Partly wooded and partly cultivated.
1891	1945	54	3,055	56.6	0.095	0.068	72.2	
1922	1947	25	9,122	365	0.717	..	152	Black cotton soil—not deep.
1935	1942	7	4,108	587	10.0	..	360	Surface soil loose sandy loam.

There is only one reservoir in the Bombay State and six reservoirs in Uttar Pradesh which have a large catchment area (more than 1,000 square miles) and the rate of silting in these does not exceed 27 foot-acres per 100 square miles of catchment area. The maximum rate of silting for major catchments is 75 foot-acres per 100 square miles of catchment per year.

The rate of silting for minor catchments is variable and depends upon a number of factors such as the physical characteristics of the catchment, capacity runoff ratio, the intensity and amount of rainfall, the form and shape of the storage basin, and the escaping capacity of the sluices with respect to normal flood discharges, *etc.*

It is noticed that the rate of silting decreases with age as also observed in the case of reservoirs in other countries described in Chapter 4. The reasons for this downward tendency have already been given in Chapter 1.

CHAPTER 3

Silt Studies of Some Proposed Reservoirs in India

BHAKRA RESERVOIR*

River	..	..	..	Sutlej—Punjab, India	
Catchment	..	..	..	21,980 square miles	
Rainfall.	..	..	..	About 45 inches	
Mean annual runoff.	.	..	..	16 million foot-acres (Calculated mean 1911-12 to 1939-40 13.8 million foot-acres)	
Storage capacity	..	..	..	4.91 million foot acres (Revised figure 7.2 m. ft. acres)	
Height of dam	..	..	..	500 feet (revised figure 680 feet)	
Annual silt deposit	..	..	..	19,800 foot-acres	} Based on total estimated load of river
Assumed silt deposited per annum per 100 square miles of catchment area.				90 foot-acres	

Catchment Characteristics

The general catchment characteristics have been described by Dr. C. S. Fox, Ex-Director, Geological Survey of India, in his note dated the July 15, 1939 and are summarised below:

The River Sutlej traverses the softer tertiary strata of the outer Himalaya, before debouching into the plains. The river above Bhakra has three large tributaries—the Lunkhar, Sir and Gambhar Khads—which roughly follow the strike of the Tertiary strata and may be quickly in floods as a result of heavy rain on their respective catchments. The Lunkhar is entirely on the relatively softer sandstones and clays of the Siwaliks (Upper Tertiary), the Sir Khad partly drains Sirmur (Middle Tertiary) bed but is largely on Siwalik rocks,

* Extracted from the Bhakra Dam Project Vol. II pp. 25, 26, 40 to 50; Wiley Committee Report pp. 23 and 29 and 1942 Revised Project Report.

the Gambhar has a lower catchment of Siwaliks and Sirmur and an upper catchment of Sabathu (Lower Tertiary) and older rocks much of which consist of shaly slates. In the 900 square miles of catchment immediately above the Bhakra gorge, the Sutlej drainage includes soft sandstones and an appreciable proportion of argillaceous rocks which would readily yield silt of the character which can not be trapped. The proportion of silt (as fine suspended matter) to coarse material (sand and shingle) is likely to be relatively high. Some fine silts will be brought down by the snow fed river from the wind-borne dust which settles along its upper catchment during autumn.

Silt Load of the River Sutlej at Bhakra

Silt surveys on the Sutlej were started in 1916, and are described in Volume II of the Bhakra Dam Project Report of 1919. They were subsequently continued in 1921 to 1926 and 1932, 1933.

The original silt and discharge observations are plotted in Figures 17 to 25. Tables XVIII and XIX give ten-day and monthly silt loads and corresponding discharges. The basic observed data are given in italics in these statements. Table XX is a record of the maximum silt concentration and maximum discharges for each month of the years in which observations were taken.

Ten-day mean discharges in cusecs and silt in foot-acres, given in Table XVIII have been plotted for all the years in Figures 26 to 34.

The silt charge in periods during which no observations were made has been taken from the graph of Figure 35 which has been prepared by plotting ten-day mean silt against ten-day mean discharge given in Table XVIII. An attempt was made to use daily silt observations for obtaining the silt discharge relationship but as will be apparent from the nine graphs of Figures 17 to 25, there are wide variations from month to month and year to year. Variations exist even in the ten-day results but they seem to even out sufficiently to enable a reasonably consistent relationship being obtained between discharge and silt. It is felt that the curve of Figure 35 is reasonably representative of conditions at Bhakra. Table XXI showing discharge-silt relation for Bhakra has been prepared from Figure 35.

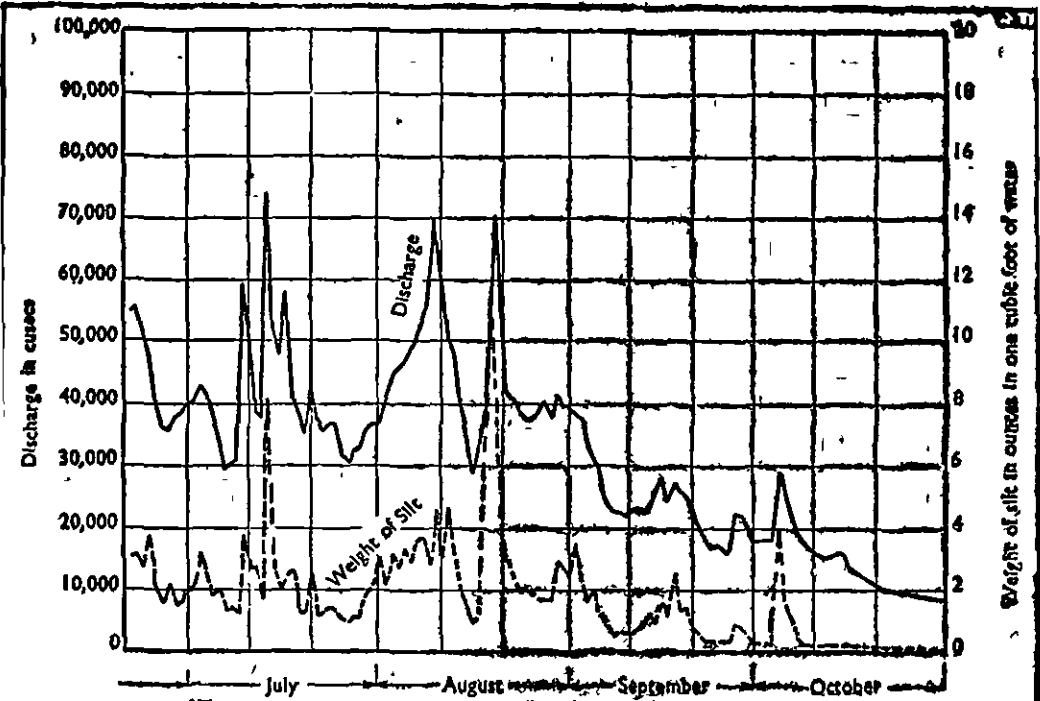


FIGURE 17 - RIVER SUTLEJ AT BHAKRA, DISCHARGE-SILT GRAPH
 (From actual observations) 1916

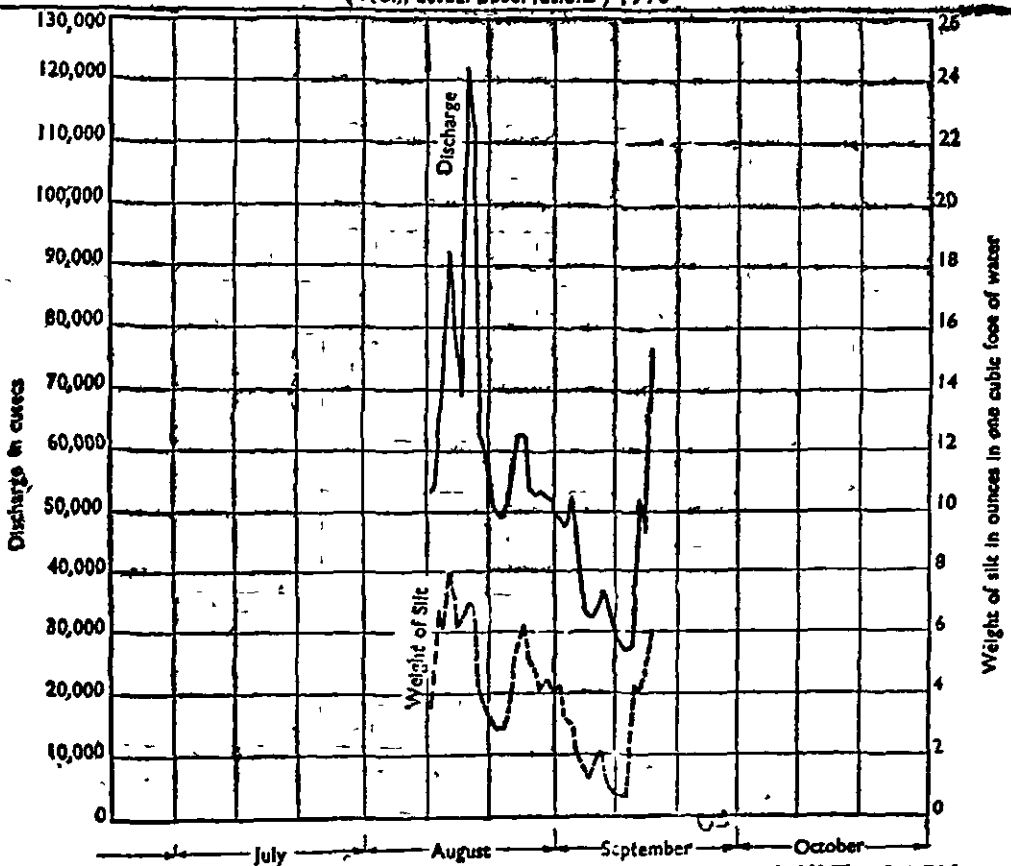


FIGURE 18 - RIVER SUTLEJ AT BHAKRA, DISCHARGE-SILT GRAPH
 (From actual observations) 1921

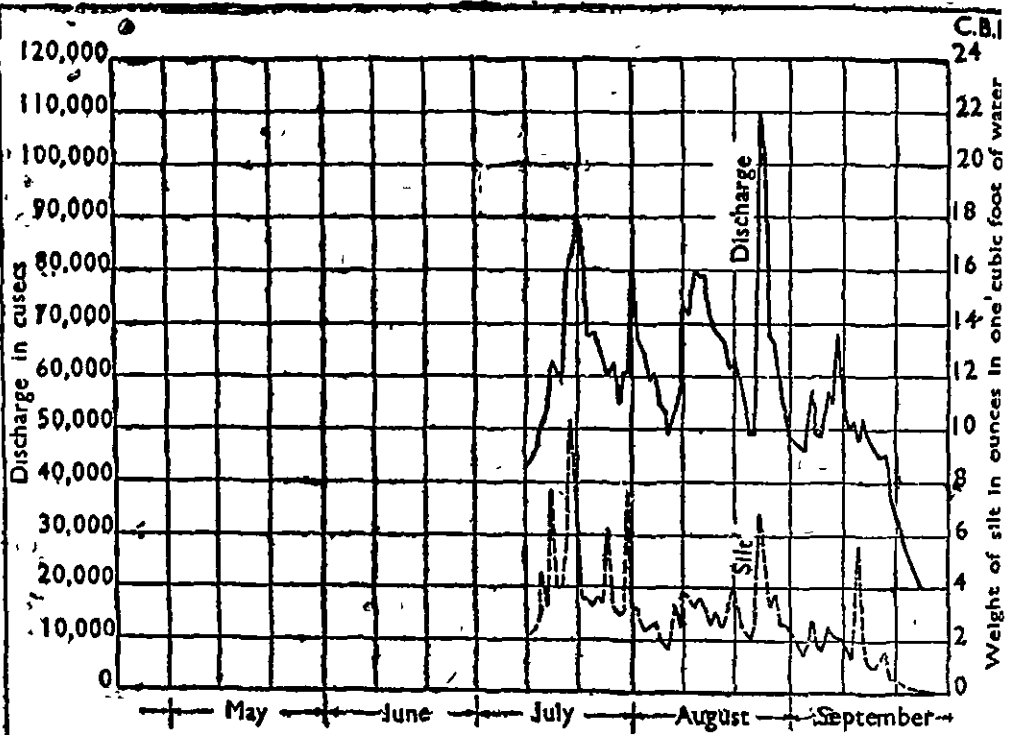


FIGURE 19¹⁹²² - RIVER SUTLEJ AT BHAKRA,
DISCHARGE-SILT GRAPH
(From actual observations) 1922

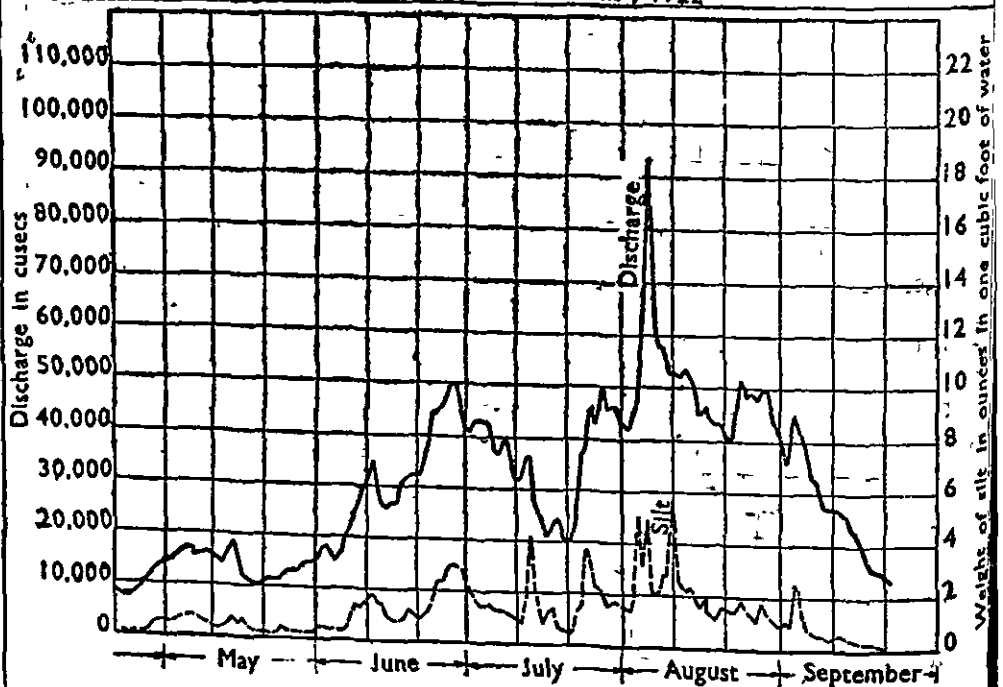


FIGURE 20¹⁹²³ - RIVER SUTLEJ AT BHAKRA,
DISCHARGE-SILT GRAPH
(From actual observations) 1923

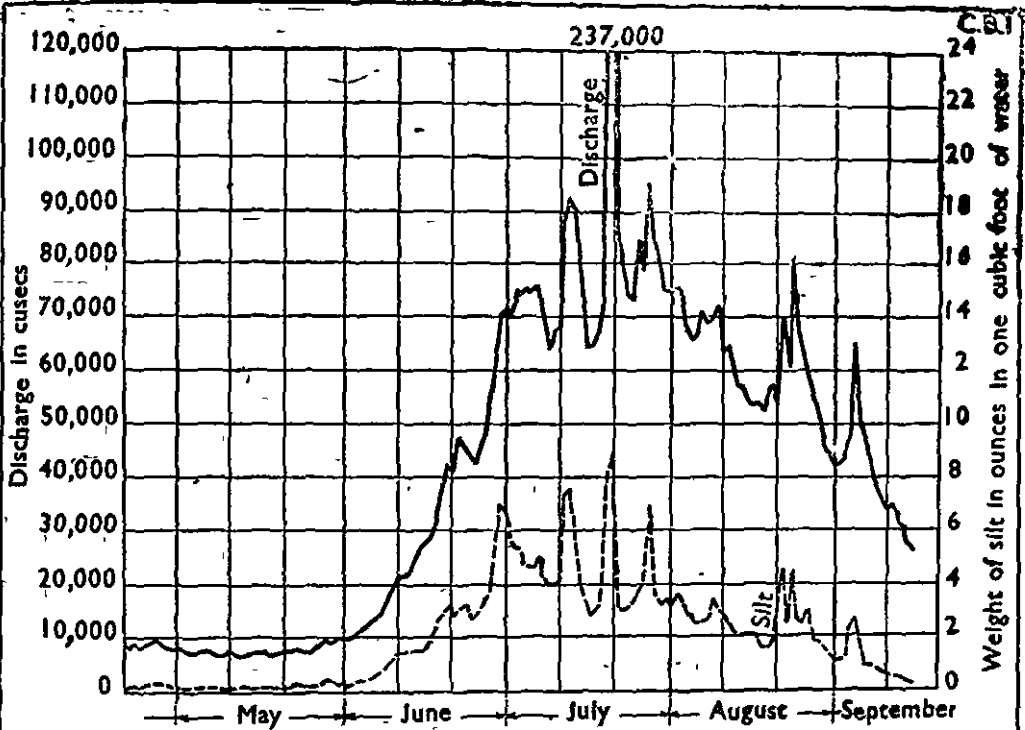


FIGURE 21 - RIVER SUTLEJ AT BHAKRA,
DISCHARGE-SILT GRAPH
(From actual observations) 1924

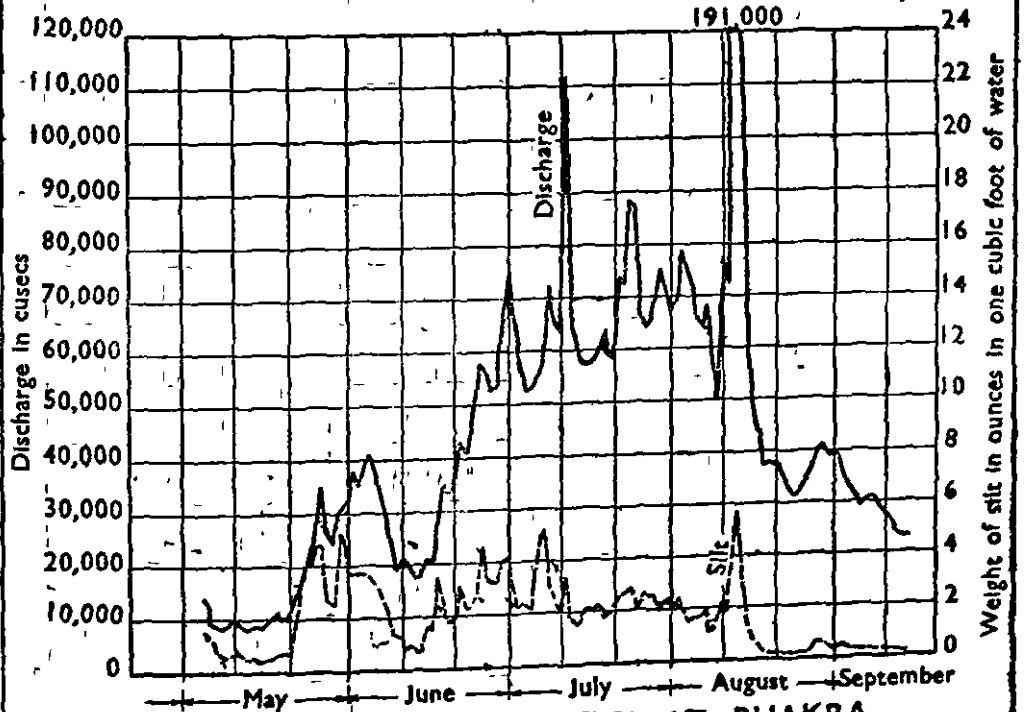


FIGURE 22 - RIVER SUTLEJ AT BHAKRA,
DISCHARGE-SILT GRAPH
(From actual observations) 1925

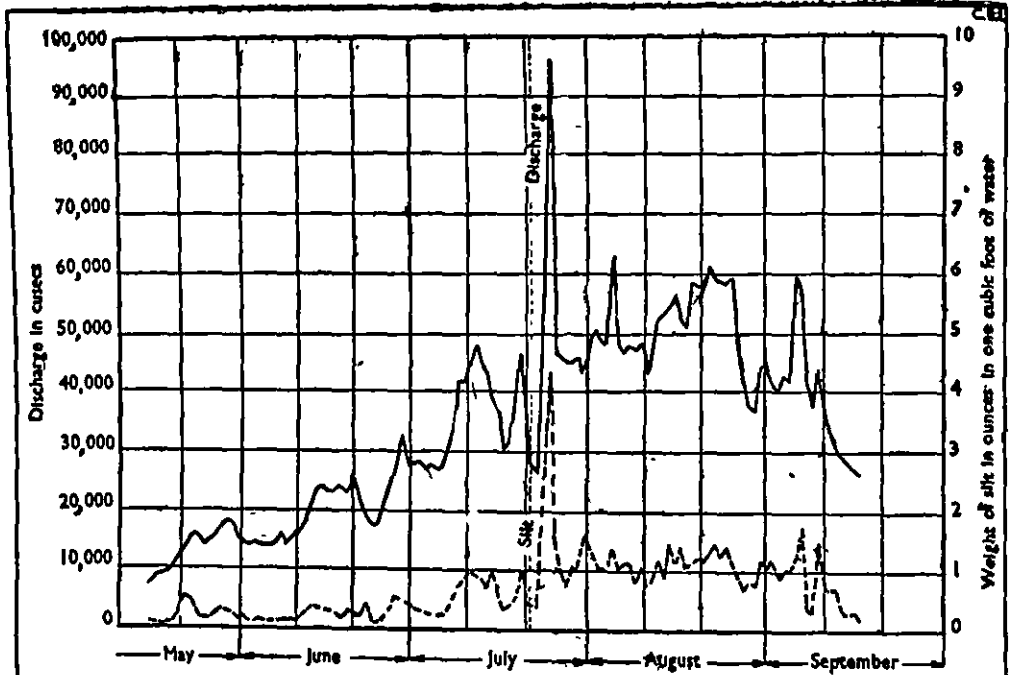


FIGURE 23 :- RIVER SUTLEJ AT BHAKRA, DISCHARGE-SILT GRAPH
(From actual observations) 1926

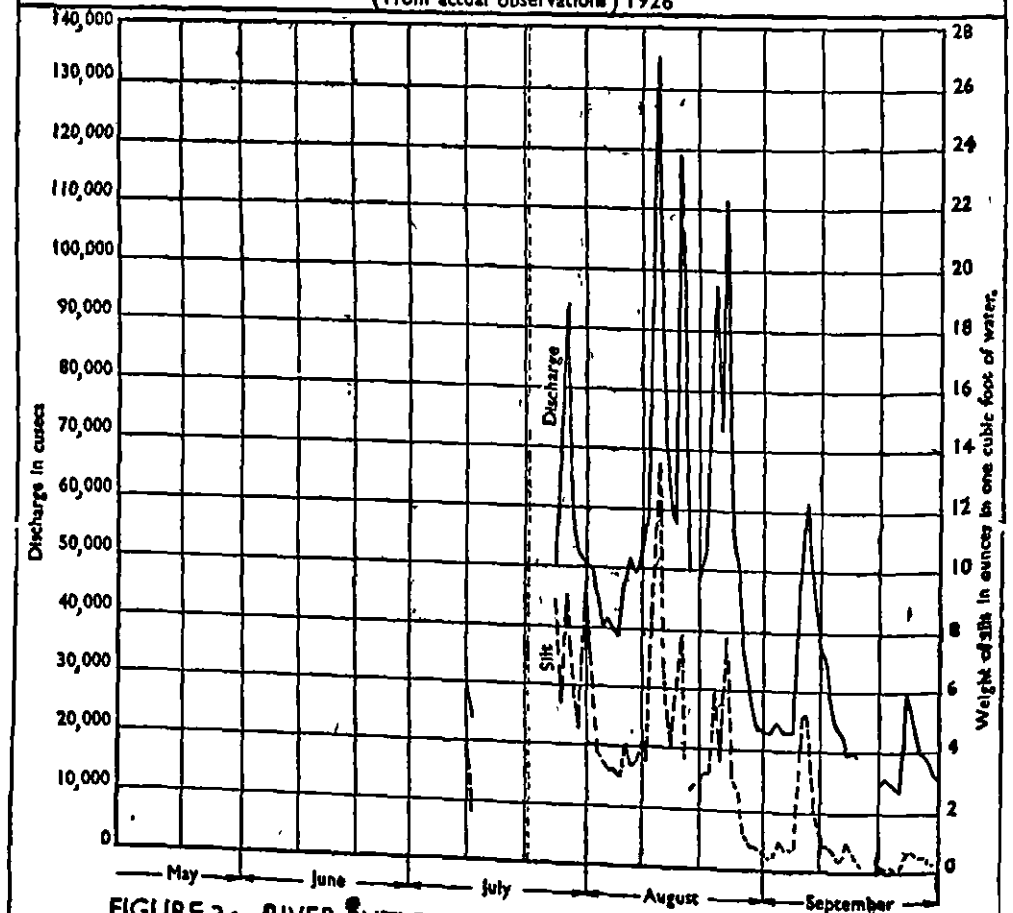


FIGURE 24 :- RIVER SUTLEJ AT BHAKRA, DISCHARGE-SILT GRAPH
(From actual observations) 1932

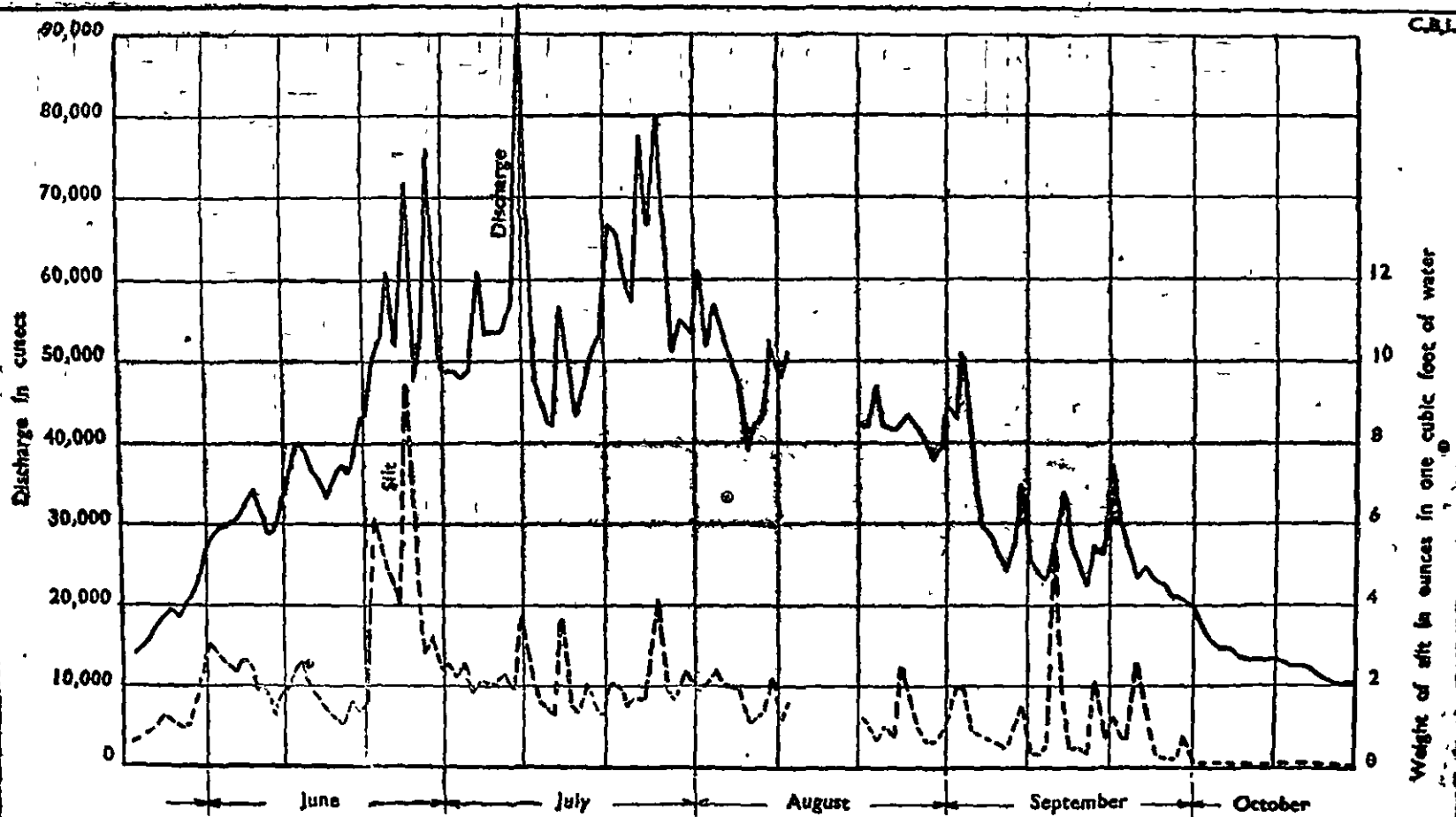
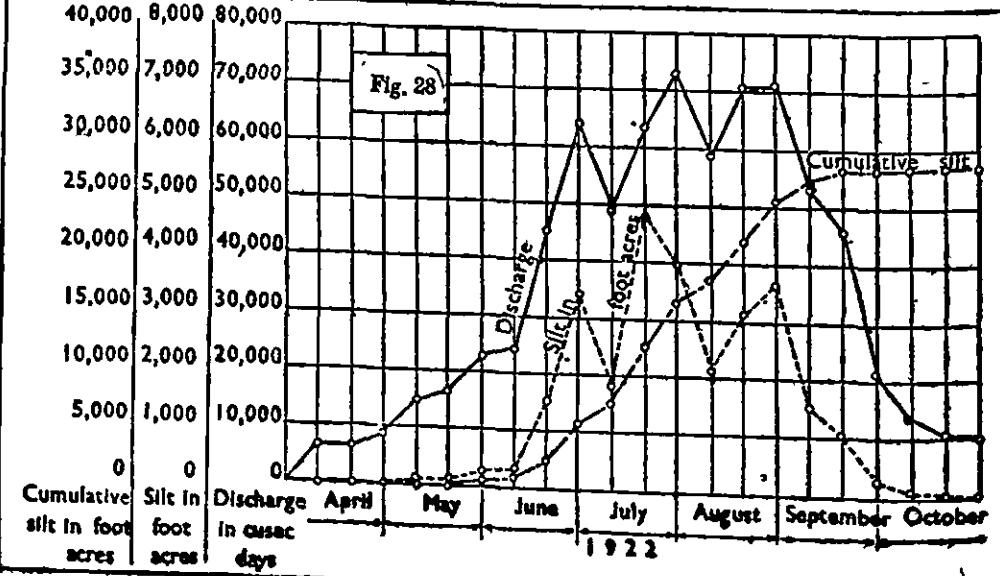
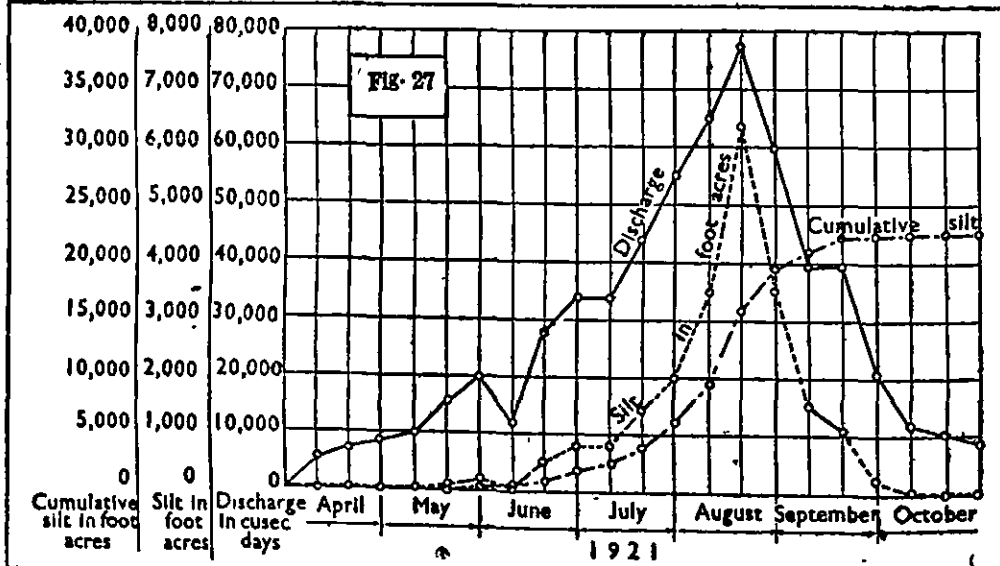
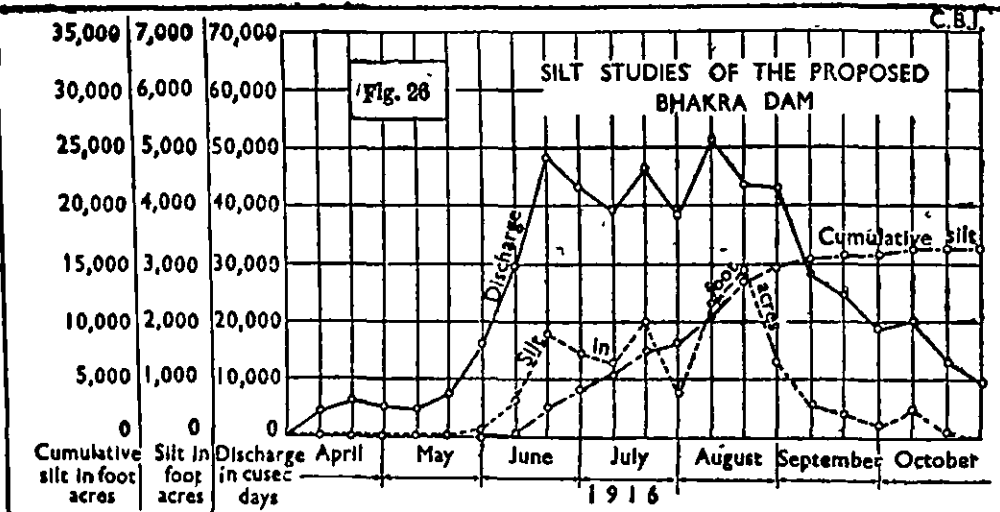
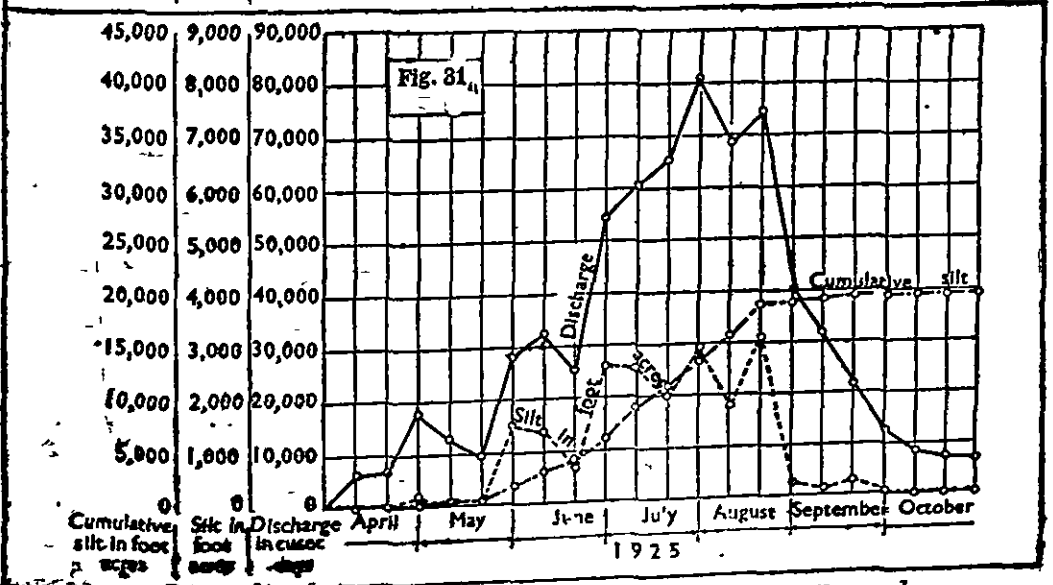
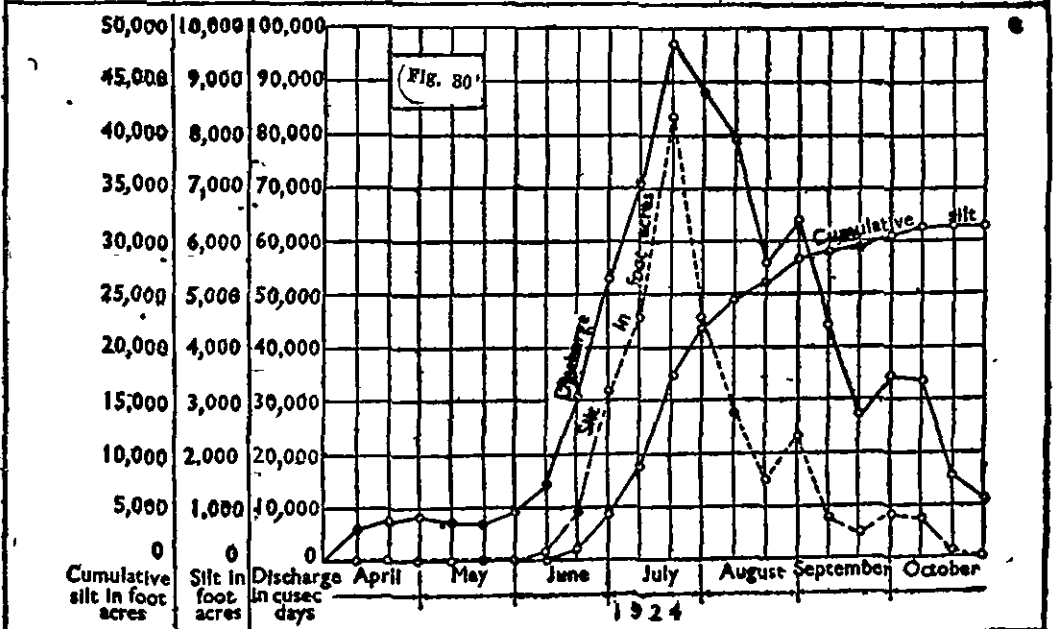
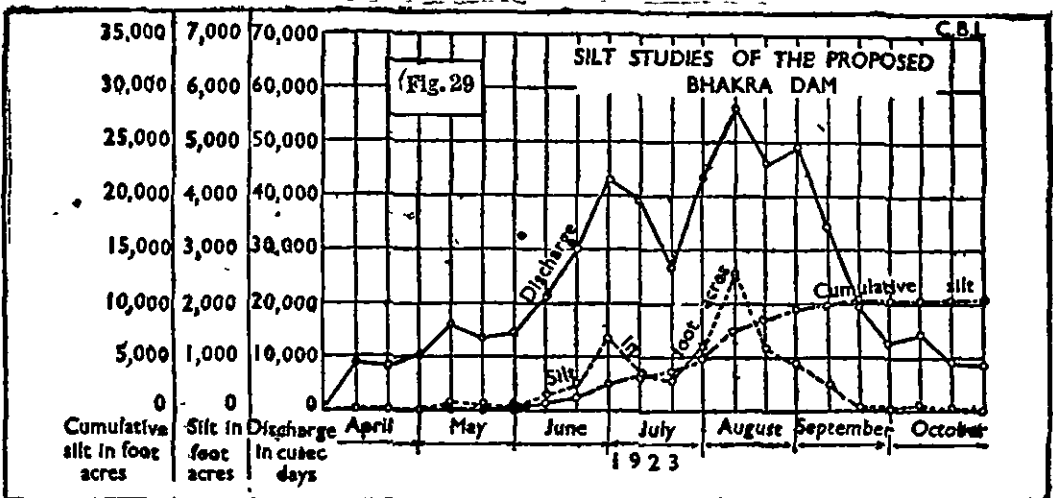


FIGURE 25 :- RIVER SUTLEJ AT BHAKRA, DISCHARGE-SILT GRAPH

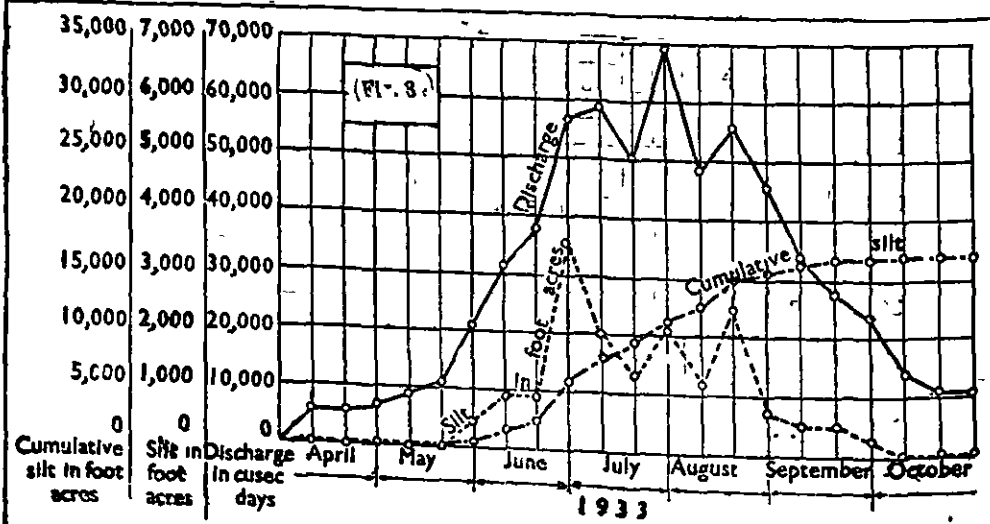
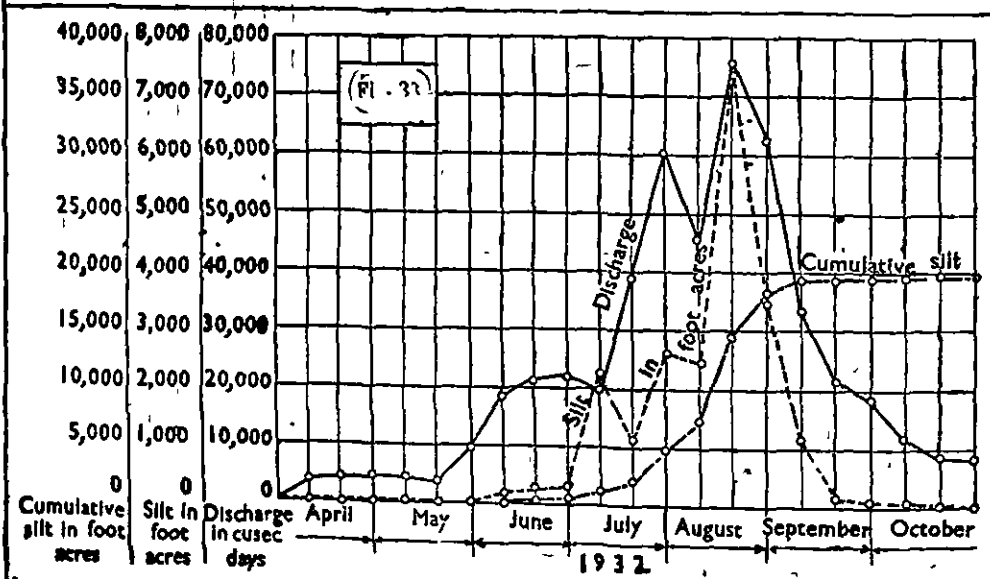
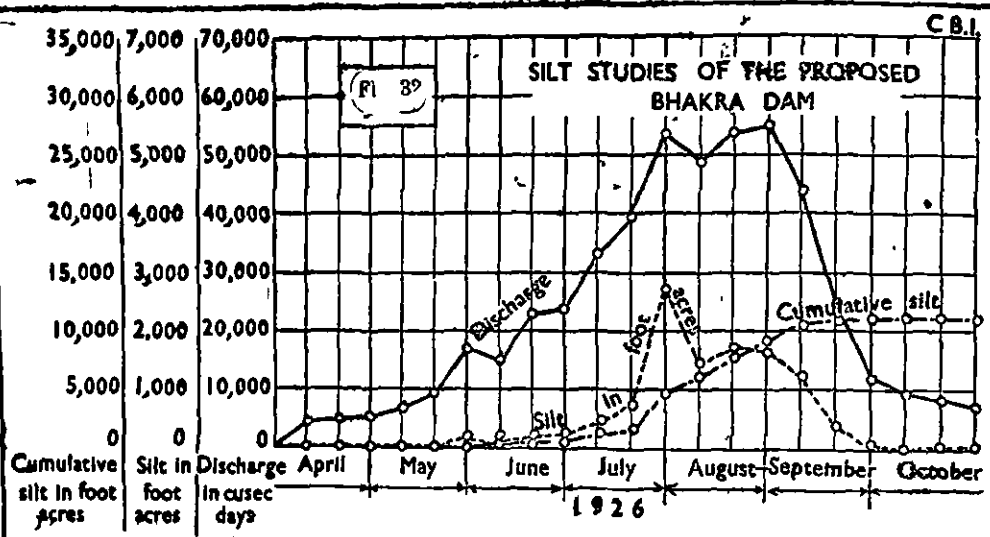
(From actual observations) 1933



Figures 26-28:—River Sutlej at Bhakra—Discharge silt graphs.



Figures 29-31 :—River Sutlej at Bhakra—Discharge silt graphs.



Figures 33-34 :—River Sutlej at Bhakra—Discharge silt graphs.

TABLE XVIII

Silt load of River Sutlej at Bhakra

Ten-day discharges and silt load in foot-acres

Weight of dry material in one cubic foot of deposit—90 lbs.

Month	Period	1916				1921				1922				1923				1924				1925				1926				1927				1928			
		Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres	Discharge in cuasec days	Silt in foot-acres	Silt percentage of discharge	Cumulative total of silt in foot-acres
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
April	1-10	44,200	8	0.0091	8	53,550	10	0.0093	10	64,180	12	0.0094	12	88,495	28	0.0158	28	61,770	11	0.0089	11	62,397	11	0.0088	11	42,613	8	0.0094	8	36,845	6	0.0081	6	54,702	10	0.0091	10
	11-20	60,530	11	0.0091	19	73,150	14	0.0096	24	66,165	12	0.0091	24	83,645	21	0.0125	49	77,425	14	0.0099	25	64,237	12	0.0094	23	45,401	8	0.0088	16	41,123	7	0.0085	13	54,290	10	0.0092	20
	21-30	52,055	9	0.0086	28	85,100	18	0.0106	42	87,580	20	0.0114	44	103,235	45	0.0218	94	83,210	23	0.0138	48	177,680	180	0.051	203	51,724	8	0.0087	25	43,553	8	0.0092	21	65,831	12	0.0091	32
	Monthly	156,785	28	0.0089	..	211,800	42	0.0099	..	217,925	44	0.0101	..	275,375	94	0.0171	..	222,405	48	0.0108	..	304,214	203	0.0334	..	139,738	25	0.0080	..	121,621	21	0.0086	..	174,922	82	0.0092	..
May	1-10	47,690	9	0.0004	37	98,925	20	0.010	62	148,440	100	0.0337	144	162,400	144	0.0443	238	70,020	9	0.0064	57	123,425	60	0.0243	263	65,526	12	0.0502	37	42,753	8	0.0094	20	90,010	20	0.0111	52
	11-20	77,010	14	0.0091	51	156,050	110	0.0352	172	161,415	120	0.0372	264	137,265	89	0.0525	327	69,915	9	0.0064	57	91,637	60	0.0408	339	90,044	20	0.0111	57	37,793	7	0.0093	36	100,236	32	0.0151	84
	21-31	163,400	110	0.0338	161	200,200	198	0.0495	370	229,943	281	0.0611	545	146,705	54	0.0184	381	91,637	31	0.0169	66	23,020	76	0.0408	339	90,044	20	0.0111	57	37,793	7	0.0093	36	100,236	32	0.0151	84
	Monthly	288,100	133	0.0231	..	455,175	328	0.036	..	539,798	501	0.0465	..	446,370	287	0.0311	..	231,572	49	0.0105	..	497,564	1,650	0.166	..	172,040	135	0.0392	102	94,363	22	0.0114	58	209,310	428	0.102	507
June	1-10	298,020	600	0.100	761	119,280	55	0.023	425	243,450	375	0.077	920	211,540	266	0.0628	647	141,835	143	0.0504	240	322,480	1,343	0.208	3,196	147,556	49	0.0166	241	185,161	100	0.051	248	313,519	934	0.149	1,441
	11-20	484,520	1,800	0.186	2,561	277,000	490	0.0885	915	453,870	1,560	0.172	2,480	300,090	460	0.0767	1,107	141,835	143	0.0504	240	322,480	1,343	0.208	3,196	147,556	49	0.0166	241	185,161	100	0.051	248	313,519	934	0.149	1,441
	21-30	433,810	1,562	0.178	4,123	339,450	800	0.118	1,715	639,550	3,400	0.266	5,880	428,965	1,356	0.158	2,463	305,300	891	0.146	1,131	252,200	637	0.126	3,823	227,824	176	0.0386	417	213,780	270	0.063	518	378,744	876	0.116	2,317
	Monthly	1,216,350	3,962	0.162	..	735,730	1,345	0.091	..	1,336,870	5,335	0.20	..	940,595	2,082	0.1106	..	940,595	2,082	0.1106	..	1,116,245	4,573	0.205	..	611,560	464	0.037	..	621,797	760	0.061	..	1,250,836	5,406	0.215	..
July	1-10	393,440	1,321	0.168	5,444	339,525	800	0.118	2,515	489,100	1,850	0.189	7,730	391,750	693	0.0885	3,156	709,750	4,565	0.322	8,876	606,700	2,544	0.269	8,970	330,331	462	0.070	1,108	190,764	2,250	0.1125	1,043	586,500	2,024	0.173	7,937
	11-20	462,740	2,037	0.220	7,481	438,700	1,450	0.166	3,965	635,140	4,843	0.381	12,573	266,140	552	0.104	3,708	969,095	8,340	0.430	17,216	651,150	1,993	0.153	10,923	396,600	757	0.0654	1,865	388,349	1,100	0.142	2,143	500,443	1,271	0.127	9,208
	21-31	383,640	799	0.104	8,280	543,700	2,079	0.191	6,044	730,840	3,980	0.273	16,553	435,015	1,182	0.136	4,890	879,840	4,555	0.259	21,771	808,743	2,890	0.179	13,353	531,032	2,701	0.264	4,606	602,720	2,629	0.218	4,772	680,573	2,107	0.153	11,315
	Monthly	1,239,820	4,157	0.168	..	1,321,925	4,329	0.163	..	1,855,080	10,573	0.288	..	1,091,905	2,427	0.111	..	2,558,685	17,460	0.341	..	2,066,543	7,427	0.179	..	1,258,263	3,920	0.116	..	1,190,833	3,954	0.106	..	1,770,606	5,402	0.162	..
August	1-10	515,780	2,318	0.224	10,598	648,000	3,500	0.270	9,544	589,510	2,145	0.182	18,698	563,935	2,544	0.226	7,434	602,700	2,767	0.20	24,538	684,909	1,795	0.131	15,648	480,433	1,436	0.147	6,002	456,275	2,463	0.270	7,235	480,356	1,100	0.124	12,511
	11-20	439,590	2,912	0.331	13,510	773,500	6,357	0.411	15,901	707,700	3,158	0.223	21,856	461,050	1,152	0.125	8,586	559,350	1,521	0.136	26,059	745,781	3,104	0.268	18,752	558,669	1,714	0.159	7,716	757,591	7,463	0.492	14,058	554,563	2,440	0.220	14,961
	21-31	431,680	1,325	0.153	14,835	595,500	3,544	0.298	19,445	709,000	3,663	0.258	25,519	496,670	809	0.0915	9,495	638,900	2,306	0.181	28,365	403,520	242	0.030	18,994	548,162	1,682	0.153	9,398	624,473	3,473	0.277	18,161	457,774	728	0.0795	15,079
	Monthly	1,387,050	6,555	0.236	..	2,017,000	13,401	0.332	..	2,006,220	8,966	0.224	..	1,521,655	4,605	0.153	..	1,890,950	6,594	0.1740	..	1,834,210	5,141	0.140	..	1,575,664	4,832	0.153	..	1,840,339	13,389	0.363	..	1,402,725	364	0.147	..
September	1-10	281,850	595	0.106	15,430	392,450	1,524	0.194	20,969	531,170	1,543	0.145	27,062	342,440	488	0.0712	9,983	440,580	798	0.096	29,163	318,340	165	0.0259	19,159	436,045	1,220	0.140	10,618	333,055	1,148	0.172	10,309	333,537	574	0.077	16,193
	11-20	246,840	431	0.0874	15,861	392,050	1,100	0.140	22,069	459,280	1,058	0.115	28,120	199,905	92	0.023	10,075	275,230	490	0.069	29,663	215,820	270	0.0225	19,429	244,366	375	0.0768	10,913	215,802	149	0.0345	19,455	275,470	533	0.097	16,726
	21-30	187,100	106	0.0284	15,967	207,250	240	0.058	22,309	217,980	275	0.063	28,395	122,930	60	0.0244	10,135	342,545	830	0.121	30,483	123,150	60	0.0244	19,459	120,459	55	0.023	11,048	184,263	96	0.0258	19,563	232,227	263	0.055	16,070
	Monthly	715,790	1,132	0.079	..	991,750	2,864	0.144	..	1,208,430	2,876	0.119	..	665,275	640	0.048	..	1,058,355	2,118	0.10	..	657,310	495	0.0377	..	800,870	1,650	0.103	..	733,160	1,392	0.095	..	841,243	1,300	0.0775	..
October	1-10	200,530	284	0.071	16,251	120,400	55	0.0229	22,364	140,420	90	0.032	28,485	143,700	95	0.033	10,230	336,580	780	0.116	31,263	82,801	18	0.0169	19,507	96,833	23	0.0118	11,071	119,004	55	0.031	10,608	143,452	77	0.0659	16,956
	11-20	134,290	44	0.0164	16,295	105,525	32	0.0152	22,396	108,425	40	0.0185	28,525	91,545	20	0.0109	10,250	157,540	120	0.0381	31,363	71,782	13	0.0091	19,520	85,662	18	0.0106	11,080	87,121	18	0.0108	10,626	111,038	71	0.065	17,007
	21-31	97,550	5	0.0026	16,300	89,360	17	0.0095	22,413	101,145	20	0.0099	28,545	86,180	17	0.0098	10,267	112,525	28	0.0125	31,411	67,426	12	0.0089	19,532	73,695	13	0.0089	11,162	82,430	15	0.0091	10,641	110,653	28	0.0127	17,035
	Monthly	252,370	333	0.0385	..	315,285	104	0.165	..	349,990	150	0.0214	..	321,425	132																						

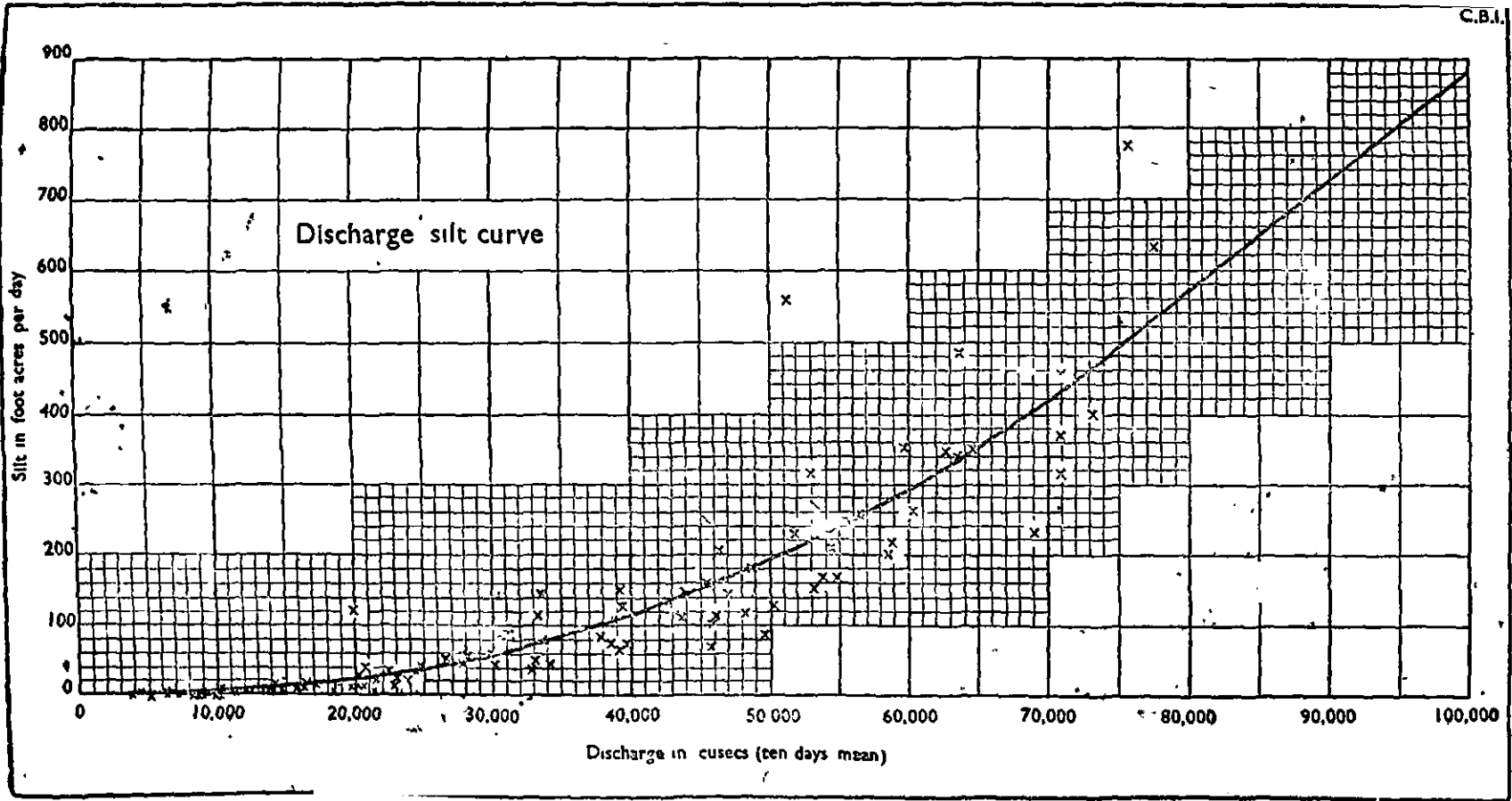


Figure 35 :—Siltload of Sutlej at Bhakra

TABLE
Silt Load of River
Monthly discharge
Weight of dry material in one

Month	Particulars	1916	1921	1922	
1	2	3	4	5	
April	Discharge {	cusec days	156,785	211,800	217,925
		foot acres	313,570	423,600	435,850
	Silt foot acres	28	42	44	
	Silt percentage of discharge	0 0089	0 0069	0 0101	
May	Discharge {	cusec days	288,100	455,175	539,798
		foot acres	576,200	910,350	1,079,596
	Silt foot acres	133	328	501	
	Silt percentage of discharge	0 0231	0 036	0 0466	
June	Discharge {	cusec days	1,216,350	735,730	1,336,870
		foot acres	2,442,700	1,471,460	2,673,740
	Silt foot acres	3,962	1,345	5,335	
	Silt percentage of discharge	0 162	0 091	0 20	
July	Discharge {	cusec days	1,239,820	1,321,925	1,855,080
		foot acres	2,479,640	2 643,850	3,710,160
	Silt foot acres	4,157	4,329	10,673	
	Silt percentage of discharge	0 168	0 163	0 288	
August	Discharge {	cusec days	1,387,050	2,017,000	2,006,220
		foot acres	2,774,100	4,034,000	4,012,440
	Silt foot acres	6,555	13,401	8,966	
	Silt percentage of discharge	0 236	0 332	0 224	
September	Discharge {	cusec days	715,780	991,750	1,208,430
		foot acres	1,431,560	1,983,500	2,416,860
	Silt foot acres	1,132	2,864	2,876	
	Silt percentage of discharge	0 079	0 142	0 119	
October	Discharge {	cusec days	432,370	315,285	340,990
		foot-acres	864,740	630,570	699,980
	Silt foot acres	333	104	150	
	Silt percentage of discharge	0 0385	0 0165	0 0214	
Total April to October	Discharge in foot acres		10,512,530	12,097,330	15,028,626
	Silt in foot acres		16,300	22,413	28,545
	Silt percentage of discharge by volume		0 150	0 1855	0 1895
	Weight of silt in tons		25,528,260	39,237,233	40,959,459
	Silt % of discharge by weight		0 216	0 267	0 273
Total Nov-March Annual Run off	Discharge in foot-acres		1,269,940	1,824,760	1,844,250
	foot acres		12,152,470	13,752,090	16,872,876

XIX

*Sulley at Bhakera
and silt load*

cubic foot of deposit=90 lbs.

1923	1924	1925	1926	1932	1933	Average
6	7	8	9	10	11	12
276,376	222,405	304,214	139,738	121,521	174,922	202,743
550,750	444,810	608,428	279,476	243,042	349,844	405,485
94 0.0171	48 0.0108	203 0.0334	25 0.0089	21 0.0086	32 0.0092	60 0.016
446,370	231,572	497,564	327,610	176,909	406,574	374,207
892,740	463,144	995,128	655,220	353,813	811,148	748,594
287 0.0311	49 0.0105	1,650 0.166	167 0.0256	37 0.104	475 0.0585	403 0.054
947,595	976,495	1,116,245	811,580	621,797	1,256,836	979,720
1,861,190	1,952,990	2,232,490	1,223,120	1,243,594	2,513,672	1,959,440
2,082 0.1106	4,214 0.216	4,573 0.205	454 0.037	760 0.061	5,406 0.215	3,126 0.160
1,091,905	2,558,685	2,066,593	1,258,263	1,190,833	1,770,606	1,595,523
2,183,810	5,117,370	4,133,186	2,516,526	2,381,666	3,353,212	3,191,046
2,427 0.111	17,460 0.341	7,427 0.179	3,920 0.156	3,954 0.166	5,402 0.152	6,639 0.208
1,521,055	1,890,950	1,834,210	1,575,664	1,840,339	1,492,725	1,785,090
3,043,310	3,781,900	3,068,420	3,151,328	3,680,678	2,985,450	3,459,060
4,605 0.153	6,594 0.174	5,141 0.1400	4,832 0.153	13,380 0.363	4,364 0.147	7,538 0.218
665,275	1,058,355	657,310	800,870	73,160	841,243	852,465
1,330,550	2,116,710	1,314,620	1,601,740	1,466,320	1,082,486	1,704,930
640 0.048	2,118 0.100	495 0.0377	1,650 0.103	1,392 0.095	1,300 0.0775	1,607 0.064
321,125	606,645	222,009	255,030	288,155	365,173	350,676
642,850	1,213,250	444,018	510,060	576,310	730,346	701,352
132 0.0205	928 0.076	43 0.0097	54 0.0106	38 0.0153	56 0.0077	210 0.030
10,525,200	15,090,214	13,396,260	9,937,470	9,945,428	12,626,158	12,169,910
10,267 0.0075	31,411 0.2070	10,532 0.146	11,102 0.112	19,641 0.1975	17,035 0.135	19,583 0.161
17,960,308	54,975,532	34,184,906	19,430,720	34,375,678	29,814,057	33,941,000
0.1480	0.296	0.210	0.161	0.23	0.194	0.228
1,645,114	1,787,650	1,540,142	1,276,074	1,213,344	1,596,004	1,521,918
12,170,314	16,877,864	14,036,432	11,213,524	11,358,772	14,222,162	13,691,834

TABLE

Statement showing maximum discharge and corresponding silt and maximum
(Silt is taken in ounces per cubic foot of

Year	Particulars	April		May	
		Discharge in cusecs	Silt in oz. per cubic foot of water	Discharge in cusecs	Silt in oz. per Cubic foot of water
1	2	3	4	5	6
1916	Maximum discharge and corresponding silt ..	..	..	..	..
	Maximum silt and corresponding discharge ..	..	..	..	..
1921	Maximum discharge and corresponding silt ..	..	..	..	..
	Maximum silt and corresponding discharge ..	..	..	..	..
1922	Maximum discharge and corresponding silt ..	..	..	..	..
	Maximum silt and corresponding discharge ..	..	..	..	..
1923	Maximum discharge and corresponding silt ..	14,100	0.62	19,500	0.81
	Maximum silt and corresponding discharge ..	14,100	0.62	15,900	0.83
1924	Maximum discharge and corresponding silt ..	9,500	0.24	9,800	0.27
	Maximum silt and corresponding discharge ..	8,600	0.28	9,300	0.40
1925	Maximum discharge and corresponding silt ..	..	..	35,700	4.93
	Maximum silt and corresponding discharge ..	..	..	31,100	5.43
1926	Maximum discharge and corresponding silt ..	..	..	18,200	0.62
	Maximum silt and corresponding discharge ..	..	..	14,000	1.10
1932	Maximum discharge and corresponding silt ..	..	..	..	..
	Maximum silt and corresponding discharge ..	..	..	..	..
1933	Maximum discharge and corresponding silt ..	..	..	27,500	3.06
	Maximum silt and corresponding discharge ..	..	..	27,500	3.06

Daily discharges are taken correct upto hundreds. Figures below 50 are neglected and those above

XX

silt and corresponding discharge in each month observed on River Sutlej at Bhakra water—parts per 1,000 by weight)

June		July		August		September		October	
Dis-charge in cusecs	Silt in oz. per cubic foot of water	Discharge in cusecs	Silt in oz. per cubic foot of water	Discharge in cusecs	Silt in oz. per cubic foot of water	Discharge in cusecs	Silt in oz. per cubic foot of water	Dis-charge in cusecs	Silt in oz. per cubic foot of water
7	8	9	10	11	12	13	14	15	16
55,500	3 21	74,600	8 18	70,600	7.92	38,200	3 55	30,000	3.89
47,900	3.84	74,600	8.18	53,700	11 02	38,200	3 55	30,000	3 89
..	..	..	.	122,500	6.96	77,000	6.16	..	..
..	..	.	..	92,000	8.1	77,000	6.16	.	..
..	..	92,000	6.13	110,000	6.99	68,900	2.14	..	..
..	..	85,300	10.47	110,000	6 99	46,500	5.69	..	..
49,700	3.04	49,500	2 00	93,100	4 93	44,500	2.62	.	..
49,700	3 04	36,400	4.17	51,500	5.67	44,500	2.62	..	..
71,300	6 31	237,000	8.4	81,000	4.47	65,500	2 61	..	..
70,000	6 93	237,000	8.4	70,600	4.58	65,500	2.61	..	..
74,100	4.22	112,000	3.44	191,100	4.71	39,400	0.49	.	..
58,500	4.79	57,900	5.42	135,500	6.02	39,400	0 49	..	..
33,200	0.98	96,000	8.75	61,100	2.60	59,600	2.32	..	..
27,400	1.12	96,000	8.75	54,100	2 94	55,900	3.55	..	..
..	..	94,100	8.99	135,100	13.53	61,800	5.27	..	..
..	..	50,600	9.29	135,100	13.53	61 800	5.27	..	..
76,300	3.27	92,800	4.04	57,300	2.44	50,700	1.93	17,100	0.10
71,500	9.50	80,600	4.21	42,100	2.62	28,200	5.69	14,800	0.13

50 are taken and next hundred figure recorded.

In computing the volume of silt, the weight of dry material has been assumed as 90 pounds per cubic foot of silt deposit. In estimating the probable volume of silt in the Boulder Reservoir, this was taken as 85.6 pounds, while the exposed deposits at the Elephant Butte Reservoir weighed on the average 92.3 pounds.

Figure 36 shows the silt load carried by the river at Bhakra (in millions of tons) and the runoff (in foot acres) year by year.

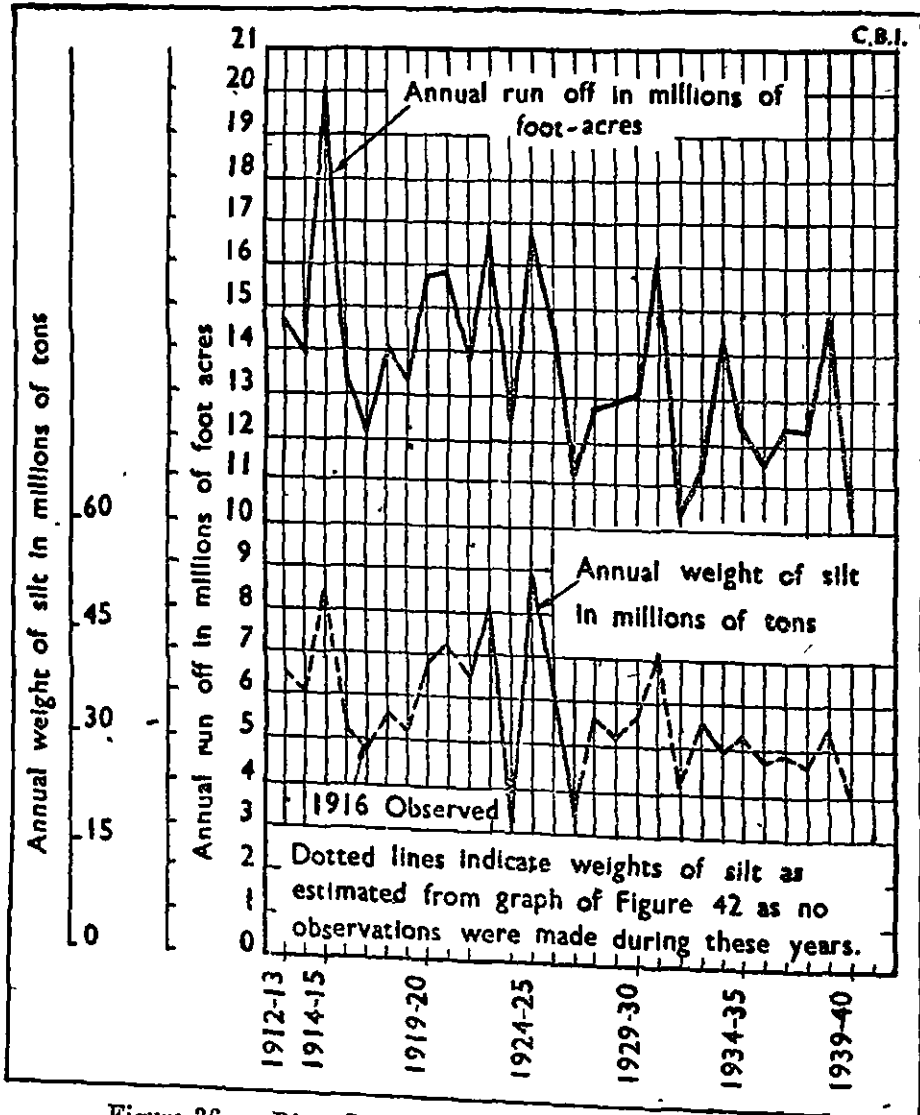


Figure 36 :—River Sutlej at Bhakra : Run-off silt graphs.

TABLE XXI
 River Sutlej at Bhakra
 Discharge/Silt Table
 (Prepared from Figure 35)

Discharge in Cusecs	Silt in foot acre, per day	Discharge in Cusecs	Silt in foot acres per day	Discharge in Cusecs	Silt in foot acres per day	Discharge in Cusecs	Silt in foot acres per day
1,000	0.1	29,000	56	57,000	259	85,000	647
1,500	0.2	29,500	58	57,500	265	85,500	655
2,000	0.3	30,000	60	58,000	270	86,000	663
2,500	0.4	30,500	62	58,500	275	86,500	671
3,000	0.5	31,000	65	59,000	280	87,000	679
3,500	0.6	31,500	67	59,500	286	87,500	687
4,000	0.7	32,000	70	60,000	291	88,000	695
4,500	0.8	32,500	72	60,500	297	88,500	703
5,000	0.9	33,000	75	61,000	302	89,000	710
5,500	1.0	33,500	78	61,500	309	89,500	718
6,000	1.1	34,000	80	62,000	315	90,000	726
6,500	1.2	34,500	83	62,500	321	90,500	731
7,000	1.3	35,000	86	63,000	326	91,000	741
7,500	1.4	35,500	89	63,500	333	91,500	749
8,000	1.5	36,000	92	64,000	340	92,000	757
8,500	1.8	36,500	95	64,500	345	92,500	765
9,000	2.0	37,000	98	65,000	350	93,000	772
9,500	2.3	37,500	101	65,500	357	93,500	780
10,000	2.5	38,000	104	66,000	363	94,000	788
10,500	3.2	38,500	107	66,500	370	94,500	796
11,000	4.0	39,000	110	67,000	377	95,000	804
11,500	4.7	39,500	113	67,500	383	95,500	812
12,000	5.5	40,000	117	68,000	390	96,000	820
12,500	6.0	40,500	120	68,500	397	96,500	828
13,000	7.0	41,000	123	69,000	403	97,000	836
13,500	8.0	41,500	127	69,500	410	97,500	844
14,000	9.0	42,000	130	70,000	417	98,000	852
14,500	9.5	42,500	134	70,500	425	98,500	860
15,000	10.0	43,000	138	71,000	432	99,000	868
15,500	11.0	43,500	142	71,500	439	99,500	876
16,000	12.0	44,000	145	72,000	446	100,000	883
16,500	13.5	44,500	149	72,500	453		
17,000	15.0	45,000	152	73,000	460		
17,500	16.5	45,500	156	73,500	468		
18,000	18.0	46,000	160	74,000	476		
18,500	19.0	46,500	164	74,500	483		
19,000	20.0	47,000	168	75,000	490		
19,500	21.0	47,500	172	75,500	498		
20,000	22.5	48,000	176	76,000	506		
20,500	24.0	48,500	180	76,500	514		
21,000	25.5	49,000	185	77,000	522		
21,500	27.0	49,500	189	77,500	530		
22,000	27.5	50,000	193	78,000	538		
22,500	30.0	50,500	197	78,500	545		
23,000	32.0	51,000	201	79,000	553		
23,500	34.0	51,500	205	79,500	561		
24,000	36.0	52,000	210	80,000	569		
24,500	37.5	52,500	215	80,500	577		
25,000	39.0	53,000	220	81,000	585		
25,500	41.0	53,500	225	81,500	592		
26,000	43.0	54,000	230	82,000	600		
26,500	45.0	54,500	235	82,500	608		
27,000	47.0	55,000	239	83,000	616		
27,500	49.0	55,500	244	83,500	624		
28,000	51.0	56,000	249	84,000	632		
28,500	53.0	56,500	254	84,500	640		

The average silt load of the river Sutlej at Bhakra works out to 34 million tons or 19,600 foot acres per year. This is equivalent to 157 thousand tons or 90 foot-acres per year per 100 square miles of catchment.

Similar wide variations in the annual silt load as well as the run off are to be noticed in the Elephant Butte Reservoir (See Figure 62 in Chapter 4).

Table XXII showing silt loads of various streams, will be of interest as it brings out the extraordinary variation in the silt load of various streams and thus demonstrates the futility of trying to estimate rate of silting of any particular reservoir on any river on the basis of figures available for another, without full knowledge of the catchment characteristics of the latter coupled with a detailed study of the silt load of the former except as an indication of the upper limit for the annual rate of silting.

TABLE XXII

Serial No.	Name of river	Name of reservoir	Catchment area (square miles)	Annual silt load (tons)	Annual silt load in tons per 100 square miles of catchment
1	2	3	4	5	6
1	Nile	Aswan	620,000	95,000,000	15,000
2	Colorado (Arizona)	Boulder	167,000	250,000,000	150,000
3	Columbia	Grand Coulee	74,000	Said to be Nil	Nil
4	Brazos (Texas)	Rosenburgh	44,000	32,000,000	73,000
5	Colorado (Texas)	Lake Austin	38,200	8,220,000	22,000
6	Do.	Tow	31,100	5,000,000	16,000
7	Rio Grande	Elephant Butte	26,312	21,700,000	82,000
8	Sutlej	Bhakra	21,960	34,500,000	157,000
9	Nuecos	Three Rivers	15,600	834,000	5,350

Comparison of Silt Loads of Bhakra and Boulder Reservoirs

The annual silt load of the Colorado above the Hoover Dam has been accepted⁽²⁹⁾ as between 200 million and 300 million tons or a mean of 250 million tons (ton equivalent to 2,000 pounds) which works out to nearly 137,000 foot acres for a catchment of 167,000 square miles or to about 150,000 ton or 82 foot-acres per 100 square miles.

The comparative estimated figures for the Bhakra and the Boulder Reservoirs are given in Table XXIII.

TABLE XXIII

	Boulder	Bhakra
Catchment (square miles)	167,000	21,960
Mean annual run-off (foot-acres)	15,000,000	16,000,000
Rainfall (inches)	10	45
Storage capacity (foot-acres)	30,500,000	4,905,150
Height of dam (feet)	726	500 earlier *
Mean annual silt load (tons)	250,000,000	34,500,000
Mean annual silt (foot-acres)	137,000	19,600
Mean annual silt load per 100 square miles (tons)	150,000	157,000
Mean annual silt load per 100 square miles (foot-acres)	82	90
Accepted for project per year (foot-acres)	60,000	
Accepted for project per year per 100 square miles (foot-acres)	36	
Weight of dry material assumed per cubic foot of deposit (lbs)	85.9	90

* Since revised in 1949.

The Bureau of Reclamation estimate of the mean annual silting of the Boulder Reservoir was 80 thousand foot-acres, against 137 thousand foot-acres subsequently recorded by the Colorado River Board⁽³⁵⁾. The actual provision made for silting in the reservoir was 3 million foot-acres in 50 years⁽³¹⁾ i.e., 60 thousand foot-acres per year. This presumably takes account of the reduction of silt due to the contemplated construction of some silt storage dams upstream of the Hoover Dam during the next 50 years.

The annual silt burden of the Colorado above Hoover Dam and of the Sutlej above the proposed Bhakra Dam are 82 and 90 foot-acres per 100 square miles of the catchment, respectively. But the storage capacity of the Boulder Reservoir is nearly twice the mean annual runoff of the river, so that all the silt must necessarily lodge in the reservoir except a very small amount which may escape with the discharge passed below the dam for irrigation and hydro-electric generation. The storage capacity of the Bhakra reservoir, on the other hand, is nearly one-third of the mean annual run off so that a considerable proportion of the heavily silt laden flood flows may be available for escapage during the silting periods, thus reducing the silt accumulation in the reservoir. What the actual reduction will be, will depend on the time of the year when

storage begins, the rate of release of water, the location and capacity of outlet works and the relative claims of irrigation and power. Sixteen thousand foot-acres per year appears to be a safe figure. This will give an annual rate of silting per 100 square miles of 72 foot-acres against 61, 57, 75, 57, 87, 64, 66, 74 foot-acres for the Elephant Butte, Lake Mentz, Roosevelt, Lake Worth, Grass-ridge, Van Rynevelds Pass, Zuni and Meiktala Reservoirs respectively as obtained from actual capacity surveys (See Table XXXVII in Chapter 4).

Further Silt Investigations

Silt observations are being started on the tributaries of the Sutlej above Bhakra and it may be possible to effect material reduction in the silting of the proposed Bhakra Reservoir by introducing among other measures a system of check dams in portions of the catchment which are most prolific in silt and detritus. But to make these effective, a careful geological examination of the entire area will be necessary in order to locate the exact position of soft strata and of hill sides which are liable to slip during heavy rains and thus provide immense solid material for the flood stream to carry.

PROPOSED BALEHU RESERVOIR

River	..	..	..	..	..	..	Beas, Punjab—India
Catchment	..	..	..	..	..	..	3,320 square miles
Rainfall	..	..	..	..	..	..	42 inches to 116 inches
Mean annual run off	..	..	..	..	..	..	9,000,000 foot-acres
Proposed storage	..	..	..	..	..	..	3,751,800 foot acres
Reservoir level R. L.	..	..	..	..	..	..	2,000

Catchment characteristics

The characteristics of this basin are similar to those of the Sutlej. The following is taken from the description given by Dr. C. S. Fox, Ex-Director, Geological Survey of India.

The Beas river above the Balehu site, drains a greater area of Siwalik sandstone rocks than Sirmur argillaceous strata but the catchment includes 75 square miles of sub-recent boulder gravels which are easily eroded. There is, however, little doubt that the detritus carried by the tributaries of the Beas in this part of the catchment will be largely coarse materials which should, by suitable measures, be tapped above the limit of the proposed reservoir. The general conclusion, therefore, is that the proportion of silt (or fine suspended matter) to coarse material (sand and shingle)

is likely to be appreciably less in the Beas discharge than in that of the Sutlej. Also that the percentage of suspended silt in the Beas flood flow should be materially less than in the flood discharge of the Sutlej as the result of heavy rain on the catchment of Tertiary rocks in either drainage basin.

Comparison of Silt Loads of Sutlej and Beas

These are general deductions based on geological considerations and there is very strong evidence to support the opinion that both the Beas and the Sutlej carry large quantities of detritus during flood after heavy rains in their catchment above Balehu and Bhakra respectively. This detritus would appear to have different proportions of gravel, sand and silt in the two rivers—that of the Sutlej having a higher percentage of suspended matter as against a large amount of coarse material (sand and shingle) in the Beas. Such deductions, though favourable to the Beas in regard to fine silt, are also to be considered as a hint that it will be prudent to discover what steps must be taken to prevent erosion of soft Siwalik rocks, especially the sub-recent gravels and where the check dams will be required to prevent the coarse detrital materials being swept into the Balehu reservoir.

Silt investigations at Balehu

Silt samples at Balehu were taken in August and September of 1939 only and are abstracted in Table XXIV.

TABLE XXIV

	August 1939			September 1939		
	1—10	11—20	21—31	1—10	11—20	21—30
Mean Discharge cusecs	31,150	54,520	43,345	84,480	26,111	13,600
Foot acres of silt carried in the period	293	778	599	2,369	135	49

Total discharge in foot-acres = 5,098,600

Total silt in foot-acres = 4,224

NOTE.—Dry silt assumed to weigh 90 lbs. per cubic foot of deposit. Discharge has been worked out from section based on observed gauges and slopes with $N=0.035$.

The result of these investigations are plotted in Figure 37.

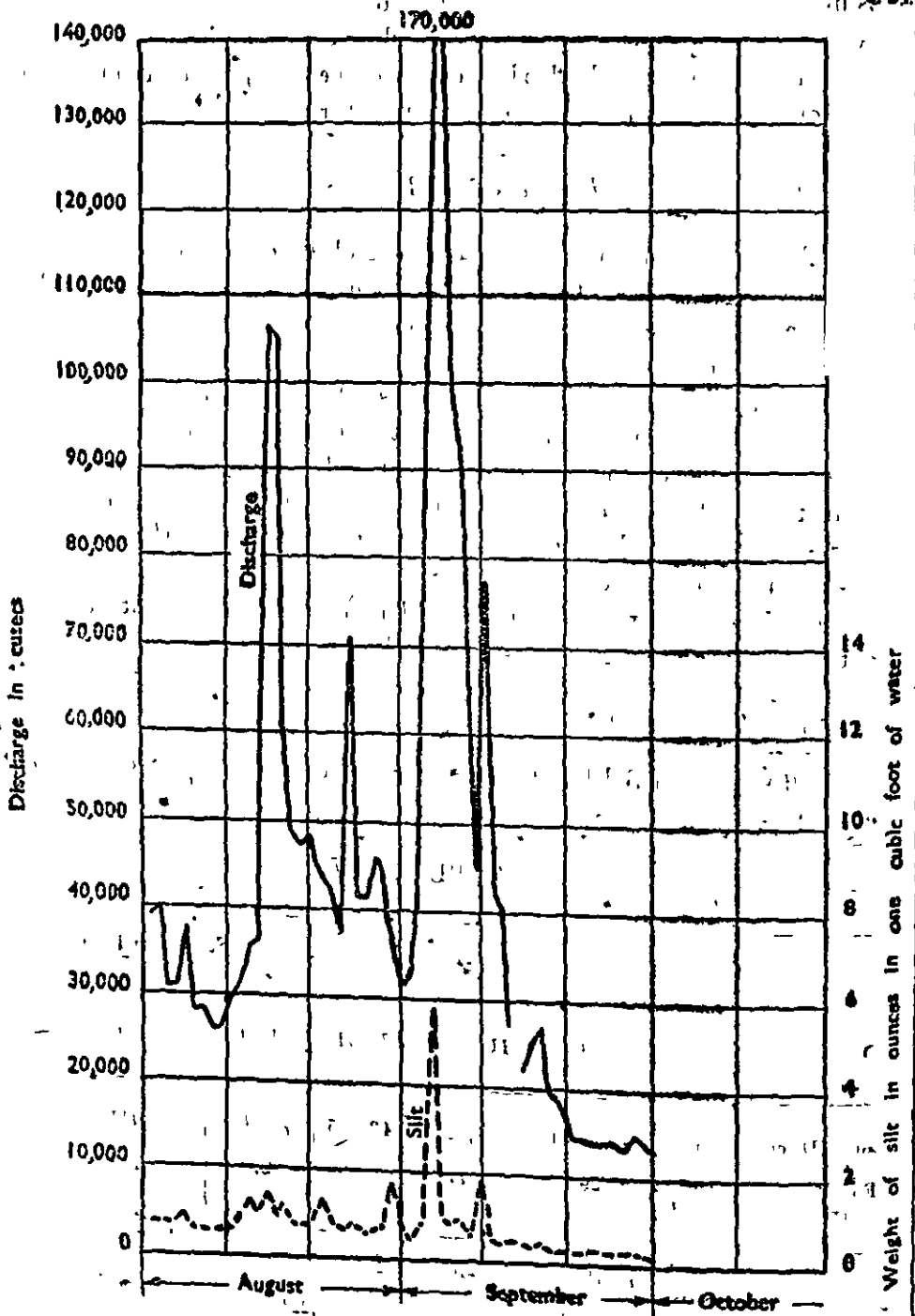


FIGURE 37 - RIVER BEAS AT BALEHU
 DISCHARGE - SILT GRAPH
 (From actual observations.) 1939

SILT INVESTIGATIONS CARRIED ON THE MAHANADI AND THE KOSI RIVERS (6)

HIRAKUD RESERVOIR

River	Mahanadi (Orissa—India)			
Catchment area	32,200 sq. miles			
Rainfall—				
Mean annual	54.4 inches			
Maximum (1919)	71.2 inches			
Minimum (1902)	37.0 "			
Run-off—				
Mean annual	50 million foot-acres			
Maximum	69.4 " "			
Minimum	20.61 " "			
Storage capacity—				
Gross at R. L. 625	5.98 " "			
Dead at R. L. 590	2.24 " "			
Live	3.74 " "			
Air temperature—				
Annual general mean	80.07° (Fahrenheit)			
Annual maximum mean	90.3° " "			
Annual minimum mean	69.4° " "			
Water temperature—				
Degrees Fahrenheit				
	1948	1949	1950	1951
Maximum—				
Morning	95°F	88.7°F	89.4°F	91.2°F
Evening	103°F	95.9°F	94.1°F	95.1°F
Minimum—				
Morning	68°F	67.1°F	66.2°F	66.2°F
Evening	70°F	68.9°F	68.8°F	68.9°F

Height of the Dam 150 feet

Characteristics of the catchment area

The Mahanadi—literally the Great River—is one of the three rivers which has its basin in the state of Orissa and is the largest of those rivers with a total length of 533 miles. It rises near Sehawa in the extreme south west of Raipur district in Madhya Pradesh (Central Provinces). After a short run through the Raipur and Bilaspur districts it then enters the Sambalpur district of Orissa and at Sambalpur becomes a river of the first magnitude with a bed width of over one mile. It has a catchment area of about 32,200 sq. miles above the Hirakud Dam site. The latter is about 9 miles upstream of Sambalpur. The maximum

and minimum daily run-off in that river at Sambalpur during the last five years have been as below :

1947		1948		1949		1950		1951	
Min.*	Max.*	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
426	1,020,102	360	1,896,056	826	1,402,446	524	1,584,184	1,058	900,946
7th June**	2nd Sept.**	12th June	17th Aug.	10th May	8th Aug.	7th June	6th Aug.	1st June	7th Aug.

*Minimum and maximum run-off in foot acres

**Dates when the particular run-off was recorded.

Silt investigations on the Mahanadi

(a) General

The silt work mainly relates to the silt carried in suspension by the river water and the investigations comprise, firstly routine day-to-day estimation of silt load and, secondly, special work directed at obtaining further information on some particular aspects of that load. Three laboratories are at present engaged on silt work at, or near, the proposed sites for dams on that river i.e. at Sambalpur for Hirakud Dam, at Barmul for Tikkerpara Dam and at Kaimundi for Naraj Dam. For the sake of brevity only work done at the Sambalpur site, which is of immediate importance for the sake of the Hirakud Dam under construction, is described here.

(b) Collection of river water samples

There are 15 sampling verticals about 300 ft. apart at the Sambalpur site on the Mahanadi during the high discharge and 5-6 during low discharge periods. The water sampling is done with the help of one-litre capacity Punjab-type bottle sampler at the conventional six-tenth of the depth of water at the sampling vertical except for special investigations when water samples are collected at other depths along vertical also (see part dealing with special investigations).

(c) Estimation of the suspended silt load

Technique: The present practice of estimating the suspended silt involves, its separation based on particle-size into three fractions viz. coarse, (above 0.2 mm) medium (0.2 mm-0.075 mm) and fine (below 0.075 mm). The separation of the coarse silt is done by sieving the silt laden water through 70-80 mesh sieve and the medium by sedimentation method by allowing the well stirred suspension to settle for calculated interval of time for particles upto and above 0.075 mm. The coarse and medium fractions are estimated on volume basis by dropping each one of them in a graduated glass tube, especially designed to read to a hundredth of a cc. under water and tapped to a limit that no

further settlement occurs. The finer fraction is estimated on weight basis from a separate sample by a special hydrometer capable of estimating silt upto about 0.02 % per litre of suspension or alternatively by actual weighment when the silt content goes very low. From the weight of fine silt its equivalent volume is computed.

Tabulation and graphic representation of the silt load from the daily figures of volume of each of the coarse, medium and fine silt and the discharge, the quantities in cubic feet and also in foot acres of each of these silt fractions and total silt are worked out for each day. The daily results are then computed on the basis of ten-day mean figures for each month separately and later for the whole year. Those figures may then be plotted. The estimated amounts of silt of each one of the three fractions and total silt on monthly basis for sambalpur has been presented in Tables XXV to XXIX* for the years 1947-1951, and that for four years (1947-1950) plotted in Figures 38-41. The cumulative annual figures of discharge and silt load for the five years have been compared in Table XXX.

TABLE XXX

Showing a comparison of the annual run-off and silt load figures from 1947-1951

Year	Annual run-off (foot-acres)	Silt load in foot-acres				
		Coarse	Medium	Fine	Total	% Silt content
1947 ..	39,179,672	3,721.32	4,383.41	25,130.63	33,235.36	0.085
1948 ..	34,138,582	2,661.51	2,802.67	23,912.64	29,406.82	0.086
1949 ..	34,814,310	2,109.89	3,028.31	21,833.71	26,971.91	0.068
1950 ..	34,923,806	1,659.21	3,241.57	18,711.42	23,612.20	0.079
1951 ..	24,662,622	774.37	1,135.84	19,085.06	20,995.27	0.085
Mean ..	33,543,798	2,185.26	2,936.36	21,734.69	26,856.31	0.081

As is clear from Table XXX the silt yield of the Mahanadi catchment above Hirakud Dam site for the five years 1947-1951 amounted to 33,235, 29,467, 26,972, 23,612 and 20,995 foot-acres (mean 26,856) foot-acres respectively. In terms of 100 sq. miles of the catchment these figures work out to 103.2, 91.5, 83.7, 73.3 and 65.2 foot-acres (mean 83.4 ft. acres) respectively for five years.

Probable rate of silting of the Hirakud reservoir on the Mahanadi

The rate of silting of a proposed reservoir may be determined either on the basis of silt load carried by the main tributaries or by comparison with sedimentation rates in other reservoirs exposed to similar conditions. As the information relating to the latter is not at present available, recourse has to be made of that available in connection with the former.

* Tables XXV to XXIX are printed on pages 82-91.

TABLE XXV

Suspended load of the River Mahanadi at Sambalpur site during January to December, 1947.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
<i>January—</i>									
1-10 ..	35,976	3,597.6		Negligible (N)	Negligible (N)	21.20	21.20	2.19	
11-20 ..	31,566	3,156.6		N	N	13.58	13.58	1.35	
31-31 ..	38,478	3,498.0		N	N	14.50	14.50	1.32	
Total ..	106,020		106,020			49.28	49.28		49.28
<i>February—</i>									
1-10 ..	30,898	3,089.8		N	N	6.92	6.92	0.692	
11-20 ..	34,950	3,495.0		N	0.05	8.41	8.46	0.846	
21-28 ..	40,254	5,033.0		N	0.03	18.66	18.61	2.320	
Total ..	106,102		212,132		0.08	33.91	33.99		83.25
<i>March—</i>									
1-10 ..	31,406	3,140.6		N	N	7.42	7.42	0.742	
11-20 ..	24,466	2,446.6		N	N	6.58	6.58	0.658	
21-31 ..	22,603	2,054.8		N	N	5.28	5.28	0.478	
Total ..	78,475		290,607			19.28	19.28		103.51
<i>April—</i>									
1-10 ..	15,803	1,580.3		N	N	2.37	2.37	0.237	
11-20 ..	14,581	1,458.1		N	N	2.27	2.27	0.227	
21-30 ..	9,867	985.7		N	N	1.52	1.52	0.152	
Total ..	40,241		330,848			6.16	6.16		108.67
<i>May—</i>									
1-10 ..	8,493	849.3		N	N	0.506	0.506	0.051	
11-20 ..	3,735	373.5		N	N	0.180	0.180	0.018	
21-31 ..	3,167	287.0		N	N	0.080	0.080	0.008	
Total ..	15,385		346,233			0.746	0.746		109.416

				N	N	0-068	0 068	0-007	
M S C H I E R	June—								
	1-10 ..	2,527	252-7	N	N	0 937	0 937	0-007	
	11-20 ..	10,051	1,005-1	N	N	0 886	0-937	0 094	
	21-30 ..	22,096	2,209-6	N	0 091	8 886	8-976	0-898	
	Total ..	34,674		380,907	0-091	9 890	9 981	119-397	
	July—								
	1-10 ..	432,983	43,398-3	7-69	9 14	633 75	650 68	65 06	
	11-20 ..	687,093	68,709 3	40-02	45-19	1,351-62	1,436 83	143-70	
	21-31 ..	3,058,756	280,796-0	1,189-29	1,748-91	4,914 82	7,853 02	713-91	
	Total ..	4,209,832		4,590,739	1,237-00	1,803-24	6,000-19	9,940-43	10,069-827
	August—								
	1-10 ..	2,779,808	277,980-8	561 48	536 47	4,452 02	5,549 97	554-99	
	11-20 ..	1,393,008	139,300 8	109 29	172-15	1,648-76	1,928 20	192-82	
	21-31 ..	2,962,641	269,330 1	1,011 85	922 90	5,084 66	7,019 41	638-13	
	Total ..	7,135,447		11,726,186	1,682 02	1,631-52	11,183 44	14,497-58	24,557-407
	September—								
	1-10 ..	3,676,967	367,696 7	648 97	775 57	3,961 84	5,386-38	538-638	
	11-20 ..	1,184,781	118,478-1	57 39	76 32	818 37	952 08	95 208	
	21-30 ..	1,267,657	126,765-7	67 56	73-00	1,515-49	1,666 05	165-605	
	Total ..	6,129,405		17,855,591	773-92	924 89	6,295 70	7,994 51	32,551-917
	October—								
	1-10 ..	801,481	80,148-1	23-04	20-09	498-31	541-44	54-144	
	11-20 ..	397,536	39,753-6	3-99	2 96	82-28	89-23	8-923	
	21-31 ..	180,618	18,410 7	0-654	0-370	32-34	33-364	3-033	
	Total ..	1,379,635		19,235,126	27-684	23-420	612-93	664-034	38,215-961
	November—								
	1-10 ..	97,574	9,757 4	N	0 1523	6-6190	6-7713	0-677	
	11-20 ..	70,837	7,083-7	N	0-0316	3-9652	3-9988	0-400	
	21-30 ..	54,540	5,454-0	N	0-0271	3 0794	3 1085	0-311	
	Total ..	222,951		19,458,077	N	0-2110	13-6636	13-8746	33,229-8256
	December—								
	1-10 ..	47,913	4,791-3	N	0 0281	2-8920	2 9201	3-292	
	11-20 ..	40,249	4,024-9	N	0-0205	1-6273	1-6478	0-165	
	21-31 ..	38,619	3,510-8	N	0 0053	0-9599	0-9652	0-088	
	Total ..	126,781		19,584,858	N	0-0539	5-4792	5 5331	33,235-3587

TABLE XXVI

Suspended load of the River Mahanadi at Sambalpur site during January to December, 1948.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
				5	6	7	8		
1	2	3	4	5	6	7	8	9	10
<i>January—</i>									
1-10	40,909	4,090.9		Negligible (N)	Negligible (N)	0.7517	0.7517	0.0752	
11-20	43,679	4,367.9		N	N	0.2991	0.2991	0.0299	
21-31	37,000	3,364.0		N	N	0.1592	0.1592	0.0145	
Total	121,588		121,588	N	N	1.2100	1.2100		1.2100
<i>February—</i>									
1-10	26,350	2,635.0		N	N	0.0927	0.0927	0.0093	
11-20	20,500	2,050.0		N	N	0.0820	0.0820	0.0082	
21-29	16,500	1,833.0		N	N	0.0652	0.0652	0.0073	
Total	63,350		184,938			0.2399	0.2399		1.4499
<i>March—</i>									
1-10	13,914	1,391.4		N	N	0.0487	0.0487	0.0049	
11-20	10,943	1,084.3		N	N	0.0392	0.0392	0.0039	
21-31	9,931	903.0		N	N	0.0272	0.0272	0.0025	
Total	34,688		219,626			0.1150	0.1150		1.5649
<i>April—</i>									
1-10	8,363	836.3		N	N	0.0195	0.0195	0.0020	
11-20	7,026	702.6		N	N	0.0174	0.0174	0.0017	
21-30	5,552	555.2		N	N	0.0135	0.0135	0.0014	
Total	20,941		240,567			0.0504	0.0504		1.6153
<i>May—</i>									
1-10	4,848	484.8		N	N	0.0095	0.0095	0.0010	
11-20	4,286	428.6		N	N	0.0065	0.0065	0.0007	
21-31	4,111	374.0		N	N	0.0070	0.0070	0.0008	
Total	13,245		253,812			0.0230	0.0230		1.6383

<i>June—</i>									
1-10 ..	2,615	281.5		N	N	0.0048	0 0048	0 0005	
11-20 ..	12,630	1,283.0		N	0 0023	0 1609	0 1532	0 1532	
21-30 ..	238,501	23,850.1		1-9215	2-7727	317 8142	322 5084	32-2508	
Total ..	253,746		507,558	1-9215	2-7750	317-9690	322 6664		324-3047
<i>July—</i>									
1-10 ..	569,532	56,953.2		5 9110	10 8235	1,217-9052	1,234 4407	123 4441	
11-20 ..	844,095	84,469.5		16 4013	42-8093	1,521-5775	1,580 7881	158 0788	
21-31 ..	1,730,589	157,328.2		106-3306	240 9427	3,204 8978	3,552-1411	322 9219	
Total ..	3,144,816		3,652,374	128 6429	294 3755	5,944 3515	6,367 3699		6,691-6740
<i>August—</i>									
1-10 ..	773,923	77,362.3		13-2594	18 1185	862 3979	893-7688	89 3769	
11-20 ..	3,471,740	347,174.0		1,411-4323	1,329-6697	3,076 1523	10,817 2543	1,081-7254	
21-31 ..	3,953,449	359,404.4		920 7565	455-0597	5,495-1495	7,370 9657	670-0878	
Total ..	8,198,812		11,851,186	2,345-4412	2,302-8479	14,433 6997	19,081 9888		25,773-6634
<i>September—</i>									
1-10 ..	1,283,430	128,343.0		68 5460	88-4918	946-9174	1,103 9252	110 3925	
11-20 ..	1,392,789	139,278.9		82-8558	166 8951	908 6038	1,156 3547	115 6355	
21-30 ..	643,864	64,386.4		7 5055	6 4717	428 5733	442-5505	44-2551	
Total ..	3,320,083		15,171,269	158-9073	261-8596	2,282 0645	2,702-8304		28,476-4938
<i>October—</i>									
1-10 ..	1,510,707	151,070.7		24 8274	27-5664	733 3179	785 5617	78-5562	
11-20 ..	291,782	29,178.2		1-3760	1 1839	66-2272	68-7870	6-8787	
21-31 ..	193,558	17,596.2		0-0447	0 4478	20-0310	20 5235	1-8658	
Total ..	1,996,047		17,167,316	28-0481	29-1890	819-6761	874-8722		29,351-3660
<i>November—</i>									
1-10 ..	121,840	12,164.0		0-0159	0-2613	10-9689	11 2461	1-1246	
11-20 ..	192,875	19,287.5		0-2057	0-6843	51 1915	52-0815	5 2082	
21-30 ..	113,952	11,395.2		0-0894	0-3422	20-6010	21-0328	2-1033	
Total ..	428,267		17,595,583	0 3110	1-2878	82-7614	84-3602		29,435-7262
<i>December—</i>									
1-10 ..	125,878	12,587.8		0-1888	0-2745	26-8872	27-3505	2-7351	
11-20 ..	55,535	5,553.5		N	0-0401	1 9929	2 0330	0-2033	
21-31 ..	47,386	4,307.3		N	0-0058	1-6941	1-7029	0-1548	
Total ..	228,599		17,824,182	0-1888	0-3234	30-6742	31-0864		29,456-8125

TABLE XXVII

Suspended load of the River Mahanadi at Sambalpur site during January to December, 1949.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
<i>January—</i>									
1—10	35,568	3,556.8		Negligible (N)	Negligible (N)	1.3913	1.3913	0.1391	
11—20	30,727	3,072.7		N	N	1.0031	1.0031	0.1003	
21—31	32,387	2,944.3		N	N	0.7433	0.7433	0.0876	
Total	98,682		98,682			3.1377	3.1377		3.1377
<i>February—</i>									
1—10	27,090	2,709.0		N	N	0.6651	0.6651	0.0665	
11—20	27,519	2,751.9		N	N	0.8511	0.8511	0.0851	
21—28	16,834	2,104.2		N	N	0.4829	0.4829	0.0604	
Total	71,443		170,125			1.9991	1.9991		5.1368
<i>March—</i>									
1—10	14,865	1,486.5		N	N	0.4908	0.4908	0.0491	
11—20	12,710	1,271.0		N	N	0.4211	0.4211	0.0421	
21—31	11,044	1,004.0		N	N	0.3508	0.3508	0.0318	
Total	38,619		208,744			1.2627	1.2627		6.3995
<i>April—</i>									
1—10	7,398	738.6		N	N	0.1842	0.1842	0.0184	
11—20	7,007	700.7		N	N	0.1815	0.1815	0.0182	
21—30	5,579	557.9		N	N	0.1308	0.1308	0.0131	
Total	19,972		228,716			0.4965	0.4965		6.8960
<i>May—</i>									
1—10	4,377	437.7		N	N	0.0751	0.0751	0.0075	
11—20	5,996	599.6		N	N	0.1586	0.1586	0.0159	
21—31	8,020	729.1		N	N	0.2561	0.2561	0.0233	
Total	18,393		247,109			0.4898	0.4898		7.3859

<i>June--</i>									
1-10 ..	33,168	3,316.8		0.0085	0.0143	12.4023	12 5151	1.2515	
11-20 ..	145,634	14,563.4		0.8202	1.0471	123 7783	125 4436	12.5444	
21-30 ..	73,515	7,351.5		0.1220	0 3159	52 1012	52 6291	5.2629	
Total ..	255,315		502,424	0.7507	1.3773	188.4598	190 5878		197.9736
<i>July--</i>									
1-10 ..	604,822	60,462.2		18.7683	35 3172	1,372.2612	1,426.3467	142.6347	
11-20 ..	615,048	61,504.8		9.0049	11.2560	682.3977	682 6586	68.2659	
21-31 ..	1,447,902	131,627.5		140.8269	183.1376	2,242.1515	2,566.1190	233.2835	
Total ..	2,667,572		3,169,996	168.6001	229.7108	4,276.8134	4,675.1243		4,973.0979
<i>August--</i>									
1-10 ..	3,451,163	345,116.3		812.9947	1,202.3639	5,436.2722	7,451.6308	745.1631	
11-20 ..	2,805,943	280,594.3		735 8184	1,029.4210	4,090.5658	5,855 8052	585.5805	
21-31 ..	1,362,528	123,866 2		62.3833	87.1566	1,115 3647	1,264.9046	114.9913	
Total ..	7,619,634		10,789,630	1,611.1964	2,318.9415	10,642 2027	14,572.3408		19,445.4385
<i>September--</i>									
1-10 ..	851,414	85,141.4		17.6778	20.4506	694 1515	732 2799	73.2230	
11-20 ..	1,988,689	198,868 9		198.3631	319.9418	2,448 9541	2,967.2590	296.7259	
21-30 ..	951,978	95,197.8		65.5262	91.5552	1,158.9671	1,316.0485	131.6049	
Total ..	3,792,081		14,581,711	281.5671	431.9476	4,302.0727	5,015 5879		24,461.0259
<i>October--</i>									
1-10 ..	819,858	81,985.8		24.6594	25.7348	919 1518	969.5460	96.9546	
11-20 ..	700,473	70,047 3		15.7488	14 8016	748.3027	778.8531	77.8853	
21-31 ..	503,246	45,749.7		4.2872	3 1127	289.0321	296.4320	26.9484	
Total ..	2,023,577		16,605,288	44 6954	43.8491	1,956.4866	2,044.8311		26,505.8570
<i>November--</i>									
1-10 ..	374,990	37,499.0		2.8838	2.3968	398 8151	404 0957	40.4098	
11-20 ..	137,950	13,795.0		0.1486	0 1806	36.1688	36 4980	3.6498	
21-30 ..	102,867	10,286.7		0 0395	0.0541	12.7095	12.8031	1 2803	
Total ..	615,807		17,221,095	3.0719	2.6315	447 6934	453 3968		26,956.2538
<i>December--</i>									
1-10 ..	74,559	7,455 9		0 0100	0 0404	7 9243	7.9747	0.7975	
11-20 ..	60,467	6,046.7		0.0000	0.0148	3.1865	3 2013	0.3201	
21-31 ..	51,034	4,639.5		0.0000	0.0000	1 4802	1.4802	0.1346	
Total ..	186,060		17,447,155	0.0100	0.0552	12.6910	12.6562		26,971.9100

TABLE XXVIII

Suspended load of the River Mahanadi at Samalpur site during January to December, 1950.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
January 1950—									
1-10 ..	31,603	3,160.3		0.00	0.00	0.4285	0.4285	0.0429	
11-20 ..	27,014	2,701.4		0.00	0.00	0.3772	0.3772	0.0377	
21-31 ..	28,215	2,685.0	86,832	0.00	0.00	0.4521	0.4521	0.0411	1.2578
Total ..	86,832			0.00	0.00	1.2578	1.2578		
February 1950—									
1-10 ..	23,586	2,358.6		0.00	0.00	0.3669	0.3669	0.0367	
11-20 ..	20,602	2,060.2		0.00	0.00	0.2960	0.2960	0.0296	
21-28 ..	23,774	2,971.8		0.00	0.00	0.7218	0.7218	0.0602	
Total ..	67,962		164,794	0.00	0.00	1.3847	1.3847		2.6425
March 1950—									
1-10 ..	28,055	2,805.5		0.00	0.00	1.3132	1.3132	0.1313	
11-20 ..	18,528	1,852.8		0.00	0.00	0.4686	0.4686	0.0489	
21-31 ..	45,025	4,093.2		0.00	0.00	6.0650	6.0650	0.5514	
Total ..	92,208		247,002	0.00	0.00	7.8468	7.8468		10.4893
April 1950—									
1-10 ..	22,043	2,204.3		0.00	0.00	1.3118	1.3118	0.1312	
11-20 ..	9,674	967.4		0.00	0.00	0.3247	0.3247	0.0325	
21-30 ..	6,862	686.2		0.00	0.00	0.1720	0.1720	0.1720	
Total ..	38,379		285,381	0.00	0.00	1.8086	1.8086		12.2979
May 1950—									
1-10 ..	4,768	476.8		0.00	0.00	0.1126	0.1126	0.0113	
11-20 ..	3,915	391.5		0.00	0.00	0.0861	0.0861	0.0086	
21-31 ..	3,464	314.9		0.00	0.00	0.0529	0.0529	0.0048	
Total ..	12,147		297,528	0.00	0.00	0.2516	0.2516		12.5495

June 1950—								
1—10 ..	2,858	285.8	0.00	0 00	0.0500	0.0800	0.0050	
11—20 ..	87,491	8,749.1	0 00	0.1141	84 6858	94.7999	8.4800	
21—30 ..	249,020	24,902.0	0 8872	0 9037	338 9441	340 7150	34 0715	
Total ..	339,369	638,897'	0 8872	1 0178	433 8799	435 6640		448.1144
July 1950—								
1—10 ..	597,876	59,787.6	8.3053	10 6159	981.4968	1,000 4180	100 0418	
11—20 ..	1,262,222	126,222.2	49.0572	108.1781	1,780.2729	1,937.5082	193.7508	
21—31 ..	2,931,924	266,538.5	381 9483	782.0545	4,311.7722	5,475.7750	497.7977	
Total ..	4,792,022	5,428,919	439.3108	900.8485	7,073 5419	8,413.7012		8,861.8156
August 1950—								
1—10 ..	5,013,169	501,815.0	852 3501	1,508,7871	5,875 9887	7,937.1259	793.7126	
11—20 ..	2,727,344	272,734.4	264.9097	531 8530	2,640.2071	3,337 0597	333 7060	
21—31 ..	629,957	57,268.8	2.5312	9 5727	323.1920	335.2960	30 4815	
Total ..	8,375,460	1,380,4379	1,119 8810	2,050 2128	8,439 3878	11,609.4816		20,471.2972
September 1950—								
1—10 ..	965,697	96,669.7	22.4346	81 8208	874.9906	979.2460	97.9246	
11—20 ..	1,286,991	128,699.1	69 6398	187 5210	1,463.3005	1,720 4613	172 0461	
21—30 ..	688,428	68,842.8	6.3411	18 9203	308 8702	334 1316	33.4132	
Total ..	2,941,116	16,745,495	98.4155	288.2621	2,647.1613	3,033 8389		23,505.1361
October 1950—								
1—10 ..	172,408	17,240.8	0 4253	0 4535	46 4045	47.2833	4.7283	
11—20 ..	145,716	14,571.6	0 1639	0 4352	33 6597	34 2488	3.4249	
21—31 ..	120,526	10,958.9	0.1265	0.2313	17 4275	17 7853	1 6168	
Total ..	438,650	17,184,145	0 7057	1 1200	97 4917	99 3174		23,604.4535
November 1950—								
1—10 ..	84,348	8,434.8	0.0315	0.1107	3 2511	3.3933	0.3393	
11—20 ..	53,374	5,337.4	<i>Nil</i>	0 0000	1.6188	1.6188	0.1619	
21—30 ..	37,921	3,792.1	<i>Nil</i>	0 0000	0.9436	0.9436	0 0944	
Total ..	175,643	17,359,788	0 0315	0.1107	5.8135	5.9567		23,610.4092
December 1950—								
1—10 ..	36,590	3,650.0	<i>Nil</i>	<i>Nil</i>	0.7227	0.7227	0.0723	
11—20 ..	33,481	3,348.1	<i>Nil</i>	<i>Nil</i>	0 5384	0.5384	0 0538	
21—31 ..	32,044	2,913.1	<i>Nil</i>	<i>Nil</i>	0 5321	0.5321	0.0484	
Total ..	102,115	17,461,903			1.7932	1.7932		23,612.2024

TABLE XXIX

Suspended load of the River Mahanadi at Sambalpur & Bridge site during, January to December, 1951.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
January 1951—									
1—10	25,331	2,533.1		Nil	Nil	0.4631	0.4631	0.0463	
11—20	22,852	2,285.2		Nil	Nil	0.4208	0.4208	0.0430	
21—31	24,028	2,184.4		Nil	Nil	0.4649	0.4649	0.0423	
Total ..	72,211		72,211			1.3578	1.3578		1.3578
February 1951—									
1—10	19,287	1,928.7		Nil	Nil	0.3531	0.3531	0.0353	
11—20	15,058	1,505.6		Nil	Nil	0.2369	0.2369	0.0237	
21—28	10,427	1,303.4		Nil	Nil	0.1638	0.1638	0.0205	
Total ..	44,770		116,981			0.7538	0.7538		2.1116
March 1951—									
1—10	10,001	1,000.1		Nil	Nil	0.1504	0.1504	0.0150	
11—20	8,816	881.6		Nil	Nil	0.1399	0.1399	0.0140	
21—31	40,717	3,071.5		0.0154	0.0154	10.3484	10.3792	0.9436	
Total ..	59,534		176,515	0.0154	0.0154	10.6387	10.6695		12.7811
April 1951—									
1—10	84,501	8,450.1		Nil	0.0855	29.4472	29.5327	2.9533	
11—20	64,275	6,427.5		Nil	0.0418	15.1061	15.1479	1.5148	
21—30	28,351	2,835.1		Nil	Nil	2.2375	2.2375	0.2238	
Total ..	177,127		353,642		0.1273	46.7408	46.9181		59.6992
May 1951—									
1—10	13,212	1,321.2		Nil	Nil	0.8488	0.8488	0.0849	
11—20	7,731	773.1		Nil	Nil	0.3409	0.3409	0.0341	
21—31	6,269	569.9		Nil	Nil	0.1609	0.1609	0.0146	
Total ..	27,212		380,854			1.3506	1.3506		61.0498

MORBI	June 1951—									
	1—10 ..	16,378	1,637.8	0.4880	0.0228	1.8200	2.3317	0.2332		
	11—20 ..	27,119	2,711.9	0.8510	0.0821	11.3642	12.2973	1.2297		
	21—30 ..	51,497	5,149.7	4.0849	0.1443	41.0966	45.3258	4.5326		
Total ..	94,994		475,848	5.4248	0.2492	54.2808	59.9548		121.0046	
July 1951—										
1—10 ..	348,442	34,844.2	5.9494	4.3012	444.4292	454.6798	45.4680			
11—20 ..	328,381	32,838.1	3.7683	2.0678	400.7438	406.6799	40.6580			
21—31 ..	473,975	43,088.6	19.5464	20.4801	2,070.8294	2,110.8559	191.8960			
Total ..	1,148,798		1,624,646	29.2641	26.8491	2,916.0024	2,972.1156		3,093.1202	
August 1951—										
1—10 ..	2,474,452	247,445.2	239.8336	386.2147	6,188.0400	6,814.0883	681.4088			
11—20 ..	2,521,746	252,174.6	230.1733	412.4149	3,912.0056	4,554.5936	455.4594			
21—31 ..	1,722,297	156,572.5	148.7336	200.6302	2,118.7076	2,466.0714	224.1883			
Total ..	6,718,495		8,343,141	616.7405	999.2596	12,218.7532	13,834.7533		16,927.8735	
September 1951—										
1—10 ..	1,219,838	121,983.8	59.9692	65.0959	1,652.2009	1,777.2680	177.7266			
11—20 ..	908,158	90,815.8	21.5865	22.9658	1,014.0934	1,058.6457	105.8646			
21—30 ..	277,812	27,781.2	11.0314	1.6361	82.4480	95.1135	9.5114			
Total ..	2,405,608		10,748,749	92.5871	89.6978	2,748.7403	2,931.0262		19,868.8987	
October 1951—										
1—10 ..	359,044	35,904.4	5.4756	3.2021	219.0917	227.7694	22.7769			
11—20 ..	587,367	58,736.7	13.3641	14.4079	755.8983	783.4703	78.3470			
21—31 ..	276,870	25,079.1	5.1701	1.1578	82.7459	89.0738	8.0976			
Total ..	1,202,281		11,951,030	24.0098	18.7678	1,057.5359	1,100.3135		20,959.2122	
November 1951—										
1—10 ..	1,26,891	12,869.1	4.0255	0.3264	20.4047	24.7566	2.4757			
11—20 ..	72,773	7,277.3	1.0264	0.1902	5.2351	6.4517	0.6452			
21—30 ..	55,141	5,514.1	0.6447	0.1093	0.9793	1.6933	0.1693			
Total ..	254,805		12,205,635	5.6566	0.6259	26.6191	32.9016		20,992.1133	
December 1951—										
1—10 ..	45,711	4,571.1	0.3453	0.0906	0.8463	1.2922	0.1292			
11—20 ..	39,801	3,980.1	0.1532	0.0788	0.7210	0.9528	0.0953			
21—31 ..	39,965	3,633.2	0.1725	0.0825	0.6681	0.9231	0.0839			
Total ..	125,477		12,331,312	0.6710	0.2517	2.2354	3.1581		20,995.2719	

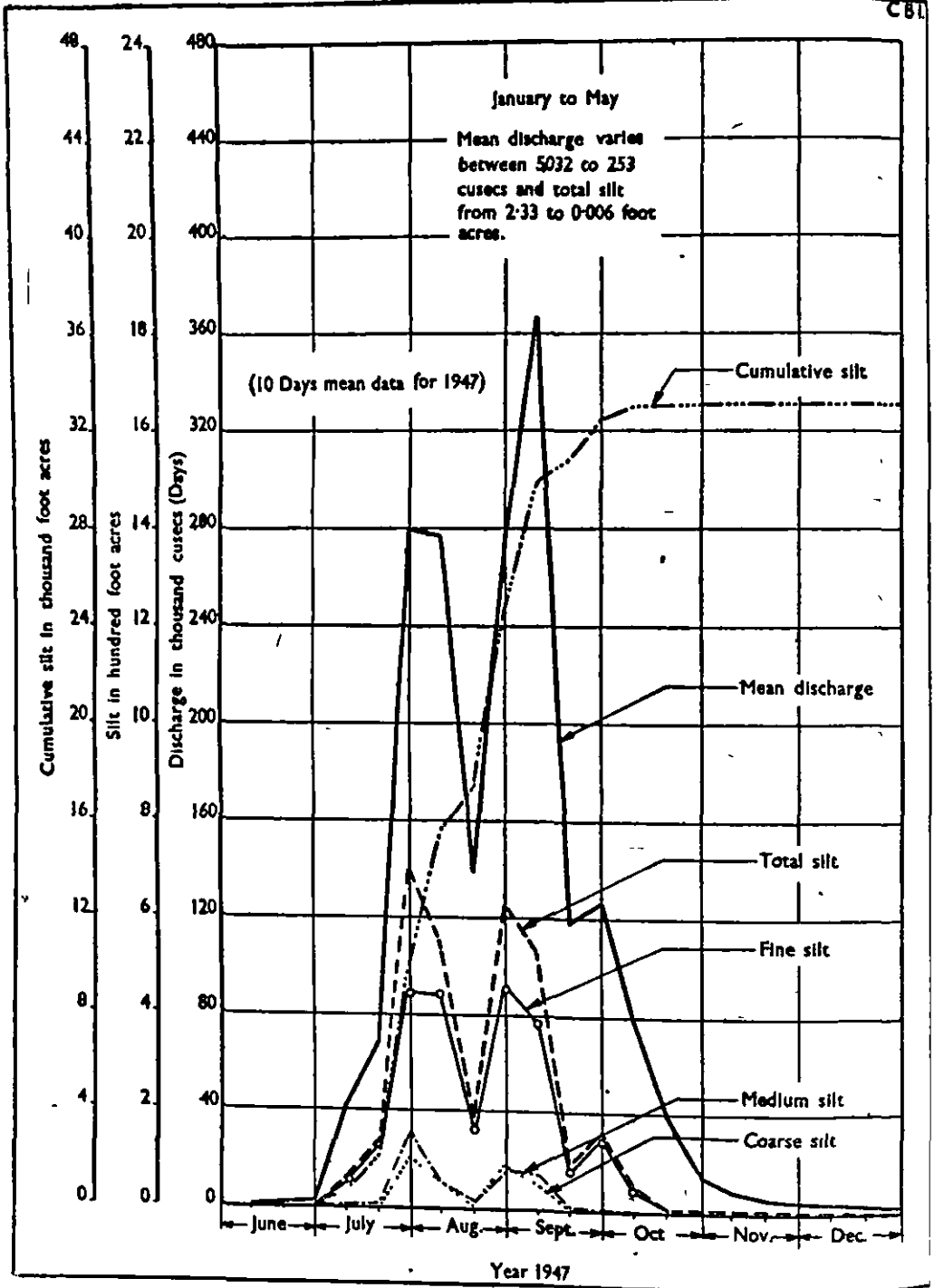


Figure 38 :—Showing silt studies of the Mahanadi for the proposed Hirakud Dam.

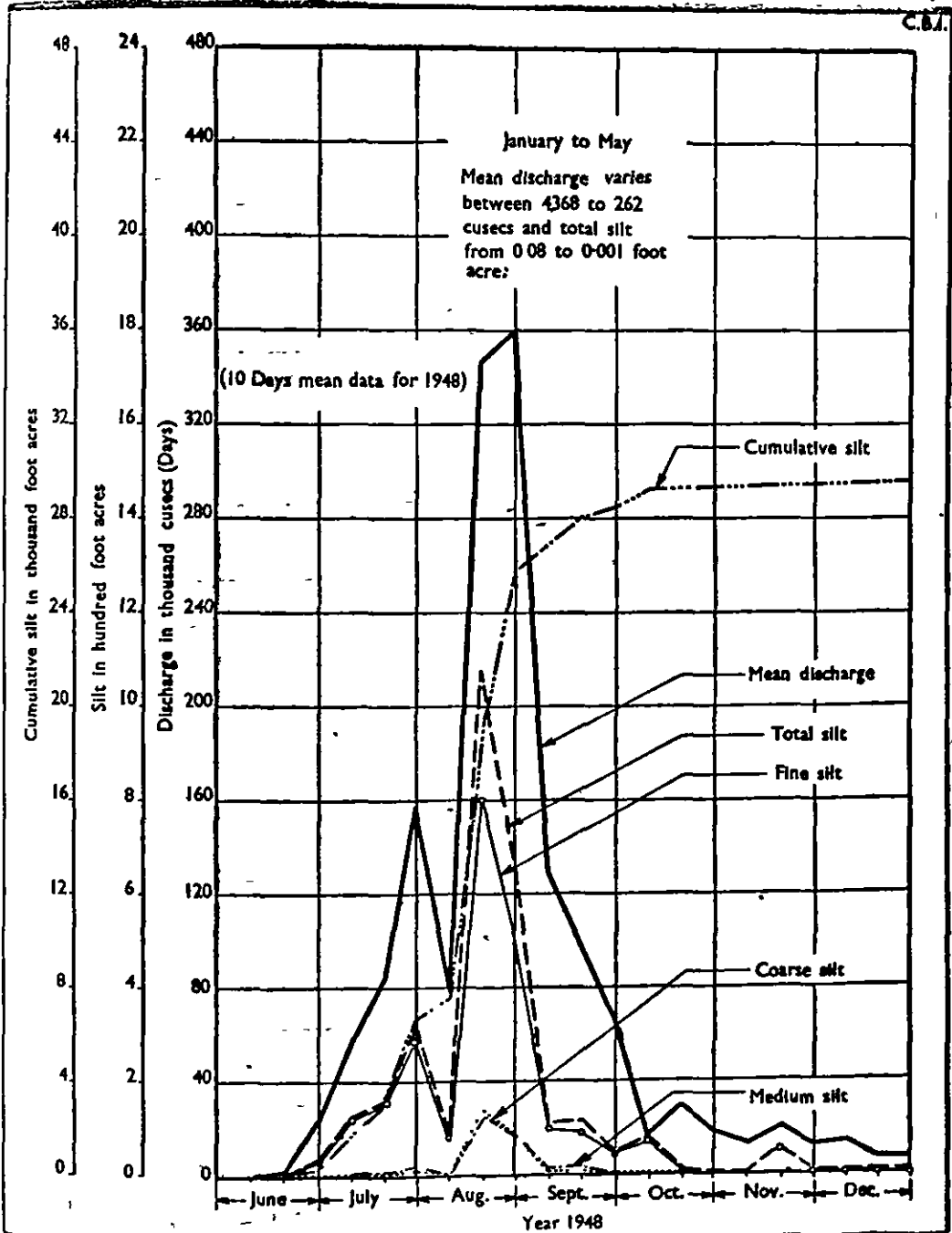


Figure 39 :—Silt studies of the Mahanadi for the proposed Hirakud Dam.

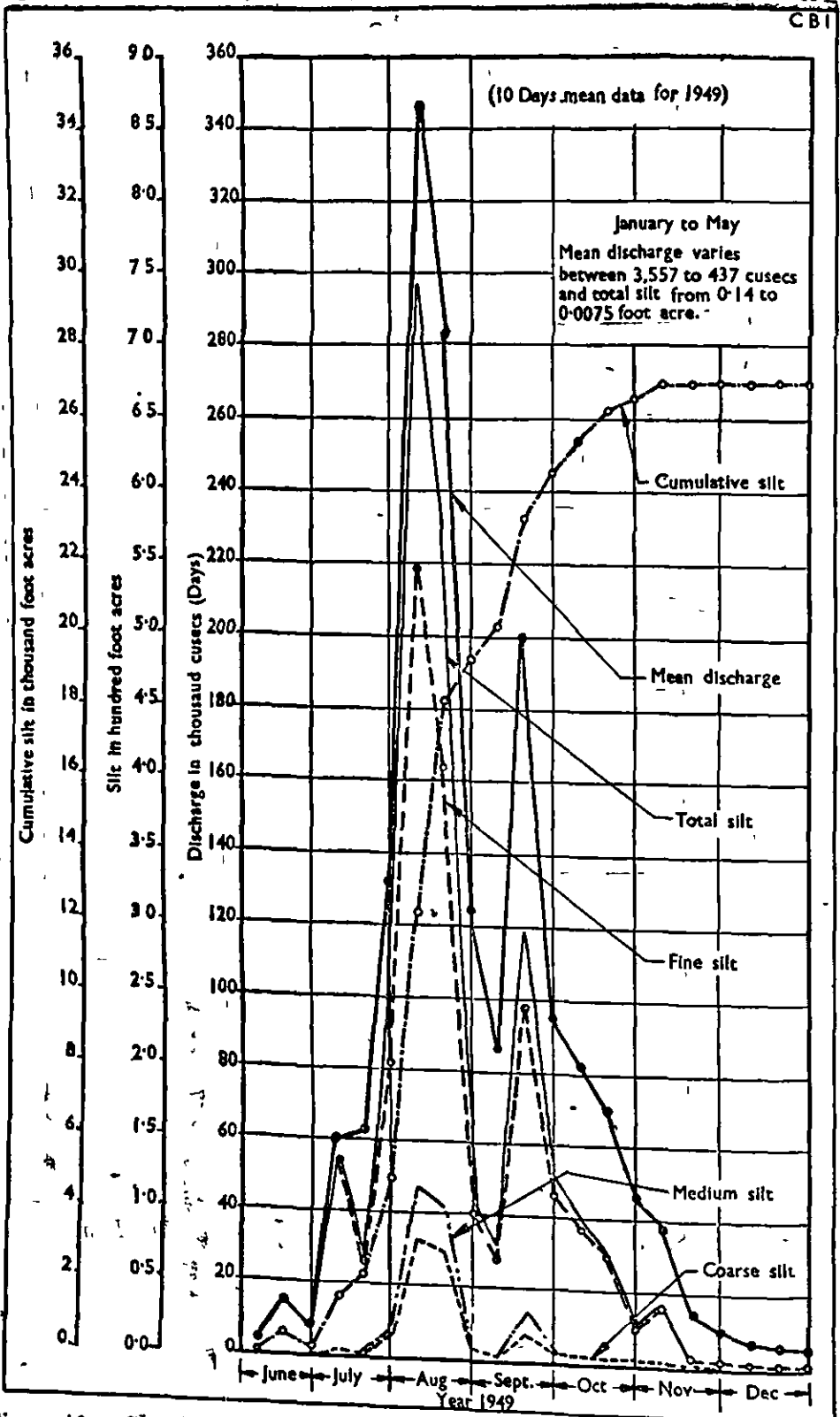


Figure 40:—Showing silt studies of the Mahanadi for the proposed Hirakud Dam.

FIG. 41 SILT STUDIES OF THE MAHANADI RIVER AT SAMBALPUR

10 DAYS MEAN DATA FOR 1950

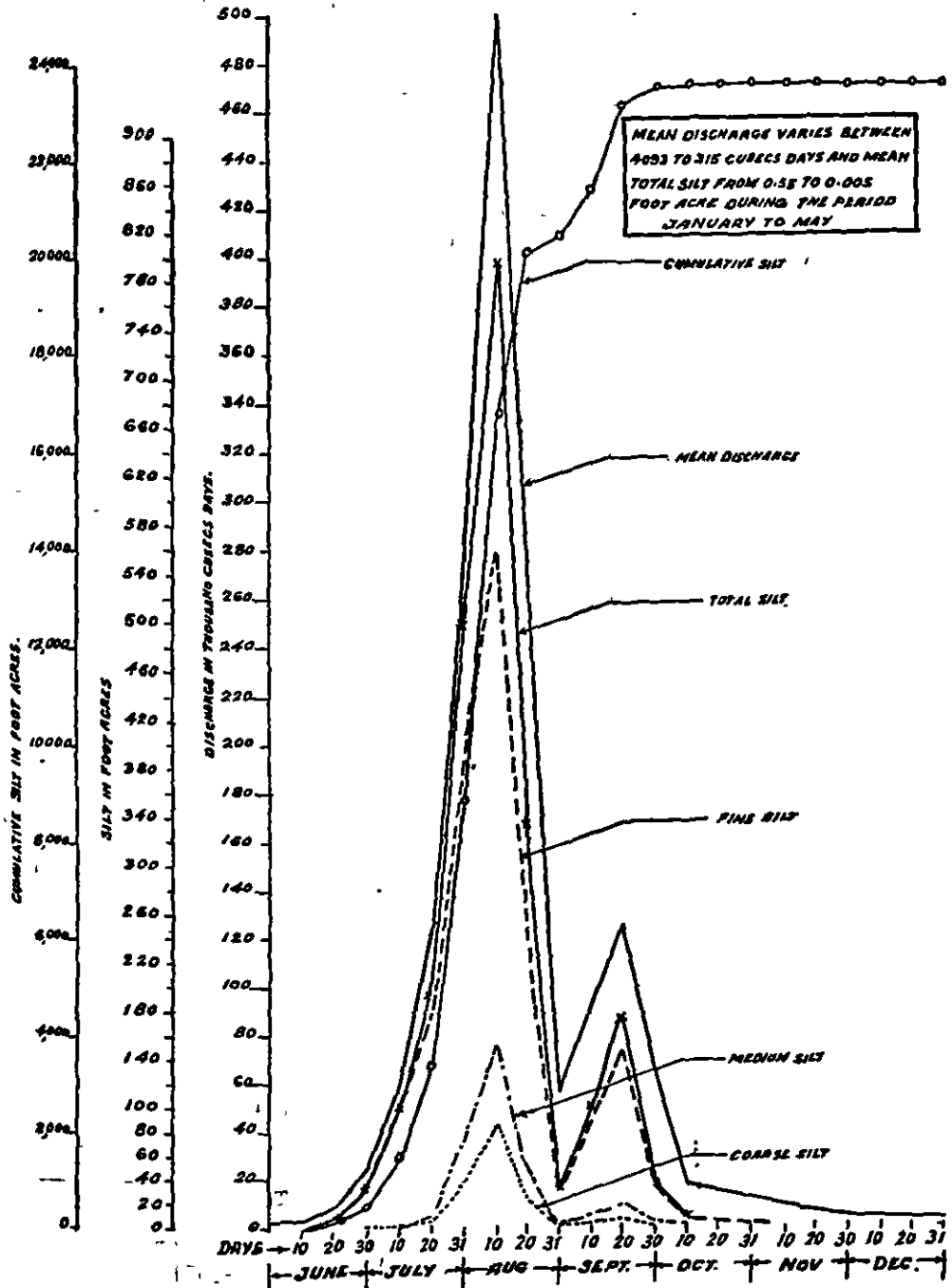


Figure 41

The live storage of 3.74 million foot-acres constitutes 7.5 per cent. of the mean annual runoff. Sluices will be provided at bed level for the full flood discharge and flood supplies during the months of June to September will be passed below the dam and not stored. The conditions there will be somewhat similar to those at the Aswan Dam where storage constitutes 6.7 per cent. of the mean annual runoff of 66 million foot-acres, flood waters passed through bed sluices and no water is stored in the reservoir during floods. There is, however, one difference. At the Aswan Dam there is at present no provision for water power generation and the level of the reservoir is dropped during floods to the normal flood level. At Hirakud, there is provision for power generation and a minimum pond level about 50 feet above flood level has to be maintained for the purpose, so that while the entire flood flow will be allowed to pass through the sluices it will have passed through the dead pond with consequent partial deposition of silt. At the Aswan Dam there is no silt deposit in the reservoir under present conditions of flood disposal. At Hirakud partial deposition will take place because of a permanent dead pond.

From an examination of the analysis of silt load it will be seen that fine silt constitutes nearly 75 per cent. of the total silt charge of that river. From the results of the fineness of the silt coming at various times of the year in the Mahanadi (see part dealing with special investigations), it is seen that it is of very fine variety which might be expected to remain in suspension for quite a long time without settling. From the size distribution curves of the Mahanadi silt it is not improbable that about 90 per cent. of it will be carried with the floods and only 10 per cent. may deposit in the reservoir.

However, for purposes of working out the probable rate of silting let it be assumed that the following percentages of various categories of silt will get deposited in the reservoir ;

	Per cent.
(1) Coarse silt	100
(2) Medium silt	80
(3) Fine silt	20
(4) Bed silt (assumed @ 10 per cent. of the total suspended silt) ..	100

On the above assumption the annual rate of silting based on the mean figure for the years 1947-1951 work out as follows :

Mean annual figures (1947-1951)	Portion likely to be deposited in the reservoir (ft. acres)
Coarse silt 2184.20 @ 100%	2,184.20
Medium silt 2936.45 @ 80%	2,349.16
Fine silt 21,758.94 @ 20% and wet density of mud as 1.4 i.e., 45 % silt and 55 % water	9,870.65
Bed silt (assumed @ 10 per cent. of the total suspended silt)	2,687.96
Total	16,891.97

On the above assumptions the period after which the live storage starts getting affected works out to 132 years on the basis of 1947-1951 silt data. In the Project this period has been put as 100 years.

PROPOSED KOSI RESERVOIR

River	..	..	..	..	..	..	..	Kosi (Nepal & Bihar, India)
Catchment area—								sq. miles
Sankosi tributary	..	..	..	..	..	..	..	7,330
Arun tributary	..	..	..	..	..	..	..	13,380
Tamur tributary	..	..	..	..	..	..	..	2,278
Sapt Kosi (combined channel below junction at Trebeni)	..	..	..	..	..	..	..	22,988
Rainfall—								
Mean annual	..	..	..	..	..	..	..	About 67 ins.

Run-off—(million foot-acres)—	1948	1949	1950
Sun Kosi	17.49	24.08	19.74
Arun	17.92	17.72	16.00
Tamur	8.71	10.31	7.39
Sapt Kosi	49.24	47.12	42.56

Storage capacity—(million foot-acres)	at reservoir level of	
	1100 R. L.	1000 R.L.
Gross	10.908	6.906
Dead	4.119 (900 R.L.)	3.112 (850 R. L.)
Live	6.789	3.794

Air temperature at Dam site—

(Degrees Fahrenheit)	1948	1949	1950
Mean annual—			
Morning	71.3°	73.1°	73.8°
Evening	76.4°	75.8°	76.8°
Maximum—			
Morning	88.7°	..	..
Evening	97.3°	..	..
Minimum—			
Morning	51.5°	..	..
Evening	59.6°	..	..

Water temperature at dam site—
(Degrees Fahrenheit)

						1948	1949	1950
Mean annual—								
Morning	..	..	..	..	..	65.5°	66.22°	66.16°
Evening	..	..	..	..	..	67.5°	67.78°	67.99°
Maximum—								
Morning	..	..	..	..	..	75.4°	74.80°	74.84°
Evening	..	..	..	..	..	77.9°	76.28°	77.00°
Minimum—								
Morning	..	..	..	..	..	55.0°	55.40°	54.86°
Evening	..	..	..	..	..	56.3°	56.80°	56.66°

Height of the dam—(above foundation EL 240)

Reservoir level at 1100 R. L.—833 feet

Reservoir level at 1000 R. L.—783 feet.

Characteristics of the catchment area

The Kosi which, next to the Brahmaputra, is the biggest river in India at its debouch in the plain, rises in Tibet and flowing across the Himalayas in Nepal joins the Ganges after traversing North Bihar. It is a perennial stream whose three main tributaries, the Sun Kosi, the Arun, and the Tamur meet at Trebeni to form the Sapt Kosi. The catchment area of the Kosi above Barakshetra, the site for the proposed dam, is 22,988 sq. miles of which nearly 2,228 sq. miles are under glaciers. The catchment area of the Arun extends beyond the main Himalayan range. The highest peaks in the world, Mount Everest and Mount Kanchinjunga, lie in its catchment area. From a preliminary reconnaissance, it has been found that the catchment area has characteristically steep slopes, indiscriminate deforestation and intense soil erosion along hill sides.

The Kosi is notorious for its vagaries and is known as the 'river of sorrow'. It has been changing its course, generally in a westerly direction and has shifted across a width of over 70 miles. In those movements it has laid waste large tracts of agricultural land in Nepal and Bihar.

The minimum perennial flow of the Sapt Kosi during dry weather is not known to have dropped below 9,000 cusecs while it is estimated that during the record flood of 1927 its maximum discharge was a little over 7 lakh cusecs. The mean annual run-off at the proposed dam site at Barakshetra during 1947-1950 has been about 46.22 million foot-acres which is about 30 % more than that of

the Mahanadi at the Hirakud Dam site. The maximum and minimum run-off in that river at Barakshetra during the five years have been as follows :

Minimum and maximum daily run-off in foot-aeres

1947		1948		1949		1950		1951	
Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
22,100	613,764	18,032	956,888	24,826	751,434	19,206	681,322	18,650	481,140
9th March*	31st July*	18th Mar.*	13th July*	26th Mar.*	19th July*	30th Mar.*	20th Aug.*	24th March*	24th Aug.*

*Date of record of that particular run-off.

Silt investigations on the Sapt Kosi

(a) *General*

The silt work mainly relates to the silt carried in suspension by the river water and the investigations comprise, firstly, routine day-to-day estimation of silt load and, secondly, special work directed at obtaining added information on certain particular aspects of silt load and bed silt. There are two field silt laboratories at the Sapt Kosi river, one at Barakshetra on the main river near the dam site and the other at Trebeni. The main part of the work has been carried at those field laboratories and the specialized work with bulk silt load and bed silt samples at the Hirakud Research station.

(b) *Collection of water samples from the river and its tributaries*

Collection of water samples is done at 5-6 verticals on the Sapt Kosi discharge site where the river passes through a narrow gorge about 500 feet wide and at 3-5 verticals on the three tributaries. Water samples are collected with the help of one-litre capacity Punjab-type bottle sampler at the conventional six-tenth of the depth of water at each vertical during normal stream flow. However, the sampling presents considerable difficulties during high-discharge period due to a velocity of over 20 feet per second that the river attains when it becomes hazardous to ply the boat. During that period the sampling from a suitable boil or failing that from near the water surface has to be resorted to. A fair amount of work is involved to come to a decision with regard to the conversion factor which has to be applied to bring the analytical data to a uniform and comparable basis.

(c) *Estimation of suspended silt load*

Technique: The practice of estimating the suspended silt load into its coarse, medium and fine silt fractions has been similar to the one described in the note for the Hirakud reservoir. The discharge and silt data for the years 1948-1950 on 10-day mean basis is presented in Tables XXXI to XXXIII and diagrammatically presented in Figures 42 to 44.

TABLE XXXI

Statement showing ten days total and mean silt load of Sapt Kosi for the year 1948.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
<i>January—</i>									
1-10 ..	153,149	15,315		21.28	7.40	17.59	46.27	4.63	
11-20 ..	141,430	14,143		16.07	6.06	14.01	36.14	3.61	
21-31 ..	145,895	13,263		14.23	4.95	8.48	27.67	2.51	
Total ..	440,474		440,474	51.58	18.41	40.09	110.08		110.08
<i>February—</i>									
1-10 ..	120,467	12,047		7.24	3.81	2.06	13.11	1.31	
11-20 ..	113,467	11,347		5.99	4.57	3.26	13.81	1.38	
21-29 ..	102,931	11,437		7.57	7.25	5.80	20.63	2.29	
Total ..	336,865		777,339	20.80	15.63	11.12	47.55		157.63
<i>March—</i>									
1-10 ..	116,264	11,626		13.34	3.48	6.55	23.46	2.34	
11-20 ..	103,099	10,310		8.85	3.14	5.92	17.91	1.79	
21-31 ..	125,124	11,375		25.69	18.34	72.69	114.71	10.43	
Total ..	344,488		1,121,825	47.88	22.96	85.18	155.02		313.65
<i>April—</i>									
1-10 ..	124,817	12,482		27.29	18.97	64.46	110.72	11.07	
11-20 ..	147,275	14,728		53.09	41.02	165.34	259.45	25.94	
21-30 ..	174,147	17,915		80.01	87.98	232.13	400.12	40.01	
Total ..	446,239		1,568,054	160.39	147.97	461.93	770.29		1,093.64
<i>May—</i>									
1-10 ..	244,842	24,484		160.54	152.39	433.92	756.35	75.64	
11-20 ..	273,864	27,386		169.72	203.20	162.65	525.57	52.56	
21-31 ..	367,499	33,409		228.58	707.87	359.58	1,296.03	117.82	
Total ..	886,205		2,453,859	548.84	1,063.46	955.65	2,577.95		3,661.89

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June—									
1-10 ..	309,376	30,938		280 06	384 90	133 78	779 61	77-06	
11-20 ..	991,667	99,167		820 40	1,810 88	2,798 63	5,429 89	542 99	
21-30 ..	646,917	64,692		740-22	986 06	1,272-88	2,949-17	299-92	
Total ..	1,947,960		4,401,819	1,841 58	3,161 82	4,205 27	9,208 67		12,870-56
July—									
1-10 ..	1,144,629	114,463		881 49	1,735-78	1,890 69	4,507-98	450 80	
11-20 ..	2,311,448	231,145		1,010 07	5,988 46	9,336 93	16,935 45	1,693 55	
21-31 ..	1,629,291	148,026	9,486,187	736 04	2,061 58	3,913 86	6,711 59	610-14	
Total ..	5,084,368			3,227 60	9,785 82	15,141 58	28,155-00		41,025-56
August—									
1-10 ..	1,842,747	184,275		732 33	1,927 51	3,865 75	6,525 59	652 56	
11-20 ..	1,848,790	184,879		545 39	1,832 09	3,171-56	5,549-03	554-90	
21-31 ..	1,988,750	180,795		643 45	2,707-74	5,037-55	8,388-75	762 61	
Total ..	5,680,287		15,166,474	1,921 17	6,437-34	12,074 86	20,463 37		61,488-93
September—									
1-10 ..	1,843,989	184,399		680 71	2,287 18	4,006 68	6,974-57	697 46	
11-20 ..	1,593,877	159,388		510-32	1,513 00	2,446 52	4,469 64	446-96	
21-30 ..	1,495,043	149,504		584 85	1,436 03	2,108 11	4,128 99	412-90	
Total ..	4,932,909		20,090,383	1,775 88	5-236 21	8,561 11	15,573-20		77,082-13
October—									
1-10 ..	1,210,137	121,014		361 04	1,145-08	2,228 72	3,734-84	373 48	
11-20 ..	853,868	85,387		163 88	449 96	841-64	1,455 28	145 53	
21-31 ..	682,278	62,025		93 34	269-24	442 46	805 04	73 19	
Total ..	2,746,283		22,845,666	618-06	1,864 28	3,512-82	5,995-16		83,057-29
November—									
1-10 ..	409,930	40,993		24-57	45 61	174 92	245-10	24-51	
11-20 ..	336,144	33,614		37-89	44 81	111-09	193 79	19-38	
21-30 ..	309,800	30,986		45-18	50-92	162 40	258-14	25-81	
Total ..	1,055,934		21,001,620	107 64	141-34	448 05	697-03		83,754-32
December—									
1-10 ..	280,425	28,048		44-57	39 78	48-89	133-24	13 32	
11-20 ..	224,729	22,473		24-61	16 92	31-70	73 13	7-31	
21-31 ..	213,325	19,393		17 53	11-74	17-08	46 35	4-64	
Total ..	718,479		24,620,099	86 61	68-49	97-67	252-72		84,007-04

NOTE.—Conversion factors were applied to the coarse and medium salt loads for periods during which water samples were collected from near the water surface.

TABLE XXXII

Statement showing ten days total and mean silt load of Sapt Kosi for the year 1949.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
<i>January—</i>									
1—10	183,249	18,325		14.11	8.70	26.74	49.55	4.96	
11—20	166,007	16,601		9.15	6.78	20.55	36.46	3.65	
21—31	173,809	15,801		7.00	5.94	23.62	36.46	3.31	
Total	523,065		523,065	30.26	21.40	70.81	122.47		122.47
<i>February—</i>									
1—10	170,361	17,036		12.43	15.57	28.98	66.98	5.70	
11—20	158,470	15,847		7.09	5.23	20.90	33.22	3.32	
21—28	133,259	15,407		4.42	3.03	13.75	21.20	2.65	
Total	462,090		975,155	23.94	23.83	63.63	141.46		263.87
<i>March—</i>									
1—10	141,393	14,139		5.02	3.98	12.39	21.39	2.14	
11—20	140,678	14,068		7.70	8.05	16.08	31.81	3.18	
21—31	145,254	13,205		5.44	4.58	22.46	32.49	2.95	
Total	427,325		1,402,480	18.17	16.61	50.91	85.69		349.56
<i>April—</i>									
1—10	167,064	16,706		33.50	53.41	271.20	358.21	35.82	
11—20	196,732	19,673		49.41	91.40	83.28	224.09	22.41	
21—30	215,036	21,504		62.04	158.38	374.31	444.73	49.47	
Total	578,832		1,981,312	144.95	303.19	628.89	1,027.03		1,376.59
<i>May—</i>									
1—10	217,562	21,756		76.52	168.25	208.35	453.12	45.31	
11—20	381,817	38,182		181.91	693.17	787.78	1,662.86	166.29	
21—31	411,082	37,371		196.11	470.65	574.25	1,241.01	112.82	
Total	1,010,461		2,991,773	454.54	1,332.07	1,570.38	3,356.99		4,733.58

<i>June—</i>									
1-10 ..	387,621	38,762	171 41	486 87	612 89	1,271 17	127 12		
11-20 ..	768,562	76,856	340 07	1,311 04	2,332 70	3,983 81	398 38		
21-30 ..	1,122,081	112,208	650 69	2,725 26	6,316 14	9,736 09	973 61		
Total ..	2,278,264		1,162 17	4,523 17	9,305 73	14,981 07			197,24 65
<i>July—</i>									
1-10 ..	1,442,469	144,247	821 38	2,713 93	8,209 16	11,744 47	1,174 42		
11-20 ..	1,557,009	155,701	844 87	6,873 10	12,787 36	20,505 33	2,050 53		
21-31 ..	1,762,696	160,245	761 82	3,477 38	6,562 93	10,802 13	982 01		
Total ..	4,762,174		2,428 07	13,064 41	27,559 45	43,051 93			62,776 58
<i>August—</i>									
1-10 ..	1,287,941	128,794	612 15	1,707 42	3,009 42	5,328 99	532 90		
11-20 ..	2,202,727	220,278	1,043 27	3,775 36	7,498 39	12,317 02	1,231 07		
21-31 ..	2,127,967	193,452	1,280 23	3,032 34	6,456 66	10,769 23	979 08		
Total ..	5,598,644		2,935 65	8,515 12	16,964 47	28,415 24			91,191 82
<i>September—</i>									
1-10 ..	1,871,644	187,164	763 10	2,766 16	5,263 99	8,793 25	879 33		
11-20 ..	1,524,645	152,465	677 54	4,382 08	10,550 85	15,610 45	1,561 05		
21-30 ..	1,065,031	106,503	413 38	1,288 48	1,889 16	3,591 02	359 10		
Total ..	4,261,320		1,854 02	8,436 70	17,704 00	27,994 72			119,186 54
<i>October—</i>									
1-10 ..	789,961	78,996	134 21	547 20	766 60	1,448 01	144 80		
11-20 ..	720,860	72,086	63 06	572 54	662 63	1,098 23	109 82		
21-31 ..	574,458	52,223	82 89	204 30	334 29	621 48	56 50		
Total ..	2,085,270		280 16	1,124 04	1,763 52	3,167 72			122,354 26
<i>November—</i>									
1-10 ..	406,596	40,660	38 37	99 38	146 93	284 68	28 47		
11-20 ..	306,092	30,609	37 41	45 03	96 18	178 62	17 86		
21-30 ..	259,528	25,953	35 99	24 95	56 48	117 42	11 74		
Total ..	973,116		111 77	169 36	299 59	580 72			122,934 98
<i>December—</i>									
1-10 ..	220,797	22,040	10 04	12 26	30 30	52 60	5 21		
11-20 ..	195,612	19,561	6 52	8 15	22 18	36 85	3 69		
21-31 ..	195,819	17,802	8 08	11 58	27 77	97 43	4 31		
Total ..	611,828		24 64	31 99	80 25	136 88			123,071 86

NOTE.—Conversion factors were applied to the coarse and medium silt loads for periods during which water samples were collected from near the water surface.

TABLE XXXIII

Statement showing ten days total and mean silt load of Sapt Kosi for the year 1950.

Days	Ten days total discharge in cusecs	Mean discharge in cusecs	Cumulative discharge in cusecs	Sediment load in foot-acres				Ten days mean	Cumulative in foot-acres
				Coarse	Medium	Fine	Total		
1	2	3	4	5	6	7	8	9	10
<i>January—</i>									
1—10 ..	162,064	16,206		6 51	7 86	26 53	40 90	4.09	
11—20 ..	164,680	16,468		5 91	6 57	28 30	40 78	4 08	
21—31 ..	154,888	14,081		6 03	6 68	22 57	35 88	3.26	
Total ..	471,632		471,732	19 05	21 11	77 40	117.56		117.56
<i>February—</i>									
1—10 ..	120,711	12,071		4 77	5 10	18 80	28 67	2.87	
11—20 ..	130,890	13,090		4 06	4 36	18 66	27 08	2.71	
21—28 ..	105,580	13,198		3 14	3 10	12 80	19 04	2 38	
Total ..	363,100		634,922	11 97	12 56	50 26	74 79		192.35
<i>March—</i>									
1—10 ..	118,230	11,824		3 54	2 32	20 64	29.50	2.65	
11—20 ..	113,073	11,307		4 20	4 38	16 36	25.00	2.60	
21—31 ..	126,454	11,499		6 19	8.55	21 47	36.21	3.39	
Total ..	357,806		119,272.8	13.99	15.25	58 47	87.71		280.08
<i>April—</i>									
1—10 ..	117,793	11,778		4 35	3.68	16 53	24.56	2.46	
11—20 ..	114,920	11,492		4 12	3 91	16 37	24.40	2.44	
21—30 ..	133,448	13,345		13 83	16.39	23 87	54.09	5.41	
Total ..	366,151		155,887.9	22 30	23.98	56 77	103.05		383.11
<i>May—</i>									
1—10 ..	156,185	15,619		27.74	25.83	177.76	231.33	23.13	
11—20 ..	161,136	16,114		35 55	33 56	242 79	311.91	31.19	
21—31 ..	204,163	20,741		169 21	191.73	508 33	859 28	78.11	
Total ..	611,474		217,035.3	222.50	251.13	928 88	1,402.52		1,785.63

<i>June—</i>									
1—10 ..	354,971	35,497		228 81	476-71	578 68	1,294-20	128-43	
11—20 ..	779,949	77,994		549-64	1,255 92	2,219 72	4,925-29	492 53	
21—30 ..	1,013,371	101,337		774-19	1,377-64	2,003-25	4,155-08	415-51	
Total ..	2,148,288		431,893,9	1,552-64	3,110-27	4,801-65	9,464-57		11,250.20
<i>July—</i>									
1—10 ..	1,127,667	112,767		712-60	1,575-61	2,636-62	4,924-84	492-48	
11—20 ..	1,130,866	113,087		546-63	1,167-99	1,989-70	3,704 32	370-43	
21—31 ..	1,873,989	152,181		1,139 56	2,213-20	4,248-83	7,601-59	691-05	
Total ..	3,932,522		825,116,1	2,398-80	4,956 80	8,875-15	16,230 75		27,480.95
<i>August—</i>									
1—10 ..	1,365,388	136,539		1,018 32	1,783-69	3,433-01	6,235 92	623-50	
11—20 ..	2,035,145	203,515		1,391-09	2,851-89	6,446-21	10,689 19	1,068-92	
21—31 ..	2,971,095	242,827		2,082 45	3,614-33	8,810-10	14,608-88	1,318-81	
Total ..	6,071,628		14,322,789	4,491-86	8,249-91	18,689-32	31,431 09		58,612 04
<i>September—</i>									
1—10 ..	2,035,604	203,560		1,686-77	2,643-44	5,314-70	9,644-91	964 49	
11—20 ..	1,318,219	131,822		815-55	1,282-90	2,005-73	4,104 18	410-42	
21—30 ..	846,604	84,660		344-13	356-70	513-71	1,214-54	121-45	
Total ..	4,200,427		18,523,218	2,846-45	4,283-04	7,834-14	14,963 63		73,875-67
<i>October—</i>									
1—10 ..	608,229	60,823		182-88	136-78	277-52	597-18	59 72	
11—20 ..	485,301	48,530		94-09	95 34	208-89	398 32	39-83	
21—31 ..	370,039	33,640		64-74	33-79	36-51	185-04	18 82	
Total ..	1,463,569		19,986,785	341-71	285 91	572-92	1,180-54		75,056-21
<i>November—</i>									
1—10 ..	289,105	28,911		56 43	19-77	56-29	132 49	13-25	
11—20 ..	262,308	26,237		44 32	17-26	55-10	116-68	11-67	
21—30 ..	210,335	21,304		28 74	14 18	41 31	84-23	8-42	
Total ..	761,808		20,748,593	129 49	51 21	152-70	333-40		75,389-61
<i>December—</i>									
1—10 ..	178,633	17,803		18 63	7-60	32 24	58 47	5-85	
11—20 ..	164,602	16,460		10 90	4-15	27 09	42 15	4-22	
21—31 ..	166,228	15,112		7 33	4 70	26-73	38 76	3-52	
Total ..	509,463		21,258,056	36-86	16 45	86-08	139-38		75 538-99

NOTE.—Conversion factors were applied to the coarse and medium silt loads for periods during which water samples were collected from near the water surface.

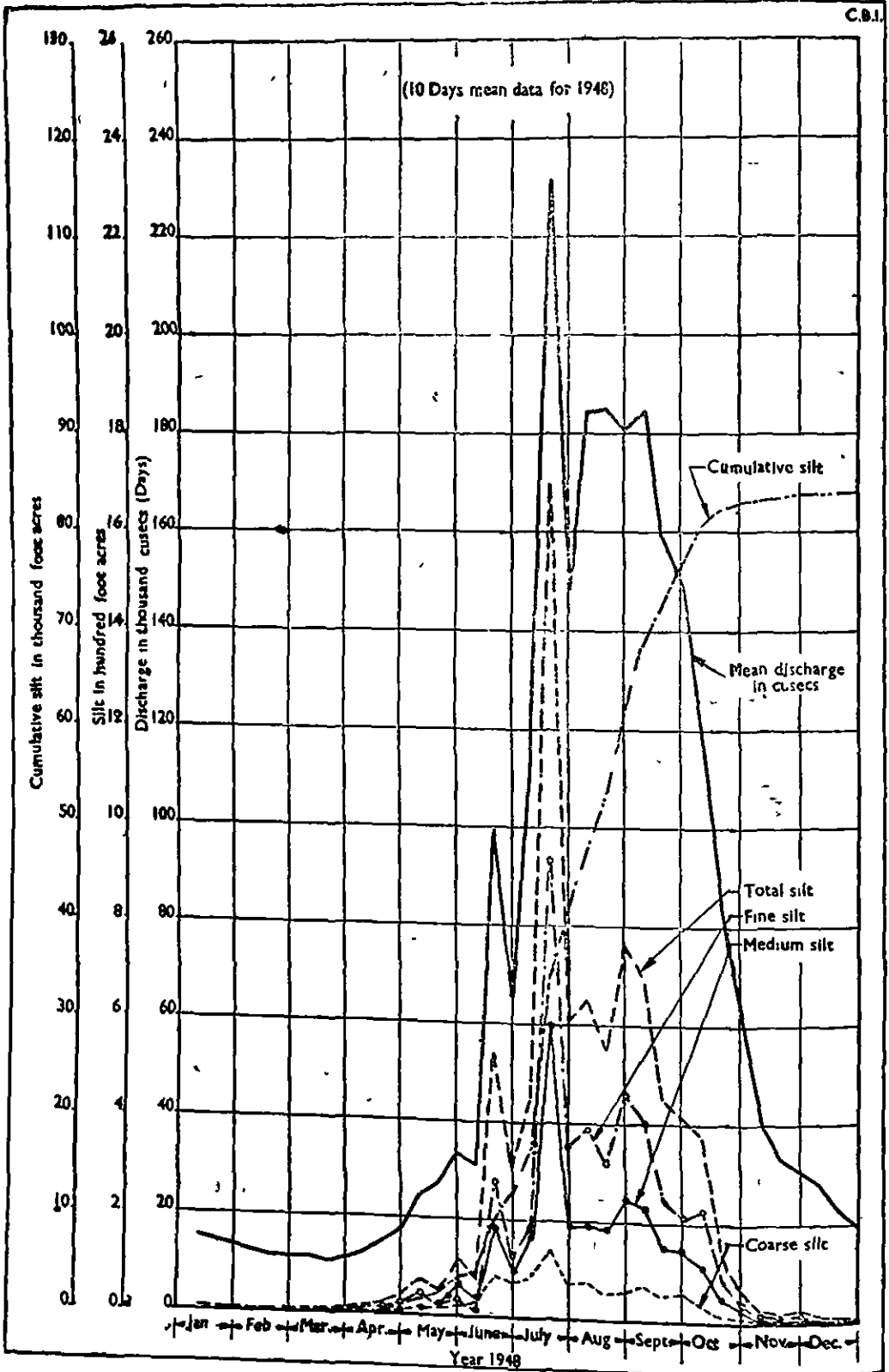


Figure 42 :- Showing silt studies of the Sapt Kosi.

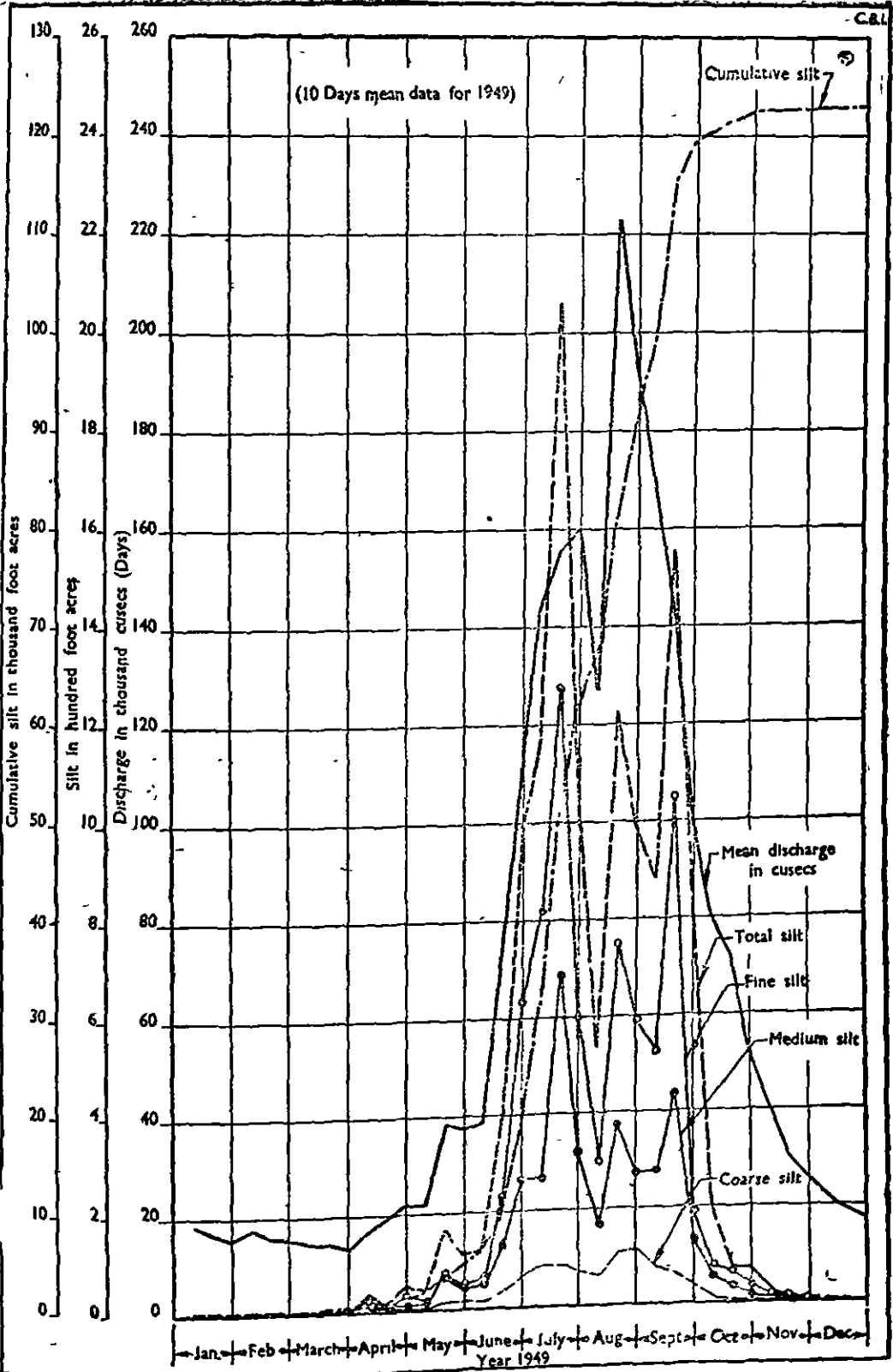


Figure 43 :- Showing silt studies of the Sapt Kosi.

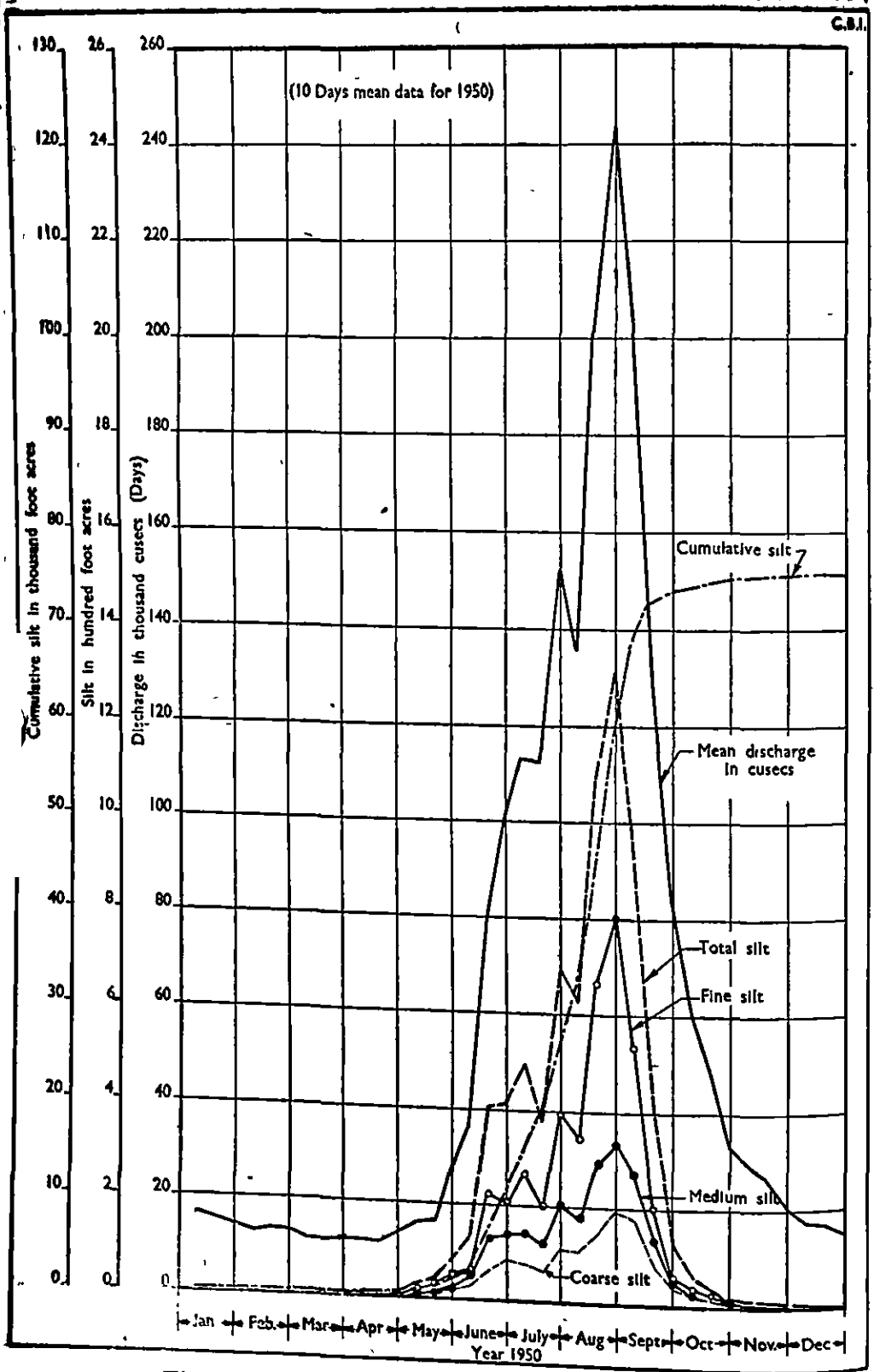


Figure 44 :—Showing silt studies of the Sapt Kosi.

Relationship between the analytical results of the coarse and medium silt fractions of water samples collected at six-tenth of the depth and from the boil or water surface.—This has been the subject of considerable research at the main river and its tributaries during the last few years. During 1948 investigation relating to that point was carried at the Sapt Kosi and at the Tamur tributary and the following conversion factors for the coarse and medium silt fractions derived.

River.	Factors for conversion of silt data obtained from surface samples to those of boil samples	
	Coarse silt	Medium silt
Tamur	2.32	1.23
Sapt Kosi	2.0	1.5

The contents of the coarse and medium fractions of silt load for the Sapt Kosi and the Tamur were therefore corrected by using the above-mentioned respective conversion factors during 1948 and 1949.

More systematic work was done during 1950 with the object of either corroborating the conversion factors derived as the result of earlier work or alternatively to obtain further information on that point. It has been shown on the basis of the work done during 1950 that :

(i) Any factor based on the low discharge period is not applicable to the high discharge period in that river and its tributaries.

(ii) Medium silt behaves, more or less, like fine silt and does not manifest the typical increasing content with depth along vertical. That conclusion is supported by the fact that the total quantity of the medium silt recorded during 1950 at Sapt Kosi comes out to 19,993.43 ft. acres against 19,530.81 ft. acres, the total for the medium silt content of the three tributaries, the flow in the latter being highly turbulent due to the presence of a number of rapids and rocky bed.

(iii) As there is little variation of sediment distribution of coarse and medium grade during turbulent flow in the Sapt Kosi and the tributaries, no definite point of average concentration can be given.

(iv) The conversion factors for coarse and medium silt fractions decrease with increasing discharge as brought out in Figure 45 and can therefore be best represented as a function of the latter. It is seen in that Figure that although the points are scattered widely, the curves for the coarse and medium grades of silt do indicate the general trend of the conversion factor closely enough for various ranges of discharge. It is further brought out that when the discharge of the Sapt Kosi exceeds 2-lakh cusecs the turbulence is so great that medium silt gets more or less uniformly distributed over the entire depth. Likewise, the coarse silt behaves in that way when the discharge exceeds 3-lakh cusecs.

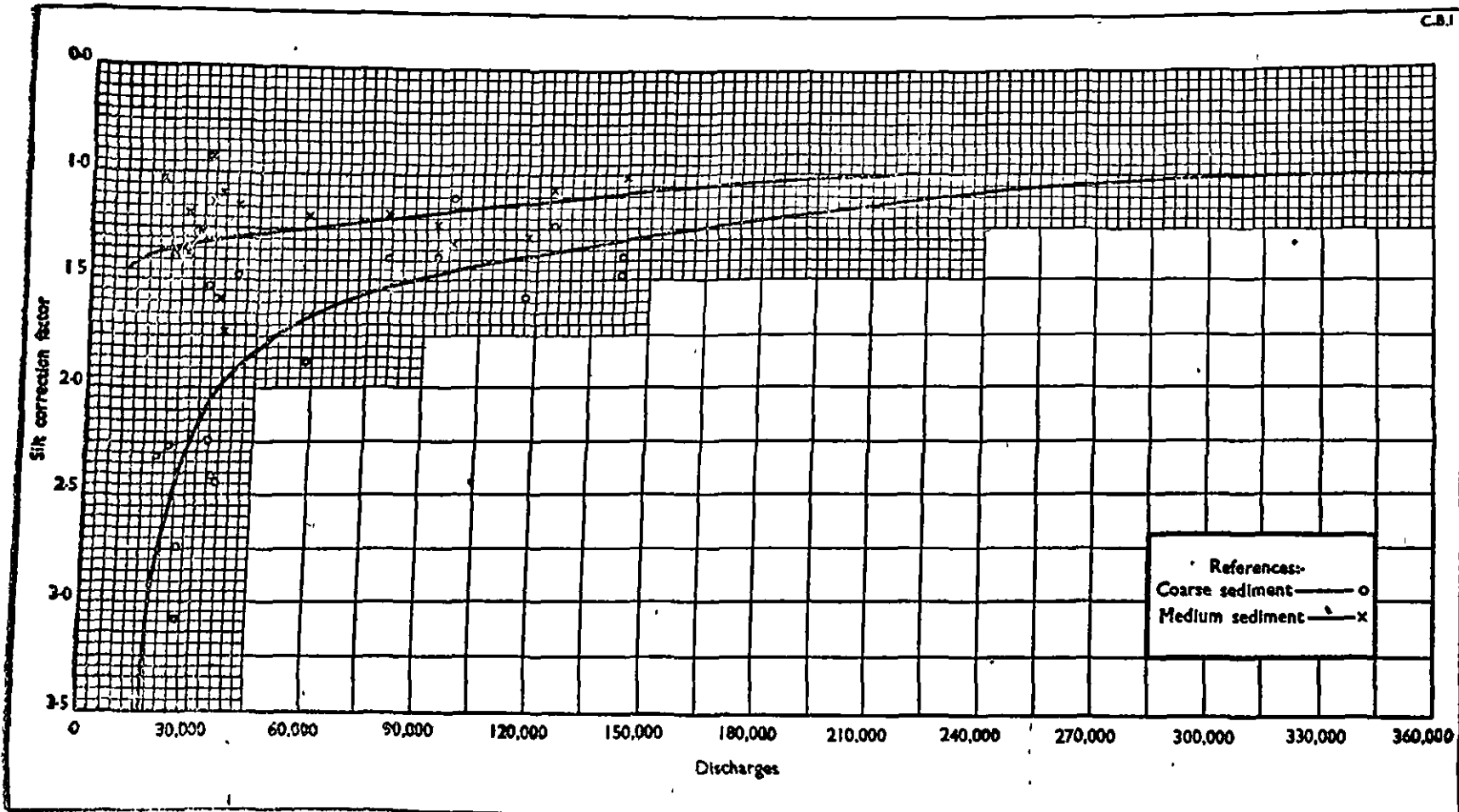


Figure 45 :—Graph of correction factors for Sapt Kosi for converting silt load from surface samples to mean silt load.

As the result of the work done during 1950 it was clearly shown that the conversion factors used during 1948 and 1949 were very much on the high side and it was decided to recalculate the data with regard to the coarse and medium silt fractions of 1948 to 1950 on the basis of the respective curves in Figures 45. A summary of the experimental and corrected data for the years 1948-1950 is given below :—

TABLE XXXIV

Showing the comparison of the annual run-off and suspended load of Sapt Kosi for the years 1948-1950.

Year	Annual run-off foot-acres	Sediment load in foot-acres				
		Coarse silt	Medium silt	Fine silt	Total silt	% silt content
1948 ..	49,240,198	Exp* 8,976.40	27,102.54	45,530.38	81,609.32	0.166
		Corr** 10,408.02	27,867.40	..	83,805.80	0.171
1949 ..	47,124,796	Exp* 7,723.28	35,714.34	76,061.64	119,499.26	0.254
		Corr** 9,467.65	37,561.34	..	12,3090.63	0.261
1950 ..	42,583,834	Exp* 9,896.76	19,993.43	42,163.70	72,073.89	0.18
		Corr** 12,087.66	21,257.64	..	75,529.00	0.177
Mean (1948-50)	46,316,276	Exp* 8,865.46	27,603.44	54,616.90	91,085.76	0.196
		Corr** 10,654.67	28,937.73	54,616.90	94,209.30	0.203

*Actual experimental data.

**Corrected by applying conversion factor from curves in Figure 45.

As is clear from the Table XXXIV the silt yield of the Sapt Kosi above the proposed dam site for the three years 1948-1950 amounted to 84,007.04, 123,091.86 and 75,528.99 foot-acres respectively (mean 94,209.30 foot-acres). In terms of 100 sq. miles of the catchment these figures work out to 370, 535 and 329 ft. acres for three years respectively (mean 411 foot-acres). Observations during coming years will help to confirm or modify this abnormal figure of annual silt charge,

Probable rate of silting of the Kosi reservoir

It is proposed to instal sluices in the dam at the lowest possible level consistent with assured operation. It is further proposed to operate the storage in the reservoir in such a way that the heavy silt laden water of the earlier floods will not be stored but allowed to pass below the dam thus carrying the maximum amount of silt charge with it. As however the flood water would normally pass through the dead pond provided for silt reserve resulting in a fall in the velocity of water flow that will affect the silt charge at the entry and some part of the silt is bound to get deposited in the reservoir. In the absence of relevant data on other similar reservoirs, it is not possible to say with any degree of certainty what part of the silt charge during floods will be retained in the reservoir and what part passes down, considering that water will be stored only after the floods are over and silt charge is relatively low (live storage of 3.8 and 6.8 million foot acres will be only 7.50 and 13.8 per cent. of annual runoff) and that water will be discharged through deep set sluices carrying bulk of the silt charge.

The mean silt figures for three years 1948-1950 work out in foot-acres as under :

Particulars.	Coarse	Medium	Fine	Total
Exp.	8,865.48	27,603.44	54,591.91	91,060.82
Cor.	10,654.44	28,895.46	54,591.91	94,141.81

The nature of variations in the silt data for the three years as indicated in Table XXXIV do not justify any but rather broad generalizations. For general interest, however an attempt has been made to work out the period after which the live storage in the reservoir shall start getting affected. As has been seen from the ultramechanical analysis of bulk silt samples about 70 per cent. of the silt load is below 0.03 mm and with the high velocities of Sapt Kosi during the flood period, such fines may not settle down in the reservoir even though the velocities will be considerably damped in the reservoir. The annual rate of silting has been computed as below :

Mean annual figures (1948-1950)	Portion likely to be deposited in the reservoir (foot-acres).
Coarse silt 10,654.44 @100%	10,654.44
Medium silt 28,895.46 @ 80%	23,116.37
Fine silt 54,591.91 @ 30% and wet density of mud as 1.5 i.e., 55% solids and 45% water	29,778.00
Bed silt 94,141.81 (assumed @ 20% of the total silt load)	19,828.36
	83,377.17

On the above assumption the period after which the live storage starts getting affected works out as 36.6 and 48.4 years for a dead storage of 3.11 and 4.12 million foot-acres respectively.

If the live storage, which is primarily meant for flood regulation, is not to be impaired after the lapse of that period, additional dams will need to be constructed higher up on the tributaries during that period. Any encroachment on the live storage will reduce the extent of flood moderation and the generation of power.

It is advisable that more data be collected at the Sapt Kosi river to examine the validity of the above figure for the life of the silt reserve capacity of the proposed reservoir.

SPECIAL INVESTIGATIONS IN CONNECTION WITH THE SUSPENDED SILT LOAD OF THE MAHANADI AND THE KOSI RIVERS

Besides the routine work relating to the estimation of suspended silt load of waters of the Mahanadi and the Sapt Kosi at the field laboratories, the following special investigations were carried at the Hirakud Research Station (6).

Variation of silt load with varying discharges of the two rivers

The variations of the total sediment load and its coarse plus medium and fine silt fractions with varying discharges in the Mahanadi and the Sapt Kosi as observed during 1948 and 1949 are diagrammatically presented in Figures 46 and 47 respectively. It is seen that there is, in general, a progressive increase in the total silt and its various fractions with increase in discharge in both rivers. However, whereas the curves showing the relationship of silt for the Mahanadi were more or less, analogous during those two years, for the Sapt Kosi, on account of relatively higher discharges attained in that river during 1949, the curves for that latter year are placed distinctly higher than those of the previous year in Figure 47. It is felt that the utility of this relationship cannot but be qualitative as the conspicuous difference in the silt load of the river carrying a similar discharge during rising and falling floods is quite well known.

Relationship between discharge and velocity of waters of the two rivers

The variations in the discharge with the velocities attained by river waters are diagrammatically presented in Figures 48 and 49. It is shown that whereas in the case of the Mahanadi, a velocity of about 8 feet/second corresponds to a discharge of over 7.5-lakh cusecs, but an equivalent velocity of the Sapt Kosi River water corresponds to only a discharge of about 50 to 60 thousand cusecs. The velocity that the latter river water attains during high floods is 15 to 20 ft/sec and at that high velocity a discharge of a little over 4-lakh cusecs may be recorded. The high silt capacity and preponderance of relatively higher sized silt particles in suspension in the Sapt Kosi in comparison to that of the Mahanadi may partly be attributed to the high velocity attained by the former.

Variation of suspended silt load with depth along the sampling vertical

A number of experiments carried out in the U.S.A. led to the conclusion that a sample taken from six-tenth depth gives the mean percentage of suspension in the vertical. Experiments conducted in Egypt indicated that the clay

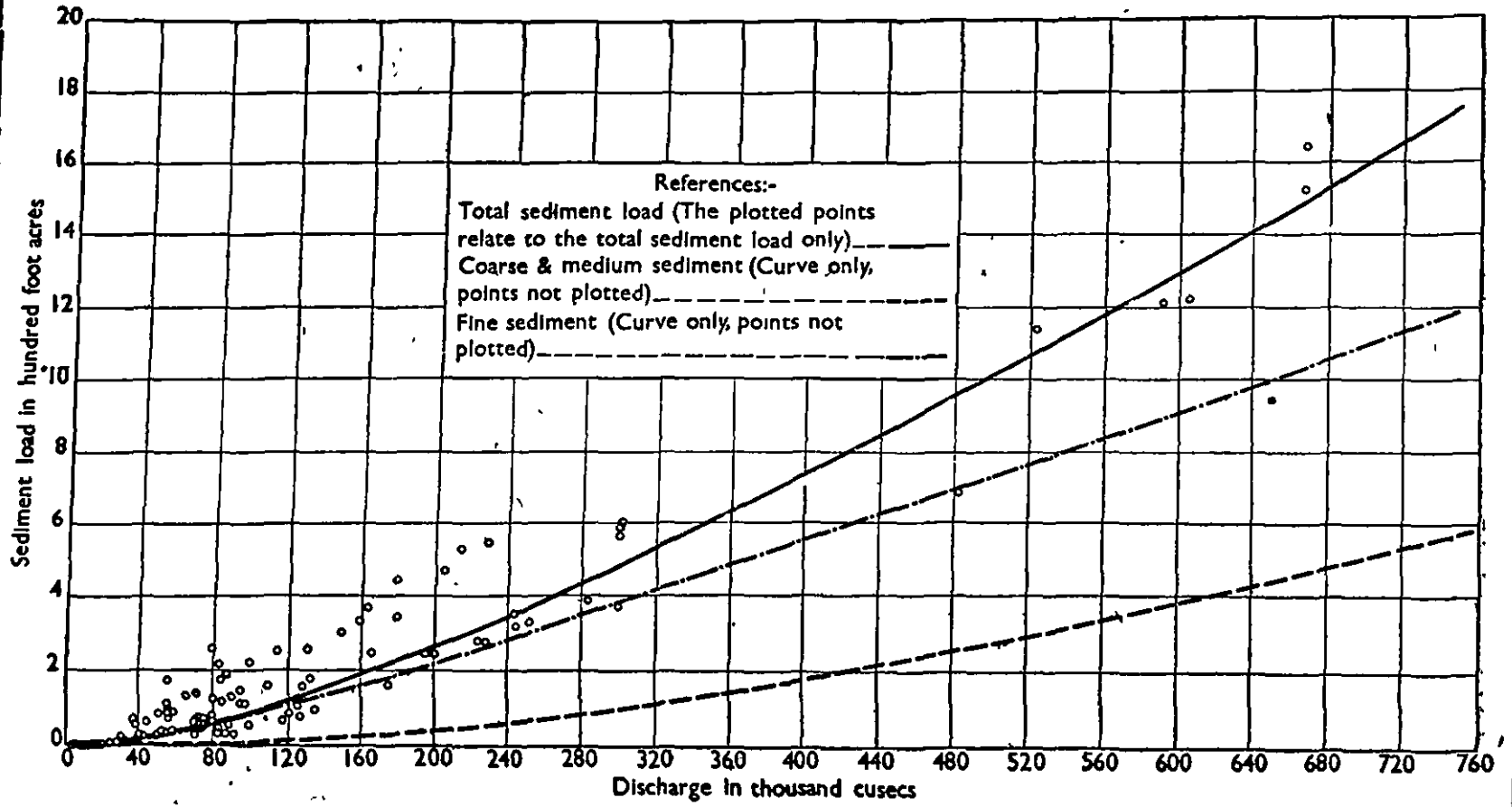


Figure 46 :—Silt load of the Mahanadi at Sambalpur—Discharge silt curves for 1948 and 1949.

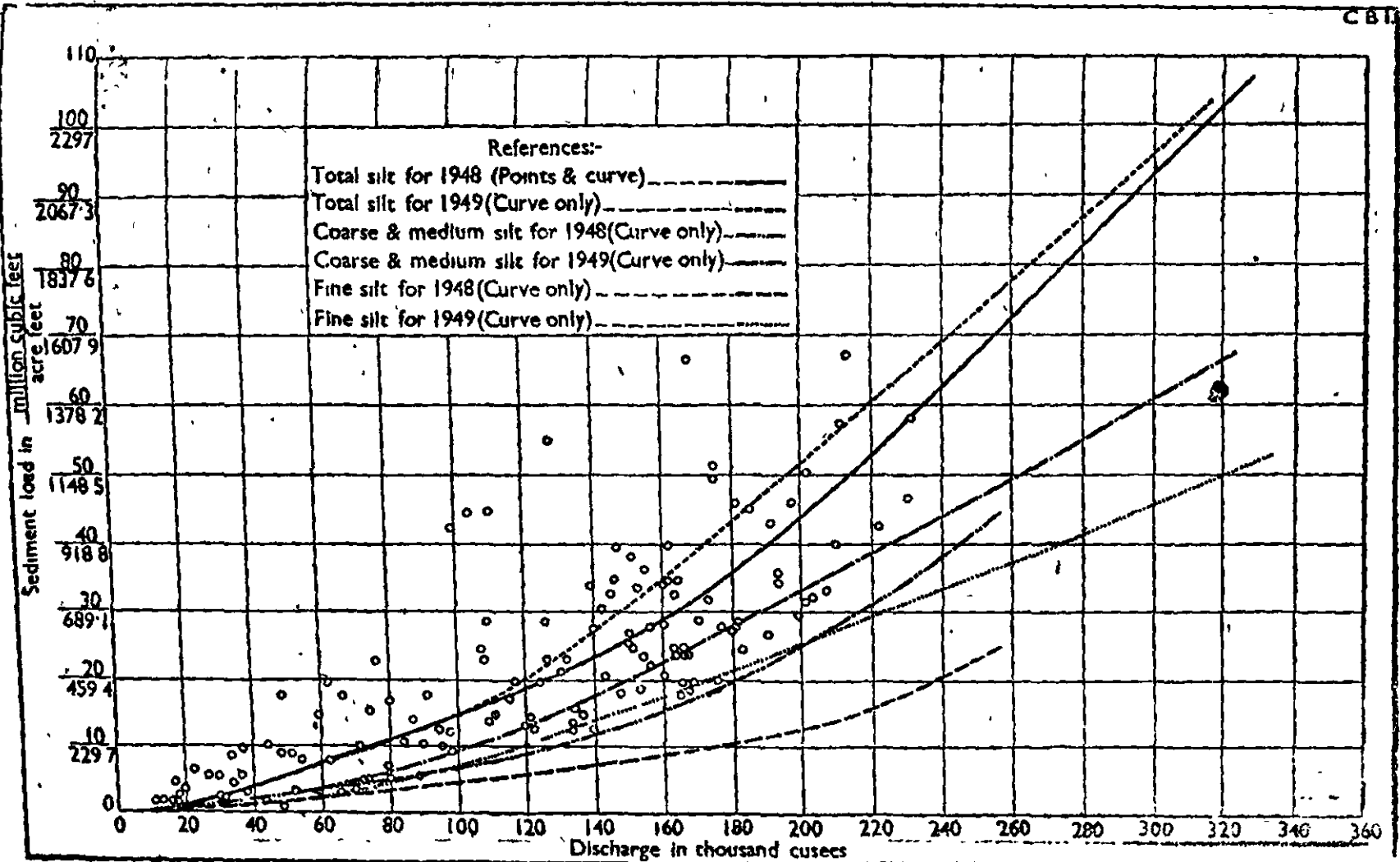


Figure 47 :- Silt load of the Sapt Kosi at Barakshetra—Discharge silt curves for 1948 and 1949

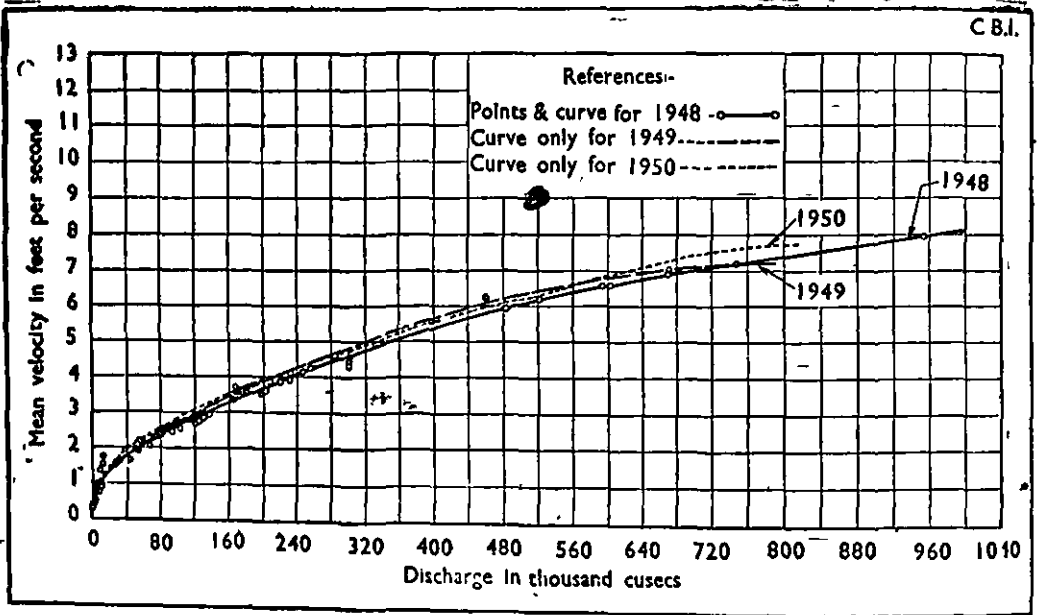


Figure 48 :—Discharge velocity curves for the Mahanadi River for the years 1948-1950.

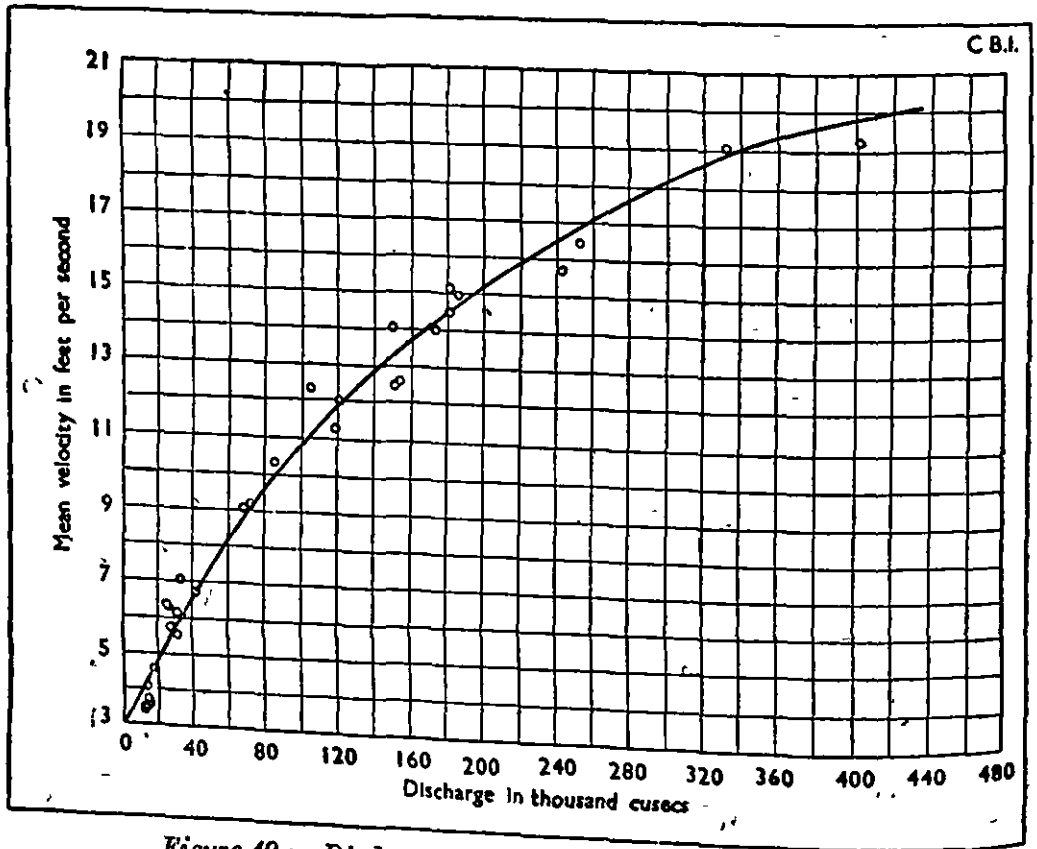


Figure 49 :—Discharge velocity curve for the Sapt Kosi River (1948)

and silts were, fairly constant throughout the depth along a vertical, the variation being almost entirely in the coarser grades. The experiments done in India have shown that the depth of mean silt point on the vertical increases with an increase in the average particle-size in suspension. It was therefore considered of interest to study the variations in different size grades of suspended load at varying depths along a sampling vertical.

Work has been carried on the aspect of silt load for a number of years in succession on the Mahanadi. During 1947, observations were taken at Sambalpur site on days when the river discharge varied from 64,525 to 638,179 cusecs and the river depth at the experimental verticals from 8 to 20 feet. Water samples were collected at $0.1, 0.2, 0.3, \dots, 0.9D$ along the vertical section of the stream. The results of coarse and medium sediment contents in cc. per litre of water were obtained and are diagrammatically presented in Figure 50. It is seen that, in general, the contents of those sediment fractions increased from surface downwards, the increase being more conspicuous in the case of coarse than the medium fraction. Moreover, the mean concentrations of those fractions correspond to the depths $0.45D$ to $0.66D$ (mean $0.55D$) for coarse and $0.4D$ to $0.7D$ (mean $0.58D$) for medium fractions respectively.

In 1948 that investigation was extended to other sites *viz.* Kaimundi (proposed Naraj Dam site) on the Mahanadi and Saplohara on the Ib, a tributary of the former. The experimental technique was the same as during the previous year. The results of the present investigations are diagrammatically represented in Figure 51 and the mean concentration points of the coarse and medium silts are also indicated. The general nature of the curves are similar to those reported in the above paragraph. The mean concentration points for the coarse and medium sediment fractions correspond to depths $0.44D$ to $0.61D$ (mean $0.53D$) and $0.4D$ to $0.63D$ (mean $0.52D$) respectively.

During 1949, besides the coarse and medium silt fractions it was considered of interest to study the variations in the fine silt fraction for which it is generally assumed for routine purposes that there is little variation along the vertical depth. The latter fraction in our routine estimation comprises particles below 0.075 mm. That fraction was divided into two sub-fractions *i.e.* particles ranging from 0.075 mm to 0.02 mm and those below 0.02 mm. That year's work thus related to four categories of silt particle-sizes, otherwise the technique was similar to that adopted during previous years.

The results are plotted in Figure 52. It is shown that :

- (i) The coarse and medium silt concentrations vary along the vertical depth of the stream and increases from surface downwards.
- (ii) The mean concentration point for the coarse and medium silt fractions in the majority of cases lie near $0.55D$ or $0.6D$, that of the former fraction being relatively at lower depth than for the latter.
- (iii) The two sub-fractions of fine silt do not manifest any marked variation from surface downwards.
- (iv) The variations in the discharge seem to affect silt concentrations at all points along the vertical, being low for lean and high for bigger discharges respectively.

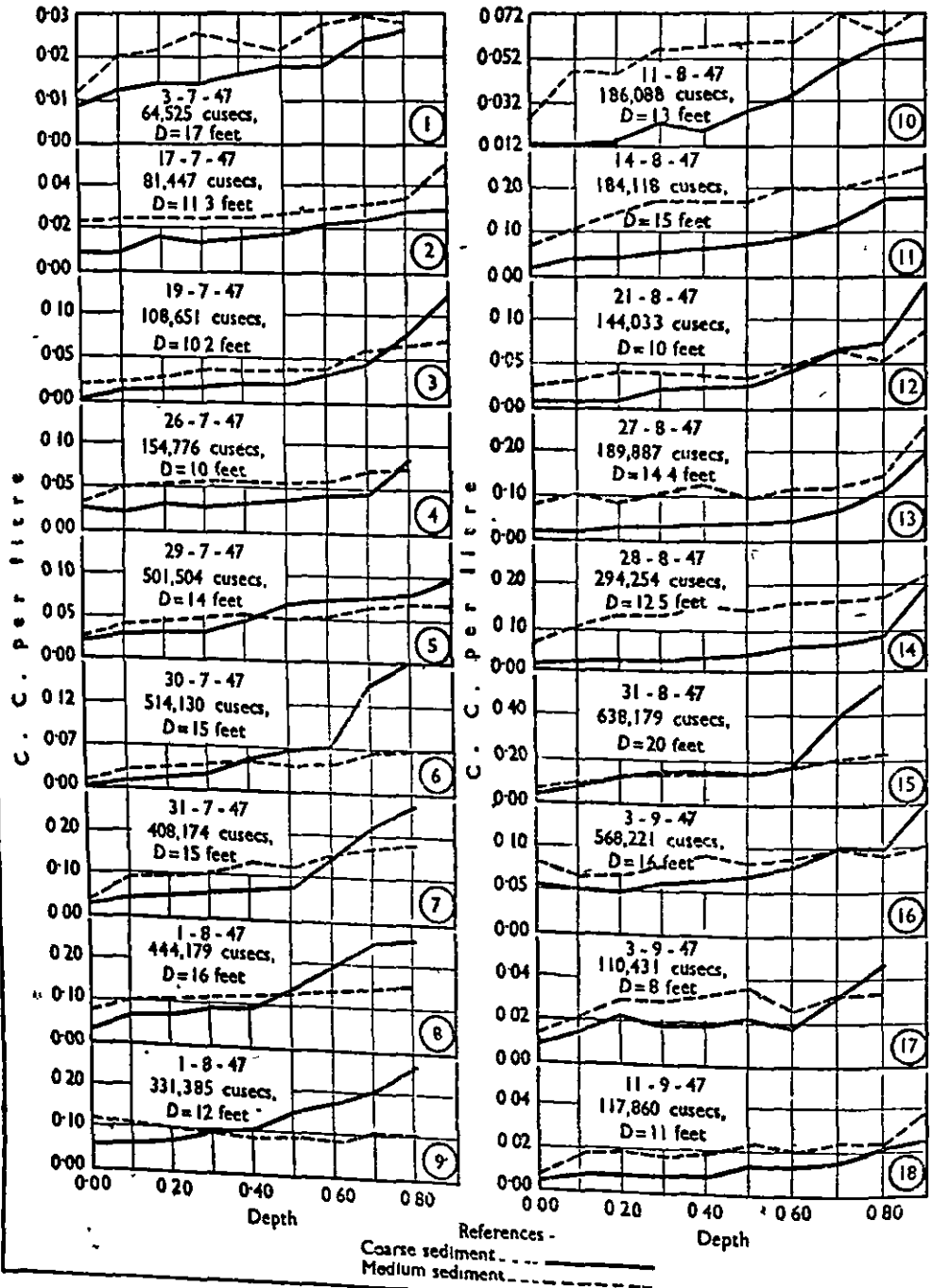


Figure 50:—(1-18) Showing the variations of the coarse and medium sediments (expressed in cc. per litre of water) along the vertical section of the Mahanadi River at Sambalpur (July-September 1947).

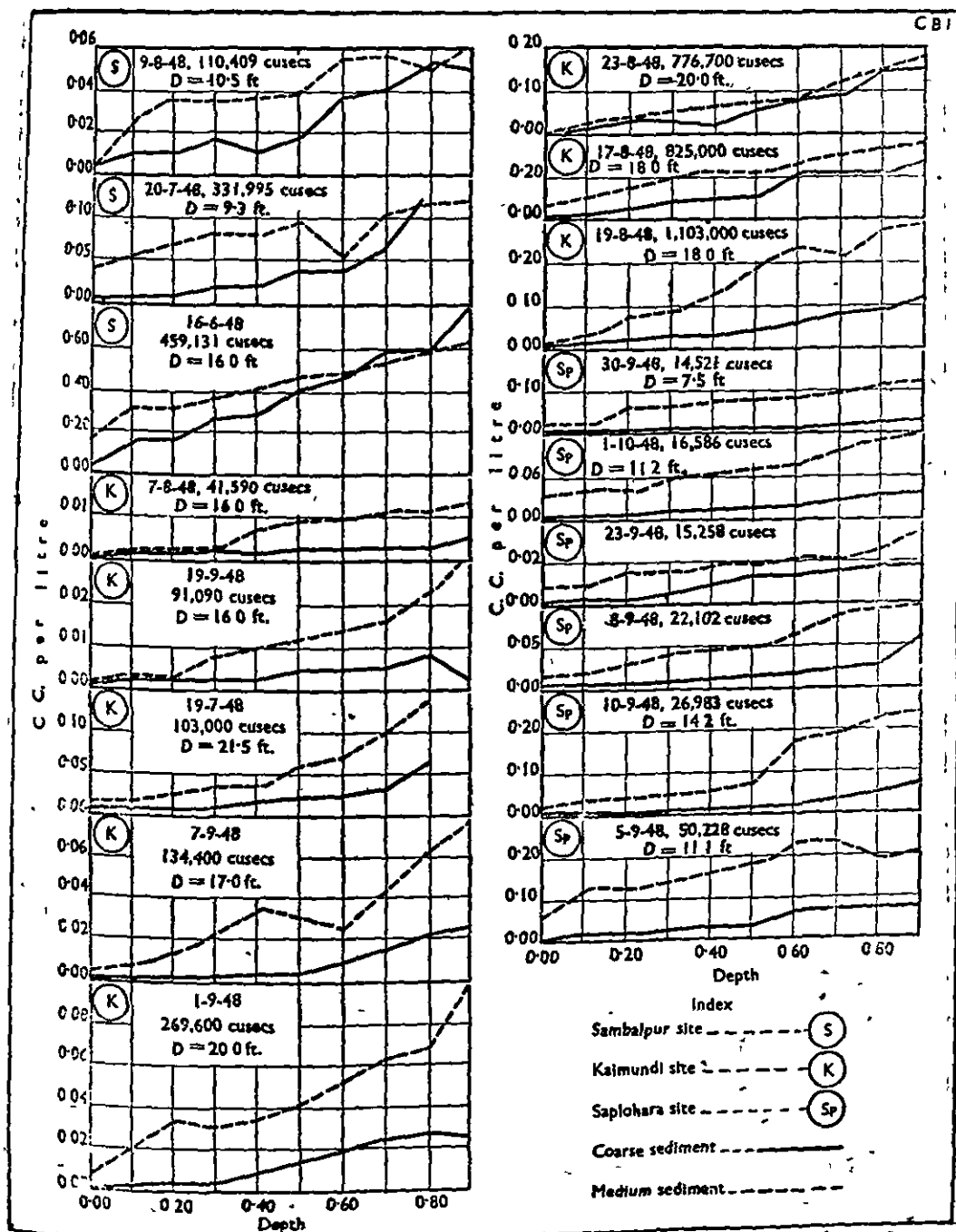


Figure 51:—Showing the variations of the coarse and medium sediments (expressed in cc. per litre of water) along the vertical section of the Mahanadi river (July-Sept. 1948)

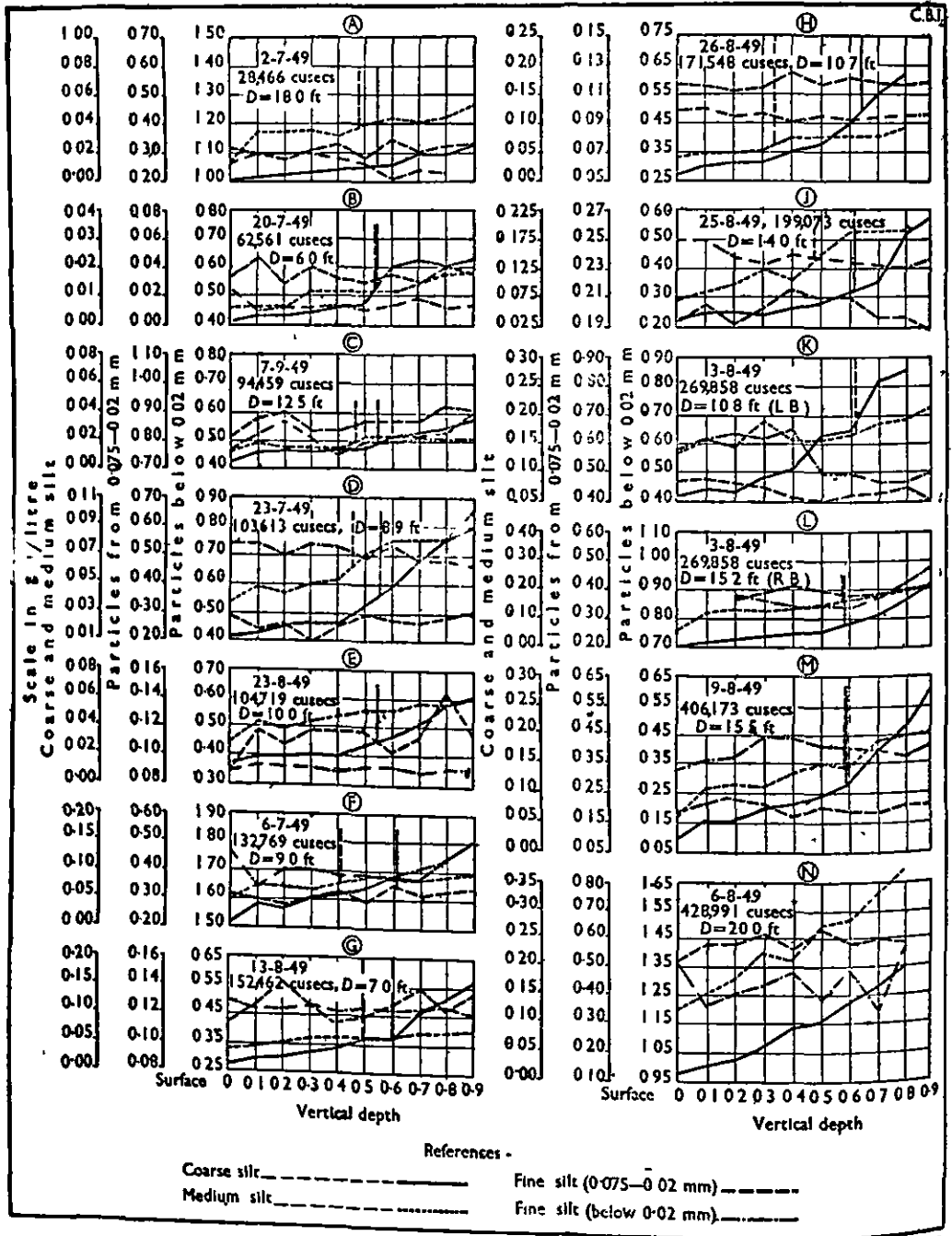


Figure 52 :—Curves showing the variation of different-sized grades of suspended silt at different depths along the vertical and at varying discharges of the Mahanadi River (Jul-Aug 1949).

Note :—Vertical lines marked on the curves for coarse and medium silts indicate the positions of average concentration of those silt sizes.

A comparison of the 'bucket' and 'bottle' sampling of water for stream

For daily estimation of the suspended load the essential requirements are the use of the right type of silt sampler and the selection of sampling site and sampling verticals to get the representative mean silt charge.

Experiments were conducted at Barakshetra on the Sapt Kosi to bring out a comparison of the silt load of water samples collected with the help of (i)-ordinary bucket and (ii) 1-litre capacity Punjab-type Bottle Sampler at a number of sampling verticals on the Sapt Kosi. The contents of the coarse and medium silt fractions in those Samples are presented in Table XXXV. The results are very interesting and bring out that :

(i) The results of coarse and medium silt contents in water samples collected by the bottle sampler fairly agree but those of samples collected by bucket tend to show wide variations.

(ii) The mean values of coarse silt content are invariably higher and those of medium silt content in a majority of cases in samples collected by the bottle method than the corresponding samples collected by bucket.

(iii) The silt charge in samples collected by bottle method along the cross-section at different verticals does not show so conspicuous variations as those collected by bucket.

(iv) The charge of coarse silt fraction in water samples collected from nearer the two banks of the river is relatively higher than those collected from verticals on the midstream. That also applies to some extent to the charge of medium silt fraction.

Experiments on similar lines were carried on the Tamur, tributary of the Sapt Kosi and the results agreed fairly with those obtained and reported for the latter. The differences in the behaviour of the samples collected by the bucket and bottle sampler are attributable to the fact that the bucket sampling being instantaneous sometimes catches the silt from eddies and at other times it does not whereas sampling with bottle, which consists in collecting four to five bottleful of sample at each site, tends to catch a sample which is much more representative of silt carried in suspension at the sampling vertical.

Variations in the nature of silt load in rivers during freshets

Certain variations in the nature of silt in suspension in the river waters at the time of successive freshets during the years may be expected. For instance there may be differences between silts coming along a winter freshet from that during the one in monsoon period. Such a study affords a progressive idea of the quality and grade of material which can be expected in the river or any of its tributaries during the year. Samples of water are, therefore, collected from the stream, in sufficient quantity to yield a cigarette tin-ful of dry silt, each time it swells due to an occurrence of a freshet. A systematic study is carried out with those bulk freshet silt samples of their particle-size distribution, fineness, wet density and void ratio characteristics and the results for samples collected from the Mahanadi and the Sapt Kosi and their tributaries are diagrammatically presented in Figures 53 to 58.

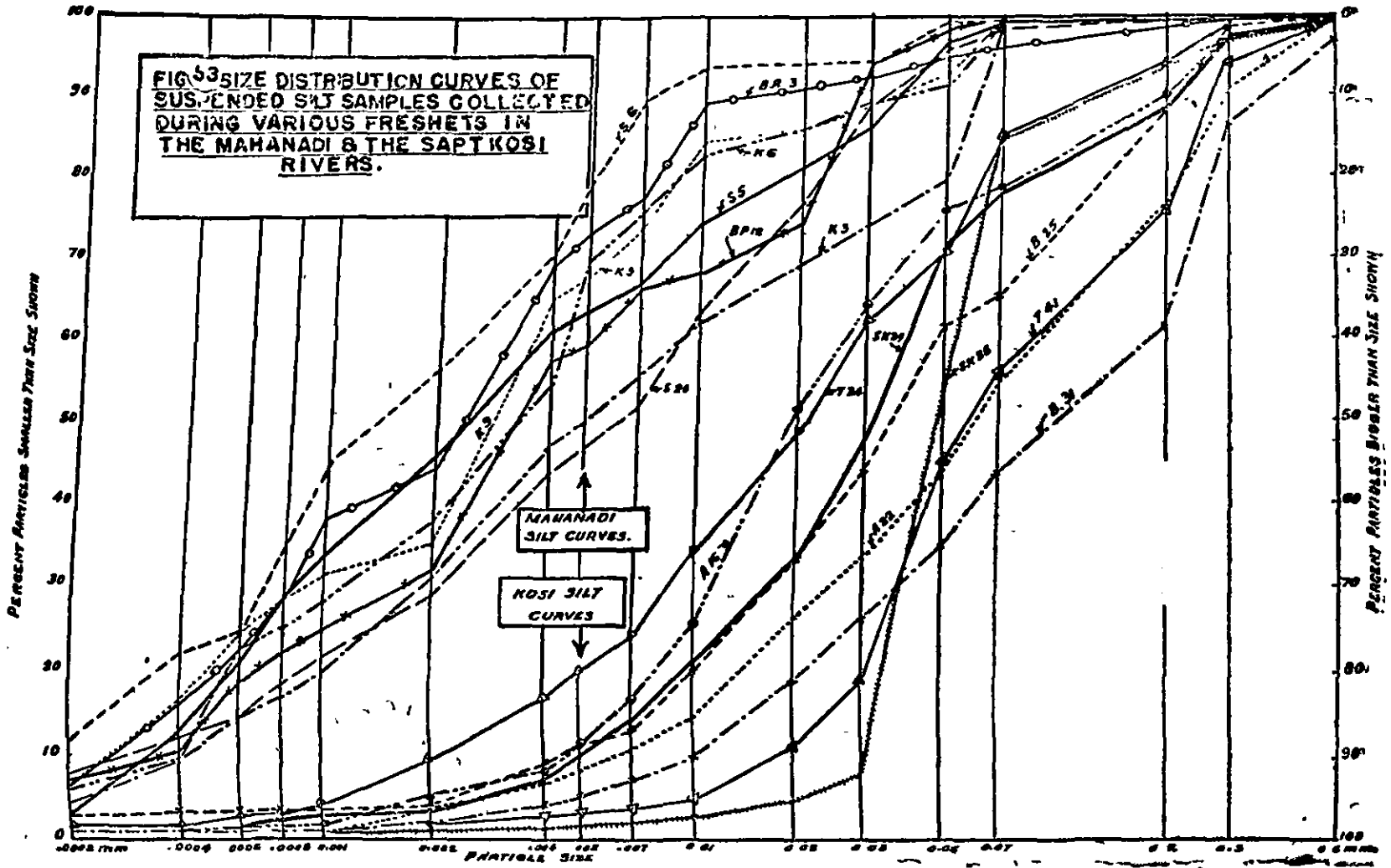


TABLE XXXV

TABLE XXXV

Date	Method of water sample collection	Course silt cc per litre								cc per litre	
		30'	60'	100'	140'	180'	220'	260'	280'	Total	Mean
11-7-50	Bucket Bottle	0.235	0.265	0.090	0.085	0.270	0.120	0.310	0.310	1.685	0.211
		0.370	0.190	0.210	0.175	0.135	0.160	0.210	0.375	1.925	0.228
12-7-50	Bucket Bottle	0.260	0.300	0.210	0.105	0.175	0.090	0.365	0.350	1.855	0.232
		0.370	0.290	0.150	0.200	0.220	0.180	0.275	0.425	2.110	0.264
13-7-50	Bucket Bottle	0.275	0.180	0.150	0.100	0.095	0.100	0.085	0.190	1.175	0.147
		0.280	0.225	0.100	0.150	0.155	0.135	0.140	0.225	1.410	0.176
15-7-50	Bucket Bottle	0.245	0.180	0.205	0.080	0.155	0.240	0.255	0.715	2.075	0.259
		0.325	0.200	0.195	0.195	0.210	0.295	0.415	0.560	2.395	0.299
16-7-50	Bucket Bottle	0.275	0.200	0.100	0.095	0.055	0.070	0.200	0.710	1.075	0.213
		0.275	0.235	0.135	0.160	0.200	0.220	0.375	0.570	2.170	0.271
17-7-50	Bucket Bottle	0.250	0.075	0.085	0.055	0.040	0.075	0.075	0.505	1.160	0.145
		0.295	0.190	0.150	0.130	0.150	0.165	0.245	0.470	1.795	0.244
18-7-50	Bucket Bottle	0.300	0.145	0.165	0.050	0.050	0.060	0.385	0.760	1.915	0.239
		0.310	0.150	0.135	0.210	0.185	0.225	0.215	0.565	1.995	0.249
19-7-50	Bucket Bottle	0.150	0.065	0.080	0.075	0.050	0.105	0.225	0.350	1.100	0.138
		0.270	0.200	0.185	0.175	0.120	0.215	0.340	0.520	2.025	0.258

20-7-50	Bucket Bottle	0-325	0 225	0-200	0-190	0-105	0-480	0-090	0-390	2-005	0-251
		0-225	0-155	0-155	0-160	0 145	0-180	0-230	0-470	1-720	0 215
21-7-50	Bucket Bottle	0-302	0-236	0 070	0 290	0-085	0-388	0-220	1-138	2-723	0 340
		0-405	0-325	0-270	0-280	0-265	0-380	0-455	0-590	2 970	0-371
22-7-50	Bucket Bottle	0-403	0-240	0 365	0-160	0 200	0 455	0-202	0-455	2-480	0-310
		0 435	0-505	0-220	0-180	0-255	0-265	0 265	0 410	2-535	0-317
23-7-50	Bucket Bottle	0-780	0-565	0 500	0-490	0-465	0-220	0-510	0-775	4-305	0-538
		0-675	0-450	0-500	0-495	0-475	0-745	0 705	0-555	4-600	0-575
24-7-50	Bucket Bottle	0-370	0 655	0-295	0-285	0-145	0-200	0-825	..	2-775	0-396
		0 540	0 525	0-495	0-340	0-280	0-515	0-475	..	3-170	0-453
25-7-50	Bucket Bottle	0-320	0-250	0-320	0-320	0 465	0-070	0-220	..	1-965	0-281
		0-450	0-310	0-290	0-300	0-320	0-575	0-425	..	2-670	0-381
26-7-50	Bucket Bottle	0-420	0 220	0-230	0-245	0-450	0 135	0-315	0-615	2-630	0-320
		0-345	0-290	0-285	0-240	0-325	0-305	0-400	0-580	2-770	0-346
27-7-50	Bucket Bottle	0-285	0-385	0-275	0-475	0-290	0-110	0-315	0-155	2-290	0-286
		0-390	0-300	0-290	0 255	0 315	0-355	0-260	0-675	2-840	0-355
15-7-50	Bottle	20'	40'	60'	80'	100'	120'	140'	}	4-720	0-327
		0-640	0 435	0-385	0-290	0-310	0-265	0-225			
		160'	180'	200'	220'	240'	260'	280'			
		0-265	0-195	0-315	0-250	0-260	0-365	0-520			

TABLE XXXV—contd.

Date	Method of water sample collection	Medium silt cc. per litre								cc. per litre	
		30'	60'	100'	140'	180'	220'	260'	280'	Total	Mean
11-7-50	Bucket Bottle	0.618	0.505	0.430	0.320	0.455	0.350	0.430	0.455	3.560	0.445
		0.560	0.440	0.425	0.320	0.395	0.305	0.350	0.420	3.215	0.402
12-7-50	Bucket Bottle	0.415	0.490	0.500	0.400	0.520	0.425	0.670	0.545	3.965	0.496
		0.530	0.465	0.390	0.435	0.390	0.440	0.525	0.580	3.755	0.469
13-7-50	Bucket Bottle	0.465	0.445	0.515	0.480	0.285	0.390	0.315	0.480	3.375	0.422
		0.450	0.325	0.500	0.395	0.425	0.345	0.345	0.500	3.285	0.411
15-7-50	Bucket Bottle	0.495	0.530	0.575	0.415	0.380	0.425	0.500	0.995	4.315	0.539
		0.615	0.500	0.495	0.500	0.525	0.535	0.650	0.705	4.525	0.566
16-7-50	Bucket Bottle	0.550	0.500	0.410	0.455	0.195	0.476	0.525	0.935	4.045	0.506
		0.545	0.500	0.500	0.500	0.525	0.440	0.545	0.730	4.285	0.536
17-7-50	Bucket Bottle	0.570	0.305	0.340	0.355	0.165	0.545	0.430	0.680	3.390	0.424
		0.625	0.550	0.525	0.545	0.530	0.525	0.630	0.680	4.620	0.578
18-7-50	Bucket Bottle	0.580	0.440	0.460	0.240	0.220	0.355	0.665	0.725	3.685	0.461
		0.775	0.550	0.555	0.510	0.530	0.545	0.600	0.680	4.725	0.591
19-7-50	Bucket Bottle	0.450	0.370	0.350	0.325	0.220	0.265	0.670	0.780	3.430	0.429
		0.530	0.430	0.410	0.390	0.330	0.525	0.425	0.650	3.690	0.461

MSOBREP

20-7-50	Bucket Bottle	0-700 0-675	0-545 0-665	0-470 0-582	0-450 0-553	0-345 0-592	0-940 0-630	0-500 0-778	0-630 0-905	4-580 5-380	0-573 0-673
21-7-50	Bucket Bottle	0-528 0-580	0-565 0-533	0-307 0-532	0-570 0-475	0-330 0-495	0-635 0-563	0-575 0-695	0-930 0-720	4-440 4-593	0-555 0-579
22-7-50	Bucket Bottle	0-775 0-675	0-675 ..	0-960 0-755	0-845 0-665	0-650 0-650	0-925 0-728	0-820 0-705	0-945 0-815	6-595 4-993	0-824 0-713
23-7-50	Bucket Bottle	1-020 1-020	0-955 0-845	0-975 0-930	1-030 0-935	0-890 0-850	0-835 0-955	1-205 1-155	1-150 1-150	8-060 7-840	1-005 0-980
24-7-50	Bucket Bottle	0-930 1-070	0-925 0-850	1-030 0-780	1-020 0-690	0-745 0-585	1-090 1-280	1-450 0-900	.. ..	7-190 6-155	1-027 0-879
25-7-50	Bucket Bottle	0-695 0-825	0-650 0-685	0-765 0-715	0-780 0-695	0-850 0-725	0-450 0-795	0-725 0-695	.. ..	4-915 5-135	0-702 0-734
26-7-50	Bucket Bottle	0-535 0-575	0-500 0-515	0-490 0-535	0-500 0-405	0-515 0-510	0-520 0-690	0-580 0-605	0-785 0-655	4-425 4-490	0-553 0-561
27-7-50	Bucket Bottle	0-625 0-630	0-800 0-545	0-695 0-600	0-615 0-540	0-560 0-625	0-460 0-740	0-805 0-625	0-625 1-170	5-185 5-475	0-648 0-684
15-7-50	Bottle	20' 0-945	40' 0-935	60' 0-900	80' 0-685	100' 0-710	120' 0-665	140' 0-665	}	10-550	0-754
		160' 0-725	180' 0-746	200' 0-620	220' 0-635	240' 0-725	260' 0-790	280' 0-860			

(a) *Particle-size distribution*

Mechanical analysis of silt samples for particle sizes ranging from ultra-fine size of 0.0002 mm to 0.6 mm, was done by employing a micro-pipette for pipetting out aliquot fractions of silt suspensions for particle sizes below 0.001 mm. The particle size distribution curves of a few typical samples representing the Mahanadi and the Sapt Kosi river systems are given in Figure 53 which bring out very clearly that the Mahanadi silts contain a much higher proportion of finer particle sizes as compared to the Sapt Kosi silts.

(b) *Fineness*

In order to obtain a single value characterization of silts from those two river systems in terms of fineness, the specific surface values of these silt samples were determined with the help of the Blaine's air permeability apparatus.

The determination of fineness required a pre-treatment to affect the breaking up of the aggregates of silt particles, formed during the separation and subsequent drying of silt from waters, to a fineness corresponding to that in wet state of suspension in water at the time of collection.

A series of trials were made with a view to evolve a suitable technique for dispersing dry silt samples as given below :

- (i) dispersing with denatured alcohol and removing alcohol by burning ;
- (ii) wet grinding with denatured alcohol and removing alcohol by burning ;
- (iii) as (ii) but removing the alcohol by evaporating it to dryness ;
- (iv) wet churning the suspension of silt in alcohol by means of a high speed cylindrical brush stirrer of the type used for Wagner's Turbidimeter equipment followed by removal of alcohol by evaporating to dryness.

It was found that pre-treatment of dry silt samples according to method (iv) described above resulted in breaking up of aggregates in these dry silt samples to the required limit of their fineness and ensured reproducible results of specific surface. Moreover a single treatment was enough for the purpose as shown from the comparative results of fineness of samples treated by those four methods given in Table XXXVI.

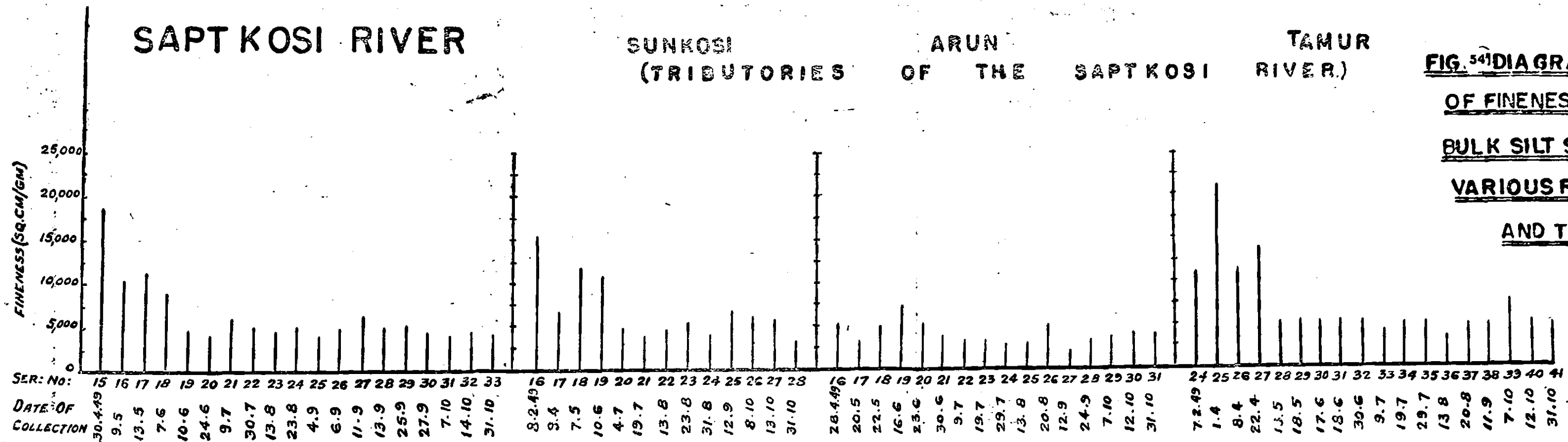
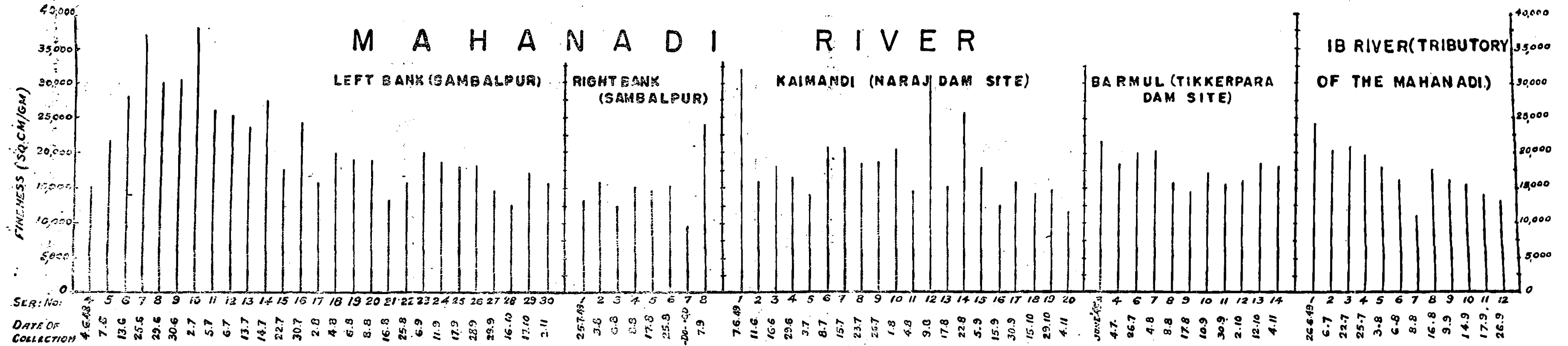


FIG. 541 DIAGRAMATIC REPRESENTATION OF FINENESS (SQ. CM/GM. BLAINE) OF THE BULK SILT SAMPLES COLLECTED DURING VARIOUS FRESHETS IN THE MAHANADI AND THE KOSI RIVER SYSTEMS.

TABLE XXXVI.

Showing comparison of values of specific surface of bulk silts after subjection to different treatments

Silt No.	Operation	Fineness sq cm/gm				
		Untreat- ed	(i) Bur- ning with- out grind- ing	(ii) Bur- ning and grinding	(iii) Grind- ing and evapora- ting	(iv) Chur- ning and evapora- ting
1	2	3	4	5	6	7
Saplohara 1 ..	1	3,221	3,294	16,010	16,820	25,510
	2	..	..	18,250	18,450	26,320
	3	..	..	19,450	19,900	..
Saplohara 2 ..	1	2,500	2,660	10,020	12,210	22,260
	2	..	..	14,030	14,320	21,930
	3	..	..	15,100	15,510	..
Saplohara 8 ..	1	2,942	3,147	7,537	7,521	12,680
	2	..	..	7,678	8,690	13,030
	3	..	..	8,358	9,090	..
Saplohara 10 ..	1	3,808	4,004	6,939	7,920	13,040
	2	..	..	7,889	8,268	13,290
	3	..	..	7,889	8,450	..
Barmul 3 ..	1	3,584	4,177	7,593	11,190	20,600
	2	..	..	12,130	13,490	22,250
	3	..	..	13,450	14,140	..
Barakshetra 2 ..	1	4,769	4,757	5,184	5,376	6,151
	2	..	..	5,374	5,578	6,142
	3	..	..	5,395	5,601	..
Arun 4 ..	1	2,747	2,738	3,477	3,730	3,869
	2	..	..	3,684	3,885	3,854
	3	..	..	3,684	3,884	..

The figures of specific surface (sq. cm/gm) for a number of silt samples are diagrammatically presented in Figure 54. On the basis of this characteristic it is shown that, firstly, the Mahanadi silts are considerably finer than those of Kosi and, secondly, the silts carried in suspension during earlier freshets in these rivers are relatively finer than those representing subsequent freshets. This study thus serves to confirm the conclusion drawn earlier on the basis of the results of the ultramechanical analysis of those sets of silt samples.

FIG. 55 RELATIONSHIP BETWEEN SPECIFIC SURFACE AND MEAN DIAMETER OF SUSPENDED SILT SAMPLES COLLECTED DURING VARIOUS FRESHETS IN THE MAHANADI AND THE SAPTKOSI RIVERS

NOTE: MEAN DIAMETER HAS BEEN DETERMINED FOR THE PARTICLE SIZES RANGING FROM 0.0002 M.M. TO 0.075 M.M.

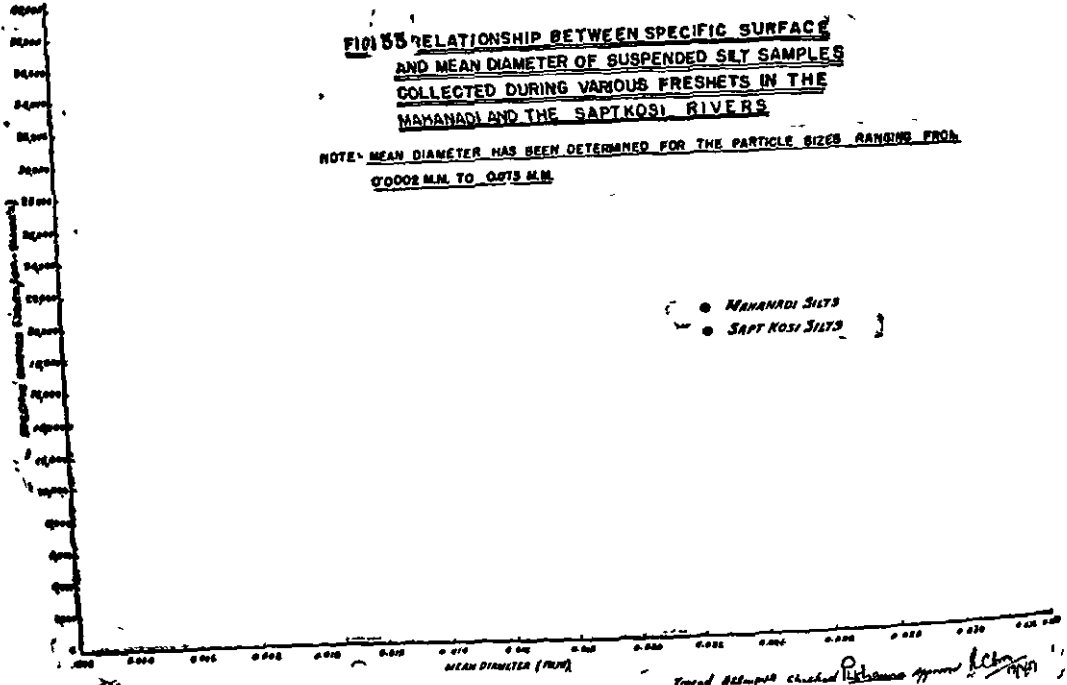
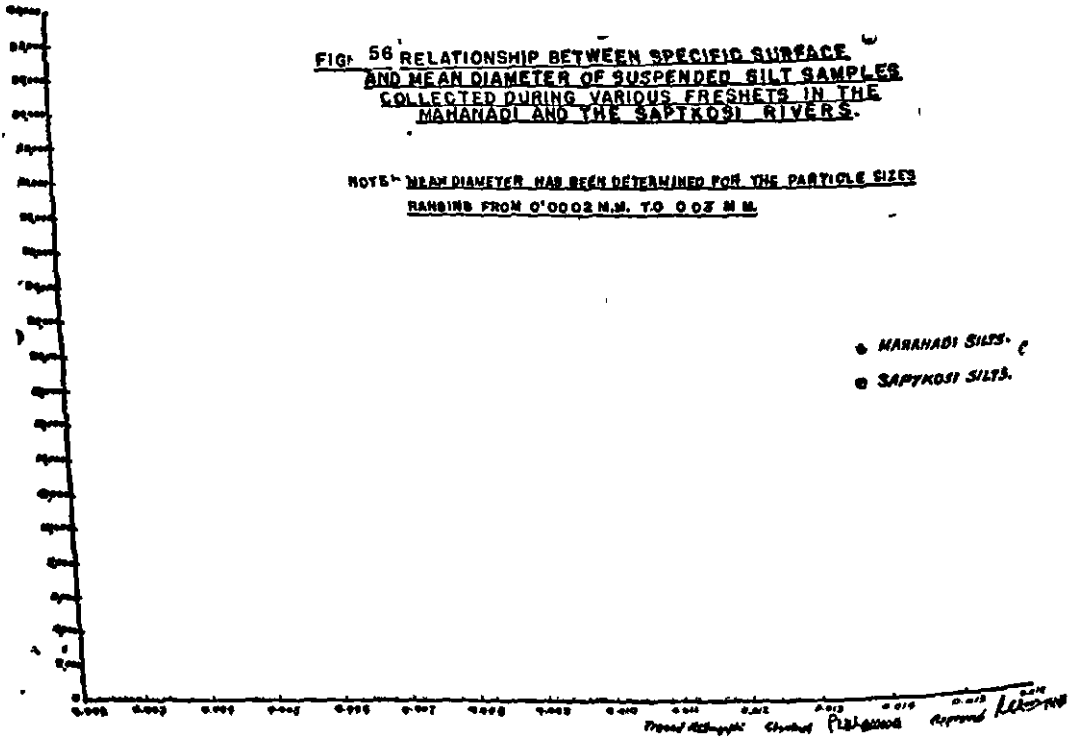


FIG. 56 RELATIONSHIP BETWEEN SPECIFIC SURFACE AND MEAN DIAMETER OF SUSPENDED SILT SAMPLES COLLECTED DURING VARIOUS FRESHETS IN THE MAHANADI AND THE SAPTKOSI RIVERS.

NOTE: MEAN DIAMETER HAS BEEN DETERMINED FOR THE PARTICLE SIZES RANGING FROM 0.0002 M.M. TO 0.075 M.M.



(c) *Mean diameter of particle sizes of silt samples*

From the particle-size distribution curves of silt samples from the two river systems, the mean diameter size of each sample has been worked out statistically. Two alternative ranges of sizes of silt particles have been considered for computations in that connection, i.e., 0.0002 mm to 0.075 mm and 0.0002 mm to 0.03 mm respectively. A plot of the mean diameters of silts on the basis of either of those particle-size ranges against their respective specific surface values are presented in Figures 55 and 56.

An attempt has been made to obtain a statistical correlation between the fineness characteristics of silts, as defined in terms of specific surface, which can be determined relatively quite quickly, and their respective mean diameters as it shall be very helpful to arrive at the latter value on the basis of the experimental results of specific surface. The correlation obtained are given below :

Range of particle sizes	Correlation Coefficient	Linear relationship
0.0002 mm to 0.03 mm	-0.713	$y \times 10^{-3} = -1361x_1 + 25.35$
0.0002 mm to 0.075 mm	-0.854	$y \times 10^{-3} = -872.1x_2 + 27.38$

where y is specific surface value in sq. cm/gm and x_1 and x_2 are the mean diameters for the two ranges of particle sizes respectively. It is seen that the correlation co-efficient for the range 0.0002 mm to 0.075 mm is relatively better than for the other range. The difference between the two correlations is, however, not statistically significant for 53 observations taken for purposes of this study.

(d) *Fineness of silts in relation to sieve analysis*

This study was made to examine the possibilities of obtaining an idea of the value of specific surface from sieve analysis at places not equipped with requisite apparatus to carry out the test for fineness. Figure 57 presents the relation between the value of specific surface for silt samples and the percentage of particle size retained on B.S.S. sieve No. 325 (0.043 mm mesh). This relationship has been obtained for freshet silts from both the rivers, the finer ones from the Mahanadi and the coarser ones from the Sapt Kosi respectively. It is thus shown that a rough approximation is possible that way.

(e) *Wet density and void ratio*

A study was made on laboratory scale with the various freshet samples to obtain a relationship of the fineness with wet density and void ratio. The results of that study given in Figure 58 indicates that the wet density decreases and void ratio increases with an increase in the fineness of silt. Beyond a certain degree of fineness of say 10,000 sq. cm/gm any further increase in fineness seems to have little effect on the wet density and void ratio.

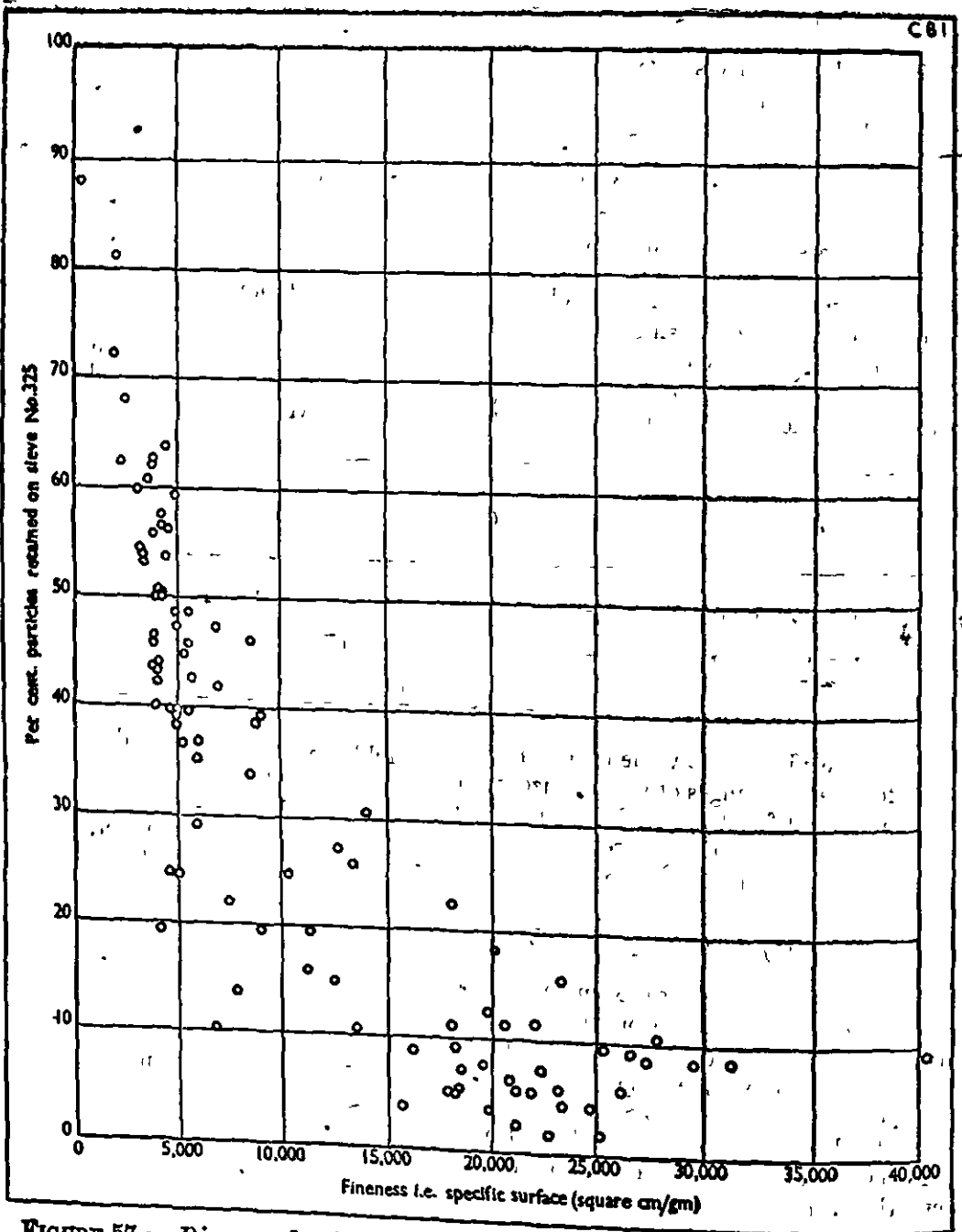


FIGURE 57 :—Diagram showing the relationship between the specific surface and percentage fraction retained on Sieve No. 325 of the suspended silts of the Mahanadi and the Sapt Kosi Rivers.

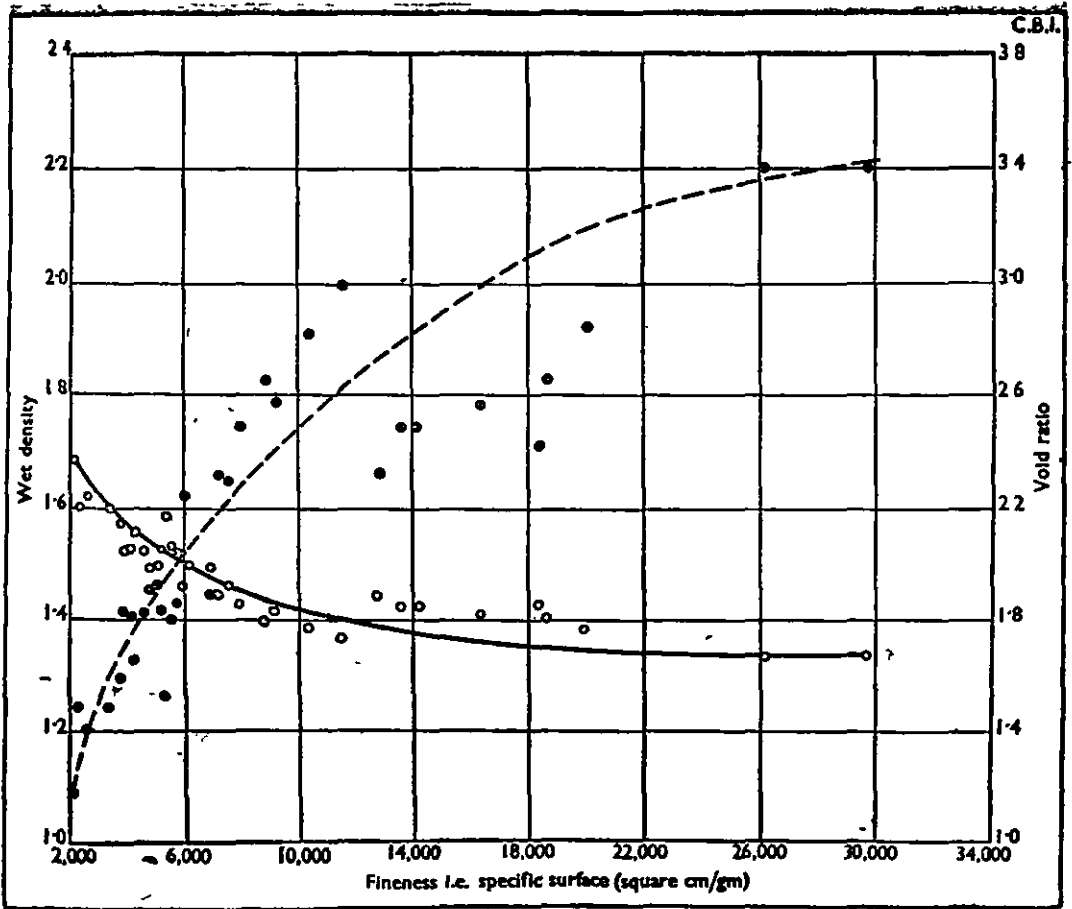


FIGURE 58 :—Curves showing the relationships of wet density, void ratio and fineness of suspended silts of the Mahanadi and the Sapt Kosi Rivers.

CHAPTER 4

Silt Studies of Some Existing Reservoirs in Other Countries

GENERAL

This section deals with the silting of some existing foreign reservoirs. Information regarding silting and connected data has been collected from published literature, office files and other notes and has been compiled in the form of a statement in Table XXXVII.

This statement deals with most of the important foreign reservoirs in the world but is by no means complete. It is presented in the hope that its circulation may help to stimulate interest in the problem and thus bring to light much useful information which may be available at the many reservoirs in India and abroad. As mentioned before, the data collected from the existing Indian reservoirs is given in Chapters 2 and 3.

The statement has been arranged in the order of areas of the catchment basins. These areas are given in column (5). The rates of silting per year per 100 square miles of catchment are given in column (20).

Some details of individual reservoirs have been given, in the order in which they occur in Table XXXVII.

For the sake of comparison the hydrological data for the Yellow River in China has also been included ⁽²⁸⁾.

TABLE
Siting of

Serial No.	Reservoir			Catchment area (square miles)	Height of dam (feet)	Storage Capacity			Mean annual rainfall (inches)	Mean annual run-off (foot-acres)
	Country	River	Name			Foot-acres	Percentage of annual run-off	Foot-acres per square mile of catchment		
1	2	3	4	5	6	7	8	9	10	11
1	Egypt	Nile ..	Aswan ..	620,000	174	4,400,000	6.7	7.1	..	66,000,000
2	U.S.A.	Colorado (Arizona)	Boulder dam	167,000	726.4	30,500,000	203	183	5-10	15,000,000
3	U.S.A.	Mississippi ..	Keokuk ..	119,000	32	370,000	0.80	3.1	32	46,000,000
4	U.S.A.	Columbia ..	Grand Coulee	74,000	550	9,645,000	12.5	136	..	80,000,000
5	U.S.A.	Colorado ..	New Lake Austin	38,200	65	37,000	1.75	0.80	21	1,827,000
6	U.S.A.	-do- (Texas)	Old Lake Austin	38,200	60	49,300	2.46	1.37	21	2,000,000
7	U.S.A.	Rio Grande	Elephant Butte	26,312	306	2,638,860	264	100	10-25	1,000,000
8	U.S.A.	Pecos ..	Lake McMillan	22,000	52	90,000	30	4.0	..	300,000
9	U.S.A.	Tennessee	Hales Bar ..	21,800	..	156,000	0.57	7.2	..	27,000,000
10	U.S.A.	Mississippi...	Coon Rapids ..	19,000	..	8,000	0.20	0.40	..	4,400,000
11	U.S.A.	North Platt	Gurnsey ..	16,200	105	72,000	4.4	4.4	..	1,650,000
12	U.S.A.	San Carlos ..	San Carlos ..	13,540	203	1,248,000	..	92	10-15	..
13	U.S.A.	Coosa ..	Lay Reservoir	9,087	77	156,525	..	17.23	54	..
14	U.S.A.	Rock ..	Sterling Pool ..	8,760	..	13,700	0.4	1.56	..	3,500,000
15	U.S.A.	Big Horn ..	Boysen ..	7,740	44	16,000	1.06	2.07	13.5	1,500,000
16	U.S.A.	Salt ..	Roosevelt ..	5,760	284	1,522,200	181	264	8-35	140,000
17	U.S.A.	Iran ..	Fall ..	5,140	..	..	..	..	..	..
18	Australia	Murrumbidgee	Burrinjuck ..	5,000	200	772,000	67	154	..	1,150,000
19	Africa	Sunays	Lake Mentz ..	4,823	..	94,619	82	19.7	12	146,000
20	..	Im ..	Fettenbach ..	4,730	..	..	..	..	..	9,090,000

XXXVII

Reservoirs

Run-off per square mile of catchment (foot-crcs)	Years of capacity surveys			Silt deposited					Remarks	Reference to bibliography on page 194.
	First	Last	Period in years	Total (foot-acres)	Annus (foot-acres)	Percentage of original capacity per annum	Per thousand of water supply by volume	Per 100 square miles of catchment per annum		
12	13	14	15	16	17	18	19	20	21	22
107	1900	1927	25							(29), (27) and (35)
90	Estimated			137,000				82	*Accepted in final designs	(25), (10), (31), (29), (10) and (9)
				60,000				36*		
386	1913	1928	15	112,000	7,460	2 0	0-18	6-3	..	(10) and (29)
1,081	..	..	..	..	..	..	..	..	..	(31)
48	1913	1926	13	30,620	2,355	7 3	1-28	6 2	..	(12) (10) and (29)
52	1893	1900	6 75	23,600	3,600	7 1	1-75	9	..	(12) and (29)
38	1916	1940	25 75	415,786	16,147	0 61	1-62	61	Erratic and violent rain- fall. Rio Grande carries the largest silt burden of any major stream in the South West.	(10) (29) and (9)
14	1893	1932	38 4	46,400	1,208	1 34	4-03	5-5	Accidental Tamarak growth reduces silting.	(10) (29) and (9) (29)
1,237	1913	1930	16 92	45,500	2,690	1-73	0-10	12	..	(29)
232	1909	1931	32	1,380	43	0 54	0-01	0-22	..	(29)
102	1927	1933	5 9	8,400	1,430	1-98	0-85	9	..	(29)
..	1928	1935	6-33	36,896	5,829	0-47	..	43	Severe over grazing	(9)
..	1913	1936	22 3	18,005	807-4	0-52	..	8 9	..	(1)
400	1912	1930	18	2,010	111	0-82	0-032	1	..	(29)
194	1911	1924	13	13,000	1,000	6 25	0-66	13	..	(29)
..	1911	1938	27	123,770	4,584	0-30	5-46	79 6	Catchment consists of highly erodible soils. Over grazing under arid conditions.	(10) (29) (9) & (31)
..	..	..	6-5	2,420	373	..	..	17-3	..	(29)
230	1910	1924	14	3,070	285	0-037	0-28	6	..	(29)
..	1-1-23	31-5-35	12-4	34,466	2,780	2-9	19-0	57	Soft Geological formation, steep slopes, poor vege- tal covering, small violent and irregular rainfall, intense sheep farming.	(20) (30),
1,922	..	..	6	1,750	292	..	0-30	6-2	..	(29)

TABLE

Silting of

Serial No.	Reservoir			Catchment area (square miles)	Height of dam (feet)	Storage capacity			Mean annual rainfall (inches)	Mean annual run-off (foot-acres)
	Country	River	Name			Foot-acres	Percentage of annual run-off	Foot-acres per square mile of catchment		
1	2	3	4	5	6	7	8	9	10	11
21	U.S.A.	..	Lake Taneycemo	4,610	..	43,980	..	9-54	..	..
22	U.S.A.	Yadkin ..	High Rock	3,930	60	289,432	..	73 65-	47 78	..
23	..	Phone ..	Genfer-See	2,800	..	72,100,000	..	25,200	..	..
24	U.S.A.	Pavette ..	Black Canyon	2,540	184	37,659	..	14 83	11-26	2,235,000
25	..	Mur ..	Pornogg	2,420	..	4,000	..	1-65	..	..
26	..	Rhine ..	Bodensee	2,360	..	..	..	..	..	776,000
27	Africa	Fish ..	Lake Arthur	2,270	..	63,630	81	28	13-8	79,000
28	U.S.A.	Clear Ek. Brazos.	Lake Penick	2,250	40	3,090	2-70	1-40	..	111,000
29	U.S.A.	W. Br. Trinity	Lake Worth	1,870	36	47,200	22 2	25	31	212,000
30	U.S.A.	Bosque ..	Lake Waco	1,662	..	39,378	..	23	25	..
31	U.S.A.	Little Tennessee.	Cheoha	1,620	230	41,600	1-38	26	..	3,030,000
32	Africa	Fish ..	Grass Ridge	1,583	..	64,500	143	41	14	42,000
33	U.S.A.	Toulumne ..	La Grange	1,500	..	2,330	0-12	1 6	..	1,970,000
34	Africa ..	Sundays ..	Van-Ryneveld	1,477	113	65,967	200	45	14	33,000
35	U.S.A.	Ocmulgee ..	Lloyds Shoals	1,375	100	112,538	..	82	50	..
36	..	Sif ..	St. Denis	1,350	..	2,800	..	2-07	..	..
37	U.S.A.	..	New River	1,320	..	13,255	..	10 04	..	..
38	U.S.A.	Umatilla ...	Furnish	1,200	..	5,500	1-16	4-6	..	485,000
39	..	Meckerra ..	Cheerfas	1,160	..	10,100	41-7	8-7	..	23,306
40	Italy ..	..	Pescara-3° snito	1,008	..	..	..	..	..	..
41	U.S.A.	Scioto ..	O'Shaughnessy	988	84	16,673	..	16-9	..	..
42	U.S.A.	..	Lake Decatur..	908	..	19,738	..	21-79	..	..
43	..	..	Puentes	800	156	21,500	..	27	13	..
44	..	Irac ..	Avignounette	772	..	800	0-09	1 04	..	890,000
45	..	Verdan ..	Quinson	695	..	1,100	..	1-58

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Reservoirs

Run-off per square mile of catchment (foot-acres)	Years of capacity surveys			Silt deposited					Remarks	Reference to bibliography on page 194
	First	Last	Period in years	Total (foot-acres)	Annual (foot-acres)	Percentage of original capacity per annum	Per thousand of water supply by volume	Foot-acres per 100 square miles of catchment per annum		
12	13	14	15	16	17	18	19	20	21	22
..	..	..	22-4	20,266	904.73	2.06	..	19.6	..	(1)
..	1927	1935	7.8	13,916	1,784.1	0.62	..	45.7	..	(1)
..	..	..	..	..	2,400	..	..	84	..	(29)
813	1924	1936	12	4,037	336.4	0.89	0.15	13.2	..	..
..	..	..	1.5	284	203	5.1	..	8.4	..	(29)
329	..	..	20	8,010	400	..	0.51	17	..	(29)
..	1-4-25	30-4-35	10.1	26,200	2,600	4.1	33	115	Same as No. 19 above	(30)
49	1920	1927	7	965	138	4.6	1.25	6	..	(29) and (9)
113	1915	1928	13.0	13,837	1,064	2.3	5.0	57	..	(12) (29) & (9)
..	1930	1935	5	7,790	953	3.34	..	57	..	(9)
1,870	1918	1930	11.83	4,350	387	0.88	0.12	23	..	(29)
27	1-1-30	1935	11.3	15,601	1,380	2.20	32.9	87	Same as No. 19 above	(30)
1,313	1895	1931	36	12,940	54	2.3	0.028	4	..	(29)
22	1-1-25	1935	10.3	9,897	941	1.44	28.5	04	Same as No. 19 above	(29) and (30)
..	1-2-10	1935	24.33	13,960	574	0.51	..	42	..	(9)
..	..	..	8	608	76	2.7	..	5.6	..	(29)
..	..	..	33.5	8,155	243.43	1.84	..	18.5	..	(1)
404	1909	1931	22	4,500	204	3.73	0.44	17	..	(29)
20	..	..	50	4,950	99	0.98	4.25	9.0	..	(29)
..	..	..	..	..	352.1	..	..	35.0	..	(3)
..	1925	1934	9.0	1,016	112.9	0.68	..	11.4	..	(1)
..	..	..	14.2	2,808	197.75	1.0	..	21.9	..	(1)
..	..	..	..	..	510	2.38	..	64	..	..
1,163	..	..	8	810	101	12.6	0.11	13	..	(29)
..	..	..	5	730	146	13	..	21	..	(29)

TABLE

Siting of

Serial No.	Reservoir			Catchment area (square miles)	Height of dam (feet)	Storage capacity			Mean annual rainfall (inches)	Mean annual run-off (foot-acres)
	Country	River	Name			Foot-acres	Percentage of annual run-off	Foot-acres per square mile of catchment		
1	2	3	4	5	6	7	8	9	10	11
46	U.S.A.	Zuni ..	Zuni ..	650	80	15,811	91	25.3	13	17,400
47	Pakistan		Khushdil Khan reservoir.	608	66	26,997	16.33	44.4	8.91	
48	U.S.A.	Ocoee ..	Parksville ..	600	125	97,000	10.2	162	55	950,000
49	U.S.A.	Medina ..	Medina ..	537	164	318,703		542.94	29	
50	..	Lech ..	Rosshaupten ..	550						1,580,000
51	..	Aare ..	Bieler See ..	532		1,010,000	58.6	1,910		1,710,000
52	..	Aare ..	Kalnach ..	525		1,500		2.86		
53	..	Sarina ..	Perolles ..	487		800		1.61		
54	..	Kander ..	Thunorsee ..	414		5,270,000	531	12,710		994,000
55	U.S.A.	..	Lake Spavnav	400		31,686		79.22		
56	..	Tiroler Ache	Chem See ..	392		1,790,000	164	4,570		1,080,000
57	..	Saalache ..	Saalache ..	386		2,800	0.28	7.25		1,010,000
58	..	Avisia ..	Avisia ..	369		1,600		4.35		
59	..	..	Djrdovia ..	328		1,600		4.87		
60	..	Bregenzer	Bodensee ..	321		39,400,000	5,070	123,000		776,000
61	..	Reuss ..	Vierwald ..	321		9,560,000	1,570	29,800		608,000
62	..	Ghun Powder	Loch Raven ..	306		1,600	0.52	5.23		300,000
63	U.S.A.	San Dieguito	Hodges ..	303	130	37,450		123.6		
64	..	Pont Du-Loup	Drac ..	290		2,400		8.30		
65	Burma		Meiktala Lake	240		30,301		126		
66	..	Wallen See ..	Linth ..	240		2,030,000		8,459		
67	..	Steyr ..	Steyrdurchoruch	222		6,700	1.31	30.2		510,000

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Reservoirs

Run-off per square mile of catchment (foot-acres)	Years of capacity surveys			Silt deposited					Remarks.	Reference to bibliography on page 194
	First	Last	Period in years	Total (foot-acres)	Annual foot-acres	Percentage of original capacity per annum	Per thousand of water supply by volume	Foot-acre per 100 square miles of catchment per annum		
12	13	14	15	16	17	18	19	20	21	22
27	1906	1932	26 2	11,330	432	2 73	24.8	66	Catchment in an advanced stage of erosion and gully developments Denudation due to intense sheep farming. Recovery due to silt control works	(29), (10)
..	1888	1940	52	5,039	97	0 35	..	..
1 583	1912	1930	18.75	20,800	1,110	1 14	1.17	185	Destruction of forest lands by fumes from roast ovens and smelters, clayey soil and excessive rainfall	(29)
..	1912	1935	23 8	6,265	263 2	0 08	..	45 4			(1), (12) and (29)
2,891	..	..	7	1,780	255	..	0 16	47		(29)
3,214	..	..	20	5,430	207	0 02	0 12	39		(29)
..	..	..	16	2,030	..	..	..	..
..	..	..	6	810	138	0 2	..	26		(29)
..	..	..	14	810	58	7 2	..	12		(29)
2,401	..	..	152	46,000	308	0 006	0 30	73		(29)
..	..	..	11 0	1,177	107	0 34	..	26 9		(1)
2,781	..	..	35	2,790	80	0 005	0.07	20		(29)
2,617	..	..	17	2,340	138	4 9	0 14	36		(29)
..	..	..	8	1,620	203	12 7	..	55		(29)
..	..	..	..	..	203	12 7	..	62		(29)
2,417	..	..	24	2,510	105	0.0002	0.14	35		(29)
1,894	..	..	27	3,200	118	0 001	0 19	37		(29)
980	..	..	20	1,330	66.5	4 1	0.22	22		(29)
..	1919	1935	16 5	1,822	110	0.29	..	36.7		(1)
..	..	..	1.1	1,220	1,110	46.3	..	360		(29)
..	1896	1936	40	7,091	177.3	0 59	..	74		(29)
..	..	..	51	3,030	60.1	0.003	..	25		(29)
2,298	..	..	22.5	575	26	0.38	0.05	12		(29)

TABLE
Siting of

Series No.	Reservoir			Catchment area (square miles)	Height of dam (feet)	Storage capacity				
	Country	River	Name			Foot-acres	Percentage of annual run-off	Foot-acres per square mile of catchment	Mean annual rainfall (inches)	Mean annual run off (foot-acres)
66	U.S.A.	Santa Ynez	Gibraltar ..	200	165	14,500	2.7	72.5	..	546,990
67	..	Cismon ..	Cismon .	192	.	10,000	2.24	52	..	446,000
70	Italy ..	..	Cismon .	186	144	4,050	.	22	..	..
71	U.S.A.	Sweet Water	Sweet Water ..	181	90	36,300	205	200	..	19,000
72	U.S.A.	Flat .	Lake Michie ..	170	85	12,671	11.5	75	42.2	110,000
73	Italy ..	Cellina ..	Mont Reale ..	168	.	1,000	1.76	5.9	78.8	56,700
74	U.S.A.	Buck Horn	Buck Horn .	130	.	1,190	.	9.2	..	..
75	U.S.A.	Cotton wood Creek.	Barret	130	179	..	.	331	18	..
76	U.S.A.	Trinity ..	White Rock .	114	40	18,158	.	159	37	.
77	U.S.A.	Cotton wood Creek.	Morena	112	162.5	68,388	.	610.61	22-30	.
78	U.S.A.	..	Burlington .	105.2	.	1,488	.	14.14	..	..
79	Italy ..	..	Cordevole-Lagodi	56	.	.	.	..	.	.
80	U.S.A.	South Pecos	Spartanourg .	92	50	2,700	.	29	47.6	.
81	Italy ..	..	Savio Quarto	83	..	.	.	.	.	.
82	Spain ..	..	Almausa .	78	68	2,400	.	31	13	..
83	U.S.A.	..	Bay View ..	72.3	.	11,866	..	164.11	..	..
84	U.S.A.	Horse Pen	Greensboro ..	72.0	30	2,870	..	40	46.8	..
85	U.S.A.	..	Lake Hurley .	70.0	.	1,226	..	17.51	..	..
86	Italy	..	Ferana-Cantangh- el.	60.0	..	.	..	..	..	..
87	U.S.A.	..	Little Rock ..	68.0	..	5,300	..	77.94	..	..
88	Italy ..	..	Scoltenna-Rio- lunato.	63.0	..	..	.	..	..	..
89	U.S.A.	Deep	High Point ..	62.8	45	4,354	..	69.33	..	..
90	Italy ..	..	Orba Orthghoto	56.0	..	..	..	..	.	..
91	U.S.A.	Pine Creek	Lake Crook ..	51.6	26	11,487	.	222.62	38-94	..
92	Burma..	..	Tangundang Tank.	51.0	..	4,290
93	U.S.A.	.	Lake Lee ..	50.5	..	821	..	16.26

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Reservoirs

Run-off per square mile of catchment	Years of capacity surveys			Silt deposited					Remarks	Reference to bibliography on page 194
	First	Last	Period in years	Total (foot-acres)	Annual (foot-acres)	Percentage of original capacity per annum	Per thousand of water supply by volume	Foot-acres per 100 square miles of catchment per annum		
12	13	14	15	16	17	18	19	20	21	22
	1920	1940	20 66	5,579	270	1-86	0 5	135	Santa Barbara Water Department Santa, Barbara clif. Aug. 1940.	
2,323	.	..	10	1,420	142	1 42	0-32	74	..	(29)
..	..	..	.	..	140	3 68		80	..	
105	1888	1927	39	5,859	150	0 41	8	83	Erratic rainfall, poor	
647	1926	1935	8 75	305	45	0 36	0 41	27	Vegetal covering.	(29), (9) (29), (9)
338	.		1	681	681	68 1	1 20	408	..	(29)
..	1907	1925	18	565	31 4	2-00	.	24	..	(29)
..
..	1910	1935	25	3,882	155	0-86	.	136	Catchment consists of limestone rocks.	(10), (29), (9)
..	1910	1935	25 7	7,184	280 0	0 41	.	256	..	(1)
..	..	..	10-0	163	16 3	1 1	..	15 5	..	(1)
..	..	..	.	..	51 6	.	.	85	..	(3)
..	1926	1934	8 2	463	56-7	2-10	.	62	..	(9)
..	..	..	..	..	259 79	..	..	313	..	(3)
..	..	..	..	..	2-5	0 10	.	3	..	..
..	..	..	24-6	2,352	95-6	0 81	.	134	..	(1)
..	1928	1934	11 5	260	23	0 80	.	31	..	(9)
..	..	..	4 5	37	8 22	0-67	.	11 8	..	(1)
..	..	..	..	..	91-77	.	..	133	..	(3)
..	..	..	11-75	83	7-06	0-13	.	10-4	..	(1)
..	..	..	..	..	73-71	..	..	117	..	(3)
..	1927	1938	10-25	316	30 8	0 71	.	49-5	..	(1)
..	..	..	..	..	86-24	..	..	154-0	..	()
..	1923	1936	13-1	732	55-9	0 49	..	112-0	..	(1)
..	1929	1936	6 0	499	83-2	1-93	..	163	..	..
..	..	..	11-1	109	15-23	1-85	..	30-3	..	(1)

TABLE
Siting of

Serial No.	Reservoir			Catchment area (square miles)	Height of dam in feet	Storage capacity			Mean annual rainfall (inches)	Mean annual run-off (foot-acres)
	Country	River	Name			Foot-acres	Percentage of annual run-off	Foot-acres per square mile of catchment		
94	U.S.A.	Medicine Creek	Wolfcreek	43 0	.	519	..	12 0	..	.
95	U.S.A.	San Leander	Lake Chabot	42 0	.	17,000	78	405	.	21,700
96	U.S.A.	.	Lake Purdy ..	41 74	.	19,080	.	457 12	..	.
97	U.S.A.	Ferozenman Creek.	Hayes Lake .	40 0	..	629	..	15 73	..	.
98	U.S.A.	.	Santa Fe .	40 0	..	1,741	..	43 53	..	.
99	U.S.A.	Satchel Creek	Lake Eldorado	33-0	..	3,213	..	97-36	..	.
100	U.S.A.	.	Sanpablo ..	32-2	.	.	..	..	..	8,800
101	Italy	..	Tidone-Molato	32 0	.	..	..	..	..	.
102	U.S.A.	..	Devils Gate ..	31-0	.	..	..	..	..	.
103	U.S.A.	San Leandro Creek.	Upper San Leandro	30 3	190	43,460	.	1,428	..	..
104	U.S.A.	.	Lake Harris	30 0	..	2,421	..	80-70	..	.
105	Pakistan	Spin Karez ..	Spin Karez ..	28 0	94	5,785	42 35	207	.	1,200
106	U.S.A.	Morgan Creek	University Lake	27-0	30	1,915	..	71	48	..
107	U.S.A.	.	Burnt Mills ..	27-0	..	170	.	6-30	..	..
108	Italy	.	Torre-Crosin .	24 0	..	..	..	..	..	..
109	U.S.A.	Turkey Creek Valley.	Lake Clinton .	23 0	52	4,415	..	192	28	..
110	U.S.A.	.	Ottawa County State Lake	20 5	.	1,001	.	48 83	.	.
111	Italy ..	..	Leta Letano .	19 0	..	..	..	..	..	..
112	U.S.A.	..	Meade County State Lake.	18 0	..	891	..	49 50	..	..
113	U.S.A.	.	Lake Sherwood	16 0	..	2,870	..	179 38	..	..
114	U.S.A.	Pine Creek ..	Pine Lake ..	15 34	..	738	..	..	..	.
115	U.S.A.	Holmesrun .	Barcroft .	14 5	..	1,847	.	127 38	..	.
116	U.S.A.	Cumarrow ..	Guthrie ..	13 3	..	3,064	.	230	33 4	..
117	U.S.A.	..	Lake Calhoun	13-1	..	286	..	21-83	.	..
118	U.S.A.	Mission Creek	Mission Lake ..	11-4	..	1,852	.	162 46
119	U.S.A.	..	Santa Anita (1936)	10-8	..	1,043	..	96-57

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Reservoirs

Run-off per square mile of catchment	Years of capacity surveys			Silt deposited					Remarks	Reference to bibliography on page 184
	First	Last	Period in years	Total (foot-acres)	Annual foot-acres	Percentage of original capacity per annum.	Per thousand of water supply by volume	Foot-acres per 100 square miles of catchment per annum		
..	..	..	5-0	55	9-82	1 89	..	22-8	..	(1)
517	1875	1923	48	3,700	77	0-45	3-5	183	..	(9), (29)
..	..	..	25 2	486-0	19-29	0 10	..	48	..	(1)
..	..	..	4-2	49	11-67	1 86	..	29-3	..	(1)
..	..	..	8 6	146	17-0	0 98	..	44-6	..	(1)
..	..	..	9 0	131	14-55	0-45	..	44-9	..	(1)
..	..	..	21 0	1,130-0	54	..	6 1	167-7	..	..
..	..	..	..	..	61-44	..	..	102-0	..	(3)
..	..	..	..	..	1,109	..	..	3,029	..	(3)
..	1927	1935	8-4	170-0	21-2	0 05	69-5	69-5	..	(2)
..	..	..	6-75	49-0	7 11	0-29	..	23-3	..	(1)
42-86	..	..	..	..	..	..	..	..	..	..
..	1931	1934	2-92	64	22	1-14	..	81	..	(9)
..	..	..	7-90	79	10-1	5 96	..	37-5	..	(1)
..	..	..	..	..	9-4	..	..	40 0	..	(3)
..	1930	1935	7-4	434	58-6	1 33	..	261-0	..	..
..	..	..	8 "	71	8-88	0-89	..	44-2	..	(1)
..	..	..	..	..	1-14	..	..	6-0	..	(3)
..	..	..	8 8	72	8-18	0-92	..	40-1	..	(1)
..	..	..	31-0	78	2-52	0-09	..	16 0	..	(1)
..	1924	19..	8-0	186	23-25	3-15	..	151-6	..	(1)
..	..	..	23-1	85	3-64	0-20	..	25-7	..	(1)
..	1929	1926	11-5	456	31-5	1-03	..	236	..	(9)
..	..	..	11 9	149	12-52	4-37	..	95-9	..	(1)
..	..	..	13-0	289	22-23	1-0	..	200	..	(1)
..	..	..	7 9	33	4-18	0 41	..	34-7	..	(1)

TABLE
Sizing of

Serial No.	Reservoir			Catchment area (square miles)	Height of dam in feet	Storage Capacity			Mean annual rainfall (inches)	Mean annual run-off (foot-acres)
	Country	River	Name			Foot-acres	Percentage of annual run-off	Foot-acres per square mile of catchment		
1	2	3	4	5	6	7	8	9	10	11
120	U.S.A.	..	Santa Anita (1938).	10 8	.	1,043	..	96 57	.	.
121	Italy	..	Gorzente Lavagnina.	10 0	.	.	.	.	.	.
122	U.S.A.	..	Lancaster	9 4	.	242	.	25 74	.	.
123	U.S.A.	Boomer Creek	Lake Boomer	9 1	..	2,811	..	308	32	.
124	U.S.A.	Laguna Creek	Upper Crystal Springs.	9 0	92 0	29,138	.	3,237 5	.	.
125	U.S.A.	.	Lake Bracon	8 91	..	2,881	.	323 34	.	.
126	U.S.A.	.	Lake Sapulpa	8 72	.	1,094	.	125 46	.	.
127	U.S.A.	Cedar Creek	Lake Olathe ..	6 20	.	532	.	85 81	.	.
128	U.S.A.	Sand Stone Creek.	Baker	5 20	25	756	..	145 4	14 0	.
129	U.S.A.	..	Lake Bennett	4 16	.	492	..	118 27	.	.
130	U.S.A.	..	Ardmore Club Lake.	4 15	..	1,797	.	433 01	..	.
131	U.S.A.	Cold Water Creek	Lake Concord	3 8	35	1,201	.	316	48	.
132	U.S.A.	..	West Frankfort	3 79	.	1,175	.	310 03	.	..
133	U.S.A.	.	Sawpit	3 00	..	.	..	.	.	.
134	U.S.A.	.	Lake Booneville	2 60	.	289	..	111 15	..	2,220
135	U.S.A.	..	Lave Oak	2 34	.	242	..	103 42	.	..
136	U.S.A.	..	Grand Sahne ..	2 12	.	531	..	250 47	..	..
137	U.S.A.	..	Wills Point ..	1 83	.	396	..	216 39	.	.
138	U.S.A.	Pine Creek ..	Lake Gibbons	1 26	35	1,414	.	1,122 22	8 94	..
139	U.S.A.	.	Franklinton ..	1 13	.	34 7	..	30 71	.	..
140	U.S.A.	.	Greenbelt Lake	0 83	.	196	..	236 14	.	..
141	U.S.A.	Little	Rogers ..	0 85	22	164	.	298	35	..
142	U.S.A.	..	Sunset Canyon	0 44	.	..	..	.	.	..
143	U.S.A.	..	Field Manufacturing Co. Reservoir Buck	..	14	184	..	.	.	..
144	U.S.A.	..	.	..	.	1,225	..	.	.	..
145	U.S.A.	..	Byllesby	.	..	8,892	.	.	.	..
146	U.S.A.	..	Washington Mills.	.	..	2,954	.	.	.	..
146a	Japan	Ishikari	Nokanan	1,107	.	4,770	.	.	.	..
146b	Japan	Oi	Senzu	110	.	4,010	.	.	.	..
146c	Japan	Sho	Soyama	578	.	26,750	..	.	.	..
146d	Japan	Kis	Oi ..	1,275	.	23,820	..	.	.	..
146e	Japan	YoJo	Shuzura ra	2,342	.	3,625	.	.	.	..
146f	Japan	Karabe	Koyadaira	251	.	1,721	..	.	.	..

XXXVII—concl'd.

Reservoirs

Run-off per square mile of catchment (foot-acres)	Years of capacity surveys			Silt deposited					Remarks	Reference to bibliography on page 104
	First	Last	Period in years	Total (foot-acres)	Annual foot-acres	Percentage of original capacity per annum	Per thousand of water supply by volume	Foot-acres per 100 square miles of catchment per annum.		
..	.	.	10 2	360	35.3	3.38	..	327.0	..	()
..	12.6	..	..	126	..	(3)
.	..	.	13.4	52.0	3.88	1.60	..	41.7	..	(1)
.	1925	1935	10 25	171	16.7	0.59	..	183	..	(9)
.	1874	1935	57 4	928	16.9	0.06	..	217	..	(1)
..	12.7	221	17.4	0.30	..	202	..	(1)
..	27.5	183	8.17	0.74	..	94.9	..	(1)
..	4.9	55.0	11.12	2.11	..	184.0	..	(1)
..	1908	1937	9.1	254.0	8.73	1.15	..	174.2	..	..
..	0.37	4.0	10.81	2.20	..	264.0	..	(1)
..	15 5	153.0	9.87	0.55	..	259.0	..	(1)
..	1925	1935	10.17	79	7.4	0.65	..	265	..	(9)
..	10	95	9.5	0.81	..	268.0	..	(1)
..	100.0	..	..	3633.0	..	(3)
..	6.7	3.0	1.19	0.40	0.53	46.0	..	(1)
..	2.20	13	5.91	3.44	..	232	..	(1)
..	13.25	22	1.66	0.31	..	82.2	..	(1)
..	23.6	121	7.13	1.29	..	293.0	..	(1)
..	1900	1936	36	78	2.2	0.15	..	174	..	(1)
..	13.33	7.4	0.56	1.69	..	50.0	..	(1)
..	1.6	10	0.25	3.19	..	791	..	(1)
..	1922	1934	12	37	3.1	1.91	..	560	..	(9)
..	6.6	..	..	1,300	..	(2)
..	5.67	75	13.23	7.16	..	..	..	..
..	23.7	284	11.98	0.98	..	..	..	(1)
..	23.7	7,354	2 5.91	2.54	..	..	..	(1)
..	33.5	2,443	72.93	2.47	..	..	..	(1)
..	32	4,700	..	3.08	..	..	..	(26)
..	14	2,520	..	4.36	..	..	..	(26)
..	10	12,440	..	2.4	..	..	..	(26)
..	24	17,210	..	5.04	..	..	..	(26)
..	25	18,470	..	2.04	..	..	..	(26)
..	83	1,431	..	0.14	..	..	..	(26)

ASWAN RESERVOIR

River	..	..	..	.. Nile—Egypt
Catchment area	..	..	..	620,000 square miles
Run-off	..	..	..	86,000,000 foot-acres
Height of dam	..	..	..	174 feet
Storage capacity	..	..	..	4,400,000 foot-acres (after second heightening)
Period of capacity survey	..	..	..	1900—1927
Silt	..	..	..	Nil till 1927
Further surveys	..	..	..	1929, 1930, 1931, 1935 and 1938. 25,000,000 tons believed to have been deposited in 1938.

Catchment Characteristics

The rainfall in this catchment occurs during the monsoon period as in the Punjab. The time of onset of the rains in Abyssinia corresponds to the date of bursting of the Indian monsoon (June 15). High temperature and heavy rains characterise the upland plateau of Uganda, where the tributaries of the White Nile take their rise. When in flood, the Atbara and Blue Nile annually bring down in suspension large quantities of silt from the Abyssinian plateau.

Conditions in the catchment of the Nile in respect of season and intensity of rainfall and silt are similar to those in the catchments of the Punjab rivers before they debouch into the plains.

The Aswan Dam

The first dam ⁽²⁹⁾ was constructed and completed in 1902 to store 865,000 foot-acres (R.L. 106.0 m). No spillway was provided but the dam has 180 sluices to pass a maximum flood of 500,000 cusecs. It was raised in 1907-1912 (R.L. 113.0 m) to provide a capacity of 1,970,000 foot-acres, and raised further to R. L. 122.0 m. giving a capacity of 4,400,000 foot-acres in 1929-31.

Silt in the Nile and its Control

The presence of silt in the Nile limits the time during which storage reservoirs on the Blue and Main Nile can be filled. To avoid any risk of silting up the Aswan Reservoir, the rule in the past was to start filling after the peak of the flood had passed and the gauge downstream had fallen to 88.0 (metres). But with the increase in capacity of the reservoir due to the heightening of the Aswan Dam the date at which filling commences has been advanced to about the middle of October when the Aswan gauge falls to 91.00 (metres). This date will have to be advanced still further to meet the programme of future development. Filling in low years may have to start at the crest of the flood. The use of this reservoir for flood control is likely in emergency. Thus a situation may arise when part of the silt-laden waters may have to be retained in the reservoir.

The bed load in the stream above Aswan cannot be heavy, and what little there is, is carried through the sluices. This is substantiated by the fact that there has been no rise of bed above the solid part of the Aswan Dam.

From January to nearly the end of July there is very little suspended solid matter in the Nile. Usually the concentration is less than 100 parts per million by weight. Towards the end of July or the beginning of August, the concentration increases rapidly to a maximum which is usually reached late in August. The maximum concentration of suspended solids occurs very distinctly earlier than the maximum height of the flood. In a good flood it may reach 4,000 parts per million for a few days. The concentration then falls off gradually until in December it again becomes less than 100 parts per million. Table XXXVIII (27) is illustrative.

TABLE XXXVIII

Suspended solids carried in the Nile past Halfa and distribution of sand, silt and clay

Date	Mean concentration in parts per million by weight					Average	Percentage*		
	1929	1930	1931	1935	1938		Sand	Silt	Clay
August—									
1—10 ..	2,600	1,650	1,030	..	..	1,760	15	40	45
11—20 ..	2,520	2,400	2,890	..	.	2,600	22	45	33
21—31 ..	2,270	2,340	3,640	.	3,190	2,860	25	45	30
September—									
1—10 ..	1,920	1,760	3,320	2,220	2,550	2,350	31	41	28
11—20 ..	1,700	1,570	2,280	1,670	1,840	1,830	36	40	24
21—30 ..	1,350	1,040	1,740	1,460	1,670	1,460	41	38	21
October—									
1—10 ..	1,060	670	1,330	1,290	1,400	1,150	42	34	24
11—20 ..	800	510	700	910	1,190	840	43	33	24
21—31 ..	680	..	560	..	880	710	45	27	28
November—									
1—10 ..	510	..	510	.	610	540	..	..	..
11—20 ..	360	..	..	..	420	360	..	..	..
21—30 ..	170	.	..	..	.	170	..	..	..

* Mean of mechanical analysis made in 1930 and 1931.

It will be seen from the above table that the percentages of silt and clay diminish whereas those of sand increase with the progress of the flood.

The distribution of the total silt load on monthly basis and its sand, silt and clay contents are diagrammatically represented in Figure 4 (Chap. I.) and Figure 59 respectively.

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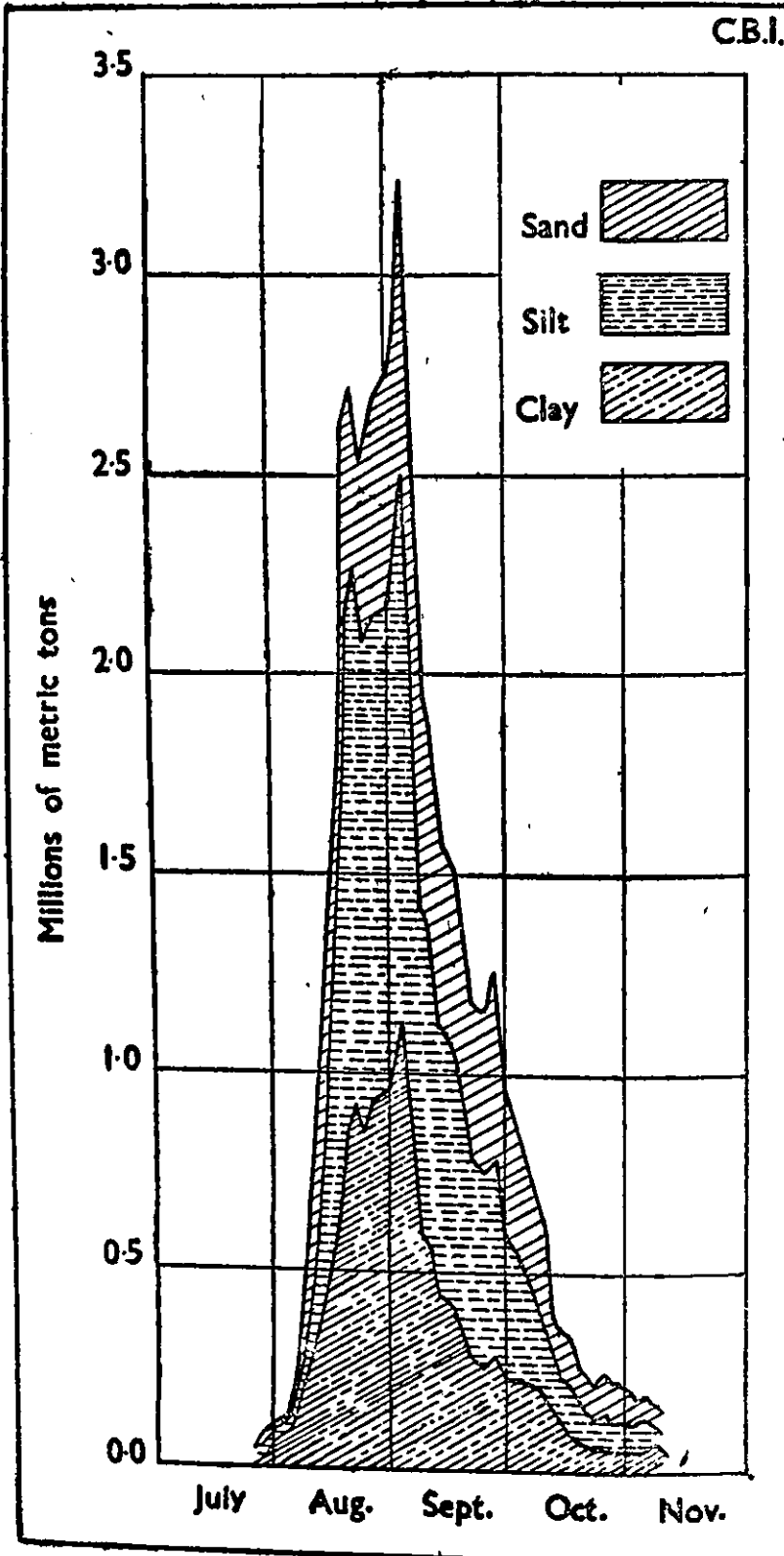


Figure 59 :—Total quantity of suspended solid passing in Wadi Halfa 1931 in millions of tons per day.

The quantities of silt loads passing Halfa which are representative of those reaching Aswan were 136, 76 and 118 million tons in 1929, 1930 and 1938 respectively. Out of the 118 million tons of suspended matter that passed Halfa between August 21 and November 16, 1938, the deposit in the reservoir is believed to have been 23 million tons.

As the storage at Aswan is only one-fifteenth of the mean annual run off and the sluices are placed at bed level capable of carrying maximum flood discharge of 500,000 cusecs. the deposition of silt will be only a fraction of the total silt brought down by the stream. Fox ⁽¹³⁾ gives a possible reason for the negligible amount of deposition. He states that the silt brought to Aswan Reservoir from the Atbara (750 miles upstream) is only the very finest material and is easily stirred and carried onwards when the floods are travelling through. If for hydro-electric development or for irrigation expansion a steady head has to be maintained at the reservoir, the silting will be more pronounced and progressive.

Remarks

This is an instance perhaps the only one—in which silt deposit in the reservoir has been, until recently, avoided completely by providing sluicing capacity equal to the maximum flood discharge by placing the sluices at bed level and by storing water at times when silt concentration was low and on the decline. It should, however, be noted that these provisions were made possible by the mean annual run-off being as high as fifteen times the storage capacity after the second heightening.

The annual suspended silt load of the Nile above Aswan is nearly 15,000 tons per 100 square miles against 150,000 tons of the Colorado above Boulder and 157,000 tons of the Sutlej above Bhakra.

BOULDER (HOOVER) RESERVOIR

River	Colorado (Arizona, Nevada, U.S.A.)
Catchment area	167,000 square miles
Rainfall	10 inches
Average annual run-off	15,000,000 foot-acres
Range of run-off	25,200,000 to 4,200,000 foot-acres
Height	720 feet
Capacity	39,500,000 foot-acres
Lake length	115 miles
Lake surface	145,500 acres
Annual estimated rate of silt	60,000 foot-acres

Catchment Characteristics

The rocks at the dam site are of volcanic origin. The average rainfall over the drainage area is about ten inches, and over thousands of square miles less than five inches. The main flow is derived from the melting of snow on the mountains of the upper basin. The principle characteristics of its flow are low waters during the autumn and winter months, with a normal flood from the melting snows usually beginning late in April, reaching its maximum in June and ending by the middle of August. This flow is modified and intensified by the torrential floods of short duration which come in general from its southern tributaries and may occur during almost any month of spring, fall or winter.

Of the catchment of the Colorado river above the Boulder Dam, the plateau region comprising an area of 60,000 to 65,000 square miles is said to contribute less than ten per cent. of the water and more than 75 per cent. of the silt load recorded at Grand Canyon [About 200 miles above the Boulder (Hoover) Dam] gauging station. This area consists of loosely cemented sandstones and sandy friable shales and to these rocks must be attributed the origin of most of the silt. This region has a low rainfall of six to ten inches and all this occurs in one to six storms during the year. These desert storms are torrential in character, well adapted to corrosion of the rather finely divided weathered material that abounds in the region.

To the arid climate may be attributed an excess of weathered material and to the torrential character of storms, the heavy though sporadic flows of silt. The sparseness of vegetation permits the torrential rains to do their work with a minimum of hinderance.

Estimate of Suspended Load

Silt studies were started on the Colorado river for the Boulder Dam in 1925.

The Colorado river above the Boulder Dam ⁽²⁹⁾ carries apparently an annual load of 200 to 300 million tons of silt. For purposes of design of dam, the annual silt deposition in the reservoir was estimated ⁽²⁵⁾ to be 137,000 foot-acres per year or 82 foot-acres per 100 square miles of catchment per year, compared with a previous Bureau estimate of 80,000 foot-acres. Subsequent estimate ⁽³¹⁾, which appears to have been accepted finally, puts it at 3,000,000 foot-acres in 50 years or 60,000 foot-acres per year or 36 foot-acres per year per 100 square miles of catchment. This presumably allows for a dam or dams to be constructed later higher up in the tributaries.

With the river unregulated, a low percentage of suspended silt occurs usually in the early summer at the peak of the annual flood resulting from the melting of snows in the upper water sheds, while the river water generally carries the highest percentage of silt in the late summer months or fall, when erratic floods are caused by rains in areas drained by its lower tributaries.

Estimates ⁽¹⁹⁾ based on the silt observations made at Yuma for a period of 207 months from January 1914 to March 1931, showed that the reservoir would be silted up in 200 years. The dry weight of the silt was taken as 85.9 lbs. per cubic foot of deposit.

Silt Discharge Relationship

There is a lack of any relationship between percentage of silt and river discharge of the Colorado river, during the months of May, June and July when the river is snow fed, but the silt concentration more or less follows the discharge in August, September and October when cloud-bursts occur. The rain water is responsible for more silt than the snow water. This aspect has already been discussed in Chapter 1 (See Figure 6).

Remarks

The suspended silt load of the Colorado above the Boulder Dam is 150,000 tons per 100 square miles which is nearly the same as that of the river Sutlej above Bhakra which is 157,000 tons. The life of the Boulder Dam as estimated by the Bureau of Reclamation Hydrologists is 275 years (23).

The large disparity in the different parts of the catchment with regard to silt contribution is of particular interest in that it points to the necessity of careful geological survey of the catchment with a view to finding means for the controlling of the sections which are most productive of silt.

THE GRAND COULEE RESERVOIR

River	Columbia, (U. S. A.)
Catchment area	74,000 square miles
Run off	80,000,000 foot-acres
	53,000,000 (minimum)
Estimated annual evaporation	200,000 foot-acres
Height of dam	550 feet
Capacity	9,645,000 foot-acres
Length of lake	150 miles
Area of lake	82,000 acres
Estimated silting	Almost nil

Catchment Characteristics

The headwaters of the Columbia river originate in Columbia Lake of the Canadian Rockies and are augmented by the principal supply from the Western slope of the Rocky mountains and from the Selkirk and Bitterroot mountains. The drainage area of 74,000 square miles includes heavily timbered mountain regions in part of British Columbia, Idaho, Montana and Washington. Deep snow at high altitudes and numerous large natural lakes near the headwaters serve to regulate the stream flow by retarding flood peaks and supplying the heavy run-off during the summer months.

Silt Load of the Columbia River*

The streams tributary to the Columbia are almost always clear and free from silt. Solid matter causing slight turbidity during part of the flood season is extremely fine and practically all of it is carried in permanent suspension. Silt will have no detrimental effect on the utility of the reservoir.

Remarks

This is a unique case. Thus the second largest reservoir in the World will have its capacity unimpaired by silting, perhaps, for all time.

LAKE AUSTIN

Constructed primarily for hydro-electric power for Austin in May 1893 with a 66 feet high dam in the river Colorado at Austin, Texas U. S. A. A Section failed on April 7, 1900. It was rebuilt in 1911-13 with the crest of the dam nine feet lower than the old one. The new dam and power plant have never been used owing to the refusal of the city to accept it on account of alleged defects.

Catchment	38,200 square miles.*
Rainfall	15 inches at headwaters to 33 inches at Austin
Mean annual runoff	1,827,000 foot-acres (New), 2,000,000 foot-acres (Original)
Storage capacity	49,300 foot-acres (Original) 32,000 foot-acres (New)

Silt Surveys

During the interval 1900-1913, much of the silt deposited in the old reservoir was washed out. The reservoir created by the New Austin Dam has silted up to such an extent that channel conditions prevail and the percentage of silt in the water passing over the spillway differs very little from that in the flow over the reservoir (10).

The mean silt load of the Colorado for a three years period in this neighbourhood was 0.36 per cent. by weight. This should give approximately 8,222,000 tons of silt per year, or 21,500 tons per 100 square miles per year which is not far different from that of the Nile above Aswan.

The silt in the dam (1900) consisted of fine impalpable absolutely gritless deposit. At the head of the lake there was some admixture of sand. On the whole area, sand constituted nearly seven per cent. of the deposits.

Table XXXIX gives the dry weight of silt deposits.

TABLE XXXIX

Sample No.	Original weight per cubic foot in pounds	Dry material per cubic foot of deposit in pounds	Sample No.	Original weight per cubic foot in pounds	Dry material per cubic foot of deposit in pounds
1	109.8	83.5	8	101.5	69.8
2	109.2	84.9	9	99.3	67.6
3	111.6	84.5	10	91.6	51.9
4	113.8	86.9	11	92.0	54.5
5	104.3	64.7	12	79.9	29.6
6	124.2	106.0	13	80.6	29.9
7	108.1	73.1	14	81.2	30.5
			15	82.7	30.7

Exposed deposits

Clay and sand

Exposed at lower stages.

Not exposed

Rate of Silting

The rate of silting is given in Table XL and Figure 60.

* Part of which is non-contributing. Approximately 13 per cent. of the drainage area was cultivated in 1930, the remainder being pasture and timber land.

TABLE XL

Period of Record	Years	Silt deposited in foot-acres			Catchment area (square miles)	Average silt deposit per 100 square miles per year (foot-acres)
		During period	Per annum	Cumulative total		
Old 1893-1900 ..	6·7	23,559	3,490	..	38,200	..
New 1913-1922 ..	9	26,740	2,970	..	38,200	7·8
1922-1924 ..	2	2,460	1,230	29,200	..	3·2
1924-1926 ..	2	1,420	710	30,620	..	1·9
Total ..	13	30,620	2,355	30,620	38,200	6·2 (Average)

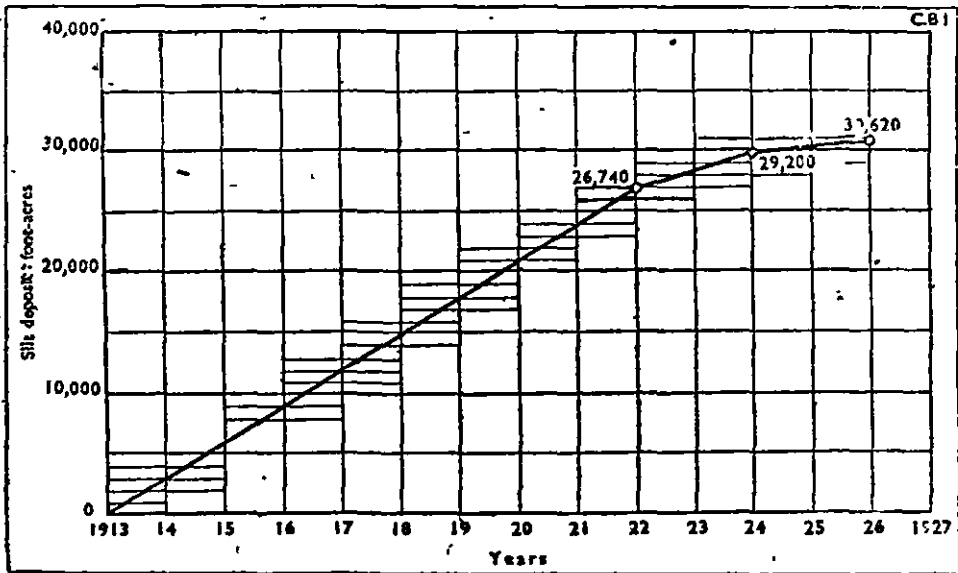


Figure 60 :—Rate of silting of Lake Austin.

Remarks

Although the reservoir has almost completely filled up in 13 years, the rate of silting per year for 100 square miles is only 6·2 foot-acres. This low figure is apparently due to the storage capacity (32,000 foot-acres) being small compared to the mean annual run off (1,827,000 foot-acres), and the silt concentration of the river water being low. Similar phenomenon appears on the Keckuk Reservoir (item 3 Table XXXVII.)

ELEPHANT BUTTE RESERVOIR

River	--	--	Rio Grande (New Mexico, U. S. A.) The upper end of the reservoir is at San Marcial New Mexico.
Catchment area	--	--	26,312 square miles
Rainfall	--	--	10 inches, 15 inches, lower areas. Head waters 25 inches
Runoff	--	--	Annual average 1,000,000 foot-acres
Evaporation	--	--	150,000 to 250,000 foot-acres
Height	--	--	306 feet
Lake length	--	--	41 miles
Lake surface	--	--	40,096 acres
Storage	--	--	2,638,860 foot-acres
Mean annual draft for irrigation	--	--	75,000 foot-acres
Constructed	--	--	191 to 1916
Storage began	--	--	January 1915

The Elephant Butte Dam is one of the largest in the United States and before construction of Boulder Dam impounded the largest reservoir in the country. The lake extends to San Marcial which is 43 miles above the dam. About 14½ miles above the dam the lake gets very narrow and continues like this to near mile 19½ from the dam. This reach of nearly five miles is called the Narrows and is particularly mentioned as the nature of silt accumulations above and below is different.

Catchment Characteristics (9)

Parts of the drainage basin are under strong erosional attack. Sheet wash and wind erosion are very general. Large areas of alluvial fans and exposed shale formation, are affected badly by gulying and dissection.

The lower part of the watershed is underlain mostly by superficial deposits of alluvium, dune sand, the Gila conglomerates and the Palomas gravel. There are also extensive areas of quaternary and tertiary basalt and rhyolite and mixed cretaceous and tertiary volcanics of several types. On the headwaters and in higher mountains lime-stones occupy broad areas.

The entire lower section of the watershed is characterised by its aridity. Over-grazing has caused destruction of natural grasses and exposed large areas to sheet wash and wind erosion. The effect of over grazing is particularly acute in soft shale and alluvial formations at the foot of the mountains.

The Rio Grande and its Silt Load

The Rio Grande carries the largest silt burden both in absolute maximum percentage of silt load to discharge during any particular flood and in ratio of total silt to total discharge to any major stream of the south-west of which results are available.

The headwaters of the Rio Grande in north central New Mexico and south central Colorado draining a mountainous area of 11,028 square miles are supplied largely by melting snows, springs, and normal run-off. The waters carry little or no suspended load. In contrast, the streams draining 13,621 square miles of the generally barren, broken central part of New Mexico, supply floods of heavily silt laden water derived from the erratic and often spectacular cloud bursts, that occur during summer and early fall. These flashy summer flood

waters usually carry four to ten per cent. and occasionally as high as 12 to 15 per cent. by weight of silt which is characterized by a high percentage of a colloidal argillaceous matter. On the other hand spring floods coming from the headwater drainage carry only 0.5 to one per cent. or less of silt.

Above the lake headwater, San Marcial, a considerable quantity of silt has deposited and the aggrading of the river bed is continuing as far up as 50 miles. The silt deposits below San Marcial are characteristically very fine textured containing a high percentage of true clay and colloidal matter. Much of the silt is so fine that no grit can be discovered in rubbing between the teeth. This is due to the fact that for 125 miles above San Marcial, the Rio Grande and its tributaries are draining a country underlain in large part only by shales. Sand deposits which are common above San Marcial, fail to enter the reservoir basin to any extent because of the retarding influence of vegetation.

Capacity Surveys (9) (5)

These were carried out in 1903-1908, 1916, 1920, 1925, 1935 and 1940. Survey of 1903-1908 and 1935 covered the entire reservoir area. The surveys of 1916, 1920 and 1929, as stated by Taylor, were made only of the upper portion of the reservoir.

The 1935 surveys mapped the entire 21,600 acres of the silt surface with one foot contours. During this survey, water stage was at an extremely low level so that all the area above the Narrows could be mapped by plane table and stadia shots despite the soft and boggy character of the silt. The area below the Narrows was sounded from a boat.

Rate of Silting of the Elephant Butte Reservoir

Table XLI and Figure 61 are considered to be the latest authentic information available.

TABLE XLI

Period of Record	Years	Silt deposited			Catchment area in sq miles	Silt deposit in foot-acres per 100 square miles of catchment per annum
		In foot-acres	In foot-acres per annum	Cumulative total in ft. acres		
1915	..	..	..	..	..	..
1916	1-91	53,995	28,270	53,995	..	107
1920	3-67	86,015	23,437	140,010	26,312	69
1925	5-00	91,725	18,345	231,735	..	70
1935	9-67	133,451	13,801	365,186	..	53
1940	5-50	50,600	9,200	415,786	..	35
	25-75		16,147	415,786	26,312	61

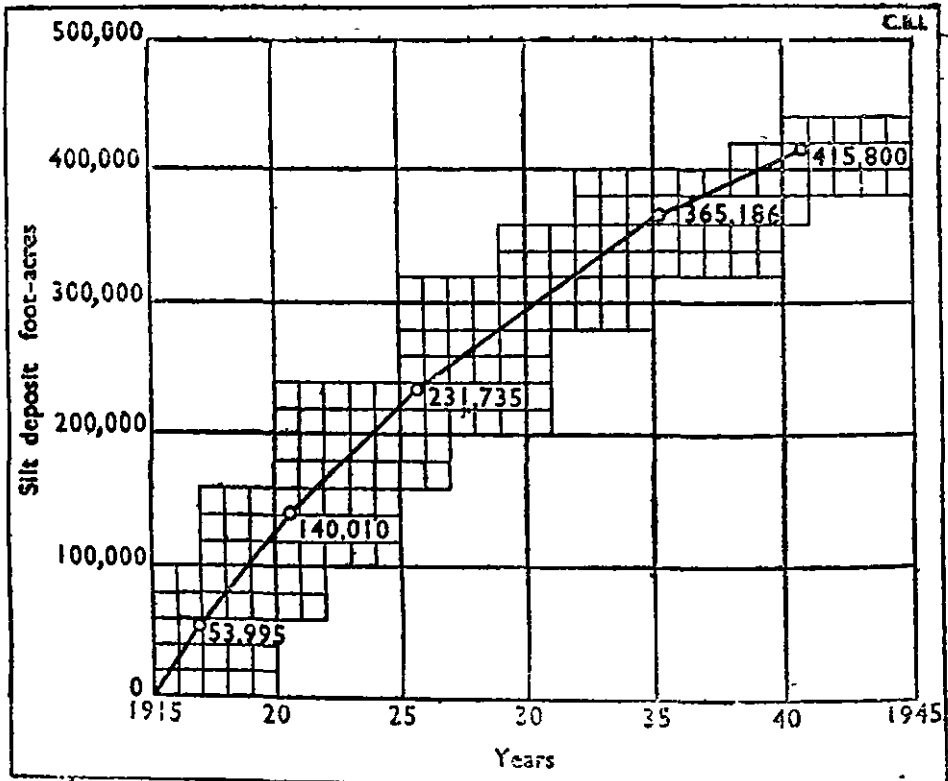


Figure 61 :—Rate of silting of the Elephant Butte reservoir

As the result of statistical examination of the data presented in Figure 61, Malhoutra has shown that the rate of silting falls off very appreciable with time. (4)

The annual suspended silt carried by the Rio Grande at San Marcial from 1915 to 1931 is shown in relation to annual run-off in Table XLII and Figure 62.

TABLE XLII

Period	Quantity of water in thousands of foot-acres	Suspended Silt		Period	Quantity of water in thousands of foot-acres	Suspended Silt	
		Per thousand of water supply by volume	Millions of tons during period			Per thousand of water supply by volume	Millions of tons during period
1915	1,350	13.6	25.0	1924	1,440	7.5	14.6
1916	1,650	13.2	30.0	1925	419	12.0	8.6
1917	1,050	6.6	9.4	1926	1,050	7.2	10.2
1918	410	6.6	3.7	1927	1,350	19.6	35.9
1919	1,580	22.8	45.8	1928	590	5.7	4.6
1920	2,220	10.4	31.5	1929	1,460	29.5	58.6
1921	1,630	19.2	42.9	1930	731	5.4	5.4
1922	964	10.2	13.3	1931	490	18.8	12.5
1923	1,220	11.7	19.4	..	..	..	..

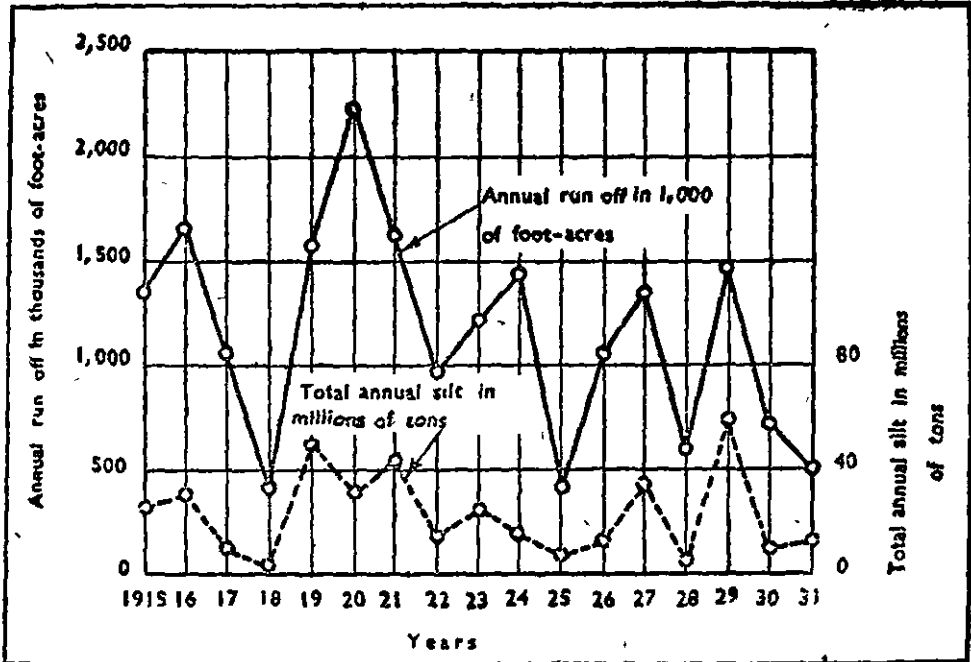


Figure 62

Total run off 1915-1931	..	..	=	19,604,000 foot-acres
Total suspended silt 1915-1931	..	..	=	369,600,000 tons
Mean annual runoff	..	..	=	1,153,176 foot-acres
Mean annual silt	..	..	=	21,741,176 tons.
Catchment area	..	..	=	26,312 square miles
Mean annual silt per 100 sq. miles of catchment	..	..	=	82,628 tons of 2,000 lbs

17 samples from exposed silt beds of Elephant Butte Reservoir in 1916 gave the volume weight relationship given in Table XLIII (29).

TABLE XLIII

Description	Maximum	Minimum	Average
Weight as taken, in pounds per cubic foot	124.3	96.7	104.7
Moisture percentage	20.9	4.4	11.6
Weight dry in pounds per cubic foot	101.2	87.9	92.3
Specific gravity	2.66	2.59	2.64
Percentage of voids	46.6	39.0	44.0

Phenomenon of Under-flow

Observations at this dam have revealed that silt laden water flows along the bottom of the lake in a very thin sheet (less than five feet depth) without diffusing in the water already in the lake. It retains a temperature higher than that of Reservoir water as it flows along beneath the clear water. When the silt laden water is being discharged from the outlet gates, it carries a silt load from two to six per cent. by weight. The character of the silt in the reservoir discharge is almost pure finely divided clay, with all particles of grit and heavier silts completely removed.

Its economic significance is of somewhat doubtful importance. The total volume carried through the reservoir in this manner to date is estimated to be only 5,000 foot-acres. This will probably increase as the storage capacity is progressively depleted. The Elephant Butte Reservoir although it has lost 16½ per cent. of its capacity within these 32 years, it will still be good enough for 160 years more (23).

Remarks

Natural rock formation, aridity and overgrazing are responsible for the large silt load of the Rio Grande river. It would have been still worse were it not for the 11,028 square miles of mountainous area (out of 26, 312 square miles of total catchment area) which supplies water from melting of snow with little silt charge.

The rate of silting at this reservoir may be considered as representative of those on streams carrying heavy silt load.

LAKE McMILLAN

River	..	..	..	..	Pecos, New Mexico U.S.A.
Catchment	..	..	..	..	22,000 square miles.
Runoff	..	..	..	..	300,000 foot-acres.
Height of dam	..	..	..	..	52 feet above original channel bed.
Storage capacity	..	..	..	..	90,000 foot-acres.
Storage begun	..	..	..	..	1893
Surveys	..	..	..	..	1932.

Catchment Characteristics

The catchment has arid climate, with total rain fall highly erratic from year to year.

Prior to 1912 the Pecos Valley above McMillan Reservoir was particularly devoid of vegetation other than low growing salt grass. The few seedlings of salt-cedar which appeared in the fall of 1912 had grown to lengths of three to five feet by 1915. Since then it has become very dense over the whole upper end of reservoir and extends some 200 miles upstream.

Rate of Silting

A notable falling off in rate of silting of the reservoir proper during the later part of the record points unmistakably to the influence of tamarisk or salt cedar growth in the valley at the head of the reservoir where it has greatly increased valley sedimentation above the lake level since 1915.

Table XLIV and Figure 63 represent the record of silting of Lake McMillan as given by Taylor.

TABLE XLIV

Period of Record	Years	Silt Deposited			Silt deposit in foot-acres per hundred square miles of catchment per year
		In foot-acres	In foot-acres per annum	Cumulative total in foot-acres	
1893-1904	10.42	18,000	1,730	18,000	7.8
1904-1910	6.42	10,000	1,560	28,000	7.10
1910-1915	4.58	13,400	2,920	41,400	13.3
1915-1925	10.00	3,500	350	44,900	1.6
1925-1932	7.00	1,500	215	46,400	0.98
	38.42		1,208	46,400	5.5

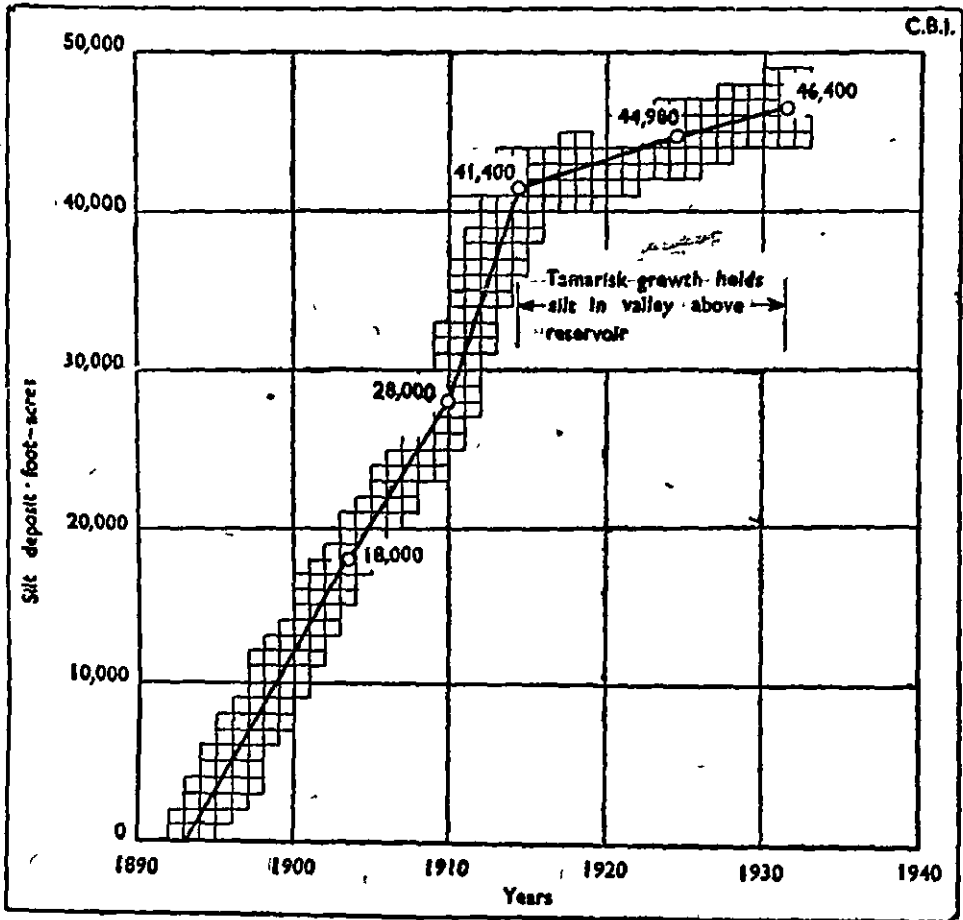


Figure 63 —Rate of Silting of Lake McMillan.

The original prediction was that the reservoir would silt up solid by 1935 but the growth of salt-cedar has altered the situation. This growth induces the river to drop most of its silt in the valley just above the reservoir.

Remarks

Lake McMillan is a definite indication of what can be accomplished in silt prevention by an increase in vegetal cover. The accidental propagation of tamarisk provides an effective silt trap.

FOUR LARGE RESERVOIRS IN SOUTH AFRICA

(items 19, 27, 32 and 34 of Table XXXVII).

The four reservoirs are Lake Arthur, Grassridge, Lake Mentz, and Van Rynevelds Pass. The first two are on separate tributaries of the Great Fish River and the remaining on the Sundays river, Van Rynevelds Pass reservoir being about 120 miles above Lake Mentz.

These two rivers are the most silting rivers in South Africa.

TABLE XLV

Major Features of the Four Reservoirs

Description	Lake Mentz	Van-Rynevelds Pass	Grass Ridge	Lake Arthur
Catchment area (square miles) ..	6,300 (includes 1,477 V. R. Pass).	1,477	1,583	2,270
Mean annual rainfall over catchment, (inches.)	12 (11 excluding V. R. Pass).	13.5	13.5	13.5
Mean annual run-off, foot-acres—				
(a) estimated	115,000	40,000	45,000	73,000
(b) actual since construction ..	146,000	33,000	42,000	79,000
Original capacity of reservoir, foot-acres	94,600	66,000	64,500	63,600
Original capacity of reservoir, as ratio of run-off.	0.82	1.65	1.43	0.87
Annual evaporation in inches (Land)	71	82	81	74.5
Date when water storage began ..	Dec. 1922	Feb. 1925	Feb. 1924	Feb. 1925
Annual rate of silting per 100 square miles of catchment foot-acres	57	64	87	115

Catchment Characteristics

The whole of this area is occupied by the karroo geological formation of about Permian age. This formation consists generally of an immense thickness of soft and easily erodible rocks, the material of which was laid down in an inland sea. Shortly after deposition they were raised to a great height, though the strata lie almost horizontally.

There is practically no forest cover in the catchment area, the chief growth being the low stunted karroo bush on which, however, sheep thrive.

The high parts of the catchment occasionally hold snows for very short periods only. The rainfall over the area varies from 20 inches at the high elevations to less than ten inches in the plains. About 80 per cent. of the rain falls in the summer half of the year, mostly from thunder storms of short violent nature. There is very little permanent flow in any of the streams which run only for short periods after violent rains.

Erosion, resulting in heavy charge of silt in the waters of the rivers, is encouraged by the soft nature of the geological formation, the steep slopes, the poor vegetal covering, the smallness, irregularity and violent nature of the rainfall and intense sheep farming in the catchment area.

Rate of Silting

Table XLVI, and Figures 64-67 show the rate of silting of these four reservoirs.

TABLE XLVI

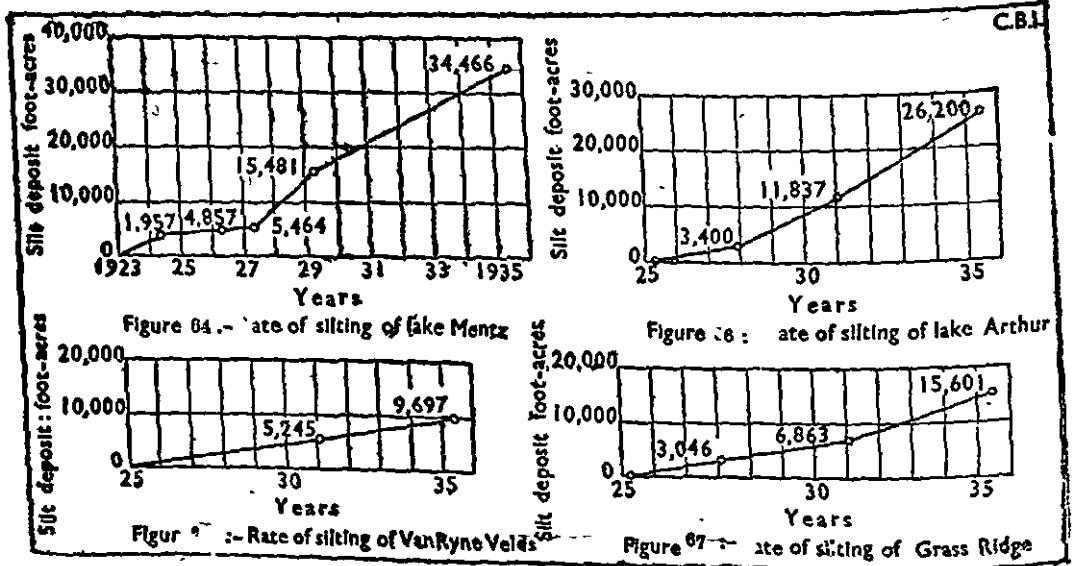
Period of Record		Years	Silt Deposited			Silt deposit in foot-acres per 100 square miles of catchment area per annum
From	To	Y—M	In foot-acres	In foot-acres per annum	Cumulative total.	
LAKE MENTZ—(Catchment area 4,823 sq. miles)						
1-1-23	30-4-24	1—4	1,957	1,468	..	30
1-5-24	28-2-26	1—10	2,900	2,127	4,857	44
1-3-26	31-3-27	1—1	607	560	5,464	12
1-4-27	28-2-29	1—11	10,017	5,226	15,481	108
1-3-29	31-5-35	6—3	12,985	3,038	30,466	63
1-1-23	31-5-35	12—5	..	2,780	34,466	7

TABLE XLVI—*contd.*

VAN RYNEVELDS PASS—(Catchment area 1,477 sq. miles)						
1-1-25	31-1-31	6-1	5,245	874	..	59
31-1-31	30-4-35	4-3	4,452	1,035	9,697	70
1-1-25	30-4-35	10-4		941	9,697	64

LAKE ARTHUR—(Catchment area 2,270 sq. miles)						
1-4-25	31-10-27	2-7	3,400	1,350	..	60
31-10-27	31-1-31	3-3	8,437	2,590	11,837	114
31-1-31	30-4-35	4-3	14,363	3,380	26,200	149
1-4-25	30-4-35	10-1		2,600	26,200	115

GRASS RIDGE—(Catchment area 1,583 sq. miles)						
1-4-24	31-1-27	2-10	3,046	1,050	..	67
1-2-27	31-1-31	4-0	3,817	954	6,863	60
1-2-31	31-5-35	4-4	8,738	2,030	15,601	128
1-4-24	31-5-35	11-2		1,380	15,601	87



Figures 64-67 :—Rate of silting of some large reservoirs of South Africa.

As in other reservoirs sand deposits are found at the upper end of reservoir getting to fine silt and clays towards the dam. Sand samples weighed about 100 pounds (dry weight) per cubic foot and the finest deposits near the surface if not exposed, weighed 40 pounds.

Remarks

The catchments of these four reservoirs have all the favouring features for maximum silt production. The geological formations are soft, slopes steep, vegetable cover poor, rendered worse by intense sheep farming and the rainfall is small, irregular and violent. These reservoirs are, therefore, illustrative of the worst type of silting. Out of these, Lake Arthur has the maximum rate of silting presumably because the tributary of river on which it is located is the heaviest carrier of silt.

ROOSEVELT RESERVOIR

River	..	..	..	Salt river 55 miles on direct line from Phoenix Arizona
Catchment	.	..	..	5,760 square miles
Rainfall	..	..	..	8 inches in desert areas to 35 inches in mountains
Mean annual run-off	..	..	..	840,000 foot-acres
Height of dam	..	..	..	284 feet
Lake area	..	..	..	16,320 acres
Storage capacity	..	..	..	1,522,200 foot-acres.
Completed	..	..	..	March 1911 (1906-1911)
Year when water storage began				1911.
Range of flow	..	..	..	From a few hundred cusecs to a maximum of 150,000 cusecs in February 1891.

Watershed Characteristics

The watershed which covers 5,760 square miles varies from desert with a mean annual precipitation of eight inches to a heavily timbered mountain region with a precipitation of 35 inches. Much of the area is covered by highly erodible soils underlain by loosely consolidated alluvial deposits or disintegrated granites. Grazing in the basin under arid conditions has generally reduced vegetal protection of soil and resulted in greatly accelerated sheet and gully erosion.

Capacity Surveys

The survey done during 1925 showed an accumulation of 101,000 foot-acres of predominantly coarse grained sediment which figure worked out to an annual rate of accumulation of 6,733 foot-acres or 116.9 foot-acres per year per 100 sq. miles of catchment. The later survey done by Hayden in 1935 brought out an accumulation of 108.8 thousand foot-acres of sediment, thus showing an increase of 7.8 thousand foot-acres during the period 1925 to 1935 i.e., 780 foot-acres per year or nearly 13 foot-acres per year per 100 sq. miles of catchment as compared to the previous figure of 106.9 foot-acres per year during the 15 years prior to 1925.

This is also in contrast with 43 and 62 foot-acres respectively coming from the neighbouring Gila and Rio Grande water sheds.

The survey of the Roosevelt Reservoir during 1935 appeared to have been made under exceptionally favourable circumstances at a time of extreme low water when the bottom of reservoir was dry except under a small pool immediately above the dam. This should have permitted direct examination and mapping of the silt deposits to any desired standard of accuracy.

Edgecombe has based his remark with respect to this reservoir made on pages 8 to 10 of his book on Silting of Reservoirs on the information derived from T. A. Hayden, Hydraulic Engineer of the Salt River Valley Water-users' Association, whose subsequent report on the 1935 survey have been quoted above.

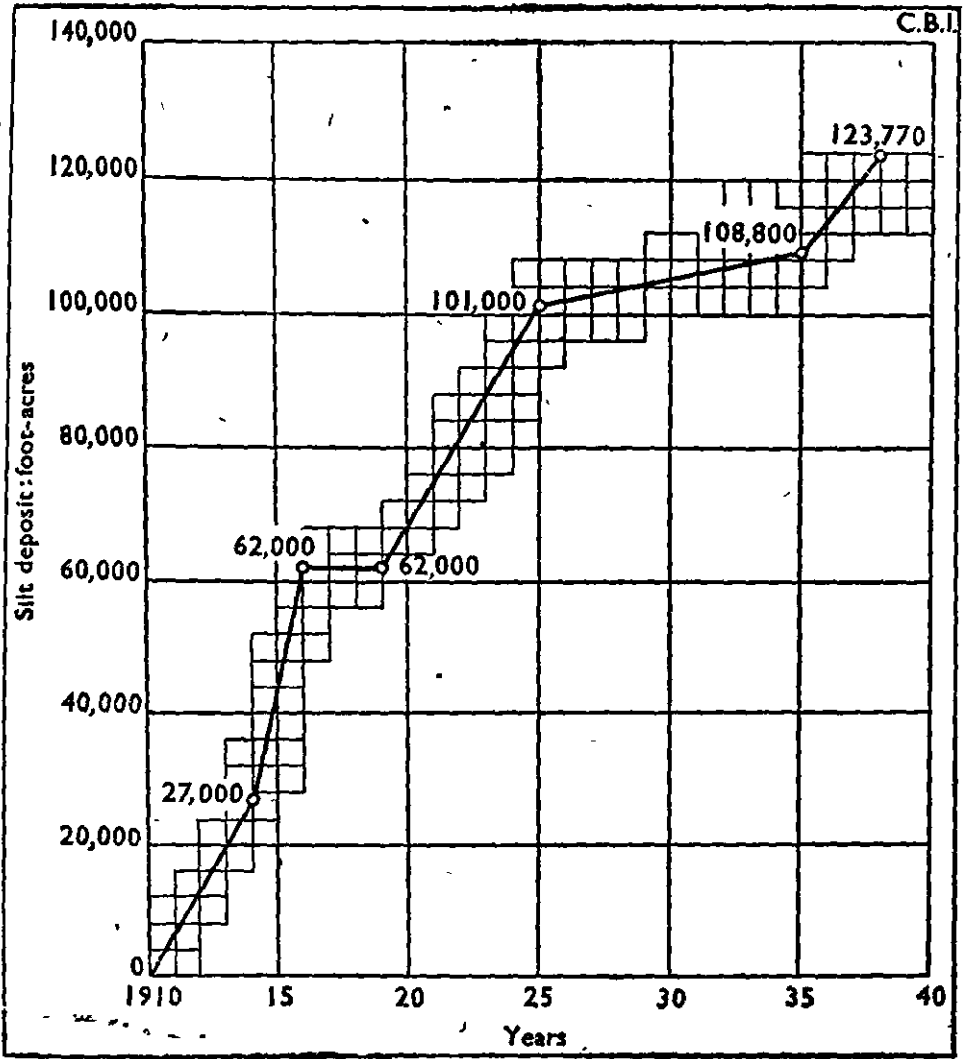
The main silt charge at the Roosevelt Reservoir is brought down by freshets during rainfall. This is in keeping with the experience elsewhere, viz., that snow-fed waters carry little silt and that the bulk of silt is brought down by rain water

Rate of Silting

This is given in the Table XLVII and Figure 68.

TABLE XLVII

Period of Record	Years	Silt Deposited			Silt deposit in foot-acres per 100 square miles of catchment per annum
		In foot-acres	In foot-acres per annum	Cumulative total in foot-acres	
1911	..	..	..	..	..
1914	3	27,000	9,000	27,000	156
1916	2	35,000	17,500	62,000	304
1919	3	0	0	62,000	..
1925	6	39,000	6,500	101,000	113
1935	10	7,800	780	108,800	13.5
1938	3	14,970	4,990	123,770	87
	27		4,584	123,770	79.6



[Figure 68 :—Rate of silting of Roosevelt Reservoir

Remarks

This is another illustration of a high rate of silting due to erodible geological formation coupled with lack of vegetable cover as a result of grazing and low rainfall in the desert portion of the catchment.

LAKE WORTH RESERVOIR

On West Fork of Trinity River five miles north-west of Fort Worth, Texas.

Catchment	..	..	..	1,870 square miles
Rainfall	..	..	..	32 or 33 inches
Run off	..	..	..	212,000 foot-acres
Height of dam	..	..	..	36 feet
Capacity	..	..	..	47,200 foot-acres
Year when water storage commenced				1914

Catchment Characteristics

The topography is rather rolling. Perhaps one-third of the area is under cultivation, the rest being devoted to forestry and grazing. A large part of the watershed is composed of sandy soil and in some reaches of colloidal clay. The flood waters enter the Lake Worth Reservoir heavily charged with silt and of a chocolate or yellowish brown colour.

The results of silt surveys are carried during 1925 & 1928 indicated as follows :—

1925	..	..	..	..	10,890 foot-acres
1928	..	..	..	..	13,837 foot-acres
Mean annual silt per 100 square miles of catchment	..	..	..	..	57 foot-acres

Table XLVIII gives the weight of dry silt of various samples taken from Lake Worth on April 26, 1929. The samples were creamy without the slightest trace of grit except nine and ten which were sandy.

TABLE XLVIII

Sample No.	Original weight of deposit per cubic foot in pounds	Weight of dry silt per cubic foot of deposit in pounds	Sample No.	Original weight of deposit per cubic foot in pounds	Weight of dry silt per cubic foot of deposit in pounds
1	73.9	18.7	6	93.1	47.2
2	75.4	21.7	7	94.4	53.9
3	75.2	22.6	8	77.6	33.4
4	79.1	29.4	9	118.9	99.2
5	90.6	45.3	10	114.3	93.5

Samples 1 to 8 were gritless colloids and passed entirely through sieves with 300 meshes per square inch. Sample 9 had 71.21 per cent. retained on 200 and sample 10 had 65.7 per cent. retained on 65 mesh.

Remarks

The sand samples generally at the head of the reservoir weigh from 93.5 to 99.2 lbs. of dry material per cubic foot of deposit. The gritless silts in the body of the reservoir weigh from 33.4 to 53.9 lbs. In spite of the low storage capacity against discharge, the silting is relatively heavy due to abnormal silt charge in the contributing stream.

ZUNI RESERVOIR

River	..	..	..	..	..	Zuni river
A tributary of the Little Colorado at Black Rock, New Mexico. (U. S. A.)						
Catchment	..	..	..	..	..	650 square miles
Mean Annual Runoff	..	..	..	..	..	17,400 foot-acres
Storage Capacity	..	..	..	..	..	15,811 foot-acres
Mean annual draft	..	..	..	..	..	4,500 foot-acres

The reservoir as originally constructed in 1907 had a capacity of 15,811 foot-acres but in 1927 *i.e.*, after 20 years' use, silting had reduced this capacity to 4,256 foot-acres or just about the mean annual draft.

The record of silting of Zuni Reservoir (Table XLIX and Figure 69) is of particular value as capacity surveys have been made almost every year since the beginning of storage in 1910. The record subsequent to 1927 has been so complicated by extensive wastage of silt over and through the dam and by silt detention in tributary valleys above the head of the reservoir that it has no definite bearing on the general rates of erosion in the water shed. But it is of particular significance in that it shows how the protective works for silt detention in the tributary valleys have reduced materially the silting in the reservoir.

TABLE XLIX

Period of Record	Years	Silt Deposited			Silt deposit in foot-acres per 100 square miles of catchment per year
		In foot-acres	In foot-acres per annum	Cumulative total in ft. acres	
1906	..	..	..	..	..
1910	4.0	1,800	450	1,800	69
1911	1.5	1,200	800	3,000	123
1914	2.1	1,200	570	4,200	83
1918	4.0	1,360	340	5,560	52
1919	1.0	680	680	6,240	105
1920	1.0	1,250	1,250	7,490	192
1921	1.0	810	810	8,300	125
1922	1.1	1,620	1,470	9,920	228
1924	1.9	380	200	10,300	31
1925	1.0	190	190	10,490	29
1926	1.0	170	170	10,660	28
1927	1.0	170	170	10,830	28
1927	0.9	450	500	11,280	77
1928	1.0	-120	-120	11,160	112
1930	1.1	800	730	11,960	..
1932	2.6	-630	-240	11,330	..
	28.2	..	432	11,330	66

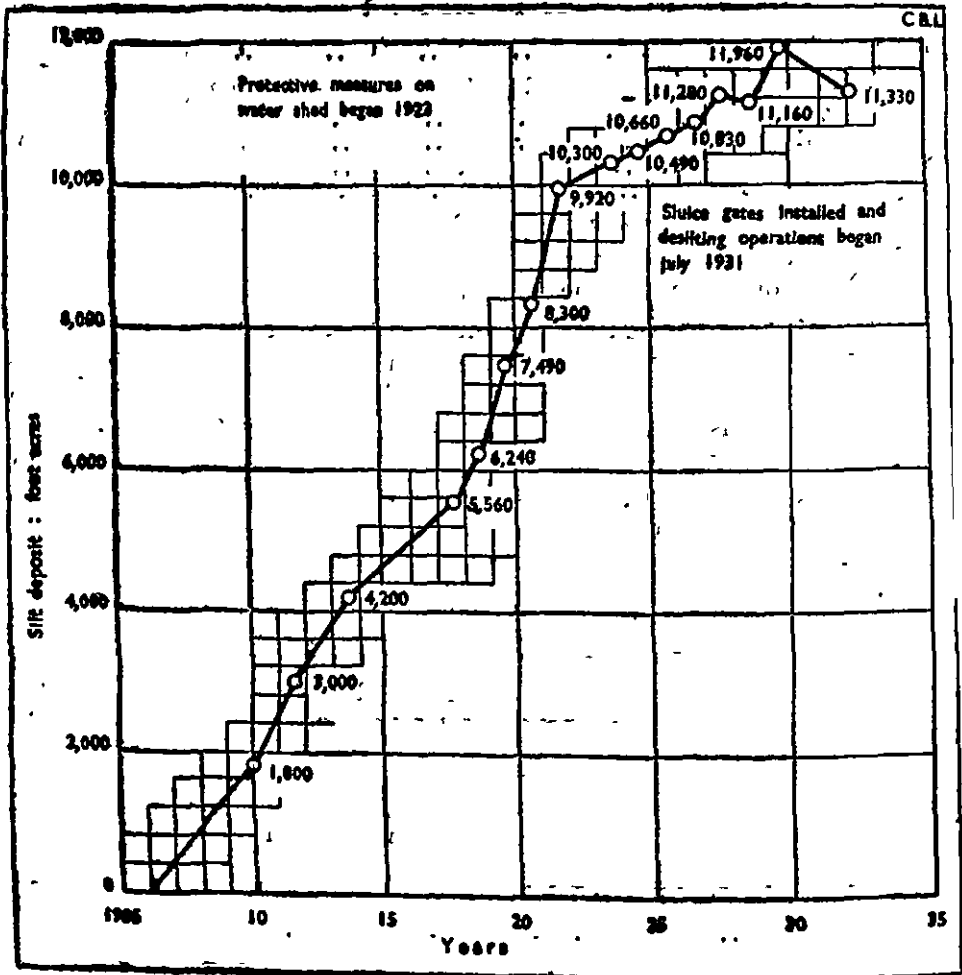


Figure 69 :—Rate of silting of Zuni Reservoir

Catchment Characteristics

The drainage basin consists mainly of plateau and mesas underlain by cretaceous sandstone and shale.

The Zuni river is an ephemeral stream carrying only flood waters and large quantities of silt. The Nutria creek is the most silt productive of its tributaries.

The high rate of silting of Zuni Reservoir reflects an advanced stage of erosion and gully development and severe sheet erosion in the catchment. Sheep breeding was introduced some 55 years ago and large flocks have been grazed on the reservation continuously, ever since.

Capacity Surveys

The survey of July 1932 was a topographical survey of the entire reservoir on the surface of the silt deposits while this reservoir was practically empty. It is probably the most accurate survey that has been made.

Protection works to hold the silt on the water shed were begun in 1923 on Rio del Los Nutrias, the principal silt producing tributary.

A sluice gate was put in 1931 and silt has been sluiced ever since. The gain in capacity for the survey of 1929 and 1932 is partly due to sluicing and perhaps partly to inaccuracies in the preceding surveys.

Remarks

The chief interest lies in the fact that the rate of silting was reduced as a result of protective measures in the most silt producing tributaries. This is a good illustration of efficient and cheap silt control. Lake McMillan is another illustration of such control though in this case it was due to the accidental growth of tamarisk in the upper part of the catchment.

PARKSVILLE RESERVOIR

River	..	..	..	..	..	..	Ocoee
Catchment	..	..	..	..	..	..	600 square miles
Rainfall	..	..	..	..	..	..	55 inches
Mean annual runoff	..	..	..	..	..	..	950,000 foot-acres
Height of dam	..	..	..	..	..	..	125 feet
Storage capacity	..	..	..	..	..	..	97,000 foot-acres

The dam is 12 miles above the mouth of the Ocoee river at Parksville, Tennessee.

Catchment Characteristics

About 70 per cent. of the drainage area is forest and wood lots. The Ducktown Mining District presents a striking example of destruction of forest lands by the fumes from smelters and roast ovens. About 20 square miles have been completely denuded. Erosion is excessive as the poisonous gases will not permit vegetal growth. This condition and the clayey soils and excessive rainfall to which this basin is subject, explain the abnormal and unnatural erosion in this catchment.

Rate of Silting.—This is shown in Table L and Figure 70.

TABLE L

Period of record	Years	Silt deposited			Silt deposit in foot-acres per 100 square miles of catchment per year
		In foot-acres	In foot-acres per annum	Cumulative total foot-acres	
1912	..	..	..	..	..
1921	9	15,600	1,720	15,600	282
1930	9.75	5,200	530	20,800	87
	18.75	..	1,125	20,800	185

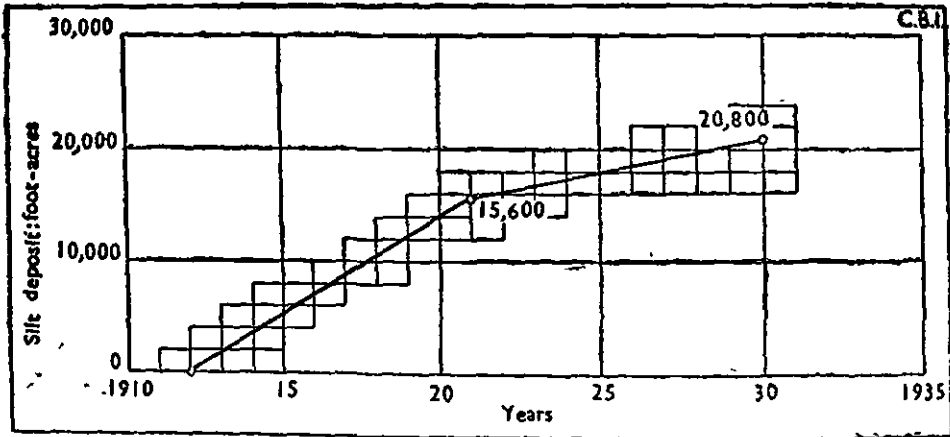


Figure 70 :—Rate of silting of Parksville Reservoir

Remarks

The high rate of silting is due to clayey soils, excessive rainfall and destruction of forest cover by poisonous gases from smelters and roast ovens.

MEDINA RESERVOIR

River	..	--	..	..	..	..	Medina, 35 miles North West of San Antonio Texas
Catchment	..	--	--	..	..	..	587 square miles
Rainfall	..	..	..	..	..	..	29 inches
Height of dam	..	..	..	..	..	..	164 feet
Storage capacity	..	..	..	..	..	..	318,703 foot-acres
Storage began	..	..	..	..	..	..	1912

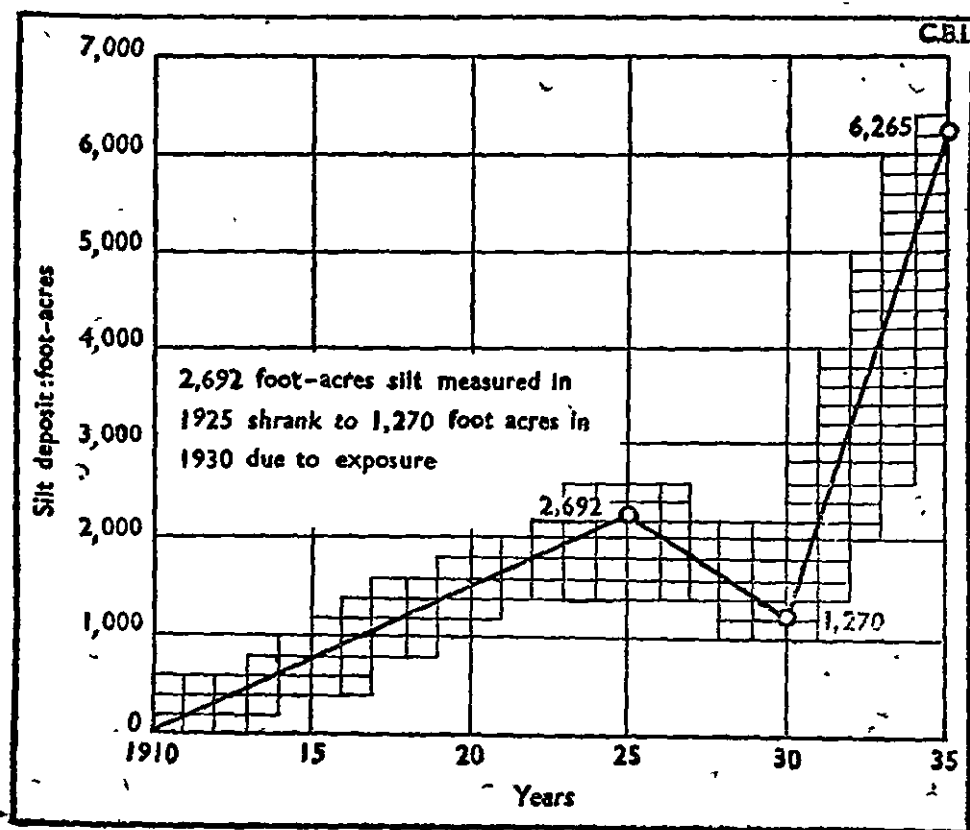
Capacity Surveys

The survey done during September 1925, after 13 years of service, showed a total silt deposit of 2,692 foot-acres or 207 foot-acres per year or 35 foot-acres per 100 squares miles of catchment per annum. The average dry weight of this material was 30 lbs. per cubic foot of deposit. The silt was grey in colour and no grit could be detected in it with fingers as there were no sandy deposits. The survey done again during Sept. 1930 was preceded by scarcity of rainfall and heavy demand of water. With the consequent lowering of reservoir level the deposits got exposed to the sun and shrunk considerably. In one place the silt depth went down from 7.2 to 2.7 feet. The dry weight of material per cubic foot of deposit went up from 30 lbs. to 80 lbs.

The silt deposits according to this latter survey worked out to 1,270 foot-acres against 2,692 of September 1925 survey, (Table LI and Figure 71). All this reduction was due to exposure and consequent shrinkage.

TABLE LI

Period of record	Years	Silt deposited			Silt deposit in foot-acres per 100 square miles of catchment per year
		In foot-acres	In foot-acres per annum	Cumulative total in foot-acres	
1912	..	..	..	..
1925	13	-2,692	207	2,692	35
1930	5	-1,422	..	1,270	..
1935	5 8	4,995	861	6,265	147
	23 8	..	263	6,265	45 4



[Figure 71 :-- Showing rate of silting in Medina Reservoir

Table LII shows the wide variation in the dry weight of silt deposit at the Medina reservoir. Samples were taken in May 1929, all passed through 300 sieve.

TABLE LII

Sample No.	Original weight per cubic foot of deposit. (Pounds)	Weight of dry silt per cubic foot of deposit (Pounds)	Sample No.	Original weight per cubic foot of deposit (Pounds)	Weight of dry silt per cubic foot of deposit (Pounds)
1	80.6	36.1	5	92.6	49.2
2	88.9	45.0	6	117.6	91.6
3	88.3	46.5	7	105.2	72.9
4	138.7	106.1	8	108.7	74.4

GIBRALTER RESERVOIR

This provides water supply for Sant Barbara California.

River	..	..	..	..	..	Santa Yaniz
Height of dam	..	..	..	..	..	185 feet.
Catchment	..	..	..	..	..	200 square miles
Lake area	..	..	..	..	..	325 acres
Storage Capacity	..	..	..	..	..	14,500 foot-acres

The water supply is very erratic. For 1921-1922 the run-off was 65,500 foot-acres which in 1923-24 dropped to 2,000 foot-acres.

Catchment Characteristics

The drainage area is hilly to mountainous in topography and is characterized throughout with sedimentary formations that have formed deep and friable soils naturally held against erosional attacks by protective cover of vegetation.

Forest Fires

Since the completion of the dam 11 fires have burnt over different parts of the basin. After the fire of 1932 only 34.5 square miles out of 200 remained unburnt.

Capacity Surveys

Re-surveys of reservoir in 1925, 1931 and 1934 have shown progressive rates of silting corresponding with accelerated erosion in increasing areas of the watershed denuded of vegetal covering by fires.

This record is of particular importance as a specific illustration of the general menace of forest fires.

Rate of Silting

This is given in Table LIII and Figure 72.

TABLE LIII

Period of record	Years	Silt deposited			Silt deposit in foot-acres per 100 square miles of catchment per year
		In foot-acres	In foot acres per annum	Cumulative total in foot-acres	
1920	..	..	..	..	..
1925	5	800	160	800	80
1931	6	1,500	250	2,300	125
1934	3	1,800	600	4,100	300
1940	6.66	1,479	222	5,579	111
	20.66	..	270	5,579	135

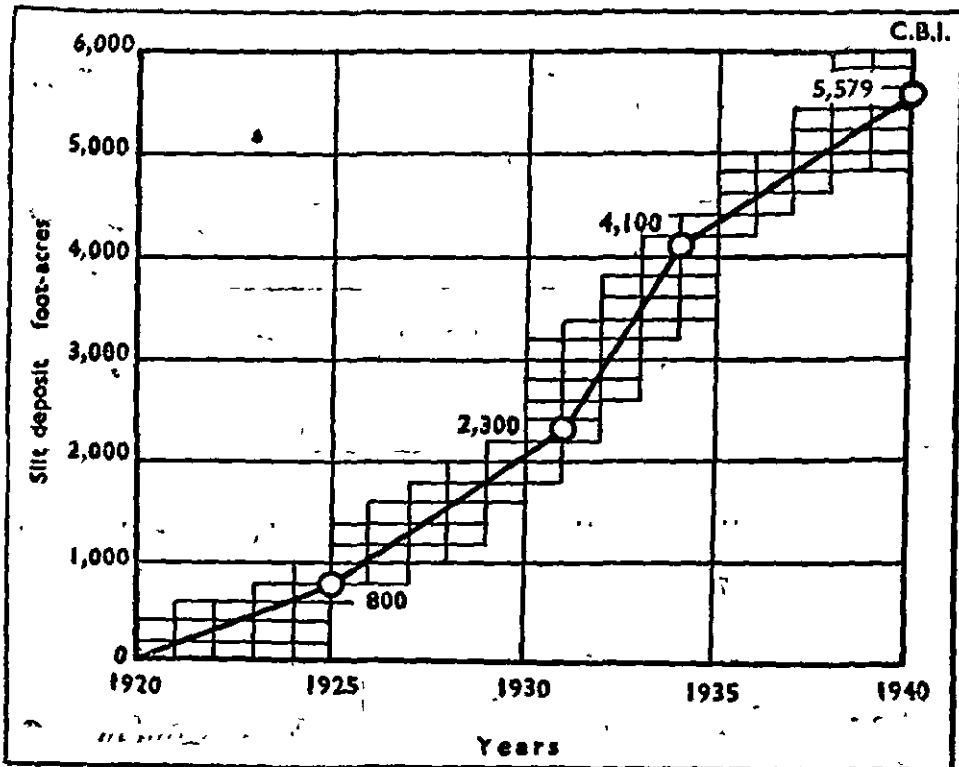


Figure 72 :—Showing the silt deposition in Gibraltar Reservoir

Remarks

The progressively increasing rate of silting is due to denudation of hill sides as a result of forest fires.

SWEET WATER RESERVOIR

This reservoir is in the San Diego County California

River	..	..	..	..	..	..	Sweet water
Catchment	..	..	..	..	..	..	181 square miles
Mean annual run-off	..	..	..	..	..	..	19,000 foot-acres
Height	..	..	..	..	..	..	70 feet original 90 feet present
Storage capacity	..	..	..	..	..	..	38,300 foot-acres
Built in	..	..	..	..	..	..	1888

Capacity surveys were made from time to time.

Catchment Characteristics

The watershed comprises, for the most part, chaparral covered mountain slopes but with some cleared land in the lower valleys. The rainfall is very erratic. Total inflow for 39 years period was 740,000 foot-acres.

Rate of Silting.—

This is given in Table LIV and Figure 73.

TABLE LIV

Period of record	Years	Silt deposited			Silt deposit in foot-acres per 100 square miles of catchment per year
		In foot-acres	In foot-acres per annum	Cumulative total in foot-acres	
1888	..	..	..	..	..
1895	7	1,137	162	1,137	90
1916	21	2,814	134	3,951	74
1927	11	1,980	173	5,859	96
	39	..	150	5,859	83

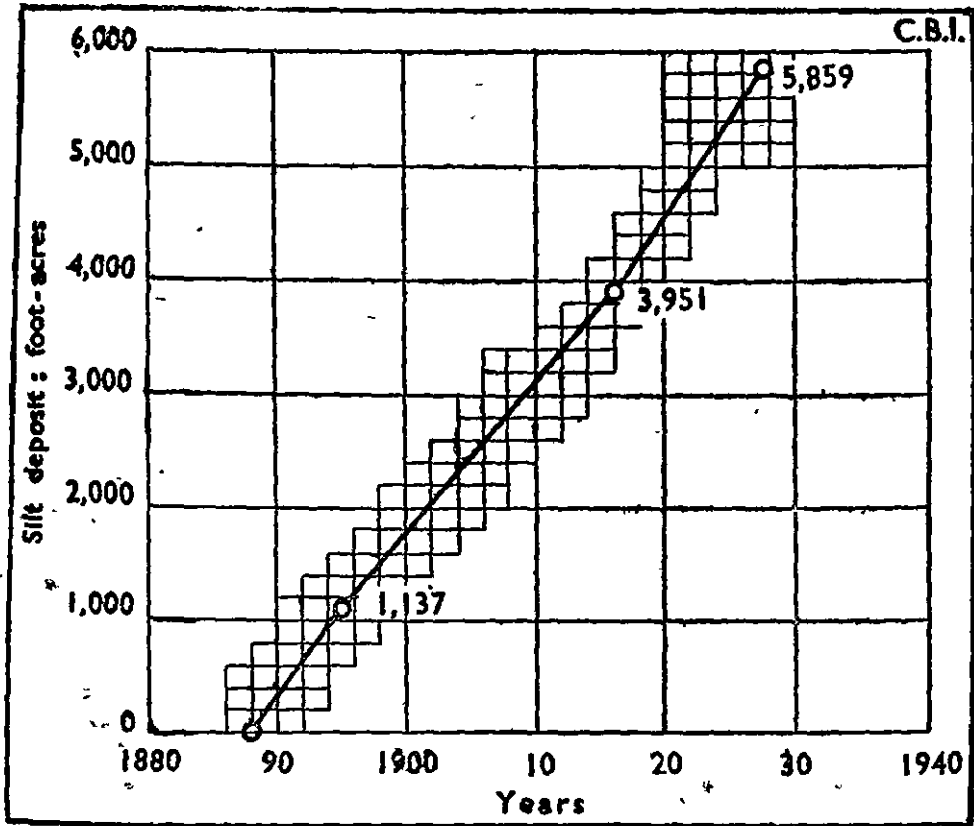


Figure 73.—Showing the silt deposition in Sweet Water Reservoir

Remarks

The high rate of silting is due to arid climate and erratic rainfall.

THE YELLOW RIVER

General—

The Yellow river is the second largest river in China next to Yangtse. Taking its origin in Singso Hai and running a course of 2,878 miles through nine provinces it drains an area of about 297,905 sq. miles. The flood ravages are continuous in the North China plains, where the silt load is very heavy. Owing to the river being confined along dykes in the lower river course and also due to the extension of the coast near the mouth, the slope of the river bed is gradually flattened, which, in turn raises the flood level and there are less chances of the silt load being carried into the sea. In the lower course of the river during the last 4,224 years there were 1,170 breaches of dykes and 422 overtopping. The change of river course has happened seven times and those would threaten highways, railways and lands.

Hydrological—

Owing to the Japanese war and also due to civil war recording of the Hydrological data was not possible in many stations till 1945, after which time a number of stations are recording the data regularly.

(a) *Meteorology*.—The basin lies between the arid N. W. and humid S. E. and has mostly a cold steppe type of climate. The annual range of temperature is—30° to 40°C, there being a severely cold winter and a fiercely hot summer. The absolute maximum temperature recorded is 45.2°C at Sian and the minimum is—32.8°C at Paotan. During winter the basin is dominated by the Mongolian Anticyclone. Rainfall is mostly in July and August (70%). Annual rainfall varies from 6 inches in loop area to 30 inches in south east. Average annual rainfall is about 16 inches. The yearly variation in rainfall is responsible for the droughts and floods.

(b) *Run-off*.—The flood season is from July to October (61%) and the water is low from November to June (39%). A comparison of the seasonal rainfall and runoff indicates that the runoff season lags behind the rainfall season by a month, both being wettest in August and driest in January for rainfall and February for runoff.

At Shenhsien station below the confluence of Wei Ho, the peak discharge of 20.25 foot-acres was recorded in August 1933 and minimum of 0.12 foot-acres in January 1927. Compared to observation made at other stations the values recorded at Shenhsien station show that the average annual mean discharge is higher, *i.e.*, 1.1 foot-acres. The following figures were recorded at Shenhsien station.

Average annual discharge	..	..	..	..	..	1.1 foot-acres
Average annual runoff (1919-44)	..	..	..	..	..	34,822,710 $\frac{1}{2}$ foot-acres
Maximum annual runoff (1943)	..	..	..	..	..	57,672,810 " "
Minimum annual runoff (1928)	..	..	..	..	..	16,775,910 " "

TABLE LV

Maximum and minimum discharge of Yellow river and its main flood producing tributaries

River	Station	Max. discharge in foot-acres	Period	Min. discharge in foot-acres	Period
Yellow River ..	Shenhsien (1919-43)	20.25	9-8-33	0.12	2-1-27
Feng Ho ..	Hotsin (1934-37)	1.58	8-9-37	0.0004	June, 35
Wei Ho ..	Hsienyang (1934-45)	7.61	Sept. 41	0.013	25-5-39
Lo Ho ..	Chuanton (1934-45)	3.25	12-7-40	0.0027	19-6-45
Ching Ho ..	Changchia Shan. (1932-45)	10.125	8-8-33	0.0016	19-6-45

(c) *Silt Load*.—Regarding its silt carrying phenomena the river is comparable to Colorado and Rio Grande in America. The Yellow river flows through loess deposits and hence there is high silt discharge during floods. The silt content of the river is an indication of the soil erosion.

Table LVI gives the Average annual silt flow in foot-acres, of the Yellow river and its tributaries :

TABLE LVI

River	Period of record	Maximum foot-acres	Minimum foot-acres	Average foot-acres
Yellow river	1934-1945	1,856,000 (1937)	82,000 (1941)	1,328,000 (9 years)
<i>Tributaries</i>				
Wei Ho	1934-1945	0.275 (1937)	0.037 (1942)	0.133
Ching Ho	1932-1945	1.17 (1933)	0.056 (1936)	0.298
Lo Ho	1934-1945	0.481 (1941)	0.0624 (1936)	0.133

Silt discharge in Lower course of Yellow river—

Not much data is available to estimate the magnitude of silt flow.

In Yellow river the maximum silt flow is in August and minimum in January. Annual variability of siltflow is 63 to 388%. Maximum silt concentration at Shenhsien recorded is 46.14% by weight. The maximum possible saturation limit of the flowing water at Shenhsien is 66.7%. Average annual concentration is 2.02%. The ratio of vertical distribution of silt between surface and bottom is practically zero at Shenhsien whereas at other places upstream, it is 1 : 3 or 1 : 2. Not much data is available about horizontal distribution of silt. The maximum mean velocity is 18.1 ft./sec (1934-1939).

The loess covered area in the basin is roughly 154,400 sq. miles or 52% of the total area of the basin. Calculations show that if the average annual silt flow of 1,328,000 foot-acres would deposit in the area below Shenhsien it means an average rising of the area of 0.85 inches per year.

Soil erosion—

The most important aspect of flood control consideration, is the erosion of top soil of loessal land. The entire watershed of Yellow river lies in the zone of very severe erosion. The soils being highly loessal, are rich in erosion potential. Rain is an important agency for erosion. Sheet erosion, gully erosion and sinkhold erosion are most common. By gully erosion and undercutting, land-falls occur which increase the silt in great volume. According to the Yellow River Commission 77,200 sq. miles of Yellow river basin between Paoton and Chengchow are subjected to severe erosion. The factors affecting the erosion are the high erosion potential of loess soils, frequency of steep slopes and gullies, rainfall, frost action, and deforestation. To control erosion in slopes tree plantations were carried out by water Conservancy Experiment Station. Most severe erosion occurs in Northern

Shensi, where the annual loss of soil may amount to 50 tons per acre. The annual loss of soil and erosion index in the water-sheds of some of the tributaries of Yellow river are as follows for 1934 :

	Yellow river at Tung- kuan	Wei Ho at Hsienyang	Chng Ho at Chang- kashan	Lo Ho at Chuang- ton
Loss of soil in tons per acre ..	9.5	24.6	9.6	48.3
Erosion index percentage ..	2.1	2.3	4.8	13.9

GENERAL OBSERVATIONS

The salient data in connection with the various reservoirs discussed in the foregoing pages, have been brought together in Table LVII and the rates of silting plotted in Figures 74 and 75. Special features regarding individual reservoirs have been mentioned briefly in column 15 of the table.

From the general trend of curves [Figures 74 & 75] it will be noticed that the rate of silting falls off, as, with the advance of years, the reservoir capacity decreases. One of the main reasons for this is the progressive reduction in volume of deposits due to settlement and shrinkage as a result of superimposed load of additional silt and exposure to weather. Also deltas progressively form at the mouths of all tributaries so that a portion of the silt is trapped in these, above reservoir level resulting in a process of aggrading of their beds. Similar aggrading of bed may occur, above reservoir head-water, on the main stream in course of time. Where the capacity of the reservoir is small, the rate of reduction will be rapid until the reservoir silts up to the section required for flood passage, beyond which there will be no further silting.

The four reservoirs of South Africa do not conform to the usual trend, perhaps because they have not been in action long enough.

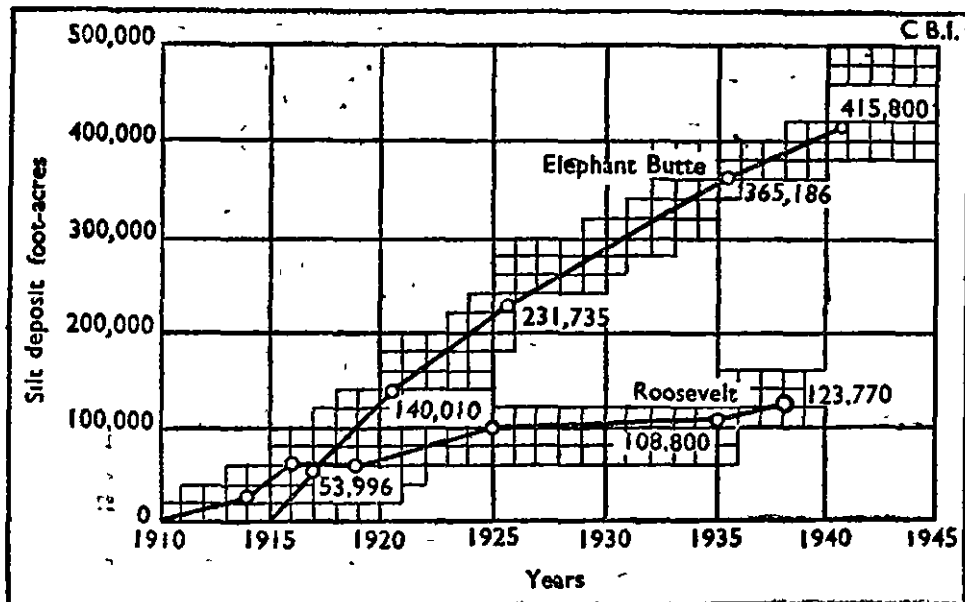


Figure 74 :—Rate of silting of Elephant Butte and Roosevelt

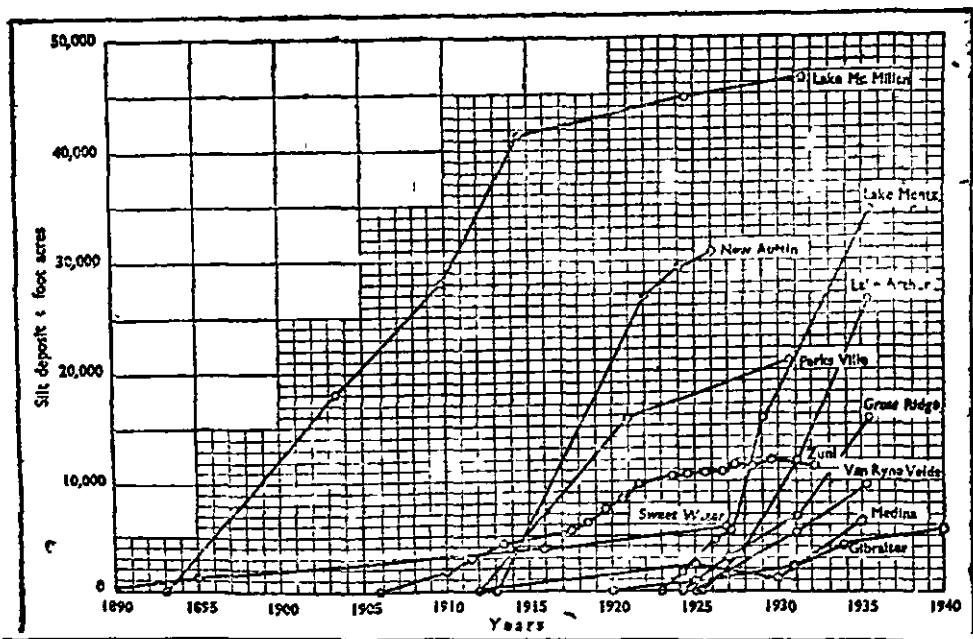


Figure 75 :—Silting of reservoirs (Based on Capacity Surveys)

TABLE

Serial No.	Name of Reservoir	Country	River	Height of dam in feet	Catchment area in square miles	Mean annual rainfall in inches	Mean annual runoff in foot-acres
1	2	3	4	5	6	7	8
2	Boulder ..	U. S. A.	Colorado (Arizona)	726.4	167,000	10	15,000,000
5	New Austin ..	U. S. A.	Colorado (Texas)	65	38,200	21	1,827,000
7	Elephant Butte	U. S. A.	Rio Grande ..	306	26,812	10-25	1,000,000
8	Lake McMillan ..	U. S. A.	Pecos ..	52	22,000	..	300,000
12	San Carlos ..	U. S. A.	San Carlos ..	203	13,540	10-15	..
19	Lake Meutz ..	Africa	Sundays ..	..	4,823	12	146,000
16	Roosevelt ..	U. S. A.	Salt ..	284	5,760	8-35	840,000
27	Lake Arthur ..	Africa	Fish ..	..	2,270	13.5	79,000
32	Grass R. Gge ..	Africa	Fish ..	..	1,583	14	42,000
34	Van Rynevelds ..	Africa	Sundays ..	113	1,477	14	33,000
46	Zuni ..	U. S. A.	Zuni ..	80	650	13	17,400
48	Parksville ..	U. S. A.	Ocoee ..	125	600	55	950,000
49	Medina ..	U. S. A.	Medina ..	164	567	29	..
65	Meiktala ..	Burma	..	..	240	..	..
68	Gibraltar ..	U. S. A.	Santayanic ..	183	200	..	546,900
71	Sweet Water ..	U. S. A.	Sweet Water ..	90	181	..	19,000

LVII

Storage capacity foot-acres	Storage Capacity	Total silt deposit foot-acres	Period in years	Annual silt deposit foot-acres	Average annual silt deposit per 100 square miles of catchment foot-acres	Remarks
	Mean annual run-off ratio					
9	10	11	12	13	14	15
30,600,000	2.03	..	..	137,000	82	82 estimated, 36 accepted for the final scheme.
				60,000	36	
32,000	0.017	30,620	13	2,355	6.2	Storage only 32,000 foot-acres against, 1,827,000 foot-acres run-off.
2,638,860	2.64	415,786	25.75	10,147	61	Erratic and violent rainfall. Rio Grande carries the largest silt burden of any major stream in the South-West
90,000	0.30	46,400	38.4	1,208	5.5	Accidental Tamarisk growth reduces silting.
1,248,000	4.18	36,896	6.33	5,829	43	Severe over grazing.
84,619	0.82	34,466	12.4	2,780	57	Soft geological formation, steep slopes, poor vegetal covering, small violent and irregular rainfall. Intense sheep farming.
1,522,200	1.81	123,770	27	4,584	79.6	Catchment consists of highly erodible soils. Over grazing under arid conditions.
63,630	0.81	26,200	10.1	2,600	115	Same as No. 19 above
64,500	1.43	15,601	11.3	1,380	87	Same as No. 19 above.
65,967	1.65	9,697	10.3	941	64	Same as No. 19 above.
15,811	0.91	11,830	26.2	432	66	Catchment in an advanced stage of erosion and gully development. Denudation due to intense sheep farming. Recovery due to silt control works.
97,000	0.102	20,800	18.75	1,110	185	Destruction of forest lands by fumes from roast ovens and smelters, clayey soil and excessive rainfall.
318,708	27	6,265	23.8	263	45.4	
30,301	..	7,091	40	177	74	Information obtained from Secretary, Centra. Board of Irrigation and Power.
14,500	0.027	5,579	20.66	270	135	Forest fires over 80 per cent. catchment.
36,300	2.05	5,859	39	150	83	Erratic rainfall, poor vegetal covering

Another noteworthy fact is that the rate of silting per year per 100 square miles of catchment is more or less of the same order of magnitude in all the arid catchments, as will be seen from Table LVIII which is an extract from Table LVII.

The estimated figures for Bhakra have also been included in Table LVIII for comparison.

TABLE LVIII

Silting of reservoirs based on capacity surveys

Name of Reservoir	Catchment area in square miles	Rate of silting per year per 100 square miles of catchment (foot-acres)
Boulder	167,000	82 (a) * 36 (b)
Elephant Butte	26,312	61
Bhakra	21,960	90(a)
Lake Mentz	4,823	57
Roosevelt	5,760	80
Grassridge	1,583	87
Van Rynvelds	1,477	64
Zuni	650	66
Sweet Water	181	83
Meiktals (Burma)	240	74
Average .. .. .	..	75

* (a) Estimated (b) Accepted.

Lake Arthur (South Africa) with catchment of 2,270 square miles has an excessive rate of silting of 115 foot-acres although the other three neighbouring reservoirs have rates of 57, 87 and 64 respectively per year per 100 sq. miles of catchment. This is probably due to the catchment of Lake Arthur being unusually silt productive.

Parksville and Gibraltar are other instances of excessive rate of silting. Both of these are typical cases of denudation, the former by destruction of forests by fumes and the latter by fires. The graph of Gibraltar shows a reverse trend.

Lake Austin and Lake McMillan show abnormally low rates of silting per 100 square miles of catchment area. In the case of Lake Austin apart from the fact that its storage capacity is smaller as compared to the mean annual run-off, the stream feeding the reservoir has an abnormally low silting content. Lake McMillan is an instance of silt prevention by vegetal cover.

Apart from these exceedingly high and exceedingly low values, the annual rate of silting per 100 square miles of catchment ranges between 57 and 90 (average 75) foot-acres although the catchment areas range from 181 to 167,000 square miles.

In Figures 76 and 77 the annual rate of silt deposit in foot-acres has been plotted against catchment area in square miles for reservoirs (including Indian, Tables I and XXVII) having catchment areas of more than 1,000 square miles. The 75 foot-acres to 100 square miles of area line has been drawn on both the figures. It will be noticed that there are no many points above this line. The upper limit for the annual silt deposit per 100 square miles, with few exceptions, therefore, appears to be at 75 foot-acres.

The Boulder Dam with a catchment area of 167,000 square miles has been plotted as an inset. Its mean annual silt yield is 81 foot-acres per 100 square miles which is not much removed from the 75 foot-acre line.

The annual rate of silt deposit for minor catchments (area less than 1,000 square miles, both foreign and Indian, is plotted in Figures 78 and 79). A line indicating the normal maximum silt deposit has been drawn on each of the two charts plotted to natural and logarithmic scales. It will be seen that the annual rate of silt deposit per square mile of catchment area increases as the catchment area decreases and if Y is the annual silt deposit in foot-acres for a reservoir of catchment area A square miles, then,

If Y_1 is the annual silt deposit per 100 square miles of catchment area then

$$Y = 5.19 A^{0.72} \left\{ \begin{aligned} Y_1 &= 5.19 A^{0.72} \times \frac{100}{A} \\ &= \frac{519}{A^{0.28}} \end{aligned} \right.$$

Area of catchment of reservoir in square miles								Annual silt deposit in foot-acres per 100 square miles
10	..	..	..	..	..	..	..	272
50	..	..	..	..	..	..	..	174
100	..	..	..	..	..	..	..	143
200	..	..	..	..	..	..	..	118
300	..	..	..	..	..	..	..	105
400	..	..	..	..	..	..	..	97
500	..	..	..	..	..	..	..	91
750	..	..	..	..	..	..	..	81
1,000	..	..	..	..	..	..	..	75

The above discussion leads to two important conclusions.

- (a) The rate of silting falls off with years.
- (b) The annual rate of silting per 100 square miles of catchment has an upper average limit of 75 foot-acres for major catchments which give rise to heavily silt laden streams. The absolute maximum rate for any major catchment will, perhaps, not exceed 90 foot-acres.

The lower limit for the annual rate of silting can be as low as zero as in the case of the Grand Coulee and the Aswan Reservoirs.

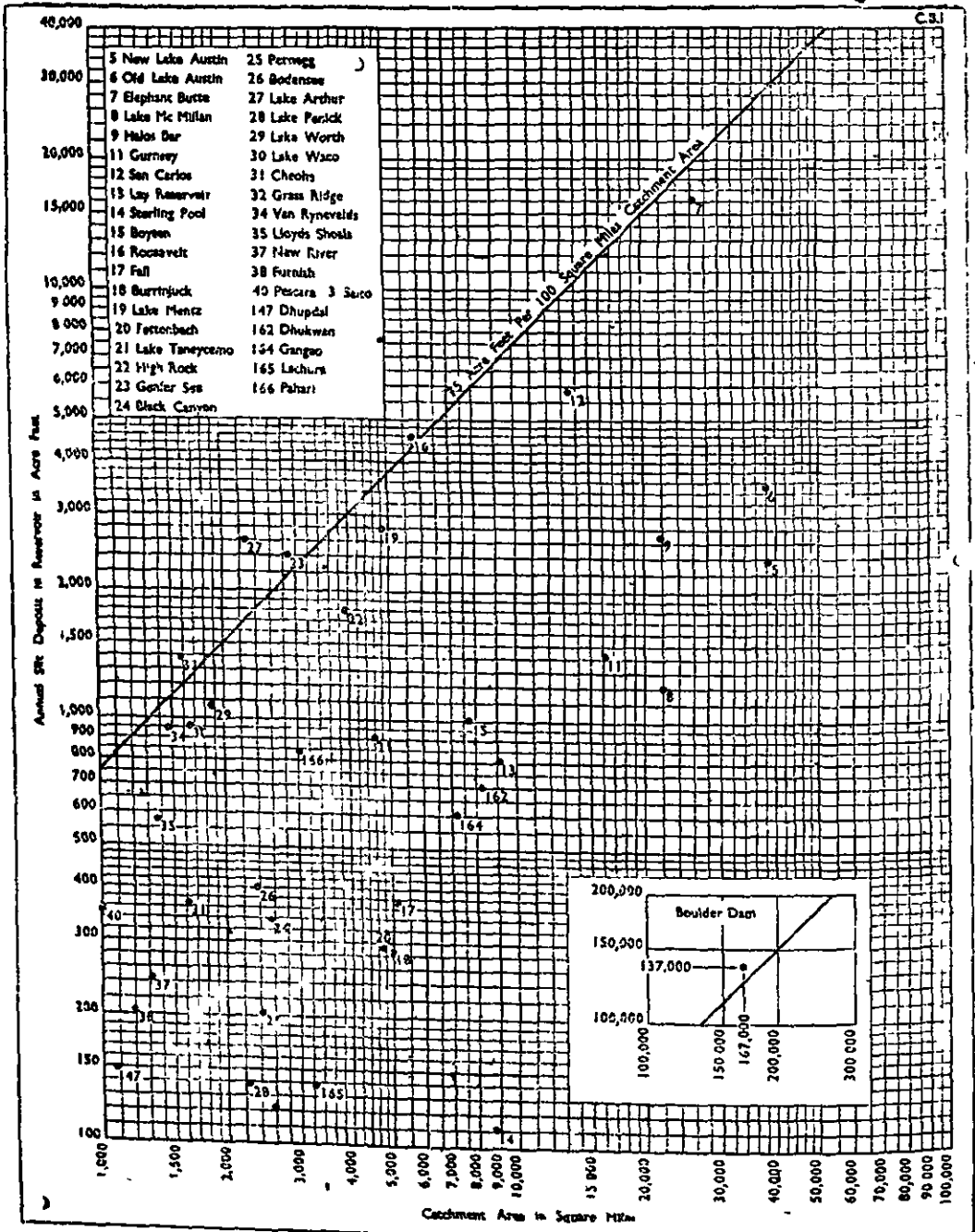


Figure 76:— Showing the annual rate of silt deposit in reservoirs with catchment areas above 1,000 square miles (Logarithmic scale).

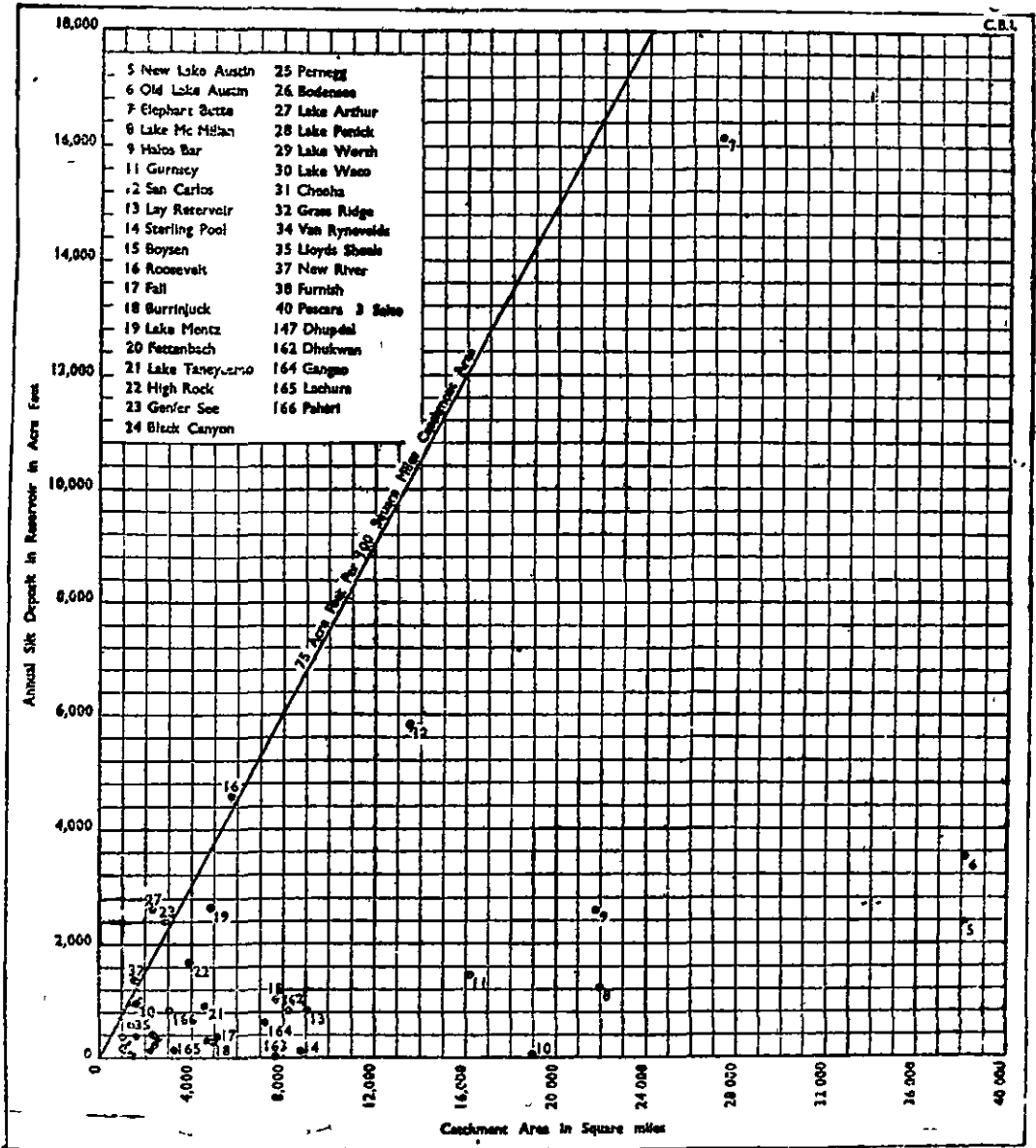


Figure 77 — Showing annual rate of silt deposit in reservoirs with catchment areas above 1,000 square miles (Natural scale)

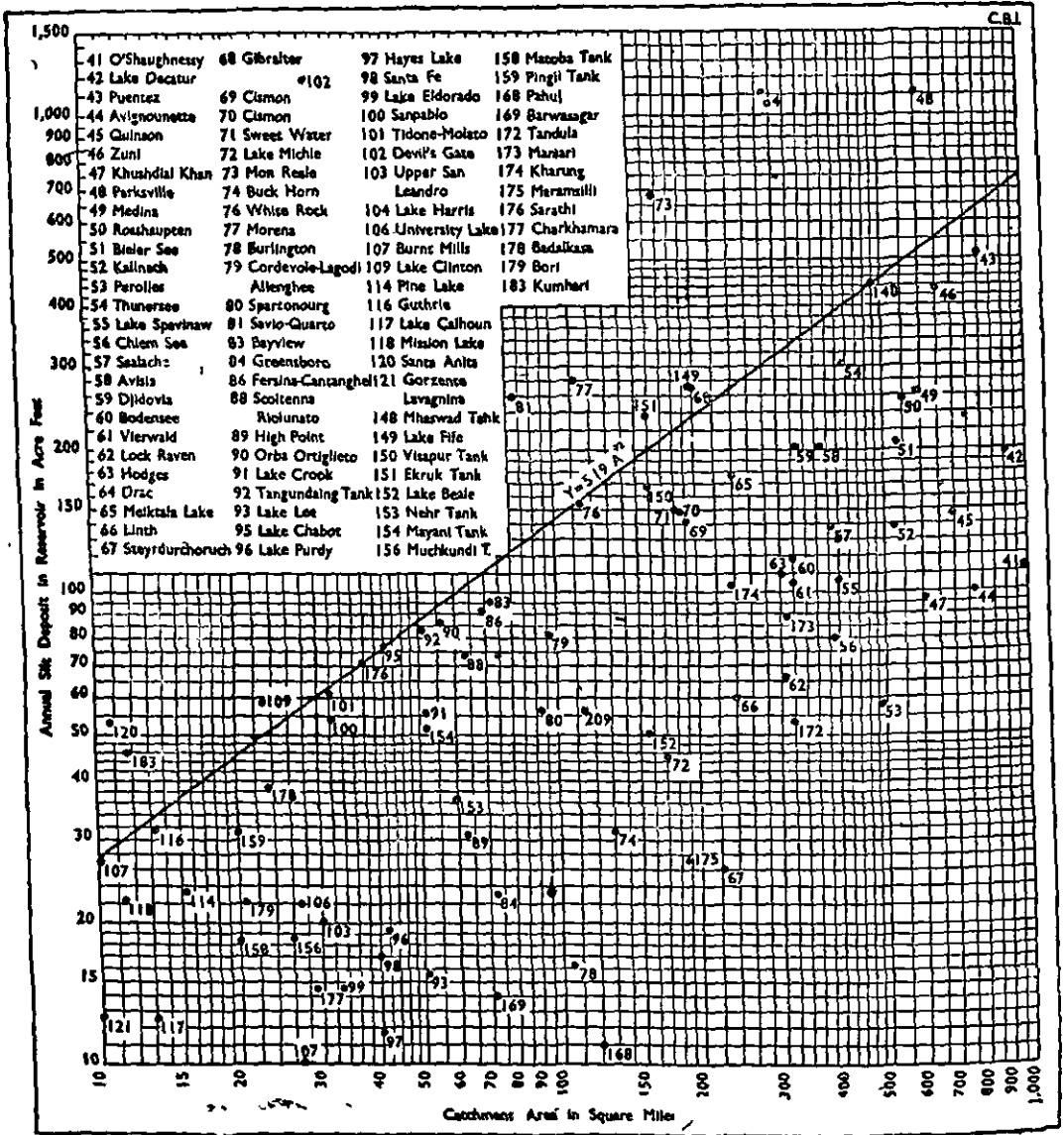


Figure 78 :— Showing annual rate of silt deposit in reservoirs with catchment areas below 1,000 square miles (Logarithmic scale)

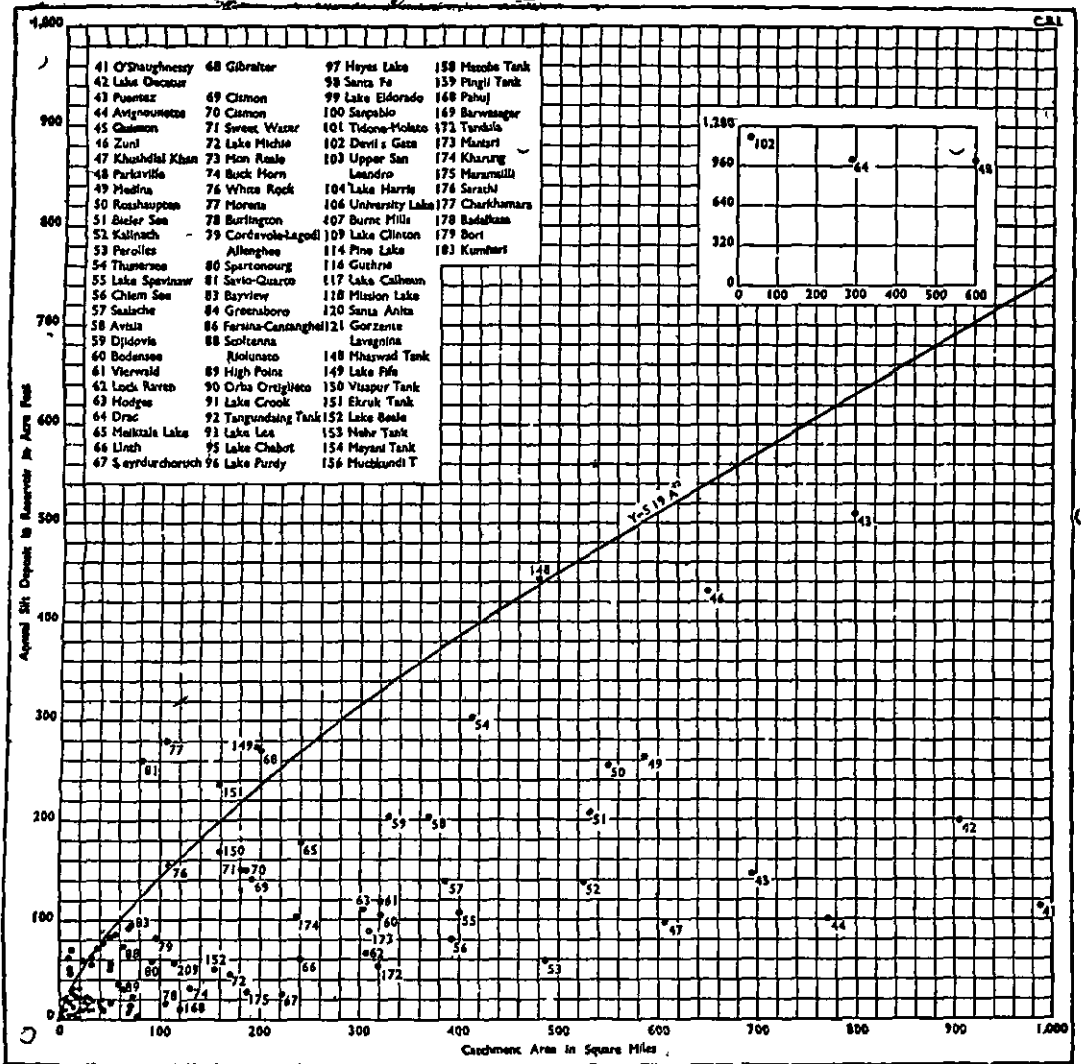


Figure 79 :— Showing annual rate of silt deposit in reservoirs with catchment areas below 1,000 square miles (Natural scale)

CHAPTER 5

Summary and Conclusions

The silting of Reservoirs is a matter of vital concern for any undertaking dependent on stored supplies, be it for irrigation, water supply, flood control or hydro-electric power. Each such project requires, for its successful functioning, a certain minimum storage capacity which must remain undiminished for a minimum specified period (generally 50 years). Hence the full capacity of the reservoir must not be less than this minimum plus the probable volume of silt deposit during that period. The correct determination of this probable silt reserve is therefore of the utmost importance for any storage scheme. The rate of annual deposition of silt will largely depend on the annual silt load brought in by the stream and the extent to which the latter will be retained in the reservoir. The problem is, thus, to determine this annual rate and to investigate if means can be devised to reduce the original silt load of the stream or to minimise its deposition in the reservoir.

Snow fed streams as a rule, carry little sediment. Rain fed streams carry heavy sediments, the concentration increasing with the increase in the intensity and the erratic nature of rainfall in their catchments. In the latter type of streams the silt concentration is, on the whole, proportional to the discharge. Flashy streams which derive most of their supplies from a few freshets only, may carry abnormal silt concentrations during such freshets (*e. g.* Roosevelt and Elephant Butte Reservoirs) but their annual silt contribution will not be materially different from that of streams running through similar catchments having the same areas but with rainfall more evenly distributed. The actual amount of total annual rainfall will not make much difference.

The catchment characteristics of the reservoir concerned can best be ascertained by means of a general geological investigation of the water-sheds of the main stream and its tributaries including special detailed examination of the sections which are most productive of silt and a study of the nature and extent of vegetable cover.

Catchments vary widely in silt production. The Columbia river above Grand Coulee Dam is supposed to be free from silt. On the other hand, the Rio Grande river above Elephant Butte Dam, the Salt river above Roosevelt Dam, the Colorado river above Boulder Dam, the Sutlej river above Bhakra, and the Zosi carry very heavy silt loads. The rate of silting in a reservoir on heavily silt laden streams averages 75 foot-acres per year per 100 square miles of catchment. The maximum rate recorded for any major catchment so far is below 90 foot-acres.

The rate of silting in any reservoir can be estimated (a) on the basis of that in existing reservoirs with similar catchment characteristics or (b) from the silt load carried by the stream concerned as calculated from a series of carefully planned experiments carried over a sufficient number of years. These experiments should aim at determining the various grades of the suspended load and as far as possible, the bed load of the stream.

The suspended load is obtained by weight and has to be converted to volume in order to work out the necessary rate of silting. Opinions differ as to the weight of dry material in a cubic foot of silt deposit in the reservoir. The figures obtained from actual tests, range from 18.7 lbs. to 106.1 lbs. Faris recommends 90 lbs. for deposits subject to prolonged exposures, 70 lbs. for those subject to short exposures and 30 lbs. for those permanently submerged. In estimating the rate of silting in the Boulder Reservoir this weight was taken as 85.9 lbs. In the case of the Bhakra Reservoir this has been assumed as 90 lbs. and for the Mahanadi and the Kosi rivers as 87.4 lbs.

Similarly, estimates vary widely for bed load, the figures ranging from 1.7 to 25 per cent. of suspended load. It is, however, generally felt that bed load in the case of large reservoirs is not of much consequence. Coarse materials like shingle, *bajri*, etc. will normally be deposited at the headwater of the reservoir, where the velocity starts getting slack on entering the reservoir, and will progressively build up a delta, thus causing a gradual aggrading of the stream bed and a reduction in the silt, depositing in the reservoir.

The rate of silting decreases with age due to shrinkage on exposure of the deposits and to the gradual formation of deltas at the mouth of tributaries which help to hold the silt above reservoir level.

The relative silting of reservoirs is best measured in foot-acres per year, per 100 square miles of catchment. The rate of silting measured as percentage of original capacity is highly misleading (See Columns 18 and 20 of Table XXXVII). Thus, the new Lake Austin (item (5) Table XXXVII) is silting at the rate of 7.3 per cent. of original capacity per year, which is very high. The annual rate per 100 square miles of catchment is, however, only 6.2 per cent. which is among the lowest on record. On the other hand, the Elephant Butte Reservoir silts annually at the rate of 0.61 per cent. of the original storage capacity and 61 foot-acres per 100 square miles of catchment. Judged as a percentage of capacity, the silting at the Lake Austin is twelve times ($7.3/0.61$) as heavy as that at the Elephant Butte, although, as a matter of fact, the latter catchment contributes 10 times ($61/6.2$) as much silt per 100 square miles as the former. The determining factor is the catchment area and not the storage capacity, as, the latter may be many times the annual run-off or only a small fraction of it depending upon the requirements and limitations of each case.

The natural rate of silting from a catchment can, to some extent, be regulated and reduced by afforestation, controlling deforestation and grazing and by suitably protecting the most silt producing portions of the catchment. But it should be clearly recognised that these control measures can only produce limited results.

A certain amount of silt control is possible by means of outlet works if of ample capacity and placed low enough, subject to the limitations imposed by run-off, the period of storage and the relative claims of irrigation and hydro-electric power.

On a reservoir silting up to the extent that the capacity fails below it, useful storage, the construction of a dam or dams higher up the main stream and its tributaries may be investigated with a view to forming new reservoirs

unless some cheaper and more convenient means of supplementing supplies can be found elsewhere.

Capacity surveys of the various reservoirs should be instituted in India on the lines of those in America, with a view to obtaining a systematic and continuous record of the silting of Indian reservoirs, due attention being paid to the volume weight relationship of silt deposits.

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NOTE.—There are a large number of publications other than those mentioned above from which information has been extracted but as these are all entered as references in one or more of the above noted publications, they have been omitted from the above list.

Appendix

Resolutions and Recommendations of the Central Board of Irrigation and Power

SILTING OF RESERVOIRS

(1) July 1939

The records from various parts of the world show that the silting of reservoirs may be serious or negligible. The Committee consider that the factor determining silting vary from site to site and must, therefore, be studied locally.

The Committee recommend that :

- (a) investigations regarding silt loads should go on ' *pari passu* ' with enquiries regarding water available for storage,
- (b) the main source or sources of the silt load should be determined and steps should be taken so far as possible before dam construction to reduce erosion in the catchment area,
- (c) every opportunity should be taken to study silt accumulation in existing reservoirs with the object of obtaining information regarding the most economical design and method of construction with reference to the life of the reservoir,
- (d) samples of silt in suspension should be taken regularly at existing river gauging sites and at or near any possible dam site. The clay content of the silt should be determined as this may exert an important influence on the volume of the deposited silt,
- (e) samples of deposits from reservoirs should be obtained so that an attempt may be made to estimate the volume of the deposited material with reference to its physical composition.

(2) July 1941

The Board approved the following Notes on Factors Affecting Silting of Reservoirs by C. C. Inglis, Esq., Dr. E. McKenzie Taylor and Rai Bahadur A. N. Khosla.

Storage reservoirs will, sooner or later, play an increasingly important part in the future development of many provinces of India. In some, they will be needed for irrigation ; in others, for generation of hydro-electric power while in others they may be used for flood control. It is highly desirable, therefore, that an early start be made towards a systematic study of the silting of such reservoirs with a view to securing representative and reliable data, under as large a variety of conditions and for as long a period of years as possible. Such a study will furnish a sound basis for correctly estimating the rate of silting of any reservoir and the height of dam required to provide the full capacity for the necessary useful storage and the additional capacity for silt reserve required to maintain the useful storage-unimpaired for the minimum specified number of years.

2. The question falls naturally into two categories :—

- (a) Correlating the volume of silt collected in existing storage reservoirs with various factors, and (b) Estimating the rate of silting in new or proposed storage reservoirs.

3. (a) The main factors controlling silt accumulation in existing storages are :
- i. Proportion of silt, if any, intercepted by an upstream lake or reservoir.
 - ii. Proportion of silt reaching the reservoir which passes out through sluices, etc.
 - iii. Degree of consolidation—i.e., weight of silt per unit volume.
 - iv. Total area of catchment and various zones into which it is considered desirable to divide the catchment in view of varying silt contributions.
 - v. Type of rainfall and snowfall in each zone.
 - vi. Effective monthly and annual rainfall in each zone.
 - vii. Mean monthly and annual temperatures in each zone.
 - viii. Monthly and annual run-off from catchment or sub-catchments.
 - ix. Slope of each zone.
 - x. Vegetation in each zone.
 - xi. Geological formation of each zone and estimated relative rate of weathering and erosion with due regard to climatic conditions.
 - xii. Total silt accumulated per year :—
 - (a) in acre feet per 100 square miles of catchment;
 - (b) in tons per square mile.

4 In the cold, arid, higher regions in the Himalayas, physical causes are mainly responsible, for the weathering and the disintegrated rock material is transported with the melting snow. These produce the grey silt found in the rivers from March until the monsoon. Landslides, so common in the Himalayas, also produce disintegrated rocky material and little soil. The second main source of silt is the erosion of the soil under the warmer humid conditions in the lower levels of the catchment. This provides the red silt during the monsoon period. It is from this latter source that the majority of the clay is derived, since clay is not produced by physical weathering at the higher altitudes.

5. Chemical weathering is essential for the production of clay and this can only take place in the lower hills where the temperatures are higher. Erosion at the lower levels is, therefore, very important as upon this will depend largely the volume-weight relationship.

6. When the object is to predict the rate of silting, two lines of investigation may be followed :

- (a) the conditions may be compared with those in other similar catchments and the estimation of rate of silting be based on silting in reservoirs in those catchments, making allowances for such differences as exist, or
- (b) the quantity of silt movement may be measured and an assumption made as regards the proportion of that likely to be trapped by the reservoir.

7. It is customary to divide silt movement into—

- (a) suspended solids, and
- (b) bed load, viz. sand, shingle, etc., moving along the channel bed

(a) *Suspended Solids* should be collected in standard silt bottles, preferably of brass to save breakage. In a straight reach, where boats can work, the sample should be taken at three points in a section at $\frac{1}{3}$, $\frac{1}{2}$ and $\frac{2}{3}$ of the width from either edge and at $\frac{1}{4}$ th the depth at each one of these points. These three samples will make up one determination of silt content and will give an approximate measure of the mean silt content over the whole section.

(b) *Bed Load*.—No method of observation of bed load has yet been standardised. Experiments are being done in this connection by the Punjab Research Institute at Madhopur with promising results.

8. During normal supplies, if the river impinges on one side and breaks up into boils and during floods when plying a boat may be risky and samples have, of necessity, to be taken at the river edge, such samples may be taken from these boils. These will be representative of the mean silt charge of the section.

9. A suitable site for observations of silt load for a proposed reservoir would be anywhere near the proposed dam site below the confluence of the lowest tributary.

10. In the case of an existing reservoir, such a site will be above the headwater of the reservoir where the water flows in a normal channel beyond the backwater effect. The results obtained in the latter case may not be fully representative, if any important tributary or tributaries join the reservoir lower down, but these will be a very near approximation. For a more detailed study, silt observations may be made on the tributaries if and when they are in flow. Where spillways exist it will be of interest to take silt samples from the flow over the latter and compare their silt load with that in the river channel, above the headwater.

11. *Capacity Surveys*.—In the case of existing reservoirs capacity surveys should be done at regular interval of years. These surveys can be carried out by observing a series of cross sections at close intervals for the entire reservoir area or as an alternative for the portion under water in conjunction with detailed contouring of the exposed area above water. For this work, to be of value, it is necessary to have a basic contour plan of the reservoir area and a network of bench marks and traverse marks spread over this area.

12. *Volume-Weight Relationship*.—Samples of silt should be taken occasionally from the various types of deposits in the reservoir with a view to determining the dry weight of these deposits. Silt deposits are of three types (1) those permanently submerged, (2) those subject to occasional exposure and (3) those subject to periodical and prolonged exposures. The first of these will have the least dry weight and the last will have the greatest.

13. It is recommended that each province select at least one site at which systematic and comprehensive silt studies be carried out over a sufficiently long period of time. Where reservoirs exist such work can generally be undertaken with little additional cost by the existing staff.

14. A detailed report on each existing reservoir or proposed dam site should be prepared in respect of catchment area, rainfall and run-off and sent to the Secretary, Central Board of Irrigation. Relevant data should be supplied in the form, Table appended.

Siting of Reservoirs

1	Serial No.	
2	Country	Reservoir
3	River	
4	Name	
5	Catchment area (square miles)	
6	Height of dam (feet)	
7	Foot-acres	Storage capacity
8	Percentage of annual runoff	
9	Per square mile of catchment	
10	Mean annual rainfall in inches.	
11	Mean annual temperature degree Fahrenheit	
12	Mean annual runoff (foot-acres)	
13	Run off per square mile of catchment (foot-acres)	
14	First	Years of capacity surveys
15	Last	
16	Period in years	
17	Suspended	Volume of silt in river in relation to volume of water
18	Bed	
19	Suspended	Weight of silt in river in relation to weight of water
20	Bed	
21	Total foot acres	Silt deposited
22	Annual foot-acres	
23	Percentage of original capacity per annum	
24	Percentage of water supply by volume	
25	Per 100 square miles of catchment per annum	
26	Remarks	
27	Reference	

(3) December 1946

Resolved that the Board considers it desirable that all Provinces and States which have large reservoirs may undertake a study of the silting of the reservoirs during the course of time and bring to their notice the following report, as accepted by the Board, of its Sub-Committee*, regarding the collection and recording of data regarding the silting of reservoirs.

Recommendations of the Sub-Committee on the collection and recording of data regarding the silting of reservoirs.

1. The Sub-Committee do not consider it feasible, at the present stage and in the light of present knowledge, to give any directive on the estimation of rate of silting in the case of proposed reservoirs. Any such estimate must depend on local knowledge and the skill of the estimator in selecting from such recorded data as is available those relating to a catchment similar, as near as may be, to the catchment he is considering.

2. The Sub-Committee point out that there are two components of the silt deposited in a reservoir.

(a) The silt in suspension in the river feeding the reservoir ;

(b) Its-bed load.

The former can be determined only very approximately. For the latter no means of determination have yet been devised. The most satisfactory data which can be selected are, therefore, instances where the total silt of both classes deposited in a reservoir has been measured.

3. There are several old reservoirs in Hyderabad State—the Pakhal Lake for instance is reported to be more than 700 years old—which are still functioning fairly efficiently and it is possible similar instances may be found elsewhere in India. If the life history of such old reservoirs could be reconstructed particularly in respect of the following, valuable information as regards overall average rate of siltation over long periods would be available not only for direct application where similar catchment and rainfall conditions prevail but also for comparison with the results obtained in other cases by various methods.

(a) Date of construction. This could be ascertained by a critical study of the old records that may be available.

(b) Original storage capacity. This could be ascertained with a fair degree of approximation by contouring the valley just below the dam and above the water-spread of the reservoir and joining up the contour lines, subject to verification by noting the actual depth of silt deposit within the reservoir limit, as far as practicable, by means of borings during the minimum water level stage. Any error that might creep in, being distributed over several centuries, the average annual rate is not likely to be materially affected.

(c) Present storage capacity.

The Sub-Committee, therefore, strongly recommend that the research officers may be requested to make necessary enquiries and investigations accordingly.

* The Sub-Committee comprised Mr. S. C. Mazumdar, Mr. T. A. W. Foy, Rai Bahadur Kanwar Sain and Rai Bahadur A. G. Maydeo.

4. The Sub-Committee wish to offer a caution to engineers who owing to lack of suitable overall measured data are compelled to utilise instances of similar catchments where an estimate of the total silt load has been made from measurements of silt carried in the stream. Such estimates, which lead to the determination of the life of reservoir, have a very definite economic angle. Project designers will be well advised to discount any facile optimism in the preparation or interpretation of such estimates of the rate of silt deposition in a reservoir.

5. The Sub-Committee consider that their most useful advice can be rendered in standardisation, as far as may be possible, of the method of collection and recording of the data of silting in actual reservoirs. They recognise that reservoirs vary enormously in size, shape and characteristics. The main and most valuable information regarding the over-all silt deposit in the reservoir is sometimes costly and difficult to collect and the best methods of obtaining it, under given physical and economic conditions, must be left to the judgement of the engineer-in-charge.

6. The main factors controlling silt accumulation in existing reservoirs are listed below and are mainly taken from "Factors affecting Silting of Reservoirs" by Sir Claude Inglis, Dr. McKenzie Taylor and Rai Bahadur A. N. Khosla to whom the Sub-Committee acknowledge their debt.

(i) Whether all silt from the catchment reaches the reservoir or a portion is intercepted by an upstream lake or reservoir, *etc.* ?

(ii) Whether all silt reaching the reservoir is trapped and if not, what proportion passes through ?

(iii) Degree of consolidation—*i.e.* weight of silt per unit volume.

(iv) Total area of catchment and various zones into which it is considered desirable to divide the catchment.

(v) Type of rainfall and snow fall in each zone.

(vi) Effective annual rainfall in each zone.

(vii) Vegetation in each zone.

(viii) Slope of each zone.

(ix) Regional geological classification of the catchment of each zone and estimated relative rate of weathering and erosion, taking climate into account.

(x) Run-off volume and peak discharge from catchment and sub-catchments.

(NOTE.—Run-off is strictly speaking not a factor, depending as it does on rainfall, catchment area, *etc.* but it is none the less useful and relatively easy to measure as compared with the other factors, which it integrates.)

(xi) Total silt accumulated per year.

(a) in acre feet per 100 square miles of catchment.

(b) in tons per square mile, considering the degree of consolidation.

7. The Sub-Committee consider that the recording of the discharges entering the reservoir should be done in the greatest possible detail if economic conditions permit. They recommend that a careful gauge capacity table or diagram be prepared for the reservoir and that the daily inflow be recorded by the estimation from the rise in gauge reading added to the measured outflow. They recommend daily discharge observations at the point or points of entering. Where this is economically not possible and the site is reasonably stable they recommend determination annually of the gauge discharge curve by periodic observations and the detailed recording of the discharges as read off this curve. Where again even this is not practicable they must leave it to the engineer concerned to give the best possible detailed estimate of the inflow:

8. Of equal importance with the measurement of the inflow is a daily recording of the releases and a clear exposition for as long a term of years as possible of the relationship between inflow, live capacity of reservoir, spillage and releases. An indication should also be given of the method of release and where this affords any special facilities, for example low level releases for disposing of any fraction of the silt entering the reservoir or specially designed outlets to dispose of density currents in the reservoir.

9. The Sub-Committee now consider item (xi) of the above recommendations quoted in para 6, which they consider the most important of all. This is that the total silt accumulated per year should be measured and recorded. As stated above they prefer direct recordings of the silt quantity to any other method of estimation. The exact method of doing so must depend on the type of reservoir.

For all reservoirs they recommend the laying down of permanent sectional lines at suitable intervals; the sectional lines being marked by concrete pillar on the flanks and the section measured annually either by levelling if the reservoir dries out or by soundings. In either case they recommend that this be done when the reservoir is at its lowest level. A further point on which information is desirable and probably easily obtainable in the case of long narrow reservoirs is the rate of advance of the delta from the head of the reservoir towards the dam. The fraction deposited in the live storage area and the dead storage area of the reservoir should also be recorded.

10. The Sub-Committee consider it desirable to determine the suspended detritus charge and the bed load in the stream entering the reservoir and in the off-taking channel. It is understood that the Board is shortly issuing standard instructions in this respect. The suspended detritus charge and the bed load should, therefore, be determined in accordance with these standard instructions, but until the sub-committee are satisfied that the methods adopted are capable of producing anything like accurate results, they do not recommend the use of the data so obtained in the problem of silting of reservoirs. They, however, consider that it might be possible to utilize this data at some future date when the technique to be adopted has proved its usefulness. The methods adopted for the collection of this data should, therefore, be recorded along with the data.

(4) December 1947

(a) Chief Engineer Jodhpur had raised a few points regarding the resolution* of the Board as under :—

(i) Due to shortage of staff Jodhpur could not take up the observations in accordance with the recommendations of the Board but if the information pertaining to measured depths of silt deposit obtained by digging the beds of tanks when they were dry, the ages of which were known accurately would be of value, the Chief Engineer was prepared to supervise the obtaining of it personally.

(ii) Regarding the advancement of delta into tank beds, he suggested that the only satisfactory way of recording would be by means of air photos taken at five years interval over a representative series of tanks ; this should not be either a difficult or costly matter to arrange.

(iii) Since there was very little silt in Rajputana rivers, yearly measurement of silt by levelling or soundings would not show significant changes, he suggested that the interval should be five years.

(iv) For flashy rivers, silt sampling is difficult to arrange and the information to be collected would not commensurate with the cost and trouble involved.

The Board examined the points raised by the Chief Engineer, Jodhpur and after discussion, decided as follows :—

(i) The information so obtained would be very useful, and Chief Engineer, Jodhpur, be requested to collect it. He should also be requested to ascertain, if possible, the dry bulk density of silt ' *in situ* ', by layers, in its wet (spongy) state and whether it is possible to distinguish the various layers—yearly or otherwise.

(ii) A good suggestion which might be adopted for all reservoirs. The period between two successive photographs would vary for each case.

(iii) The period would vary for different places and must be determined by local officers.

(iv) Agreed.

(b) Resolved that all Provinces and States be requested that :

(i) As an ultimate objective, but for the present as far as possible, at discharge observation sites on main and tributary streams, sediment discharge observations, with analysis into principal sizes, should be made concurrently with every water discharge-observation. The results should be correlated annually with erosion intensity surveys done by the Forest Department.

(ii) Every project for damming a river system should contain a report detailing, in quantitative terms, the whole relevant sediment data and the economics of action required to protect the reservoirs from rapid loss of capacity, and the rivers from undesirable regime changes.

The Board further recommends that soil conservation experts be appointed, from the investigation stage, to each reservoir project.

LIST OF PUBLICATIONS ISSUED BY THE CENTRAL BOARD OF IRRIGATION

1. Digest of Technical Notes, 1931 (Reprint).

A summary of views of Chief Engineers on the following subjects :—

- (i) Waterlogging and Reclamation.
- (ii) Effect of deforestation and afforestation on river floods.
- (iii) Design of works on sand foundations.
- (iv) Fluming of canal works.
- (v) Regulation at canal headworks.
- (vi) Design of canal falls.

2. Digest of Technical Notes, 1932.

A summary of views of Chief Engineers on the following subjects :—

- (i) Waterlogging.
- (ii) Design of works on sand foundations.
- (iii) Design of canal falls.
- (iv) Staunching of canals.

3. Catalogue of books (upto December, 1933) in the Library of the Central Board of Irrigation, Simla and its 1st and 2nd Annual Supplements (1934-36).

- 4. Hydraulic Diagrams : Energy of flow, Pressure-plus—Momentum Diagrams for the simple graphic solution of problems involving a change of section in a stream of water (Compiled by A.M.R. Montagu, M.I.C.E., etc.) (1934). Revised and Enlarged Edition 1948 by Shri N. D. Gulhati.
- 5. Glossary of Technical and Vernacular Terms in connection with Irrigation in India, together with Standard Notations. (1934). (1st Revised Edition 1941).
- 6. Fluming : A series of examples illustrating the use of Hydraulic Diagrams, C.B.I. Pubn. No. 4 by A.M.R. Montagu, M.I.C.E., etc. (1934).
- 7. The Standing Wave or Hydraulic Jump. (1934).
- 8. Observation and Record of Pressures below Works on Permeable Foundations, by Shri A. N. Khosla. (1935).
- 9. Stabilization of Soils by the use of Bitumen Emulsion—by Brigadier C. H. Haswell. (1935).
- 10. Irrigation Canal Falls. (Compiled by A.M.R. Montagu, M.I.C.E. etc.) (1935).
- 11. Annual Report (Technical) of the work of the Central Board of Irrigation, India, 1934-35.
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- 13. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1935-36. (*For the use of Board Members only*).

14. Annual Report (Technical) of the work of the Central Board of Irrigation, India, 1935-36.
15. Annual Report (Administrative) of the Central Board of Irrigation, India, 1936-37. (*For the use of Board Members only*).
16. Annual Report (Technical) of the work of the Central Board of Irrigation, India, 1936-37.
17. Notes on Waterlogging and Land Reclamation in the form of a Questionnaire. (1938).
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19. Annual Report (Technical) of the work of the Central Board of Irrigation, India, 1937-38.
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21. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1938-39. (*For the use of Board Members only*).
22. Annual Report (Technical) of the work of the Central Board of Irrigation, India, 1938-39.
23. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1939-40. (*For the use of Board Members only*).
24. Annual Report (Technical) of the work of the Central Board of Irrigation, India, 1939-40.
25. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1940-41. (*For the use of Board Members only*).
26. Water Weeds and their eradication from canals,—by C. C. Inglis, and V. K. Gokhale, with a note on Eradication of Bulrush by V. K. Gokhale and S. N. Punekar. (1941).
27. Annual Report (Technical) of the Central Board of Irrigation, India, 1941.
28. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1941-42. (*For the use of Board Members only*)
29. Annual Report (Technical) of the Central Board of Irrigation, India, 1942.
30. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1942-43. (*For the use of Board Members only*).
31. Annual Report (Technical) of the Central Board of Irrigation, India, 1943.
32. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1943-44. (*For the use of Board Members only*).
33. Annual Report (Technical) of the Central Board of Irrigation, India, 1944.
34. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1944-45. (*For the use of Board Members only*).
35. Annual Report (Technical) of the Central Board of Irrigation, India, 1945.

36. Role of Glaciers and Snow on the Hydrology of Punjab Rivers—By Shri Kanwar Sain.
37. Annual Report (Administrative) of the work of the Central Board of Irrigation, India, 1945-46. (*For the use of Board Members only*).
38. Annual Report (Technical) of the Central Board of Irrigation, India, 1946.
39. Annual Report (Administrative) of the work of the Central Board of Irrigation, 1946-47. (*For the use of Board Members only*).
40. Annual Report (Technical) of the Central Board of Irrigation, India, 1947.
41. Resolutions and recommendations (Technical) 1931-47.
42. Standards for testing soils—Tentative.
43. Land Reclamation by M. L. Mehta.
44. Annual Report (Administrative) of the work of the Central Board of Irrigation 1947-48. (*For the use of Board Members only*).
45. A manual of Library procedure. (*For the use of Board Members only*).
46. Annual Report (Administrative) of the work of the Central Board of Irrigation 1948-49. (*For the use of Board Members only*).
47. Annual Report (Technical) of the Central Board of Irrigation, India, 1948.
48. Data of High Dams in India.
49. Annual Report (Technical) of the Central Board of Irrigation, India, 1949. (*In the Press*).
50. Annual Report (Technical) of the Central Board of Irrigation, India 1950. (*In the Press*).

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