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Sediment Problems in the Indus Basin

By

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1. Introduction

Water is one of the most precious resources of West Pakistan. Although nearly 21 million acres are annually irrigated in West Pakistan which constitute one of the largest amounts of irrigated land per capita in the world, there are still 50 million acres of rich productive lands which can be developed only if irrigation water is made available. At present all the perennial supplies of the Indus river system are used by an extensive net work of irrigation canals which radiate from the rivers from the Himalayan foot hills to the Arabian Sea. It is now widely recognized that the improvement of existing irrigation and the development of new lands to meet the increasing food shortage in the country will be possible only by regulating the flood waters of the rivers which at present are going waste to the sea. This would mean construction of a large number of storage reservoirs on the main rivers of the Indus system and their tributaries.

The use and development of the rivers by a system of storage reservoirs would bring immense multipurpose benefits of irrigation, power, flood control and in other fields of human welfare, At the same time the changes in the hydraulic regime of the rivers imposed by such developments would create some new problems. The most important among these are the problems of sedimentation which may be classified under the following broad categories :—

(a) Sedimentation in Reservoirs

(b) Sedimentation in River Channels and Floodways

(c) Sedimentation in canals.

Problems of the first category will be encountered in the mountain valleys in which the reservoirs will be sited. Problems of the second and third categories will mainly arise along the 2600 miles of the Indus rivers in the plains. Irrigation Engineers in West Pakistan are already familiar

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with the sediment problems on alluvial rivers although some of these problems still remain unsolved. The new developments will create some additional problems of a type not encountered hitherto.

This paper gives an appraisal of the sediment problems in the mountain valleys of the Indus rivers and discusses in particular the planning of storage reservoirs with reference to reservoir sedimentation. The nature of the existing and new problems in the plains of the Indus rivers relating to sedimentation in rivers, floodways and irrigation channels will be discussed in a separate paper as the subject is too vast to cover all of them in a single one.

2. Formation of the Himalayas.

For an appreciation of the sediment problem it would seem advisable to describe briefly the past geological history of the Himalayas which extend from Assam to Kashmir for a length of about 1,500 miles. The western part of the Himalayas is called the Punjab Himalayas which extend from Indus to Sutlej over a length of 360 miles. The central and eastern parts are called Kumaon (200 miles long), Nepal (500 miles long) and the Assam Himalayas (440 miles long). The discussion in this paper will be largely devoted to the Punjab Himalayas. (Fig. 1 and 2).

The Himalayas can be divided into four zones viz. Trans-Himalaya, Great or Central Himalaya, Lesser Himalaya and the Siwalik. The Trans-Himalayan zone is immediately below the Tibetan Plateau and contains the great mountain ranges of the Hindu Kush, Karakoram, Aling Kangri, Kailas. They carry some of the highest peaks of the world viz. Rakaposhi (25,550 ft.), Kompire Dior (23,434), Disteghil Sar (25,869), Kanjut Sar (25,460), Harmoush (24,270), K^2 (28,250), Gasherbrum (26,470), Teram Kangri (24,489), Saser Kangri (25,170) and numerous others of over 20,000 feet elevation. The Trans-Himalayan zone is about 25 miles in width and forms the watershed between the northernly drainage of Tashgurghan, Yarkand etc. flowing into Tibet and the southernly drainage of Indus rivers destined for the Arabian Sea. There is perpetual snow and some of the great galciers viz. Batura, Yazghil, Khurdopin, Virgerab, Brotdu, Hispar, Biafo, Parmah, Baltoro, Siachen, Rimo etc. are located in this region. The rainfall is less than 10 inches and the rocks are highly metamorphosed consisting of granites, gneiss, quartzites, phyllites, slates, dolorites etc. The main Indus and its tributaries Gilgit, Shigar, Shoyk and Sutlej river rise in the Trans-Himalayan zone.

The Great Himalayan zone, below the Trans-Himalayas, is 80 to 90 miles from the edge of the plains and contains the Great Himalayan Range and in the north the Zaskar Range. The highest peaks are Nanga Parbat (26,660 ft.) and Nun Kun (23,410). The Great Himalayas form the watershed between the northernly drainage of the Indus and the southernly drainage of Jhelum and Chenab rivers. There is perpetual snow at higher elevations but the glaciers are smaller than those of the Trans-Himalayas. Rainfall is high (60 to 70 inches) particularly on the southern slopes. There

is no vegetation in the upper elevations which are snow-bound while below 15,000 elevation the vegetation consists of twisted stems, thick shrubs and grass. The rocks are both sedimentary and old metamorphosed which have been intruded by large masses of granite. The average elevation of this zone is 15,000 feet.

The Lesser Himalayan zone is 40 to 50 miles wide with an average altitude of 10,000 feet and contains the Pir Panjal, Sirmur and Dhaulandhar ranges. Ravi and Beas rivers rise in this zone. It is covered by evergreen forests between elevation 5,000 and 8,000 feet. Rainfall is very high varying from 60 to 100 inches. The rocks in this zone are both sedimentary and metamorphosed.

The Swalik zone is very wide in the Punjab Himalayas and reduces gradually towards the Assam Himalayas. Its altitude rarely exceeds 3,000 feet. The vegetal cover consists of un-healthy and depleted forests. The rainfall varies between 50 inches in the west to 100 inches in the east. The rocks are mainly sedimentary. In view of its great influence on the sediment problem, it will be discussed in greater details in the subsequent paragraph.

The Rise of the Himalayas.

The Indian peninsula is composed of fully mature and stable rock formations which were formed during the Paleozoic era, some 250 million years ago. In those times it was an island separated from the equally old and stable Tibetan plateau by a deep sea. In the late Tertiary period, some 25 million years ago, numerous powerful volcanic eruptions caused the rising of the great Himalayan mountains which was accompanied by a gigantic thrusting and folding of the earth's crust. There were a series of four great upheavals, among which the second upheaval which occurred in the Middle Miocene times is believed to be the most powerful as the Himalayas appear acquired their major features in this period. The curvilinear shape of the Himalayan ranges from Punjab to Assam indicate that the thrusts acted south-ward from Tibet in the direction of the Indian Peninsula. As a result of these movements, a great deep rift or fracture, many thousands of feet in the earth's crust, namely the Indo-Gangetic trough, was formed. The rivers rising from the Great and lesser Himalayan mountains rushed towards the deepest portions of the Indo-Gangetic trough filling it with detrital deposits. The shallow marine basins which remained after the first uplift were all obliterated and the combined flow of the Himalayan as well as the Peninsular rivers flowing into the Indo-Gangetic trough created the great "Indobrahm or Siwalik River" which flowed parallel to the Himalayas from Assam to North-west Punjab and then flowed south and westward to meet the gradually receding Miocane sea of Sind and Punjab. At the end of the Siwalik sedimentation, a third upheaval took place towards the close of the Pliocene, when the Siwalik hill ranges were formed. The fourth uplift took place at a later age when the Pir Punjal range attained its present height and the Siwalik hills were subjected to folding and over thrusting. There were minor movements ever since and some further minor adjustments of the earths surface can be expected in the future, since no part of the Himalayan belt can be said to be completely stable yet.

The Siwaliks.

The Siwalik hill ranges skirt the Himalayas throughout their 1500 miles length from Assam to North-West Punjab with remarkable uniformity. As stated earlier they were the deposits of the great Siwalik River. The sediments bear the characteristics of deposition in fresh water and their immense aggregate thickness (over 1600 feet) indicates that the site of deposition kept sinking as the sediments accumulated. The Siwaliks are made up of sandstones, grits, conglomerates, clays and silts of verying degrees of consolidation. "The coarse and often ungraded sandstones show that they must have been borne by rapidly flowing and large masses of water and laid down in wide depressions of shallow water or in swampy areas. The alternation of coarse and fine sediments suggests seasonal deposition, the coarse materials during floods of the wet season and the fine sediments during the dry season. The extraordinary similarity of deposits over long distances along the strike would show that the source of rocks were similar and that the basin of deposition was practically continuous". (Fig 3).

The Potwar Plateau.

The Potwar Plateau is a trough in the Siwalik zone lying between the Hazara mountains and the Salt Range and has an important influence on the sediment characteristics of the Indus river. It occupies an area 150 miles long and about 60 miles broad with an average elevation of 1500 feet and exposes sandstone and clays of Murree and Siwalik ages. The present Soan river is a stream of small if not insignificant volume quite disproportionate to the basin it occupies and the vast amount of detritus with which it is filled. The Potwar plateau is believed to be one of the lakes into which the Siwalik River used to flow before it joined the Indus. When this lake silted up, the course of the Siwalik River changed. In those times the Brahrumaputra River was also flowing into the Indus.

Changes in the Himalayan Rivers.

With the formation of the Siwalik ranges and the elevation of the Potwar into a plateau, the Siwalik River formed an independent drainage basin with the Sutlej River as its most easterly tributary and flowed separately from the Indus into the Arbain Sea. Ultimately "the rivers south of the Himalayas became subjected to a process of reversal of flow, their waters being forced back by the elevation of the alluvium in the Punjab to seek an outlet into the Bay of Bengal along the now aggraded and more or less level plains. The several upper parts of the Siwalik River became the modern Ganges, it having in the course of time captured the transversely running Jumma and converted it into its own affluent. The transverse Himalayan rivers, i.e. the Kali, Karnali, Gandak and Kosi, which are really among the oldest water courses of North India, continued to discharge their waters into this new river, irrespective of its ultimate destination, whether it was the Arabian Sea or the Bay of Bengal".

Further disturbances in the Himalayas caused a reversal of flow of the Brahamaputra from west to east creating a tremendous lake at the eastern

end of the Himalayas. Ultimately the water broke through the mountain ranges and the Brahamputra discharged into the Bay of Bengal. At some later stage the Ganges joined the Brahamputra, and the great delta of East Pakistan was formed.

The above sketch gives a broad idea of the stages in which the Siwaliks and the upper reaches of the Indus Plains were formed. The presently encountered strata of shales, sandstones and conglomunerate formations of these regions were the results of successive depositions of clay, sand and gravels by the great Siwalik River. The modern Indus was once a mighty river carrying the combined flow of Indus and Brahamputra into which the great Siwalik River joined in the Potwar Plateau. The formations of these regions have a significant effect on the sediment problems in the Indus Basin.

3. Sediment Loads in Indus Rivers.

The sediment loads carried by rivers depend upon the characteristics of their catchment, the physical fealturs of their valleys and the extent of man's interference with the natural conditions in their watersheds. Observed data of sediment loads in the Indus rive is meagre. The Dams Investigation Circle started sediment observations on some important rivers since 1954 and this data has proved of immense value for a preliminory appraisal of the sediment problem. The data given in this paper is largely extracted from the records of this circle and is supplemented from other sources as well.

Sediment Data of the Indus.

Statement I gives the suspended sediment observations of the Indus river and some of its tributaries during the year 1955. The data clearly shows the heavy contibutions from the rivers rising entirely in the Siwaliks viz. the Siran, Haro, Soan and other tributaries between Durband and Kalabagh. Together they contributed 77.2 million tons of sediment while adding only 7.12 MAF to the Indus flow. The Kabul river on the other hand brought only 36.3 million tons of sediment with a flow of 13.52 MAF. The unit silt runoff of the above tributaries taken togather was 3.20 acre feet per square mile compared to 0.83 and 1.35 acre feet per square mile of the Kabul and the Indus at Durband respectively.

Sediment Data of the Jhelum.

Statement II gives the observed suspended sediment in the Jhelum river and its tributaries for the year 1956. It is remarkable how clear the waters of the Himalayan river, the Kishanganga and the Jhelum at Domel area. They brought only 18.7 tons of sediment with flow of 15.51 MAF, the unit silt run-off on these rivers being 1.24 and 1.27 acre feet per square mile respectivly. On the other hand the Kunhar, Poonch, Kanshi and other tributaries between Domel and Mangla, all of which rise of flow in most part through the Siwaliks, coutributee as much as 58.7 million tons of sediment by adding only 8.50 MAF of flow, their combined unit silt run-off being 8.24 acre feet per square mile.

Statement III gives similar data for the year 1957. The Jhelum at Domel and the Kishanganga together brought 30.5 million tons of suspended sediment with a total flow of 25.39 MAF while the other tributanies together brought 25-7 tons of sediment while contributing only 7.37 MAF to the flow. In this year although the total flow at Mangla was much higher than in the previous year (32.76 MAF against 24.1 MAF) the sediment load at Mangla was actually lower (60.5 million tons against 77.4 million tons in the previous year). Analysis of the data has shown that in August 1956 the Jhelum river carried over 100,000 cusecs during the first two weeks and touched a peak of 250,000 cusecs. The sediment loads during these floods were very heavy. In 1957, on the other hand, the river flow was rather steady and hardly exceeded 100,000 cusecs with the result that inspite of the higher annual flow the sediment load was lower.

The above sediment balance sheets of the Indus and the Jhelum for a short period of observation may not lead to conclusive results. It will be necessary to collect and analyse the data for a nuuber of years before reliable conclusions can be drawn. Nevertheless there can be no doubt about the heavy contributions of the tributary riversr rising in the Siwaliks.

Sediment Loads in the Monsoon Months.

The sediment loads in rivers are very heavy during the monsoon months of July, August and September. When the rivers rise in April and May, the sediment loads also increase. The contributions during the rising period are mainly from snow-fed tributaries as rainfall during this perid is generally small. During the flood months (July to September), bulk of the contributions are due to heavy rainfall. The sediment contributions in the winter months are generally small. In general, the sediment hydrograph curve follows the flow hydrograph although there are some exceptions to this general pattern.

Statement IV gives the observed data of suspended sediment during the monsoon period July-Septmber). It is interesting to note the high clay content in Jhelum (Domel) and Kishanganga and the extremely low percentage clay in Kanshi, Haro and Soan. The other rivers have intermediate values. Similarly the extremely high silt content in the Siwalik rivers viz Kunhar, Poonch, Kanshi, Haro and Soan and the relatively high sand contributions in the Himalayan rivers viz Jhelum (Domel), Kishanganga and Indus are very significant. These features have an importamt effect on the mode of deposition in the reservoirs as discussed later in this paper.

Statement V gives the relation of sediment Loads in the Jhelum river during the monsoon period (July-September) to the annual loads. A study of this Statement along with statement IV shows that

(a) the Himalayan rivers (Jhelum at Domel and Kishan ganga) carried about 40 percent of the annual sediment during the monsoon months. The Siwalik river, on the other hand,

brought as much as 62 to 77 percent of the annual sediment during the same period.

(b) The Himalayan rivers contributed 5350 acre feet of sediment during the monsoons with a flow of 6.51 MAF. The Siwalik rivers on the other hand contributed 17,030 acre feet (nearly 3 times) of sediment in the same period while adding only 2.44 MAF. (about a third) to the flow.

These facts abundantly prove the heavy sediment contributions from the tributary rivers which rise or flow in most part in the Siwalik region.

Estimated Total Sediment loads of Indus Rivers.

The annual load of suspended sediment carried by the Indus and the Jhelum at the Kalabagh and Mangla sites is as follows :—

(Jan. -Dec.) Year	Indus		Jhelum	
	Flow (MAF)	Sediment (Million tons)	Flow (MAF)	Sediment (Million tons)
1955	83.7	260	17.9	49.4
1956	93.3	286	24.1	77.4
1957	82.0	184	32.7	60.2
Average	86.3	243	24.9	64·4

The three year average suspended sediment load of the Indus works out to 243 million tons for a flow of 86.3 MAF. The 25 year mean annual of the Indus at Kalabagh being 89.5 MAF, the estimated mean annual suspended load on the prorata basis works out to 253 million tons. Assuming bed load equal to 20 percent, the total estimated annual sedimet will be 304 million tons. On a similar basis the mean annual total sediment load of the Jhelum river at Mangla will be 68 million tons corresponding to the 25 year mean annual flow of 22.7 M.A.F-

The sediment loads in the Chenab, Ravi and Beas rivers are not known but a rough idea of sediment in these rivers can be obtained from the data of Jhelum river keeping in view their catchment areas, annual flow and the fact that these rivers except the Sutlej drain a substantial are a of the Siwaliks and may contribute even large sediment volumes persquare mile than the Jhelum. The following table gives a rough estimate of the total sediment carried by the Indus rivers at the rim stations. The sediment in the Chenab has deen estimated in relation to its flow with the

Jhelum, while the estimates for Ravi and Beas are based on the fact that most of their catchments are in the Siwaliks. The estimates of sediment laods on Sutlej are based on data of actual obsevation.

River.	Rim Station.	Catchment Area (Sq. Mls.)	Mean Annual Flow (MAF)	Estimated Total Sediment (Million tons).
Indus	Kalabagh	103,800	89·5	304
Jhelum	Mangla	13,030	22·7	68
Chenab	Marala	10,588	23·5	71
Ravi	Madhopur	3,123	6·4	25
Bias	Dera Gobindpur	5,384	12·8	40
Sutlej	Rupar	18,550	13·6	54
Total		154,475	168·5	562

In addition there are numerous rivers and hill torrents which drain the lower Siwaliks and join the rivers below the rim stations. Some of these rivers are quite large, for instance, the Khurram river on the Indus ; the Kahan, Bunha, Sukeiar and Jabba on the Jhelum ; Bhimber, Bhandar, Halsi, Dulli and Doara on the Chenab ; the Deg, Basantar, Bein and the Ujh on the Ravi ; the Black Bein on the Beas and the White Bein on the Sutlej. These rivers flow mostly during the monsoons and bring considerable volumes of sediment. Including all these rivers and other numerous torrents, the total sediment load brought by the Indus river system from their hill catchments may be roughly estimated at 600 million tons *i.e.* about 1400 crores cubic feet annually.

Comparison of Indus with Foreign Rivers.

The Sediment loads in Indus rivers are much higher than in most rivers of the World. Statement VI gives a comparison of the Indus rivers with some foreign rivers. It will be seen that the silt intensity on the Himalayan rivers of Indo-Pakistan viz. Indus, Jhelum, Kosi and Damodar is over 3 tons per acre foot which is higher than for most major rivers of the world excespt the Yellow river in China on which the silt intensity is as high as 54 tons per acre foot. The problems on the Yellow river are no doubt tremendous and for this reason it is also called the "Sorrow of China". Among the rivers in U.S.A., the silt intensity on Colorado, Rio Orande and San Juan are very high but their annual run-off are comparatively small.

4. Basic Cause and its Prevention.

If rivers carry clear water, free from silt, then there will be no sediment problems. The basic cause is, therefore, the sediment. If the sediment load in rivers is very high, as is the case in the Indus rivers, the problem becomes more difficult and acute. It is thus obvious that the solution lies in attacking the problem at the very source *i.e.* in preventing the sediment from entering the rivers. Any attempt to solve the problem after once the sediment has entered the rivers will be in the nature of a cure and not prevention.

Sediment from Himalayan Catchments.

There are two main sources of sediment namely the igneous and metamorphic mountain formations of the great Himalayan ranges and the younger, lower and still unconsolidated sedimentary rock formations of the Siwaliks. Rivers which rise in the igneous and metamorphic mountain formations, like the Indus River in its head reaches, have relatively clear water. They carry mostly coarse sediment such as boulder, rock and shingle which are rolled and pushed along the steep river beds by glacier action or running water, the suspended finer sediment being relatively small. The source of sediment in such rivers is the continuous weathering action when the rocks in the mountains disintegrate and are moved into the streams by rain and snow. The disintegration is brought about by temperature, wind and water. When changes in temperatures are abrupt, the rock masses break by sudden expansion or contraction. The presence of minerals with different coefficients of expansion and contraction aids the disintegration process. Water enters the crevices of rocks and in low temperatures freezes and expands resulting in the breaking-up of big blocks. The main transporting agencies of the disintegrated rocks are rain water and moving ice. The Himalayan rivers derive considerable quantities of sediment from the glaciers- It may not be possible to prevent the entry of these sediments partly on account of the remoteness of the catchments and partly because it will not be possible to prevent the weathering processes.

Fortunately the coarse sediment from the Himalayas does not cause serious problems. The shingle boulders and stones are carried down the steep river beds and are deposited lower down where the bed slopes become relatively flat. The river beds are aggraded and the maximum flood levels increase but they do not cause any serious problems as the valleys are deep. When reservoirs are constructed in these regions, the coarse sediment is mainly deposited at their upstorm ends and in the river valleys above them. As the water carries relatively small quantities of suspended sediment, the sedimentation problem in such reservoirs will not be as serious.

Sediment from the Siwaliks.

Rivers and streams which rise or flow in most part through the younger sedimentary rock formations of the Siwaliks carry heavy loads of suspended sediment consisting of coarse and find sand, silt and clay. Their waters are not clear and the sediment is transported in suspension. solution, saltation. are traction the quantity transported by traction being relatively small,

The source of sands is the weathering of sandstones and sandy shales while the clays and other finer materials are derived from the shale and clay formations. The disintegration of rocks is brought about by temperatures, wind water and ice. The action of ice and snow, however, is not very significent as the Siwaliks are relatively low hills. The weathering action due to wind and water on the other hand is very severe in the Siwaliks as the rocks, unlike the hard consolidated crystalline and impremeable rocks of the Himalayas, consist of pervious sandstones, friable sandy shales and loose clays. The rocks rich in alluminum silicate disintegrate into fine clay while those having a high percentage of quartz weather into coarse and fine sand.

The sediment from the Siwaliks is the main cause of the sediment problems in the Indus Basin. As it remains mainly in suspension and solution it travels long distances by stages of deposition and scouring action throughout the long journey of the rivers to the sea causing formidable problems enroute. Unlike the coarse sediment of the Himalayas which will be deposited at the upstream ends of the reservoirs and in the river valleys above, the finer sediment from the Siwaliks enters deep into the reservoirs. In the alluvial plains it aggradates the river channels, restricts the flood-ways, meanders the river courses and creates serious flood, drainage and irrigation problems.

Fortunately the entry of such sediment in the rivers can be largely controlled and prevented by maintaining healthy watersheds and by proper land use.

Healthy Watersheds.

"A healthy watershed has good plant cover, litter, humus (made up of deeayed litter) and functions like a blotter. It soaks up the water from rain or snow. Some of this water goes back into the air later through evaporation from the ground and plants. Some enters and is stored in the soil. Part of the stored water is held in the soil for plant use ; the rest moves slowly downwards to feed the streams by underground flow. When very heavy and long rains occur,.the soil may be unable to take in all the water that falls. The excess water runs off the surface but at a slow rate". A healthy watershed is a natural detention reservoir. It retards the flow during heavy rains and thus reduces the flood peaks. It retards soil erosion and hence reduces the sediment contribution to the river. It improves the river hydro-graph as the water retained in the soil during rains appears back as return flow in the low flow period. Thus a healthy watershed acts in all respects as an artificial storage reservoir built by man to regulate the flow and reduce the floods. In fact it does better as the soil is preserved and made available for growing beneficial crops and forests.

Man's interference with Nature.

Now as a result of overcutting the forests, overgrazing the grass, or burning the bushes, the protective cover over the soil has been destroyed. The soil has become compacted, cannot absorb water, with the result that the water rushes off the slopes, form gullies, carries the soil and rocks in the

channels and the small torrents begin to have higher peak floods than before. With repeated storms on unprotected slopes, this aggravated condition is multiplied until large floods occur in the main river, wreaking havoc as they rush onward. There is no water storage in the soil as the natural detention reservoirs are destroyed. Every healthy watershed of a nallah is detention reservoir. There were scores of such reservoirs on each torrent, hundreds on each tributary river and thousands on each major river. But man's unwise interference with the water-sheds has resulted in the destruction of all such natural detention reservoirs.

Source of the Trouble.

Travel through the D. I. Khan, Mianwali, Hazara, Attock and Rawalpindi Districts on the Indus; Mirpur, Gujjar Khan and Jhelum Districts on the Jhelum; Gujrat and the Kashmir area on the Chenab and there are numerous, much too numerous, examples to show that man's unwise interference with the watersheds has resulted in the destruction of all such natural detention reservoirs.

Here one will find the origin of the whole trouble. The sites from which the sediment came are claw-marked by the thousands of gullies on the rolling hills and by raw cuts in the peaceful banks along the watersheds. Here are the ugly sores from which dirty blood in the form of sediment pollutes the clear waters of the rivers and spreads disease all along their long journey to the seas. Every year millions tons of the soil of the Siwaliks is "leaving" its place leaving behind declining agriculture, infertile fields and growing poverty, thus threatening the national existence of the upland areas. year millions of tons of this every soil of the Siwaliks is "resting" in the river beds in the Punjab and Sind, choking the floodways, masking the Headworks and silting the irrigation canals creating formidable problems of floods, drainage and irrigation. History tells us that deteriorating soil and deposited soil, the double edged weapon of soil removed out of its place, has brought proud and august nations to disaster. We are told that Mosepotamia once supported 30 million people on 10 million acreas of land. Today its 5 million acreas of cultivable land can hardly sustain its 5 million people. The deserts of North Africa and Persia are ghastly reminders of the ravages of soil erosion caused by centuries of deforestation, overgrazing and abuse of land. We know that Mohan-jo-Daro was a flourishing town on the banks of the Indus some five thousand years ago. Today it stands buried under 50 feet of sediment deposits.

Solution.

The solution of the problem is well known and its basis is well founded on demonstrable evidence. The object is to stop the production of sediment. The method is the proper management of the watersheds to re-establish the plant cover and stablize the soil. Management of watersheds, and forests is a system of protecting improving and utilizing the range lands and forests in such a manner as to perpetuate the soil. How long will we allow the ugly sores in the Siwaliks to bleed ? The Siwaliks today are naked. They need cover urgently. In healing the sores and in reconstructing the Natural

Detention Reservoirs that once existed, lies the key to the solution of the sediment problem in the Indus Basin.

Soil conversation methods are well known. There is enough literature on the object. It is beyond the scope of this paper to discuss them. The need to take up these measures in the uplands as a part of a comprehensive plan for the use and development of the Indus rivers is urgent. The present soil conservation services should be expanded manifold. The visible benefits of such investments may not sound attractive. The invisible benefits are too great.

It must be understood, however, that watershed management and development of forests will not stop the weathering and erosion of bare rocks. There will always the large quantities of sediment movement from such areas. There may also continue to be much sediment produced from areas on which accelerated erosion has advanced to such a stage that stabilization is practically impossible. However, soil conservantion measures will make a big contribution to the solution of the sediment problem. Look at the Mekong and the Irrawady valleys where the vast hilly areas are covered by virgin forests and jungles. They carry five times as much flow as the Indus but their sediment loads are less (Statement VI). This is what good plant cover achieves in the control and movement of sediment and it is a tremendous achievement.

5. Sedimentation in Reservoirs.

Every reservoir is destined to silt up sooner or later. It is said that the death of a reservoir starts the very first day it is born. Geology, topogrphy, soil and climatic conditions of the watersheds have an important effect on the nature as well as the quantity of sediment delivered to a resevoir. Where parent materials are shales and lime-stones, the sand content of sediment is low. Where parent material is mianly sandstone, sand content will be high. Sediment derived from clay and friable shale formations contain much clay and colloidal matter. Clay may settle out much rapidly or be held in suspension for long periods because of the temperature or chemical nature of the water in which it is suspended. The nature of the sediment has a direct bearning on the percentage of total sediment deposited in a reservoir and on the ultimate volume of the desposited material.

The measurement of the volume of deposited sediment in a particular reservoir provides the correct basis for determining the rate of its silting. To project this rate into the future it is necessary to adjust for changing trap-efficiency and the specific weight of the deposits. Actual data of reservoir sedimentation on Indus rivers is lacking as there are no storage reservoirs in this country. In such circumstances experience on reservoirs in other countries is the only guide. Indices of rates of sedimentation usually followed in estimating silting rates of reservoirs are discussed below:-

Capacity-Inflow Ratio.

The capacity-inflow ratio which is the ratio of the reservoir capacity and the mean annual flow of the river is an useful index of the trap efficiency of a reservoir and hence its life. The trap efficiency, or effectiveness of a reservoir to retain sediment, has been found to be one of the most important factors involved in sedimentation. The smaller the capacity-inflow ratio, the greater the rate of silting, all other conditions being equal.

Capacity-Water-shed Ratio.

As inflow data is not usually available for sufficiently long periods for all rivers, it is usual to estimate the relative sedimentation hazards of different reservoirs on the basis of their capacity-watershed ratio which is the ratio between the capacity of the reservoir and the size of the drainage area of the river. In this case also the smaller the capacity-watershed ratio, the greater the rate of silting, all other conditions being equal.

Sedimentation-Index-

A some-what different method of analyzing reservoir sedimentation data is followed by the Tennessea Valley Authority. The basis of this method is that the greater the period of detention in a given reservair pool, and the lower the transit velocity and turbulence, the higher will be the percentage deposition of incoming sediment. The ratio of these two reservoir characteristics, period of detention to transit velocity, is used as a measure of the sedimentation efficiency of a reservoir. This ratio is called the sedimentation index.

It should be recognized that Sedimetation Index of a reservoir is not the same as its capacity-inflow ratio but it is this ratio divided by the mean velocity. The capacity-inflow ratio is nothing more or less than the period of detention. Regard-less of the period of detention in a pool, in the velocity and resulting turbulence are too high, the rate of sedimentation will be smaller.

Trap – efficiceny and Specific Weights.

The trap-efficiency or effectiveness of a reservoir to retain sediment is one of the most important factors involved in sedimentation. The capacity-inflow and the capacity-watershed ratios and the Sedimentation-Index are useful indices of estimating the trap efficiency. The higher these ratios, the smaller will be the trap-efficiency. Thus Kotkai, Tarbela, Kalabagh and Mangla reservoirs will have lower trap efficiences than Dhok-Pathan, Rajdhani and Lohargali reservoirs. This does not necessarily mean that their lives will be longer. The quantities of sediment brought by the main rivers into these reservoirs are so great that their useful life will be lost in comparatively shorter periods.

Progressive deposition of sediment reduces the trap efficiency of a reservoir until it becomes zero when the capacity of the reservoir is exhausted. On the other hand, progressive increase in the thickness of sediment deposits increases the specific weight of under-laying sedimdnt, thus reducing the volume occupied by a given sediment. Until full data is available, it is usual to assume that the trap-efficiency and changing specific weight counter balance each other and consequently the rate of silting progresses at an uniform rate until the storage capacity is depleted.

Distribution of Sediment in Reservoirs.

In estimating the life of reservoirs it is not only the quantity of sediment deposition that is important but also the mode and place of its deposition. There are serveral major factors that influence the mode of sediment depositon in a reservoir viz shape of reservoir, sediment characterisitcs, type of reservoir operation and sediment-reservoir volume ratio (percent of original capacity lost to sediment deposits during a given time interval). As a result of these various factors sediment deposits will transect and reduce the reservoir capacity at all elevation. In general the deposits in a reservoir resemble those in a delta made by a stream dischorging into a lake or sea. The three parts of delta deposits viz foreset beds, bottom-set beds and top-set beds will also form in a reservoir. In addition there will be a fourth kind of deposits caused by density currents. (Fig 4)

The bottom-set beds are formed of the fine sediment which settles slowly and is carried long distances into the reservoir, depositing over much of the bottom in a thin layer. The fore-set beds are composed of the coarse material brought by the river and are deposited where the velocity of the river is retarded as it reaches the reservoir level. These beds are steeply inclined. As more and more material is brought into the reservoir, the point where the fore-set beds are being formed moves further and further into the reservoir, covering the upstream ends of the bottom-set beds previously deposited. As the fore-set beds move out, the current in the river upstream is retarded because its slope is reduced and the river deposits part of its coarse material, not only on the top of the fore-set beds previously deposited, but also in the bed of the river above the water level in the reservoir. These deposits are called the top-set beds.

When river flow composed in large part of colloidal or other very fine particles, enters a reservoir of clear water, because of its greater density, it sinks to the bottom and flows down the bed of the reservoir beneath the level water surface of the clear water above. When this dense fluid reaches the dam, it spreads out and deposits very slowly in nearly level beds as shown in Fig 2. Such depositions are called density current beds. Density currents move many miles down the reservoir without visible indication on the surface.

The Bureau of Reclamation has given a design curve in its Reclamation Manual to estimate the location of sediment deposits in a reservoir (Fig 5.) This curve is based on an anal-ysis of sediment deposition of 12

reservoirs. Since then experience of sedimentation on other reservoirs has led to the evolution of other methods by the Bureau, viz, the Trignometric Method, Volume-Reduction Method, Trial and Error Method, Van't Hul and Modified Van't Hul Methods and the Area-Increment Method. It is beyond the scope of this paper to discuss these Methods.

Surveys of the first 14 years (1935—48) of sediment deposition in Lake Mead are given in Fig. 6. A total of about 2,000 million tons of sediment (dry weight) has been deposited during these 14 years. This quantity consists of approximately 45% sand and 55% silt and clay. It is interesting to note the mode of deposition of sand, silt and clay in lake Mead and its comparison with Fig. 2.

Lake Mead is a carry-ove storage and its data will not be directly applicable to the proposed reservoirs in Pakistan which are of seasonal type. Besides the mode of deposition in the Himalayan rivers will be quite different than on the Siwalik rivers. For instance in a reservoir on the Kishanganga which carries 42% sand and 51% of silt and clay, there will be heavy deposition in the top set and fore-set beds while the deposition in the bottom set beds and the dead pool will be relatively small. On the other hand in a reservoir on the Soan river which carries 7% sand and 93% silt and clay (vide statement IV) much of the deposition will occur in the bottom-set and density current beds. In the Mangla reservoir, the sediment from Kanshi, Poonch, Khad and other tributaries between Kanshi and Mangla will occupy the middle and lower end of the reservoir while the contributions from Kunhar, Kishanganga and Jhelum at Domel will be mainly deposited in the upper end of the reservoir and in the river valley upstream.

Dead Storage Capacity.

The dead storage capacity or the capacity reserved for sedimentation to be provided for a given reservoir depends upon the amount of sediment flow. The dead storage capacity is computed as usually available for 50 years. This means that the purposes for which the reservoir is designed viz. irrigation, power, flood control etc., will not be affected until the reservoir is 50 years old. Actual experience on reservoirs however shows that not all the sediment load is deposited in the portion of pool reserved for it. Part of the coarser sediment is deposited at the upper end of the reservoir thereby reducing the useful storage from the very first year while part of the still coarser sediments are deposited in the river valley upstream of the upper end of the reservoir. As sedimentation proceeds these deposits are gradually pushed and moved forward encroaching upon the useful capacity all the time. Apart from the loss of useful storage, the upstream deposits bring in additional problems of aggradation, higher flood levels, need for more land acquisition and relocation of roads and railways at and above the upper end of the reservoir.

Such problems will be encountered particularly in the case of the Kalabagh reservoir where the upstream deposition above Attock, in the Kabul and Indus rivers, will create problems of drainage and floods to Nowshera town and other neighbouring improvements.

Effect of Sedimentation.

The effects of sedimentation in reservoirs are two-fold. Firstly the capacity of the reservoir is reduced. Secondly the evaporation losses are increased. The loss of capacity would mean that the irrigated acreage dependent on storage water is rapidly returned to dependency on run-of-the river flow with a consequent shortage of water or a reduction in the irrigated area. Increased evaporation losses also have much the same effect. They are caused by two factors, firstly, the increase in the area of exposed water-surface for a given quantity in storage and secondly the increased transpiration losses from vegetation growing on sediment deposits at the upper end of reservoir. The serious effects of sedimentation also depend on the types of reservoirs as discussed below :—

Types of Reservoir.

Reservoirs for irrigation storage can be roughly divided into two categories, those providing seasonal storage and those providing "carry over" or "hold over" storage. Seasonal storages regulate the flow of the flood season for use in the following low flow season in the same year. The proposed Mangla, Kalabagh, Tarbela and other storages are of this type. They are constructed in the early stages of water resource development when the storages are inadequate to regulate the annual flow completely. Carry-over storages are those that regulate the flow in good years for use in the lean year. They become necessary as the water of a river system approach full utilization.

Seasonal storage resevoirs have a small capacity in relation to the annual river flow. For instance Mangla storage is 3.5 MAF while the annual flow of Jhelm is 22.7 MAF. Tarbela and Kalabagh have a storage of 4.2 and 6.5 MAF respectively in relation to the annual flow their of 89.5 of the Indus. Such reservoirs usually have a short life as they trap the sediment from a volume of flow which is many times capacity. On the other hand, deposition of sediment in carry-over storages is not so important as in seasonal storages because of their large capacity and the infrequent spills. It is only after a long time that sedimentation in such reservoirs affect the utilizable storage. A few examples of carry-over storages in U.S.A. are given below :—

Reservoir	Storage capacity M.A.F.	Mean Annual flow M.A-F.	Minimum Annual flow MAF.
Roosevelt	1.53	0.73	0-21
Elephant Butte	2.64	1.15	0.18
Lake Mead	35.7	12.98	4.19

Carry-over storages are therefore preferable from the sedimentation point of view. Unfortunately sites for such reservoir neither exist on the Indus nor on the Jhelum. It is only after a series of reservoirs are constructed that some of them could be used as carry-over storages. The Bhakra storage on the Sutlej with a capacity of 7.2 MAF is more a carry-over strage than a seasonal one as it is not filled every year.

Increased evapo-transpiration losses in seasonal reservoirs are not so serious as the water-supply in a considerable part of the year is ample. In fact a vegetative screen at the upper end of a seasonal reservoir grown on the deposits may be helpful as such screens reduce the sedimentry into the reservoir. In carry-over reservoirs increased losses due to evapo-transpiration are highly significent.

6. Planning Reservoirs In West Pakistan.

Reservoir sites on rivers are precious national resources. Since natural dam sites on any river are limited and a reservoir silted up represents a resource lost for ever, careful and judicious planning is essential in exploiting these irreplace-ble resources.

There are two unfortunate aspects in developing the Indus rivers in West Pakistan.

(a) All the reservoir sites on the Sutlej, Beas, Ravi and Chenab and there tributaries are located in India or Indiaheld Kashmir. The only available sites are on the Indus and Jhelum rivers and their tributaries. This means that dependable regulation of the flows of these rivers can only be achieved from the storages on the Jhelum and the Indus. This factor imposes a heavy strain on the limited storage resources on these rivers.

(b) All the good storage sites on the Jhelum and the Indus are located in the Siwalik region where the river valleys are relatively wide and flat and yield substantial storages. The Himalayan valleys are narrow and steep and their storage yield per unit height of dam is comparatively very small. The Siwalik sites have less favourable foundation conditions and greater sedimentatoin hazards. Both these factors make storage water very expensive.

The above natural and political limitations further emphasize the importance of careful reservoir planning.

Projects Initiated by the Author.

During 1951 and 1952, the author carried out preliminary studies for planning reservoir sites on the Jheum river and initiated a plan of four reservoirs viz. Mangla, Rohtas, Kamalpur and Kanshi. The Mangla and Kamalpur sites are on the Jhelum while the Rohtas and Kanshi sites are on

the tributary rivers of Kahan and Kaushi respectively. As these tributaries carried very little flow of their own, the Rohtas reservoir was proposed to be fed from the Mangla reservoir by means of a canal, while Kanshi was to be fed from the Kamalpur reservoir by means of a tunnel. Each of the off-channel storages of Rohtas and Kanshi were meant to provide replacement of the main storages of Mangla and Kamalpur respectively, the lives of the latter being comparatively short on account of their low capacity-inflow ratios (Fig 7).

There was heavy criticism of this plan from various quarters but fortunately the Central Government decided to investigate them and created the Dams Investigation Circle in 1953 headed by Ch : Abdul Hamid. All the sites have since been investigated and their feasibility established except the Kamalpur site at which detailed surveys revealed the river bed to be lower than originally estimated and that the site would be submerged by the Mangla Pond. Besides the tunnel to feed Kanshi from Kamalpur proved too costly on account of the unfavourable geology of the tunnel location. In addition to these sites the Dams Investigation Circle cartied out investigation of other sites on tributaries of Jhelum and Indus and on the main Indus itself and has been collecting basic hydro meteorological and sedimentation data on various rivers which is so essential for systematic planning and development of the water resources of the country.

During 1953-54, the author initiated another plan for integrating the water resources of the Indus and Jhelum rivers by connecting the Kotkai reservoir to Kanshi by an Upper Indus Gravity Link and creating a large off-channel storage on the Soan River at Dhok-Pathan. Later it was proposed to take off this link from Tarbela Storage by pumping as the Kotkai alignment involved expensive tunnels. Again unfortunately there was such heavy criticisum of this plan from various quarters particularly on account of its high cost. The various elements of this plan have however, been investigated since and proved feasible. It is, of course, beyond the scope of this paper to discuss these works. It is gratifying to note, however, that today, thanks to the efforts of the Dams Investigation Circle, there are a number of investigated reservoir sites which provide a useful basis for careful planning of the country's water resources and at one of these investigated sites viz Mangla, a major storage is already under construction.

Urgent needs of water an important consideration.

From the sedimentation point of view the ideal order of development would be firstly to reconstruct the natural detention reservoirs in the present unhealthy water-sheds of the Siwaliks region and secondly the sites on the smaller tributary rivers which contribute heavy sediment should be harnessed. Next in order should be the developments on the larger tributaries while the harnessing of the main rivers should be the last on the list of priorities.

However ideal the above priorities may be from the sedimentation point of view, such a program will be slow, costly and impractical from other

important considerations. For instance on the above basis, Mangla reservoir is at the wrong end of the watershed and should be the last site to be developed on the Jhelum. But the urgent needs of irrigatien and reclamation water to improve the sick lands in the Chaj and Rechna Doabs cannot be allowed to suffer. In such cases therefore the lesser evil of sedimentation has to be faced to avoid the greater evil of complete ruination of the sick lands of the two doabs. The evil of sedimentation can however be minimized simultameously taking up the watershed improvements and constructing reservoirs on the muddy tributaries as early as possible.

In general, however, preference should be given to storage sites on the tributary rivers. Although the storages on such rivers are of small capacity, they have the advantages of low capital investement and the benefits from them accrue earlier owing to their relatively shorter construction programmes.

Survey of Sites on Jhelum and Indus.

The following is a brief survey of the potential storage sites on the Jhelum and Indus rivers and their tributaries.

Sites on the Jhelum :—Jhelum has a narrow and steep valley above Domel. Although the geology of this region will permit a high concrete dam, the resulting storage will be comparatively small. From Domel to the upper end of the Mangla reservoir, the river passes through a narrow and deep valley and is not very attractive from storage point of view. Mangla appears to be the only large storage on the Jhelum. Among the tributaries, Kishanganga is even less attractive than the Jhelum above Domel as it is narrower and steeper. Lohargali and Rajdhani represent probably the only storage sites on the Kunhar and Poonch Rivers. Kanshi has a large storage but little of its own run-off.

Sites on the Indus :—The Indus river has an excellent storage site near Skardu capable of giving about 12 MAF storage. The sedimentation hazards at this site may be relatively small. The remoteness of this site and the difficult communications may not permit its exploitation for a long time to come. From Skardu to Kotkai the river passes through deep and narrow valleys, a feature which is unfavourable for large storages. Even the Kotkai reservoir yields a live storage of only 2·5 MAF for a 570 ft. high concrete dam and 4·0 MAF if the dam is increased to the maximum feasible height of 750 ft. The Attock site is excellent but it would submerge valuable lands and improvements in the Peshawar region. Tarbela and Kalabagh almost entirely harness the potential in this reach.

On the tributaries, Kalangai is an excellent storage site on the Swat river which provides useful carry-over capacity of as much as 7·5 MAF. It represents probably the only possible site on this river which can yield substantial storage. There are no storage sites on the Kabul river in Pakistan. The storages on the Siran, Dor and Haro rivers will be very small except the one at Mira Bandi on Siran for which the flow is inadequate. The Soan river has good storage sites at Morgah (near Rawalpindi). Dhokpathan and

Makhad. These can be harnessed fully only by diverting the Indus waters at Kotkai or Tarbela through the Upper Indus Link. The Makhad site, however, will be submerged by the Kalabagh reservoir.

The above survey shows a rather unhappy position of storage potential on the two rivers available for exploitation in West Pakistan. All the good sites are located in the Siwaliks with high sedimentation hazards. The very few sites available in the Himalayas are too far away to permit early development. In such circumstances judicious planning and exploitation of the sites needs no emphasis. Every year added to the life of a reservoir by careful planning will represent an important achievement.

Capacity-Inflow Ratio of Reservoirs in Pakistan.

The capacity-inflow ratio of some proposed reservior in Pakistan are given below:-

Reservoir	River	Total Capacity (MAF)	Mean Annual flow (MAF)	Capacity-inflow Ratio (Percent)
Kalabagh	Indus	8·0	89·5	0
Tarabela	Indus	5·1	64·0	8
Kotkai	Indus	3·45	62·5	6
Kalangai	Swat	3·5	6·3	56
Warsak	Kabul	0·06	13·0	0
Dhok Pathan	Soan	1·2	1·3	92
Mangla	Jhelum	4·1	22·7	18
Kanshi	Kanshi	2·0	0·2	1000
Rohtas	Kahan	2·1	0·15	1400
Rajdhani	Poonch	0·85	2·0	42
Kotli	Poonch	0·3	1·75	17
Lohargali	Kunhar	0·8	2·1	38

The above table indicates the degree of sedimentation hazards at the various sites. The smaller the capacity-inflow ratio, the greater will be the rate of sedimentation. The capacity-idflow ratio does not, however, take into account the nature of sediment loads on various rivers. For instance the capacity-inflow ratio of Kalangai is lower than that for Dhokpathan but the sedimentation hazards on this reservoir are smaller on account of the remarkably clear water of the Swat river.

Effects of Upper and Side reservoirs.

When there are more than one reservoir on a river, the reservoir at the lower and enjoys a longer life. The upper reservoir effects the lower one in three ways.

(a) The quantity of sediment inflow into the lower reservoir will be reduced. For instance if Kala bagh is constructed after Tarbela, the inflow of suspended sediment into the former will decrease from 260 million tons to 115 million tons in a year like 1955 (Statement I). With continued sedimentation in Tarbela, its trap efficiency reduces and the inflow of sediment into Kalabagh increases progressively. This process continues until Tarbela is completely silted up when practically the whole of the Indus silt flows into the Kalabagh pool.

(b) The mode of sediment deposition in the lower reservoir will be different. In the above example, as sedimentation in Tarbela proceeds only the finer sediment (clay and finer silt) escapes into Kalabagh. This type of sediment will occupy only the lower elevations of Kalabagh pool (bottom set beds and dead pool) and thus will not reduce the effective capacity as rapidly. Even after complete sedimentation of Tarbela, the nature of sediment entering Kalabagh will be quite different. Due to 300 feet deep deposits above Tarbela which extend far beyond the upper end of reservoir to varying thicknesses, the newly acquired regime slope of the river bed will be much flatter than the virgin slope and the capacity of the river to transport the quantity and grade of sedeiment will be affected in a way which will be beneficial to the lower reservoir. The physiographic changes in the torrents and tributaries directly out-falling into the Tarbela reservoir will have much the same effect.

(c) The degradation of the river bed below the upper reservoir will also be beneficial. The clear water escaping below Tarbela, for instance, picks up the sediment from the river in the reach Tarbela to Attock and below, prevents the deltaic formations above Attock due to sediment inflow from Kabul, and keeps the upper elevations of the Kalabagh reservoir clear of deposits and thus retards rapid loss in its effective capacity. This sediment will be deposited at lower elevations in the reservoir where it is not so harmful.

Tributary reservoirs also have much the same effect on the lower reservoirs on the main river. These considerations lead to the conclusion that, as a long term policy, reservoirs on the tributary rivers and at upper sites on the main river should be exploited earlier.

Economics of Storage Water.

Statement VII gives the cost of storage water from some investigated reservoir sites. This is based on the assumption that the dam and the reservoir is chargeable to the primary purpose which the reservoir is meant, viz. irrigation. This simplified assumption is adopted for purposes of comparison although the allocation of cost of the works to power, flood control and other purposes may give a different cost of unit storage.

The statement does not take into account the relative sedimentation hazards on various reservoir. Kalabagh storage may appear at first sight to be cheaper than Mangla. But if the life of the reservoir is taken into account their relative economics will be quite the oppoisite as Kalabagh is subjected to the hazards of 304 million tons of sediment annually, nearly five times the total sediment load of the Jhelum at mangla. Thus in considering the relative economics of storage water, the durability or dependability of water, apart from its capital cost yer acre-foot, is very important. A storage of one M.A.F. on the Damodar river (India) is ten times cheaper than a similar storage on the Indus. Similarly on the Mahanadi river (India) which carries as much flow as the Indus, a unit storage will be five times cheaper than on Indus from the sedimentaton point of view. (Vide Statement VI).

The primary purpose of storages in the Indus Basin is irrigation. Experience indicates that a normal irrigation project in this country takes at least 10 years for full development. As the loss of effective reservoir capacity starts from the very first year of its operation, and in some cases even earlier (The entire dead storage capacity of Alamogordo, U.S.A. was lost during a flood in 1937, while the dam was still under construction), there will be a shortage of water for the project before its last acre is developed or the projected irrigated acreage has to be reduced. Thus it will be necessary to plan for the replacement of a reservoir before the effects of its sedimentation are felt. This factor gives a different picture of the ecomenics of storage water in the Indus Basin.

Non-Silting Reservoirs.

In view of the heavy sedimentation hazards on the Indus rivers, any long-term measure to develop dependable storage supplies lies in creating non-silting reservoirs. Such storages are possible on the apparently insignificant tributary rivers. Rohtas and Kanshi are examples of such off channel storages on the Jhelum. Rohtas can be fed from Mangla and Kanshi from a diversion dam on the Jhelum river near Jataput. On the Indus, the Soan river valley shows great promise. The Morgah site has a potential of 2·0 MAF, Dhok-Pathan 12 MAF., Wadala Kas 2·5 MAF and Makhad 6 MAF. Tarbela storage can feed Dhok Pathan and Makhad and Kotkai can feed Morgah and Wadala Kas reservoirs.

Off-channel storages involve costly diversion works and connecting links and tunnels. Their chief merit is their almost permanent life. The nation's resources may not permit the development of such storages except

the more attractive ones like Rohtas. The ultimate development of the water resources, however, will depend on such storage. They will be useful both as seasonal as well as carry-over storages.

7. Conclusions.

Rivers are necessary to create reservoirs and yet, as Prof. Rollin D. Salisabury of Chicago University has rightly said, "Rivers are the mortal enemies of reservoirs". Reservoir sites in Pakistan are generally poor in geology, unfavourable in topography and extremely limited in number. The rivers which create them are more deadly in accelerating their death than some of the muddiest rivers in the world. With such limitations on one hand and the great demand of water for irrigation on the other, the task of developing "permanent irrigation agriculture" in the country is not easy. The few available reservoir sites are the most precious national resource, more so than natural deposits of coal, iron ore, petroleum and other irreplacable wealth. We must use them well and not waste them. We must promote their life and not hasten their death.

To be able to achieve the above objectives, it is necessary to understand the sediment problem and to know our rivers and our water-sheds more intimately than at present. Our country cannot afford to invest large sums on reservoirs if their service value or usefulness is lost in a short period of time.

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References.

1. Lane, E. W.	"Sediment Engineering as a quantitative Science" Proc. of the Inter-Agency Sedimentation Conference U. S. A- 1948.
2. Maddock, Thomas	"Reservoir Problems with respect to Sedimentation" Proc. of the Inter-Agency Sedimentation Conference, U. S. A. 1948.
3. Gottschalk, L. G.	"Analysis and Use of Reservoir Sedimentation Data". Proc. of the Inter-Agency Sedimentation Conference, U. S. A. 1948.
4. United Nations	"The Sediment Problem." Flood control series No. 5, 1953.
5. Karpov, A.V.	"Indus River Valley". Hydrotechnic Corporation U. S. A., 1958.
6. Wadia, D.N.	"Geology of India." 1957.
7. Thomas, H. E.	"First Fourteen years of Lake Mead" Geological Survey Circular 346, U. S. A., 1954.
8. Bureau of Reclamation.	"Interim Report, Distribution of Sediment In Reservoirs", June 1954.
9. Brown, C. B.	"Factors Affecting Useful Life of Reservoirs" Inter-society Conference on Irrigation and Drainage San Francisco 1957.
10. Krishnan M. S.	Geology of India and Burma 1943.
11. Wadia, D. N.	Memoirs of the Geological Survey of India Vol, LI, Part 2 1928.

Suspended Sediment Data of the Indus (Jan.—Dec. 1955)

River	Catchment sq. miles	Flow MAF	Sediment (1,000 AF)	Percentage sediment by wt.	Unit silt Run-off (A. F. per sq. mile)	Sediment (million tons)
Indus (Darband)	63 600	62·42	85·7	·20	1·35	144·8
Kabul (Warsak)	26,000	13·52	21·5	·22	·83	36·3
Siran (Thapla) (1)	1,070	·17	1·2	·99	1·12	2·0
Haro (G. T. Road) (1)	600	0·15	1·9	1·80	3·17	3·2
Soan (Makhad) (2)	5,100	2·07	10·7	·61	2·10	18·1
Other tributaries between Darband and Kalabagh (3)	7,430	4·73	31·73	·93	4·27	53·9
Indus (Kalabagh)	103,800	83·06	152·73	·25	1·47	260·0

(1) Data for July to September only.

(2) Data for June to October only.

(3) Computed values.

Suspended Sediment Data of the Jhelum (Jan.—Dec. 1956.)

River	Catchment sq. mile	Flow MAF	Sediment (1,000 AF)	Percentage Sediment by wt.	Unit Silt Run-off per sq. mile	Sediment (Million tons)
Jhelum (Domel)	6,000	9·51	7·6	·11	1·27	12·8
Kishanganga (Muzaffarabad)	2,820	6·00	3·5	·08	1·24	5·9
Kunhar (G. Habibullah)	910	1·93	2·4	·16	2·64	4·1
Punch (Palak)	1,710	2·65	3·6	·19	2·10	6·1
Kanshi and other tributaries between Domel and Mangla (X).	1,590	4·02	28·7	1·00	18·05	48·5
Jhelum (Mangla)	13,030	24·11	45·8	·26	3·51	77·4

(X) Computed values

STATEMENT III

Suspended Sediment Data of the Jhelum

(Jan. - Dec. 1957)

River	Catchment Sq. Miles	Flow MAF	Sediment (1000 AF)	Percentage Sediment by wt.	Unit silt Run-off A.F. per sq. Mile.	Sediment (Million tons)
Jhelum at Domel	6,000	17·76	12·11	0·09	2·02	21·5
Kishanganga at Muzaffarabad.	2,820	7·63	5·89	0·10	2·09	10·0
Kunhar at Garhi Habibullah	910	2·60	2·67	0·14	2·94	4·5
Poonch at Palak	1,710	2·97	3·74	0·17	2·19	6·3
Kanshi Nallah	435	0·17	1·15	0·96	2·65	2·0
Other tributaries between Domel and Mangla (1)	1,155	1·63	10·20	0·87	8·67	16·9
Jhelum at Mangla	13,030	32·76	35·58	0·15	2·74	60·2

(1) Computed values.

STATEMENT IV

Sediment loads during monsoon months (July, August, September)

(Values in 1000 A. F.)

Site	Year	Sand.	Silt.	Clay.	Total Sediment.	Flow (MAF).
1. Jhelum (Domel)	1955	2·32	1·56	0·56	4·44	3·03
	1956	0·61	2·51	1·03	4·15	3·06
	1957	0·74	0·95	0·53	2·22	5·84
	Average	1·22	1·67	0·71	3·60	3·98
	Percent	34	46	20	100	
2. Kishan-Ganga. (Muzzaf-farabad).	1955	0·93	1·00	0·71	2·64	2·84
	1956	0·56	0·52	0·17	1·25	1·82
	1957	0·94	0·61	0·36	1·91	2·94
	Average	0·81	0.71	0·41	1·93	2·53
	Percent	42	36	22	100	
3. Kunhar (G. Habi-Bullah)-	1955	0·53	0·99	0·24	1·76	0·34
	1956	0·61	0·61	0·14	1·36	0·71
	1957	0·45	0·55	0·17	1·17	1·20
	Average	0·53	0·72	0·18	1·43	0·92
	Percent	37	50	13	100	
4. Poonch (Pelak).	1955	1·71	2·59	0·77	5·07	1·60
	1956	1·17	1·75	0·44	3·36	1·78
	1957	0·32	0·68	0·19	1·19	0·74
	Average	1·07	1·67	0·47	3·21	1·31
	Percent	34	52	14	100	
5. Kanshi	1957	0·04	0·65	0·02	0·71	0·07
	Percent	5	92	3	100	

Statement IV (Continued).

Site.	Year	Sand.	Silt.	Clay.	Total Sediment.	Flow (MAF)
6. Jhelum (Mangla)	1955	8·88	11·53	2.16	22.57	5·97
	1956	16·53	14·58	2·36	33·47	9·75
	1957	5·32	4·51	1·83	11·66	11·14
	Average	10·24	10·20	2·12	22·56	8·95
	Percent	46	45	9	100	
7. Indus (Kalabagh)	1955	42·17	53·12	9·22	104·51	39·24
	1956	45·72	73·16	13·73	132.61	51·04
	1957	33·76	25·28	10·34	69.98	44·11
	Average	40·55	50·72	11·09	102·36	44 79
	Percent	40	50	10	100	
8.Haro (G.T.Road)	1956	0·08	1.09	0·06	1·23	0·30
	1957	0·01	0·12	0·02	0.15	0·10
	Average	0·05	0·6	0·04	0·69	0·20
	Percent	7	88	5	100	
9. Soan (Makhad)	1955	0·69	7·60	7·67	3·96	2·00
	1957	0·11	1·79	0·11	2.01	0·40
	Average	0·40	4·69	0·39	5·48	1·20
	Percent	7	86	7	100	

STATEMENT V

Relation of suspended sediment in Monsoon period to Annual

Site.	Sediment (1000 AF)			Sediment content (%by. wt.)	
	Annual	Monsoon	Percent	Annual	Monsoon
Jhelum (Domel)	9·29	3·60	39	0·106	0·130
Kishanganga (Muzzaffarabad)	4·47	1·93	43	0·092	0·10)
Kunhar (Garhi Habibullah	2·38	1·43	63	0·161	0·220
Poonch (Palak)	4·18	3·21	77	0·229	0·330
Kanshi	1·15	0·71	62	0·950	1·620
Other tributaries between Domel and Mangla.	15·36	11·68	67	3·36	20·900
Jhelum (Mangla)	36·83	22.56	58	0·207	0·350

Note :—All figures are based on averages of three years data (1955, 1956, 1957) except in the case of Kanshi which is for one year (1957) only.

STATEMENT VI

Comparison of Sediment Loads in Various Rivers

River	Station	Drainage Area (sq. miles)	Annual Flow (MAF)	Total sediment (Million tons)	Silt Intensity (tons per A.F.	Silt contents (% by wt.
Indus (Pakistan)	Kalabagh	103,800	89·5	304	3·28	0·230
Jhelum (Pakistan)	Mangla	13,030	22·7	68	3·04	0·207
Kosi (India)	Chatra	23,800	49·2	174	3·45	0·286
Mahanadi (India)	Naraj	50,900	73	62	0·85	0·067
Damodar (India)	Rhondia	8,500	8·1	28	3·45	0·285
Irrawaddy (Burma)	Prome	141,000	425	291	0·69	0·057
Mekong (Indochina)	Kratie	261,000	400	80	0·20	0·020
Red (Indochina)	Vietrie	43,500	100	130	1·30	0·079
Yangtze (China)	Chikiag	394,000	416	504	1·21	0·097
Yellow (China)	Shensien	276,000	35	1890	54·00	4·400
Pear West (China)	Wuchow	121,000	205	28	0·13	0·011
Colorado (U.S.A.)	Grand Can. yon	137,000	13	261	20·10	
Mississippi (U.S.A.)	Natchez	1,150,000	435	147	0·34	
Rio Grande (U.S.A.)	San Mareial	27,700	1·2	28	23·30	
San Juan (U.S.A.)	Bluff	23,900	1.8	51	28·30	

STATEMENT VII

Unit Storage Cost of Water on some Investigated Sites.

Reservoir	Live Storage M.A.F.	Storage cost (Crores of Rs.)	Cost of Unit Storage (Rs. per A.F)	Capacity-Inflow Ratio (Percent
Mangla	3·5	74·5	213	18
Kalabagh	6·4	78·0	122	9
Tarbela	4·2	70·2	168	8
Kotkai (High Dam	2·5	177·0	706	6
Rohtas	2·0	25·0	125	1400
Rajdhani	0·75	19·2	257	42
Lohargali	0·7	33·7	482	38

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FIG. 1

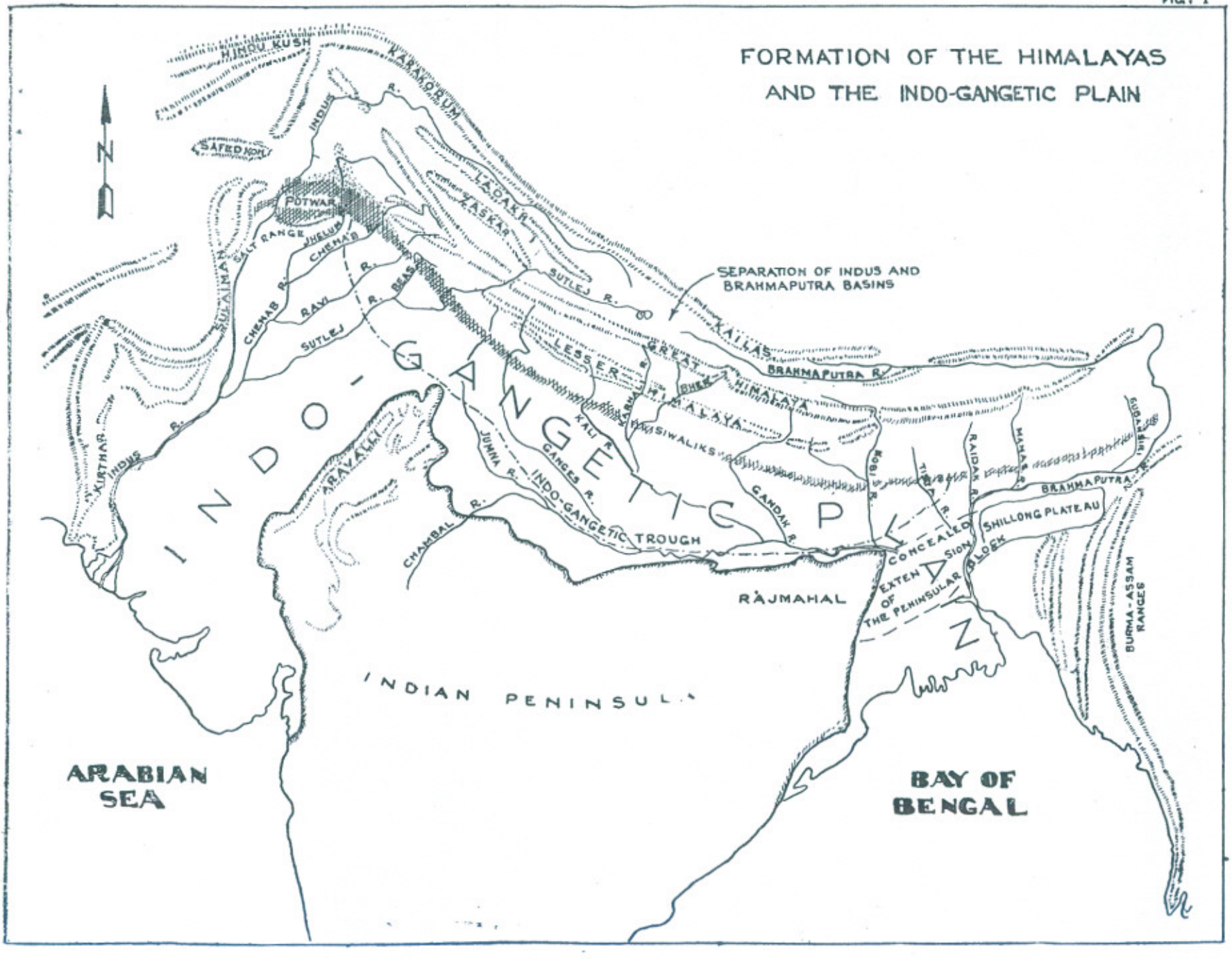
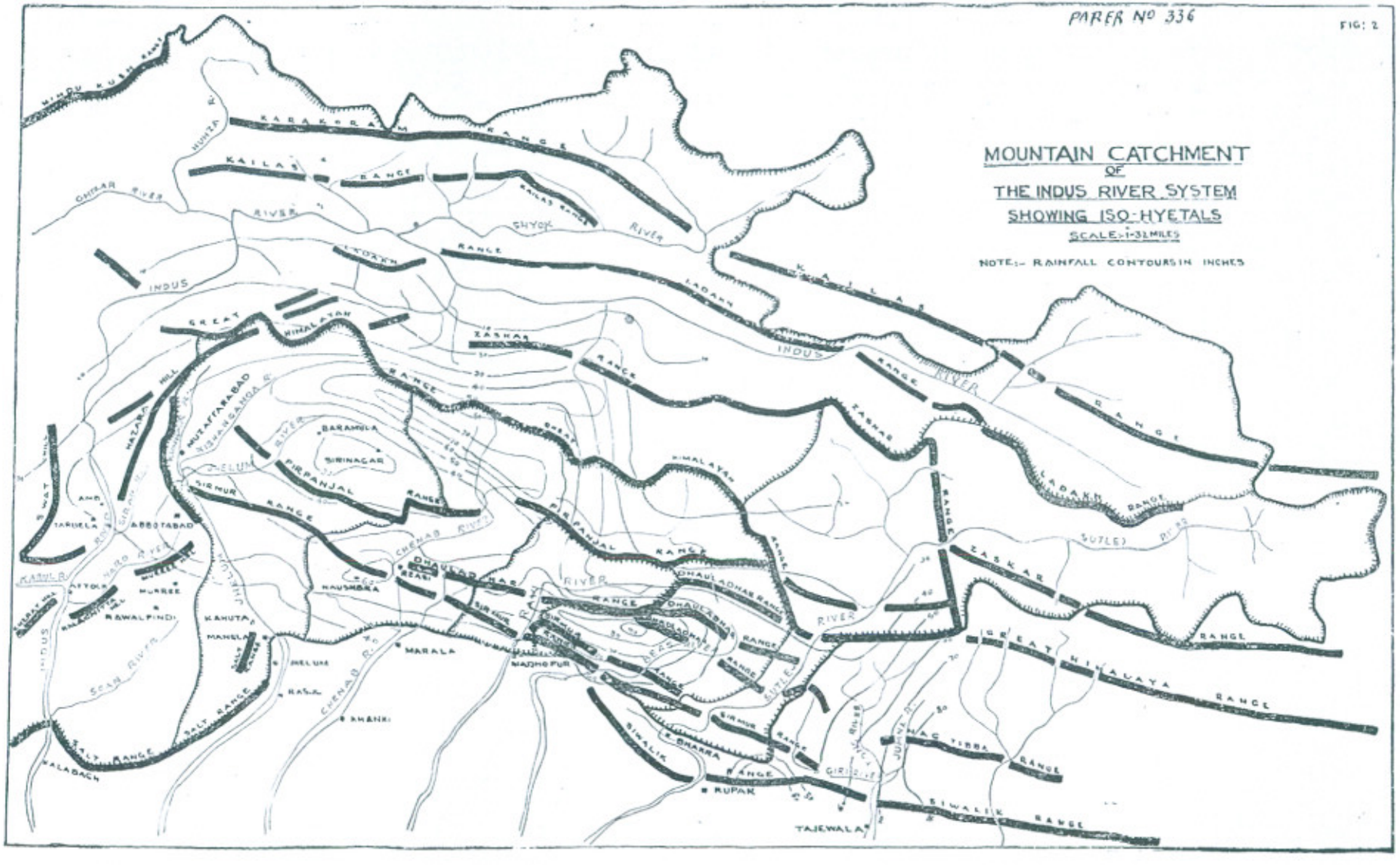
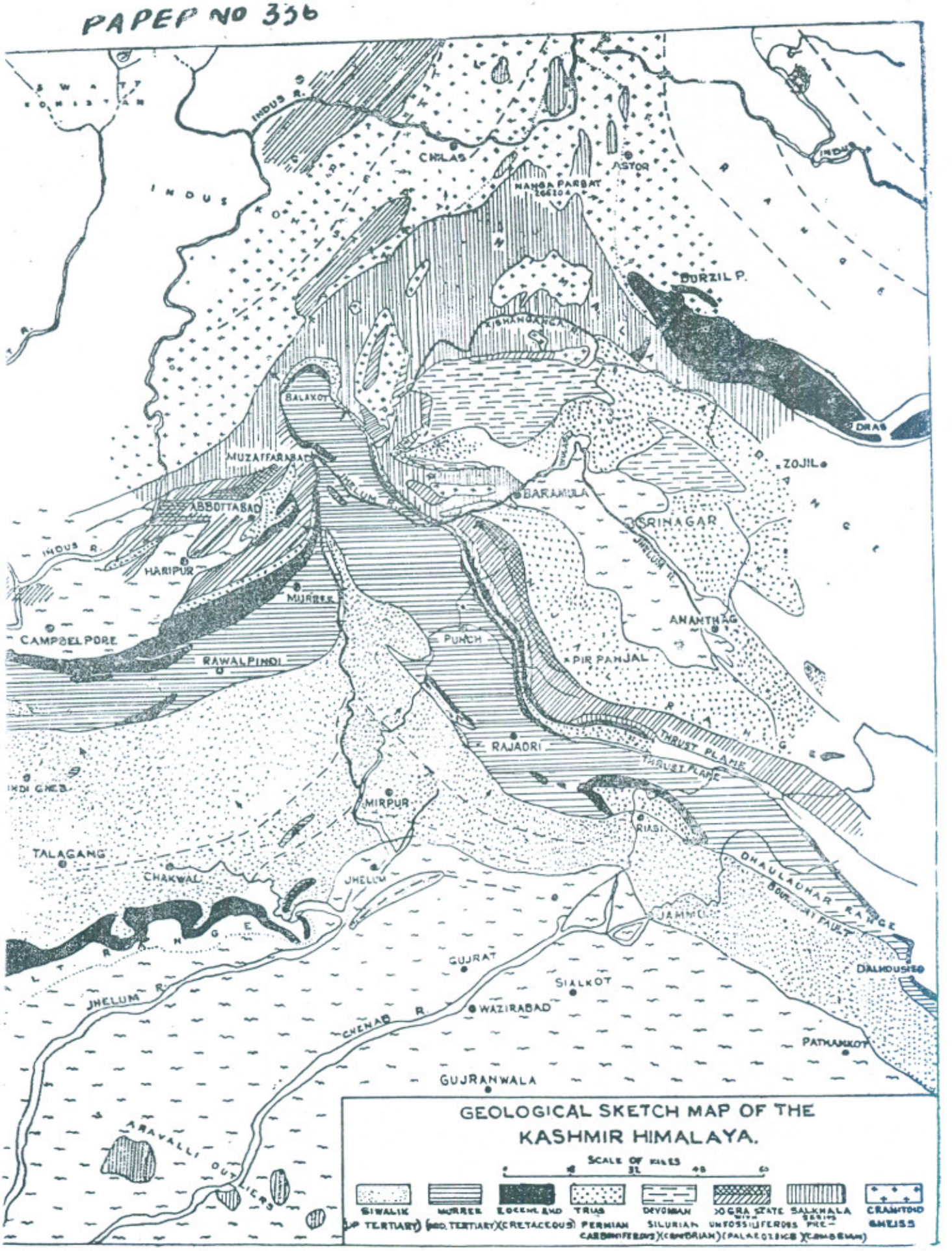


FIG: 2


MOUNTAIN CATCHMENT
OF
THE INDUS RIVER SYSTEM
SHOWING ISO-HYETALS
SCALE:-1-31MILES
NOTE:- RAINFALL CONTOURS IN INCHES
HINDU KUSH RANGE
KARAKORAM RANGE
KAILAS RANGE
KAILAS RANGE
HUNZA R.
GHILAR RIVER
SHYOK RIVER
INDUS
GREAT HIMALAYAN RANGE
LADAKH RANGE
ZASKAR RANGE
INDUS RIVER
GANGE
HAZARA HILLS
MUZAFFARABAD
NEELUM RIVER
JHELUM RIVER
BARAMULA
SRINAGAR
PIRPANJAL RANGE
SIRMUR RANGE
ABBOTABAD
TARUELA
KABUL R.
HARO RIVER
KHAIRA GALA
ATTOCK
HURREE
RAWALPINDI
KAHUTA
MANELA
INDUS
SOAN RIVER
SALT RANGE
KALABAGH
JHELUM
KALA
CHENAB R.
KHANKI
MARALA
NAUSHERA
DHAULADHAR RANGE
RAVI RIVER
BEAS RIVER
SUTLEJ RIVER
NAUSHERA
NAUSHERA
DHAULADHAR RANGE
DHAULADHAR RANGE
RANGE
NAUSHERA
NAUSHERA
SIWALIK RANGE
BHARRA
SIRMUR RANGE
GIRI R.
JUMNA R.
RUPAR
TAJEWALA
NAG TIBBA RANGE
SIWALIK RANGE
GREAT HIMALAYA RANGE

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INDUS R.
CHILAS
ASTOR
NANGA PARBAT 26620'
INDUS
BURZIL P.
KISHANGANGA R.
DRAS
ZOJIL
BARAMULA
SRINAGAR
JHELUM R.
ANANTNAG
PIR PANJAL
RAJAURI
THRUST PLANE
BALAKOT
MUZAFFARABAD
JHELUM R.
ABBOTTABAD
INDUS R.
HARIPUR
MURREE
CAMPBELPORE
RAWALPINDI
PUNCH
INDI GNEB
MIRPUR
RIASI
TALAGANG
CHAKWAL
JHELUM
DHAULADHAR RANGE
BOUNDARY FAULT
JAMMU
DALHOUSIE
GUJRAT
SIALKOT
JHELUM R.
CHENAB R.
WAZIRABAD
PATHANKOT
GUJRANWALA
ARAVALLI OUTLIERS
GEOLOGICAL SKETCH MAP OF THE
KASHMIR HIMALAYA.
SCALE OF MILES
0 16 32 48 64
SIWALIK (UP TERTIARY)
MURREE (MED. TERTIARY)
EOCENE AND (CRETACEOUS)
TRIAS PERMIAN CARBONIFEROUS
DEVONIAN SILURIAN (CAMBRIAN)
JOGRA STATE WITH UNFOSSILIFEROUS (PALAEOZOICS)
SALKHALA SERIES PRE- (CAMBRIAN)
CRANITOID GNEISS

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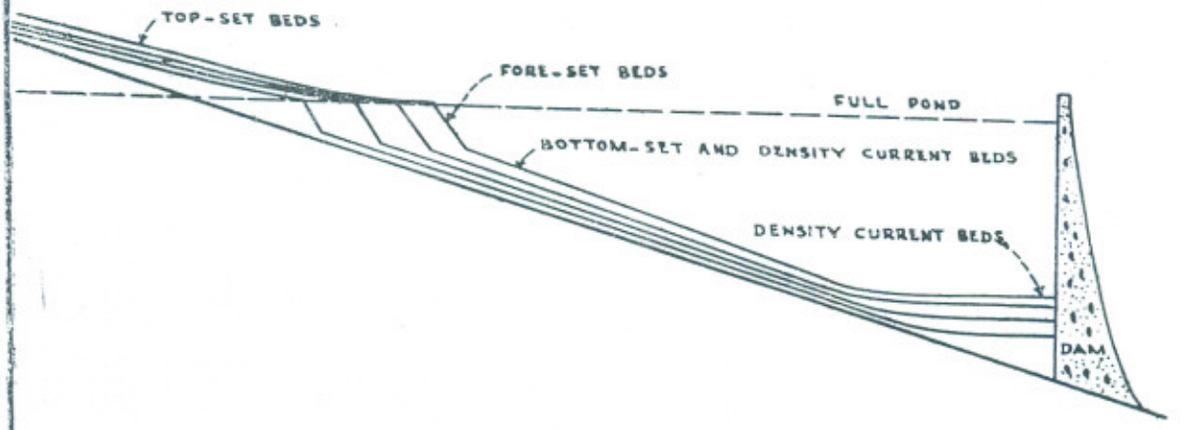
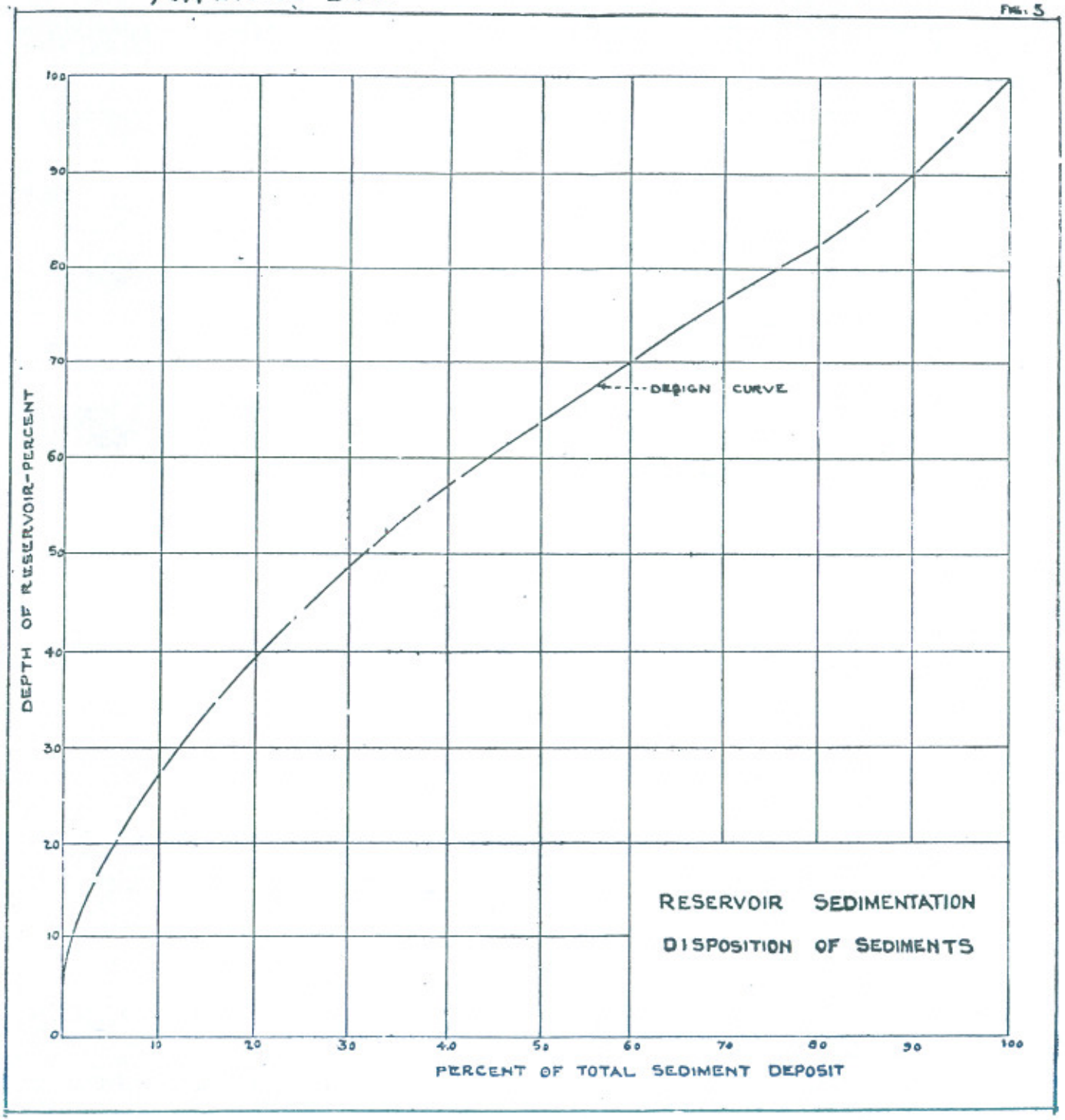


FIG. A LONGITUDINAL SECTION THROUGH A RESERVOIR FORMED BY A DAM

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FIG. 5



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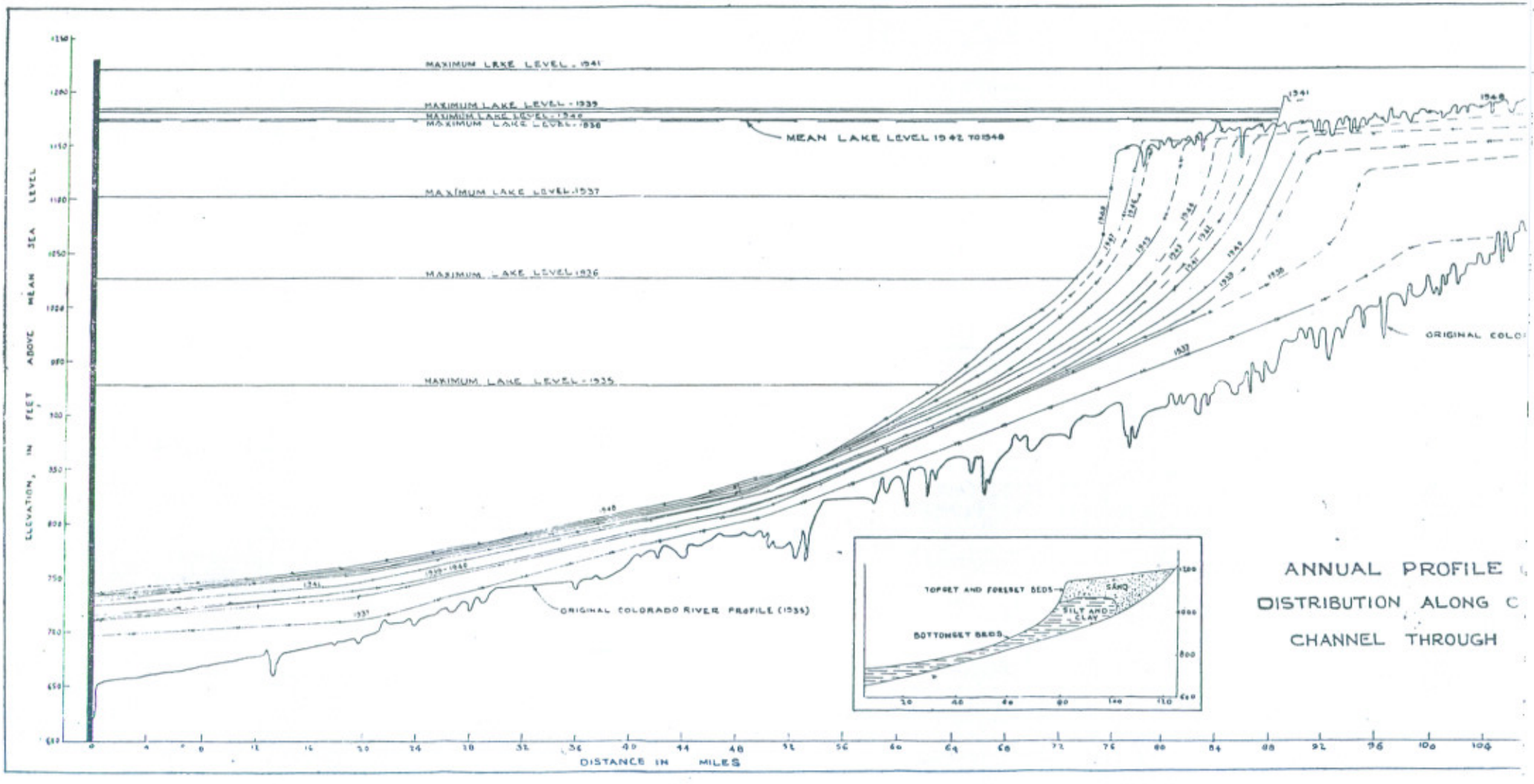
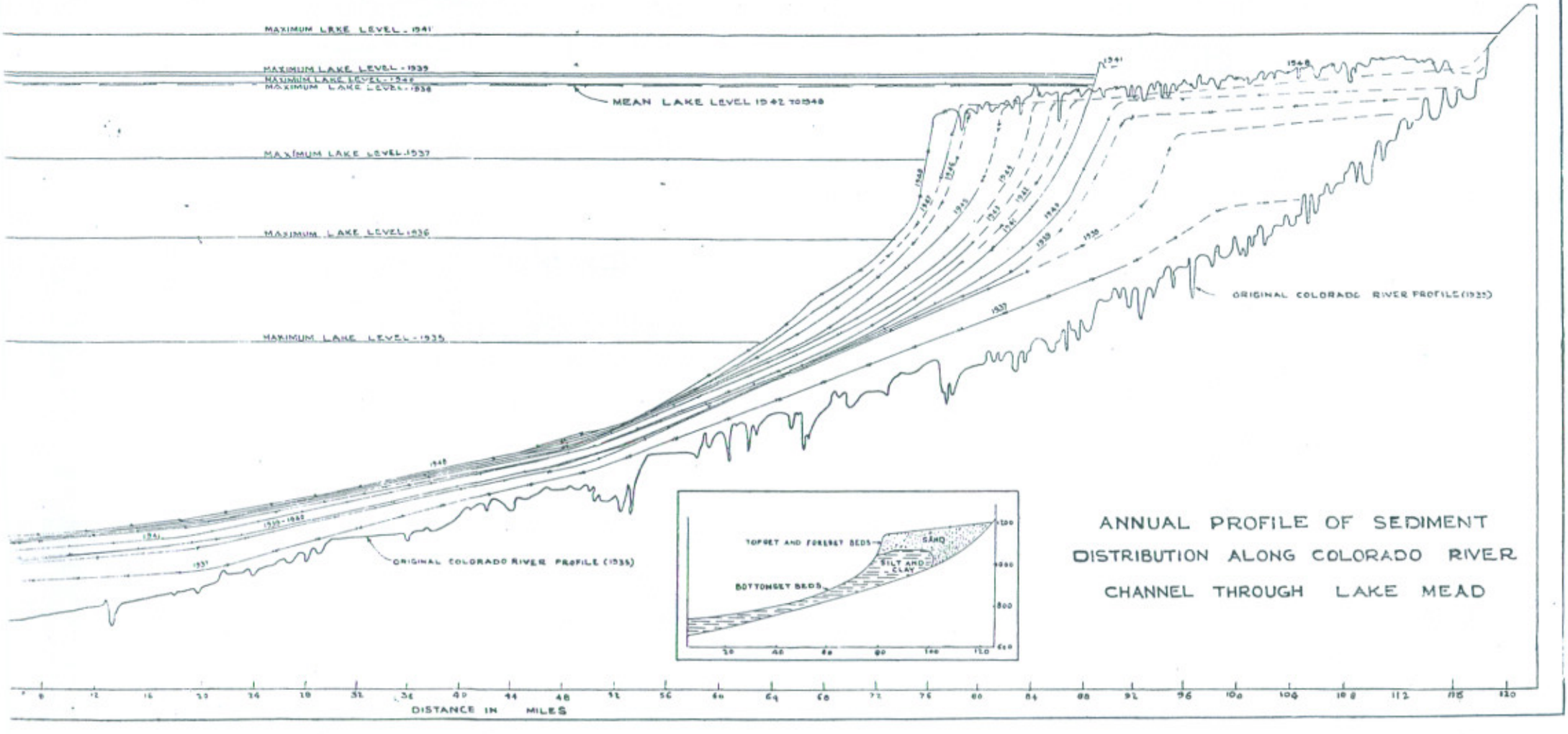

MAXIMUM LAKE LEVEL - 1941
MAXIMUM LAKE LEVEL - 1939
MAXIMUM LAKE LEVEL - 1946
MAXIMUM LAKE LEVEL - 1938
MEAN LAKE LEVEL 1942 TO 1948
MAXIMUM LAKE LEVEL 1937
MAXIMUM LAKE LEVEL 1926
MAXIMUM LAKE LEVEL - 1935
ORIGINAL COLORADO RIVER PROFILE (1935)
ELEVATION, IN FEET ABOVE MEAN SEA LEVEL
DISTANCE IN MILES
TOPSET AND FORESET BEDS
SAND
SILT AND CLAY
BOTTOMSET BEDS
ANNUAL PROFILE
DISTRIBUTION ALONG C
CHANNEL THROUGH

FIG. 6



ANNUAL PROFILE OF SEDIMENT DISTRIBUTION ALONG COLORADO RIVER CHANNEL THROUGH LAKE MEAD

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FIG. 7

