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Artificial Cut-off at Islam Headworks

By

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INTRODUCTION

Islam Headworks is a diversion weir on River Sutlej situated at Longitude 72°-33E Latitude 29°-50N in the district of Bahawalpur. The Headworks is 23 miles away from the Vehari Tehsil Headquarters and 67 miles from Bahawalpur. Three canals, namely Bahawal, Qaim and Mailsi take off from the Headworks with authorised full supply discharges of 5400, 463 and 4883 cusecs. The Bahawal Canal is a perennial canal while the other two canals are non-perennial.

Formation of horse-shoe bends, in meandering alluvial streams, takes place, when the downstream arm of a bend, in its downwards travel is obstructed by a hard patch. Such bends would naturally eliminate themselves, at the climax, when the river cuts across the neck. A natural cut off, thus formed in a river, has serious repercussions.

Malshah loop, was a bend of river Sutlej upstream of Islam Headworks, which developed into a Horse-shoe bend. The existance of the bend created immense pressure on the retired embankments and vitiated the river approach to the Headworks. Considerations of the problems and the fear of unfavourable consequences of a natural cut off which seemed imminent, led to the decision of making an artificial cut off.

As a result of the short circuiting of this major loop, which developed very rapidly, the silt load, in the river increased manifold. Mailsi Canal, the non perennial canal on the right, having unfavourable approach condition, received the main brunt of the silt load.

This paper describes the development of horse-shoe bends in meandering rivers and the considerations which led to the decision for the artificial cut off. Data observed during the development of the cunnete is presented, as well as the result of excessive silt entry into Mailsi Canal.

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Meandering of Alluvial Rivers.

From a dynamical point of view, the variables involved in the stability of alluvial rivers are the flow, the hydraulic properties of the channel; and the sediment load carried by the stream. The rivers have two recognised modes of adjusting their characteristics according to the conditions of flow and sediment load imposed upon them. These are aggradation and degradation. A river will aggrade, when its sediment discharge capacity is less than incoming load and it will degrade, when its sediment load is considerably smaller than its carrying capacity. An aggrading river will be divided in a number of small channels divided by shoals formed by the deposition of the load, while a degrading will actively erode its bed and sides to gather greater sediment load.

As the rivers tend to stabilise by balancing the conditions imposed on them, they develop into meandering streams. This pattern of rivers is the most stable one and occurs when the rivers have generally enough capacity to carry the incoming load.*

Man has often wondered, as to why the rivers are not straight and they zig-zag in their downward journey to the Sea. A number of hypotheses have been framed to explain the phenomenon of meandering, ranging from the effect of earth's rotation to the difference in slope required for transporting the given alluvium and the slope of the alluvium.

In the following an explanation of the phenomenon is given, both regarding the initiation and development of meanders.

Mechanics of Meandering.

In order to determine the basic principles of meandering, a detailed study was undertaken at the Vicksburg experiment station of U.S. Army Corps of Engineers by Captain J. F. Friendkin (Reference 1).

In one of the experiments, it was verified that when a constant rate of clear water flow was passed in a straight trapezoidal channel (without any initial angle of attack), moulded in Mississippi River Sand, the initially straight channel, developed into a shifting sinuous channel of meandering rivers. It was noticed that as the flow progressed, erosion from the banks overloaded the stream and deposition took place in the form of a bar, and the local disturbance caused by the bar, initiated the meandering. From the various experiments conducted under the study, it was found that the only requirement for meandering, when other factors of changing flow conditions and irregular bank lines were absent, was the Bank erosion.

**Note* :—Even in meandering rivers, the conditions may not be uniform all along the length nor they may be permanent and particular reaches may be aggrading or degrading depending on the prevailing conditions.

The presence of a strong helicoidal secondary current in channels curved in plan, has been recognised for a long time. The spiral flow has not only been verified in rigid models, where wet pulverised coal introduced at the outer edge of the flow would travel to the opposite edge, but also in natural rivers. (Reference 4) From purely theoretical considerations, it can be shown that any curvature of flow in plan, would give rise to the spiral flow.

In case of a flow curved in plan (Figure 1)considering the water surface being normal to the resultant of gravitational and centrifugal forces, the curve for the water surface is given by

$$Z = \frac{V_n^2}{g} \log_e \frac{R}{R_1},$$

Where Z = ordinate with respect to the elevation at the inner edge.

Vn = Surface velocity.

R = Distance of the element from the axis of rotation.

Rl = Distance of the inner edge from the axis of rotation

g = Acceleration due to gravity.

The difference in elevation, between the two edges is therefore

2.3 $\frac{V^2}{g} \log_{lo} \frac{R_2}{R_1}$, where R_2 is the distance of the outer edge from the axis of rotation.

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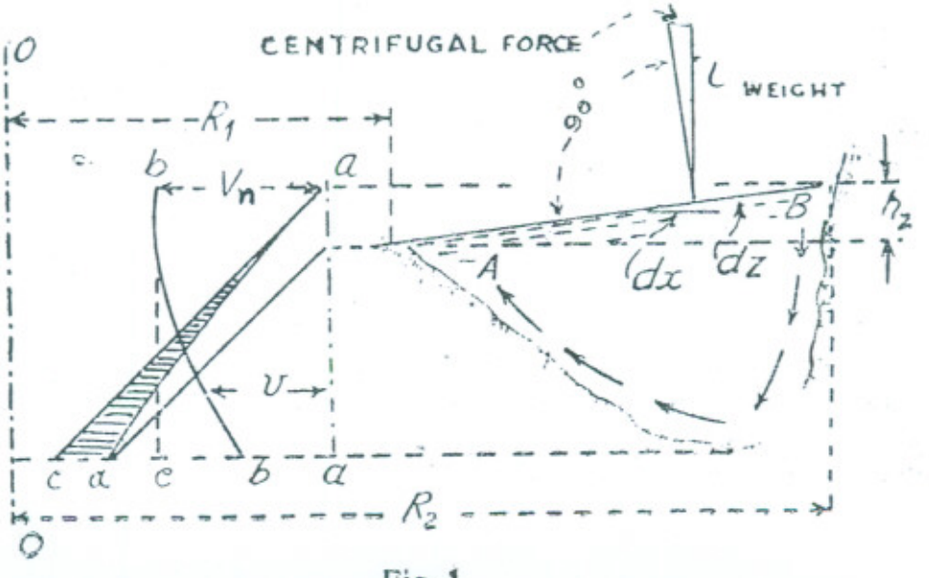


Fig. 1

Now considering the concave bank, the hydrostatic pressure distribution on the bank is represented by the straight line *ac* But as the velocity along the vertical drops towards the bottom, being zero at the bed, the pressure due to the centrifugal force would be represented by line *da*. The excess of hydrostatic pressure corresponding to the area, *acda* must produce downward movement of the water particles, which in turn may be represented by a cross current BA, accompanied by a negative current on the surface. This circulatory current will erode the material at the concave edge and deposit it at the opposite (convex) edge.

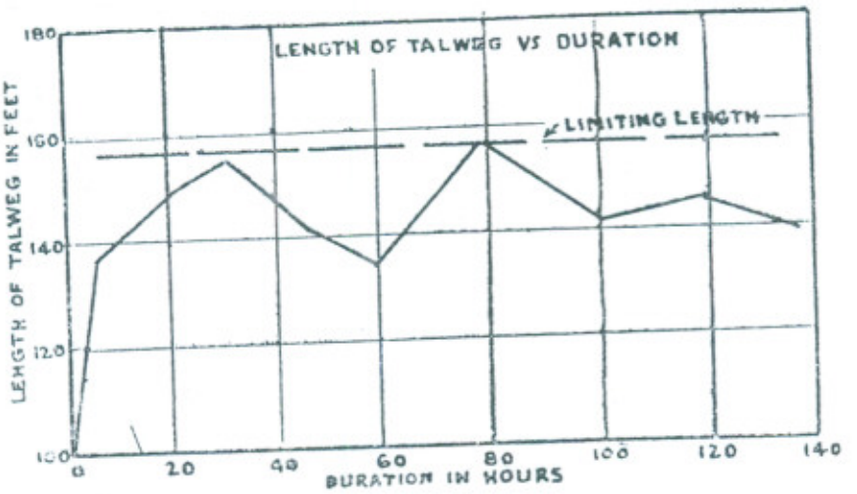
The foregoing shows that in a straight alluvial channel, if there was some irregularity to cause curvature of streamlines in the plan, circulatory cunrrent would be set up, giving rise to the development of a meander.

It is however debatable, whether the irregularity in the shape of varying erodibility of the alluvium etc. is the starting point of meandering or the straight channel by itself develops the circulatory current and thus creates the "irregularity", which may in turn accentuate the former. The subject of secondary currents existing in turbulent flow is intimately connected with this issue and it is possible that the strengthening of these currents noticed with increased sediment load may be responsible for the generation of the single spiral flow. This particular explanation is dealt with in greater detail under the "Problem in Mailsi Canal". Doctor Hans. A. Einstein during his visit to Lahore (oct. 1961) has informed that he has recently concluded a theoretical-cum-experimental study which shows that in sediment bearing laboratory channels, provided rough banks are existing, the single spiral secondary current is initiated leading to formation of bars. With the publication of his particular results, the problem of the causation of meanders may be solved. However for our present purpose the mechanics of meandering, starting with an "irregularity" in the channel suffices.

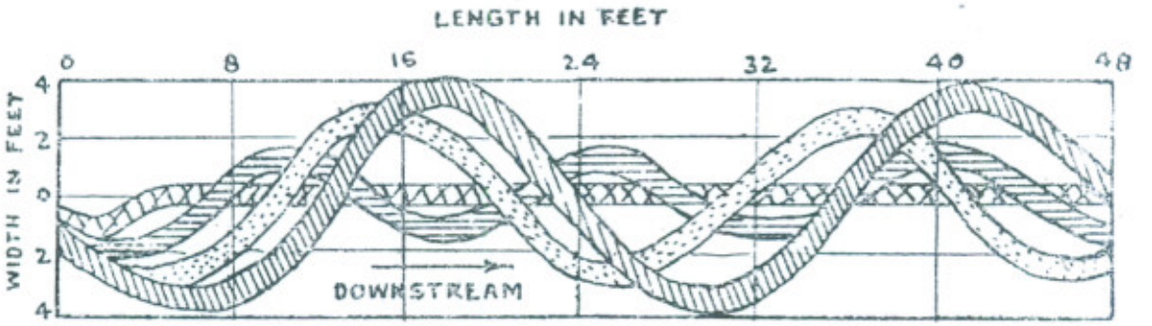
In the experimental study at Vicksburg, it was noticed that after the meandering had started, the development of meanders did not stop on achieving a particular length or breadth, but progressed indefinitely and when the length of the bend was so large that the resistance to the flow was greater in the bend, than across the bar opposite it, the channel cut through the bar, forming a chute development. This was one mode of length adjustment adopted by the channel and for a constant flow, with a particular initial angle of attack, the channel exhibited the presence of a limiting length and width, beyond which the meandering would not develop. Figure 2 (reproduced from plates 23 and 25 of reference 1), shows the pattern of meander development and existance of limiting length of channel. It may be noted that the bends in their development, consistantly migrate downstream.

In this study it was also noticed that the meander pattern, once it had developed depended on the hydrograph of flow imposed on it, as well as the initial angle of current attack. During low flows the attack was mainly directed towards the upstream ends of the concave bends. But as

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LIMITING LENGTH OF RIVERS



TALWEG TRACES



LEGEND

INITIAL CHANNEL
AFTER 3 HOURS OF FLOW
AFTER 6 HOURS OF FLOW
AFTER 10 HOURS OF FLOW

FIGURE 6

MEANDERING LABORATORY
RIVERS IN UNIFORM
BANK · BED MATERIAL

(REPRODUCED FROM PLATE NO. 23 AND 25 FROM "A LABORATORY STUDY OF THE MEANDERING OF ALLUVIAL RIVERS" BY J. F. FRIEDKIN)

the flow increased the attack progressively shifted downstream and medium flows attacked the middle parts and high flows, the dowstream parts of the bends. The reason for the variation in the location of the attack lies in the ability of the flow to take turn, which is more at low flows (with less momentum) and less at high flows (with more momentum). Similarly high dominant discharges, produced large meanders and *vice versa*. For the angle of attack, it was noticed that for a given discharge and slope, an increase in the initial angle of attack, increased the width of the bends, but reduced their length, so that the bends were sharper and the sinousity greater.

In natural meandering alluvial rivers, there is a tendency to continuously increase their length and they have limiting lengths and widths much like the laboratory rivers. However in this case, there are some other modes of length adjustment as well apart from the chute developments. These are flattening of bends and natural cut offs. The shape and development of a bend depends on the bend preceeding it, because the angle of attack verily depends on the direction of the incoming flow. Thus many a time, a bend in a natural river, will stop or reverse its development, if the angle of attack, is reduced. This will necessarily reduce the length of the river.

Development of Cut-Offs.

In all the experiments carried out at Vicksburg Station, with uniform bed material, it was noticed that the bends travelled downstream uniformly so that in no case a horse-shoe bend, in which the flow would be directed up-valley, was formed. Any adjustment in the length of the channel, occured by chute formation. It was deduced that if the erosion rate at the two ends of a bend was equal, the ends would never catch up with each other, but when, the bank material at the dowstream end was less erodible, a horse-shoe bend would form, in which the flow would be developed up valley, creating a narrow neck (Figure 3). The persistence of this condition would create a natural cut off, which has been often witnessed in natural rivers.

Cut-Offs as a River Training Measure.

Artificial cut-offs are a useful river training measure but their usage is generaly restricted to river channel improvement for floods, when they are carried out in conjunction with bank revetments. In special cases, cut-offs have been executed at river structures, when the development of horse-shoe bends, had caused problems for the retired embankments, and in tidal rivers for increasing the tidal range.

It has been explained that a natural cut off would occur, when the neck of the horse-shoe bend, was eliminated by erosion of the concave banks from either side or by natural flow during floods. It was noticed that whenever a natural cut off, occured, it was accompanied by violent changes in the river both upstream and downstream. The excessive energy available to the river upstream of the bend caused a severe erosion

of the banks. On the downstream side, the excessive sediment load borne by the stream deposited and caused deterioration of the river channel by aggradation, resulting in a braided channel. The increased velocities generated upstream of the cut offs, as well as the aggradation on the downstream side, created hinderance to navigation, when the rivers were being used for this purpose. The sudden release of the valley storage upstream of the cut off, increased the flood heights downstream. Moreover, the natural cut off, by virtue of its location, tended to give an unduly straight path to the river, which condition being the opposite of meandering pattern, was temporary and always led to the development of new meanders, endangering agricultural lands etc. at unpredictable places.

The outcome of the rash development of natural cut offs, had created a prejudice, coloured by fear, in the minds of engineers responsible for river training. Later, when artifical cut offs were made in Europe, the channel was excavated to the full river size, with the result that the sudden adoption of the shorter course through the excavated channel, created almost as detrimental consequences as the natural cut offs and this experience was enough to confirm the prejudice against the use of artificial cut offs.

The first full-fledged scheme of cut-offs for the river channel improvement for control of flood stages, was executed on Mississippi River in U.S.A. This scheme has been well summarised in the memorable paper by the late G. H. Matthes. (Ref. 5). The paper gives a chronological history of the development of the idea for implementing artificial cut offs on the Mississippi River and the details of the results achieved. It was on the lower Mississippi River, after the observation of a natural cut off. (Yucatan Cut Off) through a tributary, that the idea of a pilot cut or cunnete was developed. It was observad that the short circuiting of the 12 miles loop through a 2.5 miles long tributary, did not bring about the changes associated with the cut offs. The following criteria were developed, for executing an extensive programme of cut offs.

(*i*) The cut off should not tend to straighten the river unduly, while shortening it.

(*ii*) To offset the effects of rash development and to utilize the river energy for excavating its channel, and filling the abandoned one, pilot cuts should be used.

(*iii*) A narrow channel a mile or two in length was superior as a cut off route, to a short cut across a narrow neck of land.

(*iv*) In the proposed alignment the aim should be to preserve hydraulic gradients not exceeding those prevaling in the stretches where the river was known to possess an "Orderly channel".

As the Mississippi River cut offs are truly the fore-runners of any such scheme, it seems pertinent to present a summary of the object of the scheme as well as the results obtained.

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DEVELOPMENT OF NATURAL CUT-OFF

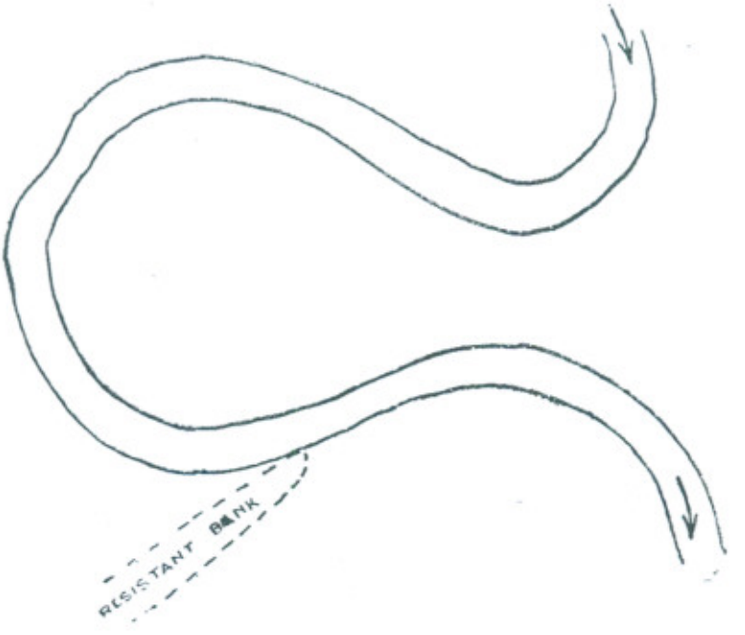


Fig. 3

The primary object of the Mississippi River cut-offs was the lowering of flood stages, along the lower Mississippi river. Between Memphis and Baton Rouge (a distance of 680 miles along the river) 16 cut off were in operation till 1946 of these two were natural and 14 artificial. The total shortening of the river on account of the cut offs was 151.9 miles, while some additional channel improvement measures reduced it by an additional 18 miles. An overall reduction of about 25% was obtained in the original river length of 680 miles. The gauge reduction for comparable flood discharges at Arkansas City was 12-13 feet as an effect of 12 cut off's below this point. A list of these cut offs along with their data is reproduced from Reference 5 in Apendix 1.

River structures like Bridges, Diversion, weirs, etc. create an obstruction to the meandering patterns of the rivers. The meanders in their irresistable downward journey are obstructed by these structure with the result that horse-shoe bends are formed and create pressures on the guide banks and retired embankments, One such cut off was reported by M. A. Wahidi in his paper "River Tranining Works of Empress Bridge at Adamwahan". (Ref. 8) In this case, the River Sutlej had framed an embayment around the right guide bund, and was threatening the railway approaches. The author had shown from previous river survey records that near the bridge site, the river was capable of making natural cut offs at a Loop/Chord ratio of 2.8-2.1 and this was adopted as the design criterion for the pilot cut. As will be discussed later the development of a natural cut off during high floods is dependent among other factors on the erodibility of the area between the neck and existance of suitable channels. As a matter of fact the criteria for the design of pilot cuts are different and should not be confused with the ratio at which a natural cut off will take place.

Other cases of the use of cut offs, have been downstream of the headworks, when the aggarading river channel was sought to be rectified. In tidal rivers, cut offs have been resorted to, for increasing the tidal range upstream but the use of a pilot cut in such cases is impossible on account of the two way flow.

River Course above Islam Headworks.

A brief hisiory of the river course upstream of Islam Headworks is presented with a view to give an insight into the behaviour of this river and the development of some natural cut offs.

The river course for 1929 is presented in plate 1, Point A is a convenient reference point arbitrarily selected. Its coordinates with respect to the weir are 51,000, E and 26,000 N respectively. The point marks a semi fixed point of the river at the upstream extremity of the river survey. The straight line distance between point A and the weir is 57,300 feet and has been used as the referring length for comparing the tortuosity of the river course during various years.

River courses for the years 1932 and 1933 are shown in plate 2. The formation of a natural cut off along BC. in 1933 may be noted. The

loop neck ratio (measured along river centre line) increased to 2.3 before the cut off occured. The cut ff was helped by 2 factors *viz* the artificial elimination of bend opposite Murphy spur in 1932 and existence of creeks across the neck, which are explained below.

The effect of artificial steepening of gradients over the ruling gradients at any point in a river is to straighten the river upstream in the first instance. This happens, because in the preceeding bend the current attack is directed to the bar, the same as happens with the increase of river stage to bank full discharge. The erosion of bars progreses upstream and flattens the bend thereby generating still steeper gradients. Under these conditions fairly developed loops may be cut off. (it is only later, when the aggradation starting from downstream of the point reaches upstream that meandering develops again).

The existence of creeks across the neck is actually what a pilot cut provides in an artifficial short circuiting. Cross section of the creeks are not available but it would show that the development was not rash and at the end of the flood season, both the courses were active.

Plate 3 , shows the river courses for 1941 and 1942. Development of a horse shoe bend in 1941 at almost the same place as the 1932 loop may be noted. The talweg neck ratio of the bend, increased from 2.9 in 1938 to 4.75 in 1941. In 1942, as the bend was naturally cut off, the ratio was 6.3. The cut off took place during a high flood with a peak discharge of 2,84,000 cs(the highest at the Headworks till then).

The same year another cut off developed downstream of the Headworks. (The development in this case is more like a chute enlargement). The development took place through creeks existing across the bar. The effect of this cut off on the river levels downstream of the Headworks was to increase the retrogression, then being experienced. It has been reported that for low flows, the retrogression was as much as 5 feet over the preceeding years' levels. Incidentally this points out the use of cut offs for improving the modularity of weirs, when the downstream accretion can sometime be reduced by eliminating a few sharp bends.

From 1942 onwards, the bend which had so tenaciously stuck to R.D. 30-33 of the left retired embankment started downstream migration. It is intresting to note that the bend, which had twice short circuited itself in 1933 and 1942, was to form Malshah Loop, later cut off artificially in 1959. A little upstream, in the 1942 river course, bend EF may be noted. This bend also developed into a horse shoe bend and short circuited itself in 1948, with a loopneck ratio of 2.9.

Plate 4 depicts river courses for 1953 and 1954. Another natural cut off in bend JK, about 9 miles upstream of the weir, in 1954 may be noticed. The development of Malshah loop in a horse shoe bend is also apparent. The natural cut off increase of 1954 is a typical one and the outline of the bend in various years is given in plate 5. The loop-neck ratio

of the bend increased from 2.15 in 1952 to 3.27 in 1953 and 5.42, at the time of cut off development.

The foregoing summary of river behaviour upstream of Islam Headworks, indicates that 5 cut offs took place in the period 1929-1959, including 4 natural and one artificial (1959). The total shortening due to the cut offs, amounted to 16 miles. The loop neck ratio of the natural cut offs as measured along the centre line of the river, varied from 2.3 to 6.3. Data regarding these cut offs, is given in table 1.

TABLE No. 1

Cut Offs. Upsteam Islam Headworks, 1929-1959

Year.	River length along the loop (1000 feet)	Neck distance between river centre line (1000 ft.)	Shortening of River length (1000 ft.)	Loop/Neck ratio
1933.	19.5	8.5	11	2.0
1942.	21.5	3.5	17	6.3
1947.	26.0	9.0	17	2.9
1954.	19.0	3.5	15.5	5.4
1959.	25.0	5.7	19.3	*4.4

* Artificial cut. off.

While discussing the mechanics of meandering alluvial stream, it has been stated that the meanders have a tendency to develop indefinitely, but there are certain factors, working simultaneously, which counteract this tendency, so that over long stretches, rivers are known to meticulously maintain their lengths. These factors are developments of chutes, natural cut offs, and flattening of bends.

The tortuosity of River Sutlej upstream of Islam Headworks has been calculated from River Survey Plans for the years 1929 to 1961, as the ratio of river length to the distance between point A (Plate 1) and the Weir. The values of this ratio for various years are given in table 2 and plotted in plate 6 . The years, when cut offs occured are indicated. It may be seen that both the values of maximum and minimum tortuosity as well as the average line, have an increasing tendency. This shows the effect of diversion weirs on alluvial rivers which is to increase the tortuosity upstream. There are two reasons for this behaviour. The first is that the meanders in their continuous downstream journey are obstructed by the weir, and the second lies in the fact, that the river deposits coarser portions of its load in the pond while the finer fractions are moved down and the coarsening of the material increases the tortuosity. Line AB in plate 6, represents, the average line computed by least squares and has a positive slope.

Another interpretion of this tortuosity diagram could be to qualitatively predict the sediment load approaching the weir. It was not verified but it is believed, that given other factors equal, in years of large tortuosity, the bank erosion would reduce, as well as the river slope and velocity. The sediment load of the river would therefore be less than the years in which the tortuosity is less.

TABLE No. 2

TORTUOSITY OF RIVER SUTLEJ U/S ISLAM HEADWORKS.

Year.	*Tortuosity	Y	*Tortuosity
1929.	1.44	1946.	1.74
1930.	1.52	1947.	1.83
1931.	1.53	1948.	1.48
1932.	1.52	1949.	1.52
1933.	1.32	1950.	1.46
1934.	1.36	1951.	1.53
1935.	1.42	1952.	1.74
1936.	1.48	1953.	1.94
1937.	1.40	1954.	1.40
1938.	1.48	1955.	1.53
1939.	1.48	1956.	1.71
1940.	1.60	1957.	1.58
1941.	1.64	1958.	1.60
1942.	1.34	1959.	1.18
1943.	1.51	1960.	1.29
1944.	1.62	1961.	1.53
1945.	1.53		

* River length (along centre line) / Referring length, (57,300 feet distance of point A from weir).

Problem at the Headworks.

The river course at Islam Headworks for 1958 is shown in plate 7. The following aspects, which have a direct bearing on the problems at the Headworks may be noted.

(*a*) Sand shoal at the nose of Right Guide Bund. 'A'.

(*b*) Southern creeks downstream of the G. H. Spur. 'B'.

(*c*) Horse shoe bend. 'C'.

(*a*). **Sand shoal at Right Guide Bund.**

A sand shoal opposite Right Guide Bund of Islam Headworks has always existed there. The shoal was originally caused by the diversion of the river into the Headworks in 1926 and its growth received impetus by the river approach from behind and at right angles to the guide bank, which existed till the construction of Murphy Spur in 1933. Thereafter the river naturally hugged the left side of the weir (because the perennial Bahawal Canal was located on this side) and the shoal being always situated on the convex side of the approach curve, persisted. The size of the shoal has been oscillating in the past depending on the river approach.

The existence of the shoal, masks the right pocket which feeds Mailsi Canal. The entrance to the right pocket has thus been through a re-entrant angle with consequent turbulence and suspension of the sediment load. This condition has been responsible for poor silt exclusion from the Mailsi Canal. Now the greater the size of the shoal, the more obtuse has been the re-entrant angle, with greater silt entry into the Canal. In 1958, the river approach was such that the river current travelled from the Murphy Spur onto the Nose of Left Guide Bank, and then into the centre of the weir thereby giving an impetus to the growth of the shoal.

(*b*). G. H. Spur at Islam Headworks is in fact an extension of the G. H. Bund constructed for closing the southern creeks during the initial diversion. The creeks in their alignment cross L.R.E. at R.D. 5 near the Headworks. In the past, there has been little or no pressure of flow in these creeks.

With the breach in the shank of G. H. Spur in 1956 and its progressive erosion in the following years, the river came closer to the creeks. Although the ponding effect at the Headworks, would hamper the development of any meander behind the Left Guide Bund, the flow in these creeks, created parallel flow and excessive build up of pressure near R.D. 5-15. of L.R.E. The earthen embankments are neither designed for parallel flow, nor they can withstand it for long and therefore a breach along this length of the embankment was possible. This would have meant a colossal loss to the agricultural property, lines of communication etc besides involving a loss of the river control. The development was therefore fraught with danger and constant efforts were made during the flood seasons of 1957 and 1958 to check the erosion of G. H. Spur and to choke up the creeks with permeable dikes.

(c). Horse-shoe Bend.

The development of various bends, which were naturally cut off, have been described previously. The reason for the development of a horse-shoe bend, as discussed before is the hinderance to the downstream migration of the lower arm of a bend by erosion resisting patches, guide banks, etc. In this case, the development of the bend may be attributed to the first cause. The Khadir land downstream of the G. H. Spur was not occupied by the river since 1926 and had obviously been compacted by flooding during medium and high floods. On the other hand, the upper portion of this bend, was traversing through, an area, occupied by the river occurse during the last 5-10 years. The difference between the erodibility of the soil at the two ends of the bend, had therefore generated this horse-shoe bend. In the bend itself the flow from G. H. Spur to Murphy Spur was parallel to the Weir and was causing excessive pressure on the retired embankments.

The above factors continued to vitiate the safety of the Headworks and the embankments during the flood seasons of 1957 and 1958.

Again considering the loop, it may be noted that the talweg-neck distance ratio of the loop, had increased to 4.2, at the end of 1958 flood season. In view of the experience gained from natural cut off in this reach of the river, it was apparent that the loop had very nearly reached its breaking point and may short circuit during the next flood season. The after effects of such a cut off, close to the Headworks during a medium to high flood were too serious to be ignored.

It was against this threat, and the necessity of improving the river course upstream of the Headworks, that a decision was made in the winter of 1958 to artificially cut off, this bend.

DESIGN OF THE CUNNETE

Design Criteria for Pilot cuts.

Some broad principles for the design of cut offs, have already been discussed under the head "Cut Offs as a river training measure". The following is a summary of the design criteria for the pilot cuts derived from the experience of Mississippi River and else where (References 2 & 14).

(1). Capacity.

The capacity of the cunnete should generally be limited to 8-10% of the river discharge at the beginning.

A small capacity of the counnete, helps in two ways. Firstly, it is more economical to let the river scour its own channel and secondly the development of the cut proceeds at a steady pace. The latter factor is very important. With smaller cunnetes, the development, causes a gradual reduction, in the discharge through the main course and the silt load generated in the reach upstream of the cut off is absorbed in the bend.

If the capacity of the cunnete is comparable to the river section, the development will be sudden with all the unfavourable consequence of a natural cut off.

(2). **Entrance and Exit.**

The lay out at both the entrance and the exit of the cunnete should aim at avoiding shock losses. The cut should be made tangential to the direction of the main river course approaching and leaving it. The out fall is sometimes located slightly upstream of the tangent point, to counter the flow coming through the bend. The entrance is also provided with a bell-mouth with double the width in the first 300-600 feet.

As the development of the cunnete starts at the lower end and progresses upstream, bell-mouthing of the lower end is not necessary.

(3). **Alignment.**

An effort should be made to provide a mild curvature in the alignment of the cunnete. The curvature should be flatter than the dominant curvature of the river itself;

The aim in providing a curvature is to increase the tractive force over the perimeter for accelerating the development and for enhancing the capacity of the cunnete to transport silt load.

(4). **Section.**

The section of the cut off should be designed to provide, enough velocity for scouring itself. In general the cunnete, should be made as deep as possible, subject to the limitations of the method of excavation and availability of suitable equipment.

The section for the cunnete can either be computed from the Regime theory or from the Tractive-Force-theory. According to Lacey's Regime theory, if the bed grade is perfectly incoherent and the channel is in regime, the expression RS^2 is a function of the silt grade, where 'R' is the hydraulic radius and 'S' is the slope. Assuming that the existing channel is reasonably stable for the dominant flow, and that the material traversed by the cunnete is the same as that of the river, the pilot cut should have RS^2 equal to or larger than that of the river. Further assuming that the same head is available to the river and the cunnete, the slopes in the two courses are inversely proportional to their lengths. Thus it is deduced, that the cunnete section should be such that

$$\frac{Rc}{Lc^2} > \frac{Rr}{Lr^2},$$

where 'L' is the length of the course and suffices 'r' and 'c' refer to the river and the cunnete respectively.

There are some other variables involved in this relationship such as shock losses at the curves ; greater compaction of the material travered by the cunnete ; reduction of the head available to the cunnete by obstruc-

tion of the flow at the lower end etc. ete. In practice therefore it is difficult to obtain a self-scouring section for the cunnete, unless the length of the river is 1-3/4 to 2 times the length of the cut. According to the Tractive Force Theory, scour along a section will be initiated if the Tractive Force exerted by the flow is more than the critical tractive force for the material constituting the cunnete. (The tractive force varies along perimeter and is more over the bed than over the sides and its distribution along the perimeter, has been calculated in various manners (References 3 & 16). Thus, the cunnete section should be designed so as to provide a greater shear along the perimeter, than the critial value for the material. This may entail some difficulty in the case of cohesive materials because the values of critial tractive force for them are not definitely known.

The cut should be made as deep as possible to enable any hard strata or obstruction etc; to be removed. The width of the cunnete is relatively unimportant.

(5) **Multiple Cut offs.**

Cut offs aiming at the elimination of a full 'S' curve should normally be avoided. However where such a cut off, has to be made, the upper bend may be cut off first, to obviate the overwhelming of the flow through the upper cut, by that through the bend. The entrance to the lower cunnete should be located slightly downstream in conformity with the resultant flow generated at the tail end of the upper cut.

Along long stretches of the river, where a series of cut offs are to be made, it is a good practice to start from the lower end. This improves the sediment bearing capacity of the lower channel before the augmentation of the load from the upper cut offs begin.

Design.

The alignment of the cunnete for artificially short circuiting the loop, is shown in plate 8. The cunnete had a length of 5700′ with a constant bed width of 30 feet. The side slopes were provided as $1\frac{1}{2}$: 1 in the head reach upto R. D. 3500, and 1 : 1 lower down. The bed levels of the cunnete were fixed as 447.0 at the head and 446.0 at the tail. Longitudinal section of the cunnete is show in plate 9. A bell mouth entrance was also provided.

(*a*) *Capacity and water surface profile.*

It had been observed that the river upstream of the headworks had a slope of 0.5 feet/mile at a discharge of 60,000 cusecs. Considering this value to be applicable at the beginning of the operation of the cunnete, the flow through the cut was computed. It was noticed that the flow in the cunnete is non uniform and the channel is short *i.e.* the condition at the outfall effects the entrance condition. The computation of discharge and water surface profile therefore involved trial and error solution. Beginning

with an assumed value of discharge in the cunnete, backwater curve from the tail end was computed upto the head and the working head available checked for the value of discharge. The computed hydraulic data is also shown in plate 9. It was found that for a river discharge of 60,000 cs, the discharge in the cunnete would be 2500 cs. with velocities of 4.5 and 6.0 feet/sec. at head and tail respectively.

In view of the topography of the site, some assumptions had to be made for simplification of the computation. These were tolerable because the accuracy required was not of a high order. The velocity at the tail end, would be slightly higher than the value indicated, because of the steeper side slope adopted there.

(b). *Section*: For a discharge of 60,000 cs. the hydraulic radius in the river, at the discharge site (U/S of the bend) has an average value of 8.5 feet. The river length being 4.4 times the length of the cunnete, the value of hydraulic radius required in the cut only 0.4 feet. The actual value varied from 7.8 feet at the head to 6.5 feet at the tail and the value of mean tractive force worked out to 0.18 and 0.34 lb/ft^2 at the two sections respectively.

Appendix 2 reproduced from Ref. 16 gives the values of critical Tractive force for various cohesive materials, It would be noted that the bed shear developed in the flow was sufficient to erode Fairly Compact and Compact sandy clay (sand content less then 50%) at the head and tail respectively sections for which the limiting values are 0.157 and 0.327 lb/ft.^{2} It may be repeated that the cunnete was entirely situated in an area abandoned by the river in the last 5-10 years and bore holes showed the strata to vary from loose silt to fairly compacted silt with lenses of clay. It shows that the section adopted for the cunnete was larger than a self scouring one, both from the considerations of Regime and Tractive Force theories.

Opening the Cunnete.

Perhaps the most delicate operation, in an artificial cut off is the opening of the cunnete. As the cunnete is opened to the river, its tail end is the first to scour on account of the fall available. The scour travels upstream and simultaneously takes place along the length of the cunnete. Upstream of the cunnete, a steeper slope is generated in the river and increases the sediment load. As some water is withdrawn in the cunnete, the discharge in the main course reduces, with consequent silting up of the bed. The increased sediment load, generated in the river accelerates this silting up. Downstream of the cunnete as the heavily silt charged waters outfall, they meet the flatter slope of the river and silt deposit takes place. This deposit obstructs the flow in the main course and also helps its silting up The cunnete itself is not spared of the augmented silt charge and if its intake is not properly situated with respect to the river bend, its

slope is inadequate, or its length is too large, silt deposition takes places. Similarly, if there is some obstruction in the flow through the cunnete, in the form of an inerodible section or some buried tree etc., the cunnete may be easily choked up, leaving no alternative to the river, but to follow its old course. Moreover if the cut is opened, at a stage for which the velocity within the cunnete is non scouring or if the river after an initial opening at the requisite stage drops down suddenly, the cunnete may choke up. (The adoption of the old course in such an exigency is not too difficult for the river because the newly deposited silt can be easily picked up again).

The effect of the cunnete on the river is a progressive scouring of the bed upstream and deposition of the silt load below the outfall. The net result is a reduction of the slope available to the cunnete, which retards its development.

The foregoing explains, that as the cunnete is opened, there are various contending factors, (both favourable and unfavourable to its development) acting simultaneously. The net balance of these factors determines, whether the cut off will develop or not. The opening of the cunnete, therefore calls for a judicious selection of opportunity. For the cunnete at Islam Headworks, the following conditions were decided for its opening.

(*a*). The discharge in the river should be 60,000 cusecs (the same for which the calculated profiles had indicated, scouring velocities all along the length).

(*b*). Discharge below Suleimanki, should be rising for at least a couple of days and should be enough to generate a low flood (80,000 cusecs) at the Headworks.

The lower limit of the discharge was mainly fixed from the consideration of scouring velocities in the cunnete. The opening of the cunnete, at a rising stage is very important, because the slope of a rising river is greater than the slope at the falling stages.

As explained earlier, the direction of the current attack and sand travel, along a bend, vary with the stage. The intake being situated at the lower end of the bend, the path of the sand travel would not entail a direct entry into the cut, for low and medium floods. This factor is only effective during the early life of the cut. As the development of the cut ensues the river regime is upset and the direction of current and path of sand travel change. But the early stages of the development are important in as much as they determine, the initial scouring and development of bank attack within the cunnete.

In conformity with the above noted criteria the cut was opened at 9.30 A.M. on 8.7.59 by cutting through the check bund at the head. The discharge upstream of the Headworks was 55040 cusecs and rising. The river below Suleimanki Headworks. (about 100 miles upstream), was experiencing the first low flood of the season for the river.

DEVELOPMENT OF THE CUT.

The river course upstream of the Headworks for 1958, along with the layout of the cunnete is depicted in Plate 8 .

Two creeks intersecting the cunnete at its R. D· 2200 and 3500 may be noted, as they played an important part in its ultimate development.

To keep an effective watch on the development of the cut and to record its various phases, the following observations were initated in the cut.

(*i*) Water Surface levels in the Cut.

Three gauges A,B, and C, (Plate 8) were fixed at R.D. 500, 2200 and 4500 of the cut respectively.

Gauge B was fixed just upstream of the intersecting creek.

(*ii*) Cross section of the Cut.

The Cross section at R. D. 2000 of the cut was used for observation of development and discharge. The section was defined by a wire rope stretched across the cunnete. It was selected because it was upstream of any intersecting creek and erosion of the head was not expected to vitiate the section.

Area of cross section and mean velocity were observed at this section. The velocity was measured by averaging out the velocities of a number of surface floats, in a run of 200 feet and converting it to mean velocity. The fast current within the cunnete obviated the use of more accurate measurements, which were also not called for.

iii). River.

The discharge in the river was calculated at the Headworks, as per practice in vogue. The pond level maintained, was also recorded.

Development.

Before the cut was opened, some flow was entering the cut through the creek at R. D. 3500. This had scoured the portion of the cunnete below it. At the time of breaking the check bund, the head across the bund was 3.1 feet. (This is against a calculated value of 3.5 feet and the difference can be explained by the heading up caused by the flow through the creek). The check bund was removed by cutting it in the centre. A small section was excavated upto below the water surface level. The remaining portion was rapidly scoured out by the water flowing through the gap, and aided by manual labour. Within an hour of initiating the flow, the cut was drawing about 2500 cusecs at head, with an estimated velocity of 7 ft/Sec. The cut showed signs of rapid development.

A few days after opening, the tail end of the cunnete silted up to about 1.0' below the water level. However, within the cut, the discharge was increasing and the flow taking place through the creeks at R. D. 2200 and 3500. The set back caused by the choking of the tail, was counterbalanced by the creeks and the development progressed.

The flow through the creeks, was causing some anxiety by pressure on the shank of old T. Head and Murphy Spurs and it was feared that the development may go wrong through a diversion in a course leading to the spurs. However the creeks silted up in about a week's time, but not before, the head reach had sufficiently enlarged and a good portion of silt load had been absorbed.

In the cut, the left bank was more rapidly eroded, as provided by the initial layout of the cunnete. After the creeks had also silted up, a narrow, but fast stream was developed by the river, through the tail, slightly towards the right of the original outfall. There were heavy heaps of silt on either side of this channel. At this stage, the river showed no hesitation in its decision and the entire flow was diverted through the cut. The old course, was silted up to some extent all along, but the main choking up was witnessed at the junctions with the new course.

Analysis of Observations.

The observations recorded, during the development of the cunnete, are given in appendix 3. A graphical represenation of these value, is given on plate 10, which shows, the pond level maintained at the Headworks; river hydrograph; percentage of the total discharge through the cut ; average bed level at the cross section, and area, mean velocity and water surface level at the typical cross-section. The effect of various factors on the development of the cut is discussed below :—

(*a*). Pond Level.

As the tail of the cunnete was within the pondage effect of the Headworks, its effect on the cut was important. At the time of opening, the pond level at the Headworks was 453.95. It was maintained at this level for about 4 days and was then raised by about a foot, to 454.85. The pond level was initially kept low, to provide the maximum working head to the cunnete and was then raised to slow down the pace of development and to control the silt entry into the channels.

(*b*) Hydrograph.

As discussed earlier, the development of the cunnete, depends to a great extent on the hydrograph of flow imposed on it. Luckily, it was possible to select a highly favourable stage for opening the cut. The discharge in the river rose from 55040 on 8.7.59 to 90490 cusecs on 10.759. Thereafter, the river gradually fell and the discharge was only 16620 cusecs on 17.7.59. The discharge increased once again and this time, it rose to a medium flood (downstream discharge greater than 1,00,000

cusecs). It was during the last stages of this flood, that the river was entirely flowing through the cunnete.

The first rising stage of the river accomplished the initial development and thereafter, the fall brought about both a tranquilisation of the conditions, as well as the silting up of the old course. The second rise (i.e. the medium flood) was again abrupt and resulted in a rapid increase of the percentage flow through the cut.

(*c*) Percentage flow through the cunnete.

Observations of discharge through the cunnete, were daily made at R. D. 2000 from 8.7.59 to 28.7.59. On 29.7.59 the current at the section became so fast that it was no more possiblc to observe the cross section and so the flow through the cut was determined indirectly, by observing the discharge in the main course, upstream of G. H. Spur. The velocity observations in this case were made with a current meter.

In view of the variation in the river stage, the percentage of total flow passing through the cunnete, has been plotted, rather than the actual discharge. It would be noticed that the development of the cut, was moderate till 22.7.59 when about 25.4% of the total discharge in the river was passing through thc cunnete. Thereafter a very steep rise took place and the percentage flow increased from 25.4% to 72.0% on 26.7.59 and the largest jump of 26.5.% took place on 25-26 July.

The rise in percentage discharge during 22-26 July seems more accentuated, because of low flow in the river. It shows that the cut had enough capacity for the prevailing discharge. Thereafter rise was comparatively moderate and 100% flow in the cut was observed on 12.8.59.

The proportion of the total flow through the cut actually presents the history of its development.

There is a positive development for the first six das after which there is some viccissitude, mainly due to the silting up of the cunnete and the river at the outfall. The flow through the creeks fully developed on about 22nd July and the one at R.D. 3500 was more active than the other. It was then that inspite of low river discharge, very rapid development took place. Choking of the creeks, caused another halting of development on 28.7.59. The development again started, as the flow through the tail commmenced. The final stages of development are generally asymptotic, but in this case it was the sharply falling flood, which sealed off the main course.

(*d*) Average Bed R.L. and Area of Cross Section.

These two curves show the physical development of the cut at the particular section (R. D. 2000). Factors effecting them are the same as described above.

Role of the Intersecting Creeks.

Before the pace of development of this cut off is discussed the role played by the intersecting creek may be elucidated.

It has been described, that in the initial phases of development of the cut, the river at the outfall was choked up and the silt deposit travelled upstream in the cunnete. Normally this should have been a halting point for the development, because the heavy silt load carried by the river at this stage, would deposit, in the cut or the main course, wherever, there was some obstructions. Some silting of the main course does take place due to the reduction of discharge, when the cut is opened but this newly laid deposit is susceptible of easy erosion, because it has not yet consolidated and because the full river section is available to the flow. On the other hand in the cunnete itself, a silt deposit (or a tough patch of clay for that reason) is not easy to erode, because of the low capacity of the section available. The choking up of the cunnete is therefore a common phenome non. It is generally experienced in long cunnetes. In the case of Willow cut off on Mississippi River, the length of the pilot cut was about 4 miles and although the loop-neck ratio was about 3, the cunnete did choke up during low river stages and had to be dredged (Ref. 5).

The creeks, at this stage, carried the discharge and allowed the upper reach of the cunnete to develop. Later as the creeks, were also choked up the cunnete had sufficienty developed and it was possible for the flow to erode a passage through the deposit at the tail end.

It has been previously discussed that one reason of prejudice against the use of cut offs was that the retrogression of the river course upstream, invariably caused, a deterioration of the channel below it, as a direct consequence of quick development of the cut off. In the artificial cut off, this aspect is overcome, selecting a narrow pilot cut, which will develop over some years, and would help in absorbing the sediment load, in the main course, which is kept open for the purpose. Unfortunately, the development in the cut off at Islam, was also very quick, and the deterioration of the river just below the cut off was experienced. The creeks during this period, by drawing the flow, helped, in absorbing some portion of the silt load, but this did not entirely obviate the problem. However this points out the necessity of leaving the old course and subsidiary channels open during the development of cut off.

Rapid Development.

The cunnete, was opened on 8.7.59 and on 12.8.59 *i.e.* in 36 days, it was drawing 100% river discharge. Some enlargement of the cunnete did take place after that, but the main river course did not receive any more flow. To make a comparison, between the Mississippi River cut off and the cut off at Islam, the percentage discharges are plotted for Marshal, Willow and Malshah cut offs, in Plate 11. The contrast between the pace of development is obvious. The factors contributing to rapid development of the

cunnete are many, including the existence of intersecting creeks. They are discussed below:—

(a) **Proximity of the Headworks.**

In a river stretch away from a control point, the silt deposit, downstream of the cut causes an obstruction and raises the water level, thereby reducing the working head available to the cunnete. The process of erosion is thus showed down. In this case the downstream level, being within the back water of the Headworks, was more or less fixed. Although the pond level was raised by about 1 foot after 4 days, the effect was not much. It can therefore be surmised that the proximity of the Headworks, did not let the natural slowing down of erosion take place.

(b) **Erodibility of the strata.**

It has been described earlier, that the area within the neck of the loop was recently abandoned by the river, and consisted of slit and sand with intermittant layers of clay, which were easily erodible. It is therefore clear that the stratum traversed by the cunnete had not yet compacted, and was such that its erosion did not pose of a problem to the river. leading to its rapid development. This is an important factor in artificial cut off and should therefore be given due weight in selecting the cunnete size.

(c) **Loop Neck Ratio.**

Under 'Design Criteria' for the cunnetes, it was stated that generally the talweg neck ratio should be 1.75 to 2.0 before an artificial cut off can be successfully executed.

Reference to the study of river course upstream of the Headworks had also shown that for the natural cut offs, that occured during the recorded history of this stretch of the river, this ratio varied from 2.3 to 6.3. At the Adamwahan bridge site (about 70 miles downstream of Islam), the same ratio for natural cut off has been reported as 2.1 to 2.8 (Ref. 8). In the present case, the loop-neck ratio, at the time of development was 4.4. It would, therefore appear, that a major factor, contributing to the rapid development was the high loop-neck length ratio. In fact, according to the observation of the river behaviour the loop was already on the verge of a natural cut off. It appears that the cut off could have been advantageously planned in 1956-57 or even with the 1958 position, the cunnete could have been lengthened by giving a slightly longer path, or made tighter. In marginal cases of artificial cut offs, it is very likely for the pilot cut to choke up, thereby necessitating dredging. In view of the non availability of such equipment, in the country, a sufficient margin was kept for obviating such a contingency, but it back fired.

Result of the cut off.

The reasons which led to the decision of cutting off the loop, have been previously explained. These were, excessive pressure on the retired

embankments and in the southern creeks ; abnormal approach to the Headworks and the expected natural cut off.

As a result of the artificial cut off, these factors were corrected to a varying degree. During the flood season of 1959 and later, very little pressure has been noticed on the retired embankments and there is no longer a tendency for the river diversion into the Southern creeks. Soon after the development of the cut, old T. Head Spur D/S of the Murphy Spur, also came under action and the obliquity of approach to the Headworks reduced considerably. These aspects were welcomed as a great relief by all concerned with the operation of the Headworks.

However, there was one aspect, that created a major problem and it was the huge silt load generated in the river. As concluded earlier, the cut off, more nearly approached, the conditions of a natural cut off, in as much as it developed very rapidly. The benefit of the absorbtion of silt load, in the main river course, was thus not available to it and despite the relief offered by the creeks, the silt deposition upstream of the Headworks was heavy. Mailsi Canal, which takes off from the right bank, is more susceptible to fluctuations in the silt load due to its location with respect to the river approach. This canal therefore received excessive silt load. Bahawal and Qaim Canals, on the left bank, also received increased sediment charge but the condition was not so serious. Unfortunately no silt observations were made at the Headworks for the river or the canals prior to 1960 and therefore a quantitative evaluation cannot be made, but the huge silt deposits upstream and downstream of the weir, found during the next closure were a sufficient indication.

About 22 millions cubic feet of silt were deposited in the first 15 miles of the channel in a period of about two months and the resulting upheavel of its regime, caused serious damage to all the structures. (See plate 13).

Silt Problem in Mailsi Canal.

Weekly silt soundings are observed at Islam Headworks in the first mile of the canals. The average bed at each 500′ interval is computed from silt soundings observed at 20, interval across the section.

Average depths of silt or scour with respect to the designed bed for Mailsi and Bahawal Canals for 1958 and 1959 are plotted in plate 12, alongwith the upstream River Hydrographs, for the two years. The silt/scour curves for both the canals for 1959 show an abrupt rise in the bed on 30.7.59. Part of it is due to the rising stage of the river, and part due to the effect of the cut off. In view of the difficulty in correlating the river sediment load with discharge in the absence of requisite data, it would not have been normally possible to split up the contribution of the two factors. Luckily however, the hydrographs for years 1958 (from 26.7.58 to 6.8.58) and 1959 (27.7.59 to 6.8.59) are very nearly similar both in the discharge variation and the rising characteristic. It is safe to assume that the effect

of the river stage on the silt entry into the canal would be same in both the years and hence the contribution of the cut off for this period can be determined. For Mailsi Canal the silt deposit in 1959 was 3.5 feet against 2.25 during the corresponding period in 1958. (It may be noted, that the silt/scour depth values are just a qualitative indication of the silt entry and do not carry any quantitative interpretation of the same).

In order to study the deposit of silt along the head reach of Mailsi Canal (Up to R. D. 76) longitudinal sections of the canal were observed on 6/8/59 , 21/9/59, 24/ 9/59, and 14/10/59. It has been calculated from these observations that the total deposit between 6/8/59 and 14/10/59 (70 days was about 22. 0 million cubic feet. The channel during this period, showed a marked tendeny to meander and deep scour pits occured downstream of the structurees. Floors and other protection at the structures, were widely damaged and one pier of foot bridge at R. D. 20 and the left flank wall of the Karampur Regulator (R.D. 76) were competely damaged. The channel lost in capacity and had to be closed.

Effect of excessive silt entry into Canals.

In the design of stable channels, under Regime Theories, total sediment transport is not involved as a direct variable (Attempts by Inglies and Blench are inconclusive in as much as the determination of constants and validity of equations has yet to be tested). As an operational measure the sediment entering the canals is vigorously reduced by use of one or more of the following methods :—

(*i*) River Approach.

(*ii*) Design of Headworks and Training works.

(*iii*) River Regulation.

(*iv*) Silt excluders and extractors.

(*v*) Silting tanks.

and the sediment content in the canals are not high. Simon and Albertson in their paper, "Uniform water conveyance channels in Alluvial Material,, (Ref 11) have observed on the basis of field study of stable channels and laboratory studies of form of bed roughness that

(I) ".....if a channel is to be stable (no appreciable bed/or bank scour or accretion occuring with time) the Froude number defined as $V\sqrt{GD}$ must in most cases be less than 0.3 for alluvial material in the sand range size and finer.....,, .

(2) ".....the Magnitude of sand-silt sediment load which can be transported is, likewise severely limited usually to less than 500 P.P.M.,, (Page 46-47 ref : 11)

Mushtaq Ahmad and Abdur Rehman (Ref 12) have calculated the sediment carrying capacities of regime channels by tractive force theory using methods evolved by various workers, and have also drawn a relationship between the average sediment load, Lacey's silt factor, flow velocity, Shear velocity and fall velocity of the particle using Laurse's data and Lacey's Regime equations. This relationship gives the average silt intensity in channels of silt factor 1.0 at velocities 2.0 fps and 4.0 Fps as 220 PPM and 650 PPM respectively.

Now as the sediment load entering a regime channel increases, beyond its capacity silting up of the bed commences from the head reach and the channel tends to adopt a steeper slope corresponding to the silt charge, and clearly shows meandering tendencies in the form of bar formations and bank erosion.

The phenomenon of secondery circulation in open channels is intimately connected with the meandering tendency and hence a summary of knowledge partaining to it will be presented here. This is largely drawn from reference 6.

Vanoni, while experimenting on sediment suspension in straight laboratory flumes found that symmetrical velocity distribution of clear water flow became distorted by the addition of very small amounts of sand. The distortion appeared with average sediment concentrations of 750 PPM and was more pronounced with higher concentrations (3000 PPM). He also observed that the sediment appeared to be transported in clouds or ribbons parallel to the flow and at low flows when appreciable material was moving along the bottom, the ribbons appeared as bands of sand on the bottom. He believed that the longitudinal bands were created as a result of secondary circulations caused by the presence of suspended load.

Powell and Nemeyni, in their discussion of the paper, expressed that the non-uniform sediment distribution was rather a result of the secondary circulation than a cause of it. Professor Nemenyi, gave an exhaustive summary of the subject, and deduced from theoretical considerations that secondary currents of appreciable intensity would be normally present in turbulent flow even if the fluid is perfectly homogeneous. The experiments of Terada of Tokyo Imperial University, where, secondary currents were generated in a steep channal uniformly heated from below and observation of velocity across the cross section of turbulent flow with movable bed by Hugh Casey were also quoted by him.

Vanoni in reply to the discussion of his paper, stated that the density gradients produced by non-uniform sediment distribution (even though caused by the inherent secondary flow) would tend to cause appreciable circulations, greater than those occuring in clear flows.

Inspite of the uncertanity regarding the true explanation and effect of secondary circulations within turbulent flow, it can be concluded that with increasing sediment concentrations the circulation would increase. Under this condition in the open channels, if some disturbance is caused by say non-uniformity of friction, along the banks, varying erodibility of banks and presence of curves etc. etc. these strong circulations are modified to

give rise to a single secondary current, resulting in a meandering tendency, and erosion of banks. It is believed that at low sediment contents, the strength of the secondary current is not large enough to erode relatively compact berms, which have formed out of fine silt deposition.

Effect of Meandering Tendency on Structures.

As the meandering tendencies are developed in the channel the flow is not normally distributed but a deep channel containing the main flow is formed along one bank and then travels across to the opposite bank in a zig-zag fashion.

As these meanders develop upstream of structures, the discharge intensity across the section varies and at the bridges or other structures founded on piers, a greater discharge intensity will be experienced by the spans on the same side as the talweg. Similarly, the flow approaching a structure may become oblique, rather than normal. Both these conditions, will cause scour at the Upstream and Downstream of the structures due to the increase the of discharge intensity and the formation of swirls at the junction of the fast current and the sluggish body of water. The scour will generally start at the downstream end and will be more pronounced there. Moreover, as these meanders, move downstream, the position of the talweg will shift from one bank to the other and the position of the scour and the swirl will correspondingly alter.

On Mailsi Canal, as the excessive silt entry progressed, the meander formation was clearly observed. The first damage to be noted at any structure was at the foot bridge a R. D. 20180. This bridge has open foundations 4.0 ft. below the designed bed level of the channel with dry brick flooring. On 3.9.59 sudden scouring of the left berm downstream of the bridge, was noticed and simultaneously the second pier of the bridge from left cracked and settled nose long, damaging the adjacent spans. Soundings taken downstream of the bridge indicated scour depth 30′ below the design bed level. The bays on the right were drawing much less discharge and the one at the extreme right was practically choked by reverse flow. The same phenomenon was experienced again and again on the all the structures, (the structures were saved by stone dumping in the effected portions and other methods which need not be described here). The inception of scour was generally sudden and was invariably accompained by the erosion of berms on the effected sides. It was also thought at one time that the scour may be generated by the creation of a fall, as a silt bar moved to the upstream of a structure. This explanation was not found tenable, because firstly no additional difference of water levels on the upstream and downstream sides was witnessed (which should be a necessary consequence) and secondly it would not explain the oblique approach witnessed at the structures.

During 1960 and 1961 flood seasons, the river upstream of the Headworks, increased its length by 10 and 30% respectively over the length of 1959, but the stable conditions do not appear to have been achieved.

Large sediment deposits are still present above the Headworks and in the right pocket and the silt entry in the Mailsi Canal continues to be excessive. Analysis of silt samples, in the boils downstream of the head regulator of the Mailsi Canal, show as much as 4.5 grams/Litre of coarse and medium sand entering the channel for an upstream river discharge of 85,800 cs. The pattern of scour at the structures has been repeated, during the last two years as well.

Conclusion.

For a given alluvium, the rivers have been found to maintain their limiting lengths and widths and any artificial shortening is soon restored, unless the erodibility of the banks is reduced by protection. The utility of artificial cut offs for river training lies in conjuction with bank protection, and in near future, when we are forced to pay more attention to the improvement of our rivers, this method will find its wide spread use.

The experience with the cut off at Islam Headworks, has been described in detail to bring out the profits attendant upon this method. The rapid development of the cut off was an unpleasant happening and its results were accentuated by the close proximity of the loop to the Headworks. On the other hand, if the loop had been allowed to cut itself naturally during a high flood, the consequences would have been much worse.

It is clear that in the absence of dredging equipment, it would be difficult, if not impossible, to tackle many marginal cases, of cut offs. and at other places, we may again tend to provide larger cunnetes (than necessary) for the same reason, with unfavourable consequences.

Excessive silt entry in canals, is already troubling us, at a number of places. In coming years, as, the diversions of supply at various Headworks increase the problem will become a great menace. The experience of Mailsi Canal, has been explained to focus some attention on this problem.

The meandering of alluvial rivers is highly important to the life and culture that has concentrated on the alluvial plains. Some discussion of the phenomenon was included, mainly to develop the idea of cut offs. We would do well to study our river in greater details.

Generous help was taken from a number of publications, in the preparation of this paper. The list is given in the bibliography at the end, and acknowledgement has been made in the text as far as possible.

Bibilography.

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7. Applied Hydraulics, Edited by H. Rouse. John, Wiley and Co. U.S.A.

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11. "Uniform water conveyance channels in Alluvial Material" by Doctors Daryl, B. Simons and Maurice L. Albertson. Proceedings, of the American Society, of Civil, Engineers, Journal of Hydraulics Division Vol. 86 No. Hy. 5 May 1960.

12. "Silt Carrying capaycity of a channel and critoria for canal closure against excessive silt entry" by Dr. Mushtaq Ahmad and Abdur Rehman Paper No. 350, Proceedings of the West Pakistan Engineering Congress 1961.

13. "Theory and Design of stable channels in Alluvial Materials" Thesis submitted by Daryl B. Simons in Partial fulfilment of the requirements for the Degree of Doctor of Philosophy to colorado state University. Fort Collins, May 1957.

14. Regime behaviour of Canals and Rivers by Professor T. Blench. Butterworths Scientific Publications, London.

15. Regime Flow in incoherent Alluvium by Gerald Lacky; CBI Publication No. 20.

16. "Progress Report on studies on the Design of State Channels by the Bureau of Reclamation". By E.W. Lane. Proceedings American Society of Civil Engineers, Vol. 79 Sept. 1953.

APPENDICES

No. *Subject*

1. Cut-offs on the Mississippi River between 1929-1942.
2. Limiting values of tractive force in cohesive materials.
3. Data Pertaining to the Development of Artificial cut-off at Islam Headworks.

APPENDIX I.

Cut Offs on the Mississippi River (U. S. A.) between 1929—1942.

No.	Name.	Opened.	Location of Upper End.	Distance in miles as of date cut off was made.			Length of dredged cut in ft.
				Across neck.	Around bend.	Net Shortening.	
1.	Hardin.	March, 18, 1942.	673.0	1.86	18.82	16.96	5900
2.	Jackson.	April, 26, 1941.	624.4	2.40	11.06	8.66	11300
3.	Sunflower.	Feb. 16, 1942.	621.9	2.43	12.87	10.44	10300
4.	Caulk.	May 13, 1937.	568.5	2.0	17.2	15.2	4400
5.	Ashbrook.	Nov. 19, 1935.	542.0	1.9	13.3	11.4	4530
6.	Tarpley.	April, 21, 1935.	535.0	3.6	12.2	8.6	13000
7.	Leland.	July 8, 1933.	531.7	1.4	11.2	9.8	—
8.	Worthington.	Dec. 25, 1933.	507,0	3.8	8.1	4.3	17600
9.	Sarah.	March 23, 1938.	498.2	3.2	8.5	5.3	12600
10.	Willow.	April 8, 1934.	457.7	4.7	12.4	7.7	22000
11.	Marshall.	March 12, 1934.	443.9	3.1	7.3	4.2	13600
12.	Diamond.	Jan. 8, 1933.	420.0	2.6	14.6	12.0	9175
13.	Yucatan.	Fall of 1929.	404.4	2.6	12.2	9.5	—
14.	Rodney.	Feb. 29, 1936.	385.4	4.1	9.9	5.8	13000
15.	Giles.	May 25, 1933.	363.8	2.9	14.0	11.1	10000
16.	Glascock	March 26, 1933.	342.1	4.8	15.5	10.8	20800
		Total. ...		47.4	199.2	151.8	168205

Natural cut off ; no artificial channel was dredged.

APPENDIX 2.

***USSR Limiting Velocities and Tractive Forces in Cohesive Material.**

Compactness of Bed.

Description.		Loose.		Fairly Compact.		Compact.		Very Compact.	
Void Ratio.		2.0 — 1.2		1.2 — 0.6		0.6 — 0.3		0.3 — 0.3	
Principal cohesive material of bed.		Limiting mean Velocity ft./Sec. and Limiting tractive force lb/ft².							
Sandy clays (Sand content less than 50%)	...	Vel : 1.48	T. Force 0.040	Vel : 2.95	T. Force 0.157	Vel : 4.26	T. Force 0.327	Vel : 5.90	T. Force. 0.630
Heavy Clayey Soils.	...	1.31	0.031	2.79	0.141	4.10	0.305	5.58	0.563
Clays.	...	1.15	0.024	2.62	0.124	3.94	0.281	5.41	0.530
Lean Clayey Soils	...	1.05	0.020	2.30	0.096	3.44	0.214	4.43	0.354

(*Reproduced from table 6, item 16 of Bibilography).

APPENDIX 3

Data Pertaining to the Development of Artificial Cut-Off at Islam Headworks.

DATE	*RIVER DATA		CUNNETE DATA		DATA OF TYPICAL CROSS-SECTION R.D. 2000					
	Pond Level	Discharge cs.	†Discharge cs.	Percentage of total discharge	Average water surface ‡ slope%	Average π bed R.L.	Width Bed Ft.	Water surface Level.	Area□ FT²	Mean Vel : Fps.
8.7.1959	453.85	55,040	2,500	4.6		446.65	30	456.29	429	
9.7.1959	453.85	85,056	5,627	6.6	0.86	447.21	50	457.61	632	8.9
10.7.1959	453.70	90,488	7,480	8.3	0.85	445.68	60	457.08	796	9.4
11.7.1959	453.90	59,714	7,385	12.4	0.56	444.83	70	456.43	912	8.1
12.7.1959	454.50	51,625	8,172	15.8	0.49	445.32	80	456.65	1041	7.85
13.7.1959	454.50	46,114	8,375	18.1	0.42	445.47	90	456.40	1160	7.22
14.7.1959	454.50	40,065	8,710	21.7	0.39	443.30	100	456.58	1469	5.93
15.7.1959	454.65	31,478	6,366	20.2	0.28	442.69	100	456.15	1481	4.30
16.7.1959	454.65	19,711	4,723	24.0	0.15	442.11	100	455.62	1504	3.14
17.7.1959	454.65	16,622	4,476	26.9	0.15	442.35	100	455.65	1477	3.03
18.7.1959	454.65	22,353	4,585	20.5	0.19	442.68	100	455.85	1460	3.14
19.7.1959	454.65	22,553	5,276	23.4	0.22	442.21	100	455.88	1521	3.47
20.7.1959	454.65	22,553	5,670	25.2	0.21	441.63	100	455.95	1615	3.51
1 .7 .1959	454.65	20,011	5,828	29.1	0.19	440.86	100	455.80	1661	3.51

22.7.1959	454.65	22,753	5,787	25.4	0.22	441.60	100	456.00	1603	3.61
23.7.1959	454.55	37,225	10,597	28.5	0.36	440.60	110	456.45	1944	5.45
24.7.1959	454.50	43,056	17,286	40.1	0.36	440.29	150	456.55	2650	6.07
25.7.1959	454.50	43,056	20,027	45.5	0.35	441.10	180	456.50	3003	6.67
26.7.1959	454.50	43,006	31,010	72.0	0.32	439.45	240	456.45	4307	7.2
27.7.1959	454.50	40,215	27,091	67.5	0;33	442.75	253	456.15	3551	7.63
28.7.1959	454.50	61,038	40,232	66.0		442.65	310	457.00	4674	8.61
30.7.1959	454.25	1,11,422	81,942	73.5						
4.8.1959	453.80	1,40,092	1,27,592	91.2						
9.8.1959	455.35	91,287	85,523	93.6						
12.8.1959	455.50	42,594	42,594	100.0						

Notes : * River data observed at the Headworks as per usual practice.

† Cunnete discharge observed at cross, Section R.D. 2000 upto 28.7.59 and indirectly after wards.

‡ Observed over gauge 100 ft. above and below.

π Excluding Side Slopes.

□ Computed by mean ordinate method from depths observed at 10' interval.

LIST OF PLATES

Plate No.	Subject	Year
1	Course of River Sutlej at Islam Headworks	1929.
2	Course of River Sutlej at Islam Headworks	1932-33.
3	Course of River Sutlej at Islam Headworks	1941-42
4	Course of River Sutlej at Islam Headworks	1953-54
5	Development of a Natural cut-off in River sutlej	
6	Tortusoity of River Sutlej upstream of Islam Headworks.	
7	Course of River Sutlej at Islam Headworks for	1958 - 1959
8	Plan Showing Gauges and Cross-Section lines for the Cunnete	
9	Longitudinal Section of the Cunnete	
10	Data Pertaining to the Development of the cut - off	
11	Comparative Performance of Artificial cut-offs	
12	Silt Deposits in Head Reaches of Mailisi and Bahawal Canals.	
13	L—Section of Mailsi Canal Showing silting, up from 6.8.59 to 14.10.59	

PAPER NO. 352

PLATE 1

COURSE OF RIVER SUTLEJ
AT
ISLAM HEAD WORKS
YEAR 1929
SCALE 1 INCH

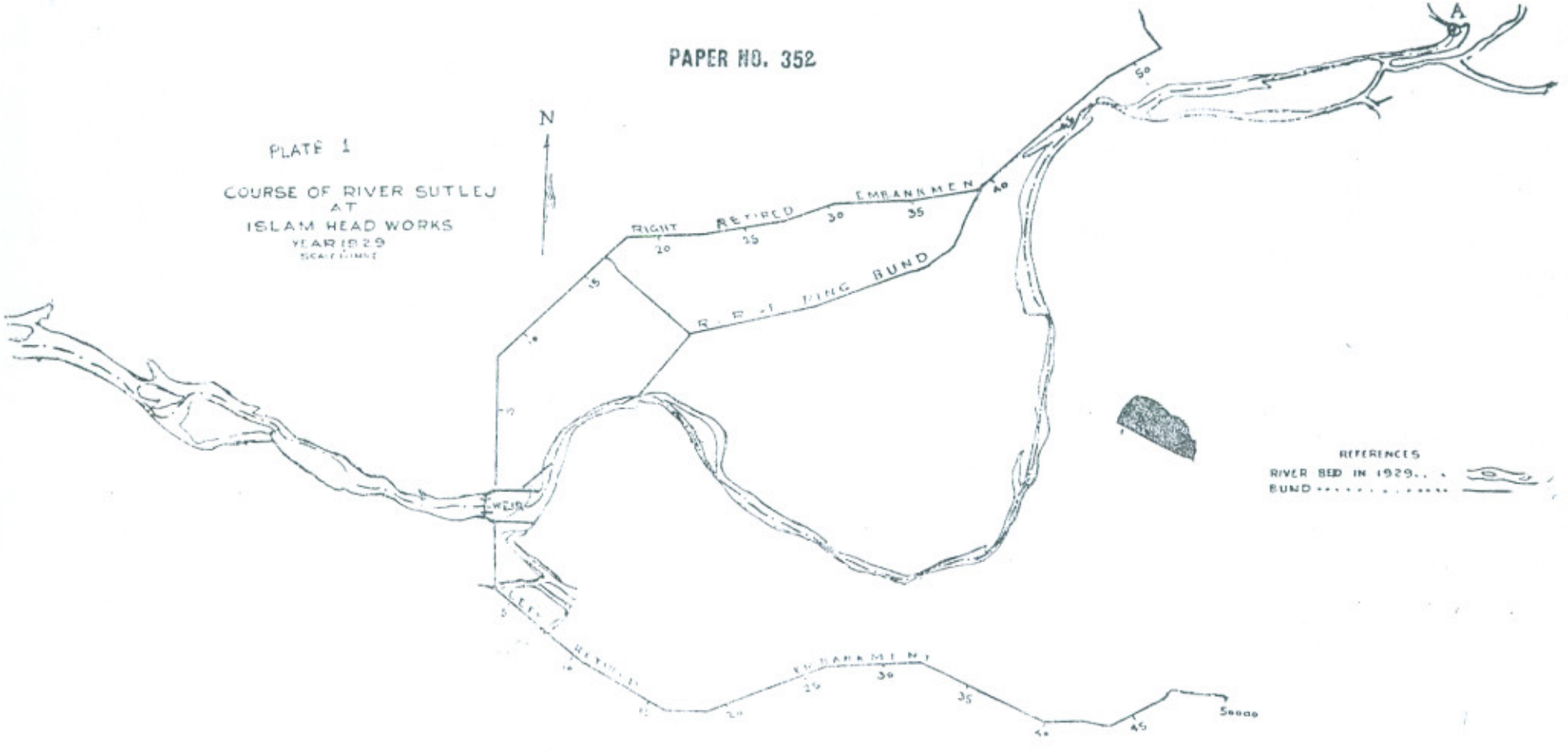


PLATE 2

PAPER NO. 352

COURSE OF RIVER SUTLEJ
AT
ISLAM HEADWORKS
YEAR 1932-33
SCALE 1" = 1 MILE

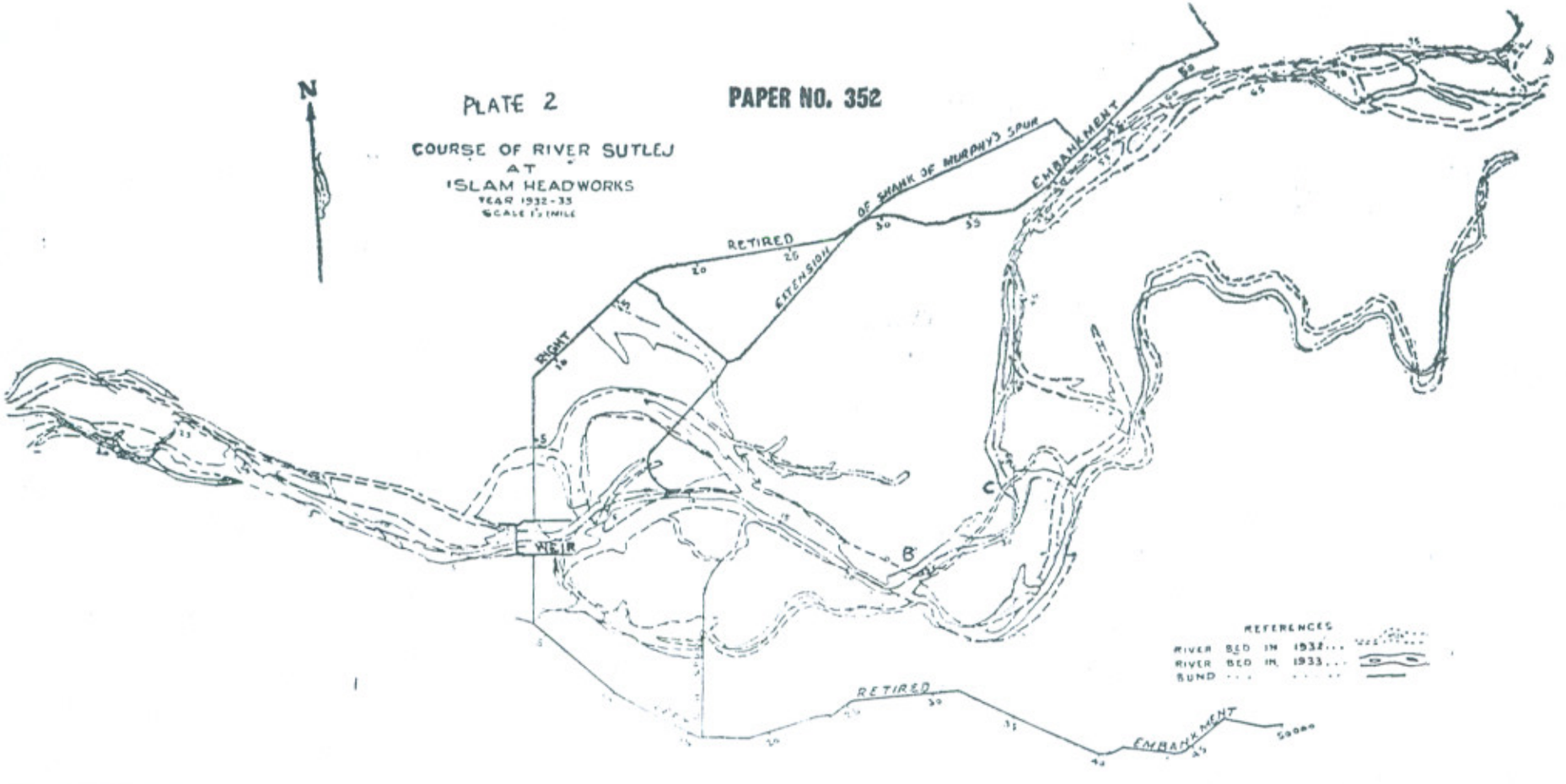


PLATE 5

PAPER NO. 352

COURSE OF RIVER SUTLEJ
AT
ISLAM HEADWORKS
YEAR 1941-42
SCALE 1/31680

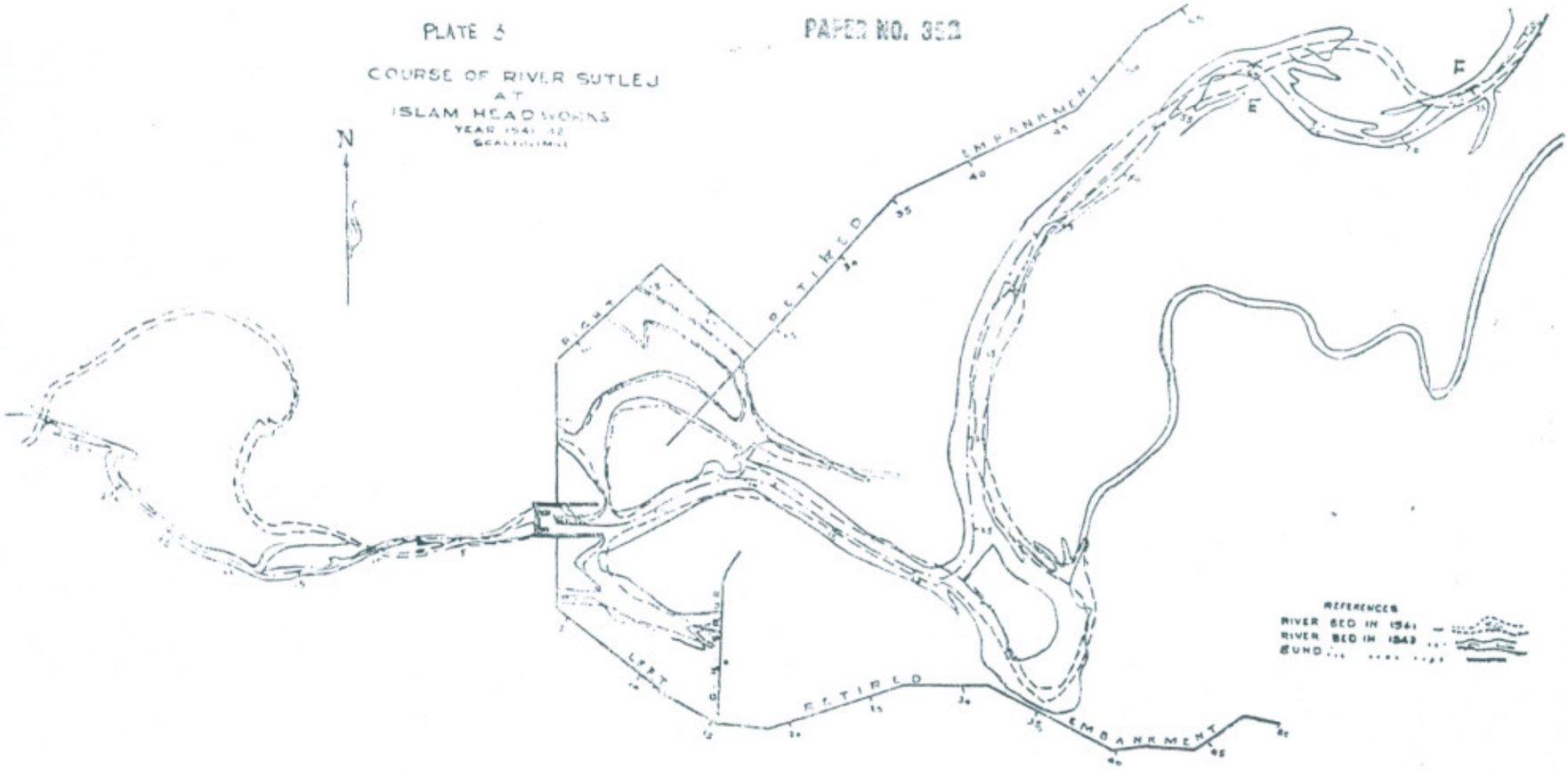
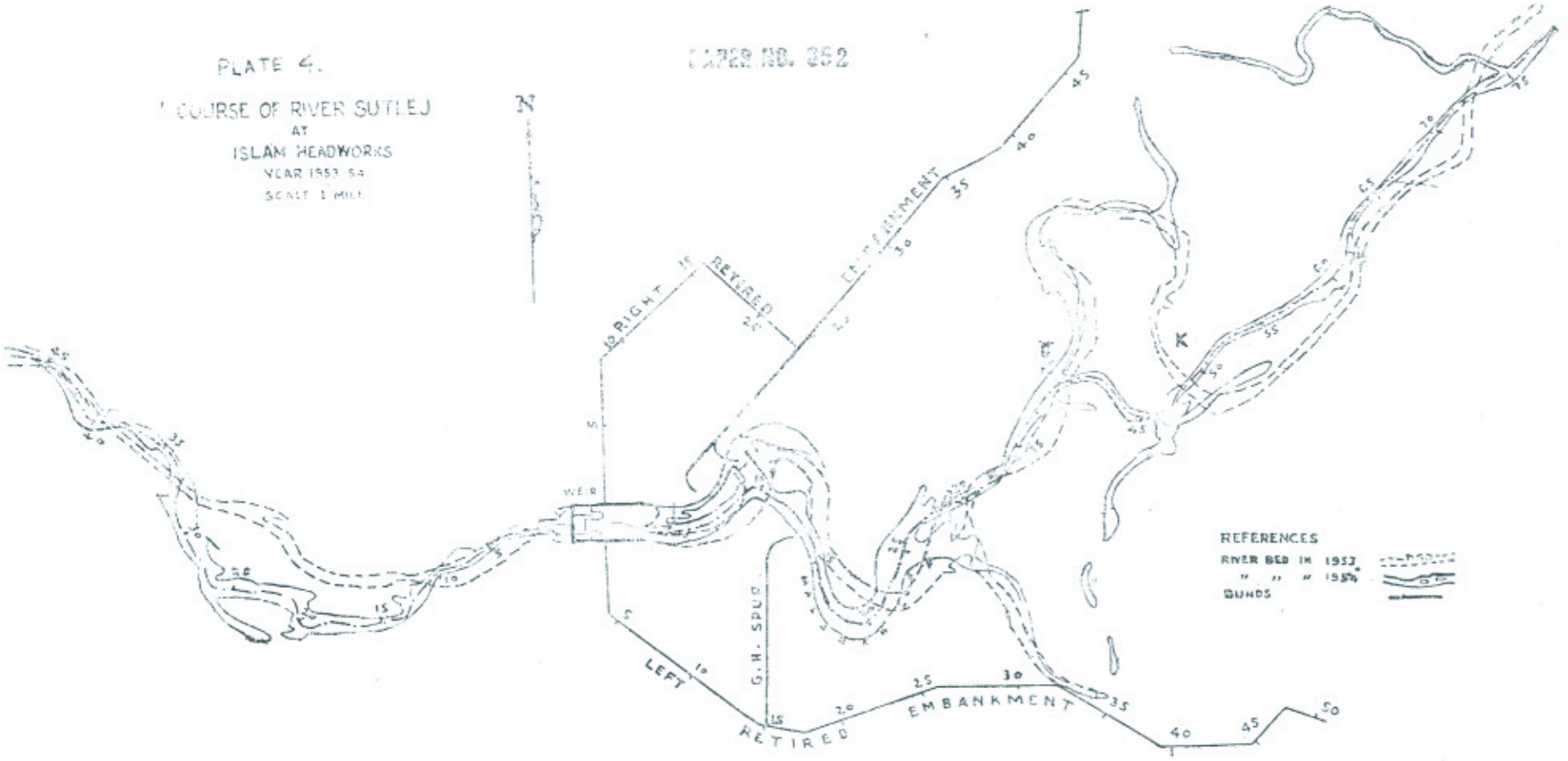


PLATE 4.

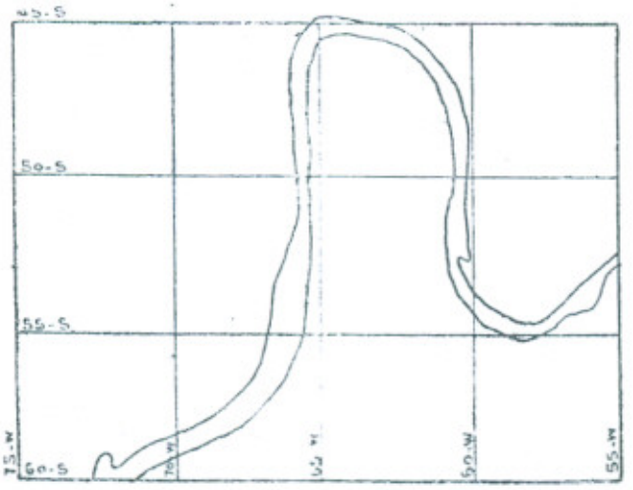
COURSE OF RIVER SUTLEJ
AT
ISLAM HEADWORKS
YEAR 1953-54
SCALE 1 MILE

PAPER NO. 352

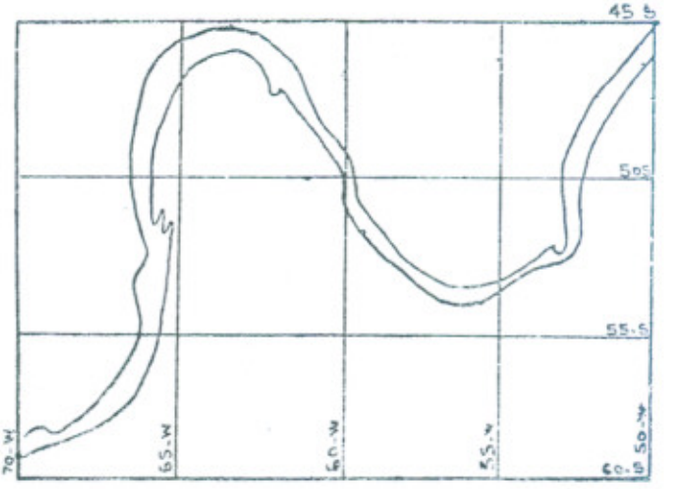


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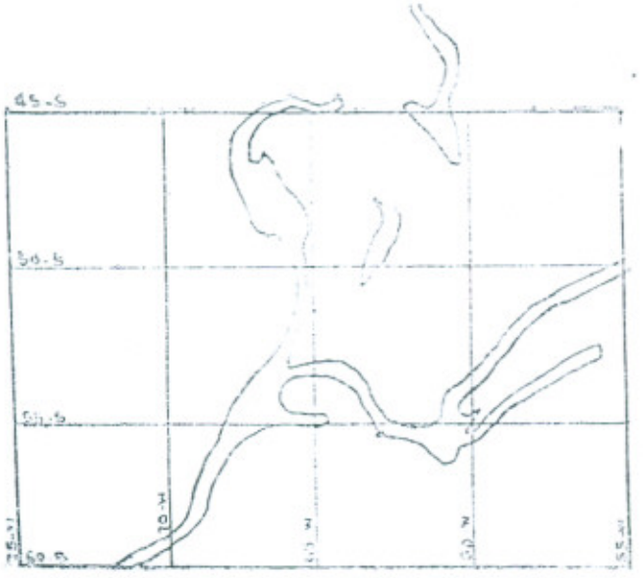
1952



1951



1954



1953

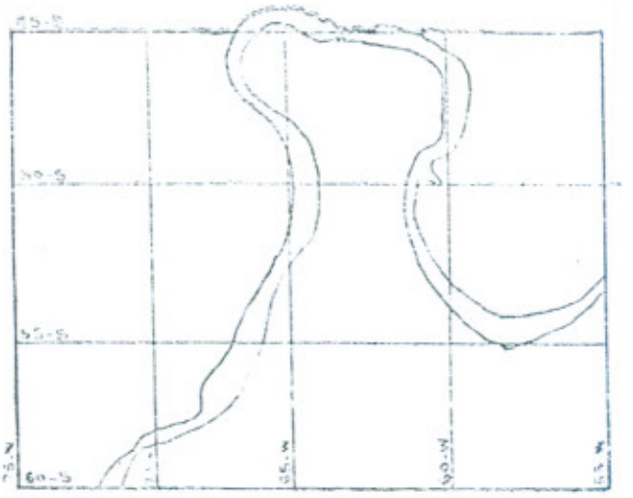


PLATE 5

DEVELOPMENT

OF

A NATURAL CUT-OFF IN RIVER SUTLEJ

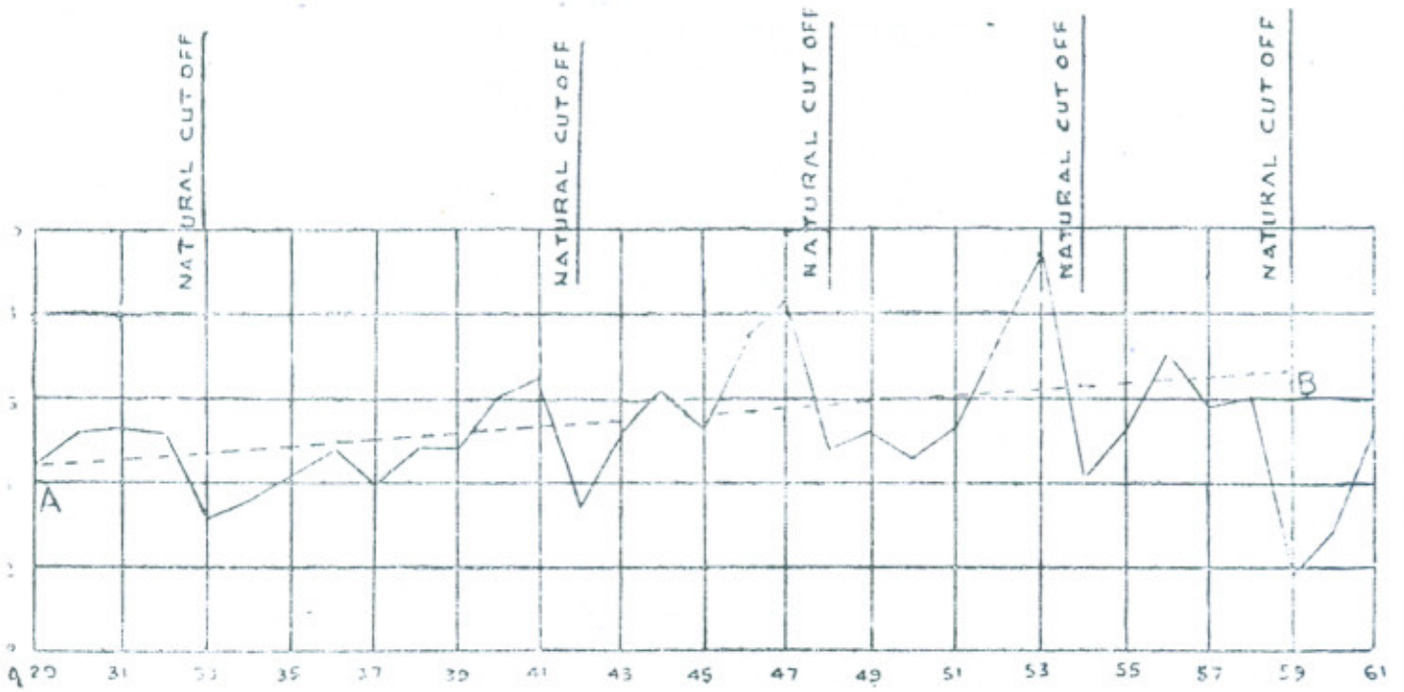
U/S ISLAM HEAD-WORKS

SCALE = 1 MILE

PLATE 6.

PAPER NO. 352

*TORTUOSITY OF RIVER SUTLEJ
UPSTREAM ISLAM HEADWORKS



LINE A.B REPRESENTS AVERAGE TORTUOSITY FROM YEAR 1929 - 1959.
(COMPUTED BY LEAST SQUARE METHOD)

* RATIO OF RIVER LENGTH TO REFERRING LENGTH - SEE TEXT

PAPER NO. 352

PLATE 7

COURSE OF RIVER SUTLEJ
AT
ISLAM HEAD WORKS
YEARS 1958 & 59
SCALE 1" = 1 MILE

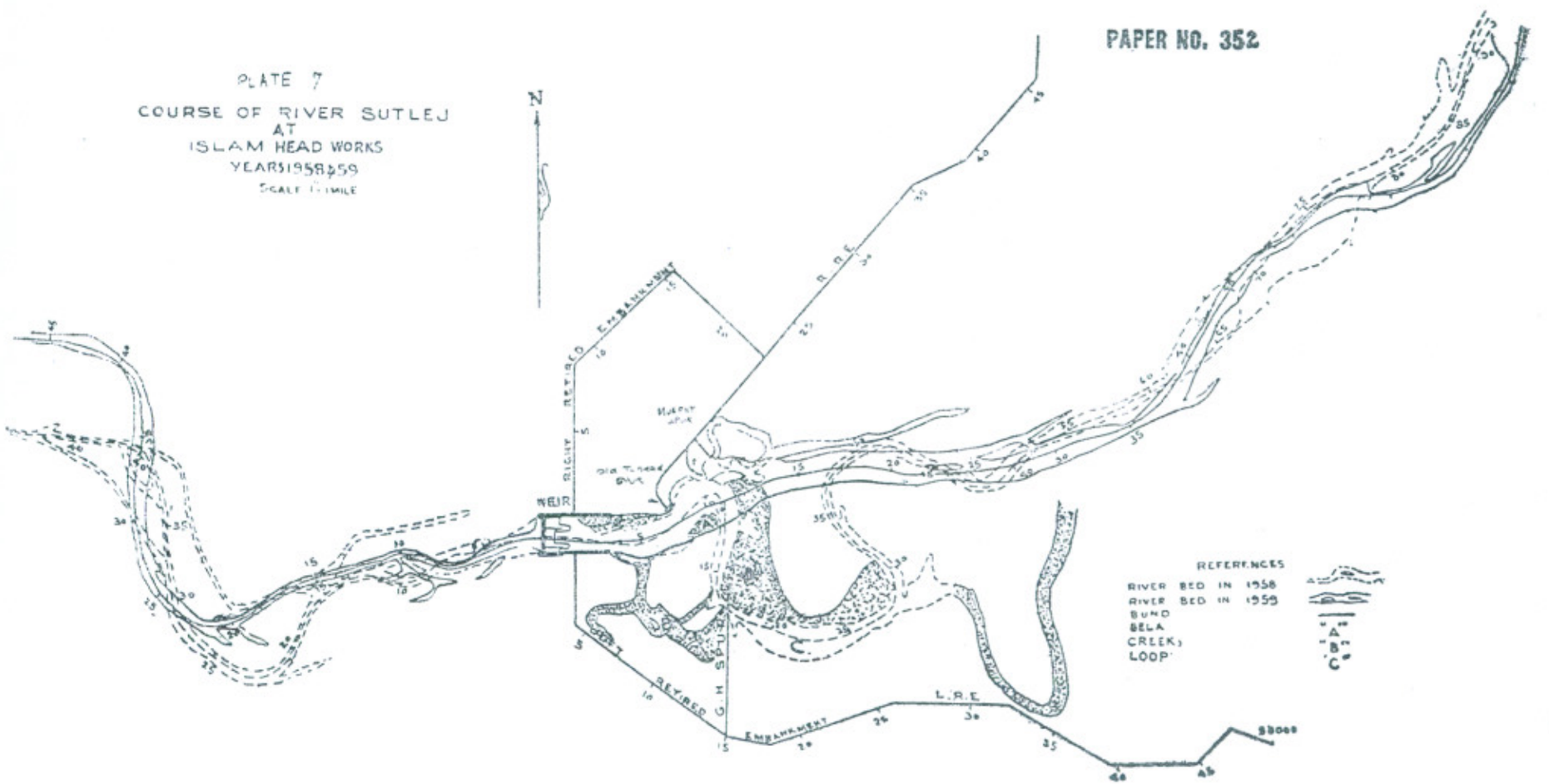
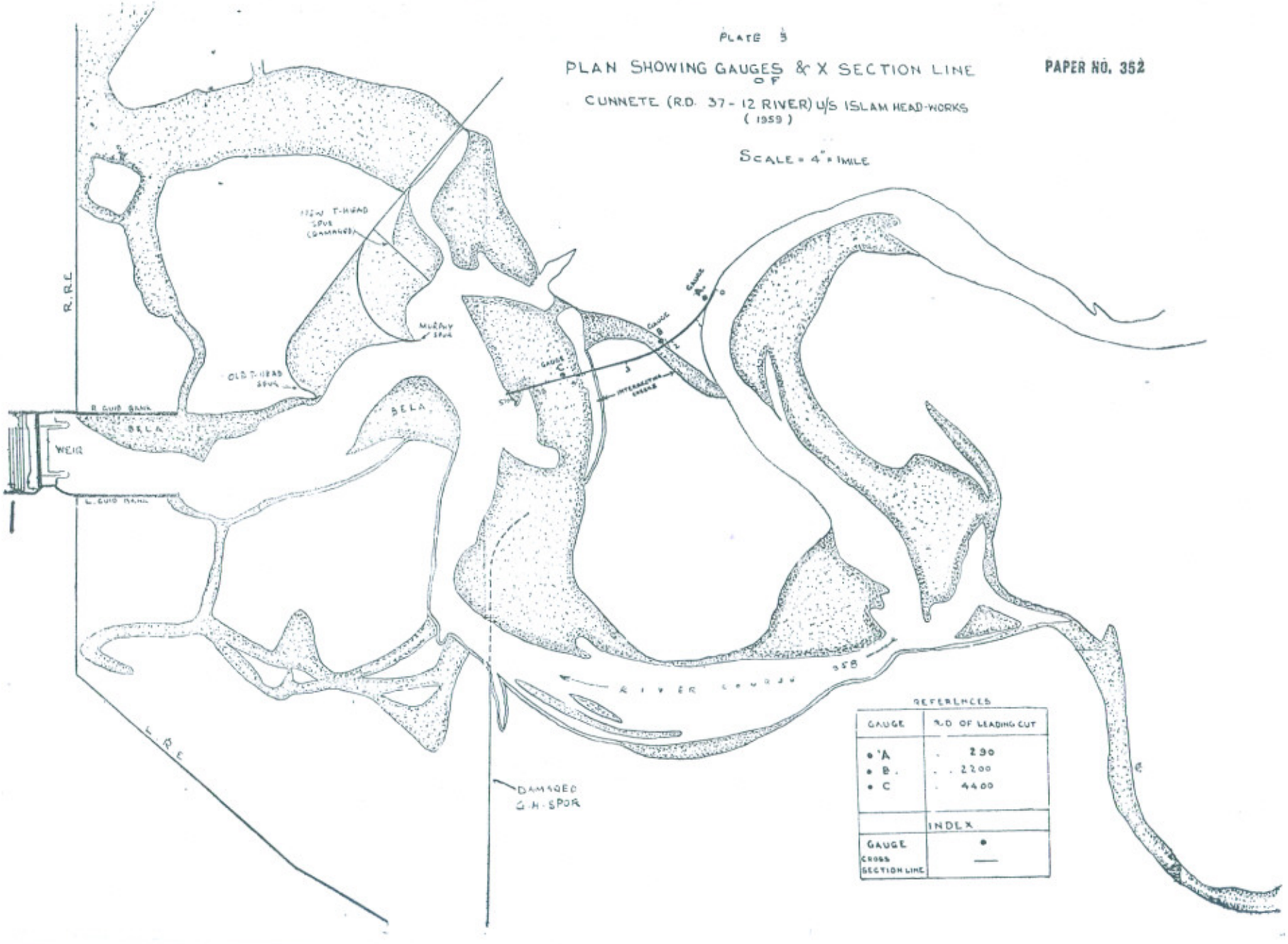


PLATE 5

PAPER NO. 352

PLAN SHOWING GAUGES & X SECTION LINE OF CUNNETE (R.D. 37 - 12 RIVER) U/S ISLAM HEAD-WORKS (1959)

SCALE = 4" = 1 MILE



REFERENCES

GAUGE	R.D OF LEADING CUT
• A	290
• B	2200
• C	4400

	INDEX
GAUGE	•
CROSS SECTION LINE	—

PAPER NO. 352

DATA OF CUNNETE

1. LOCATION : UPSTREAM ISLAM H/WORKS CONNECTING R.D 3585 OF RIVER
2. LENGTH OF CUT = 5700 FT
3. BED SLOPE : 1 IN 5700
4. BED R.L AT OFF TAKE = 447·00
5. BED R.L AT OUT FALL = 446·00
6. BED WIDTH = 30·0
7. SIDE SLOPE = 1½:1 UP TO R.D 3500
   & 1:1 R.D 3500 TO 5700
8. SOIL = SILT & SAND WITH INTERMITTENT LAYERS OF CLAY

CALCULATED DATA OF CUNNETE.

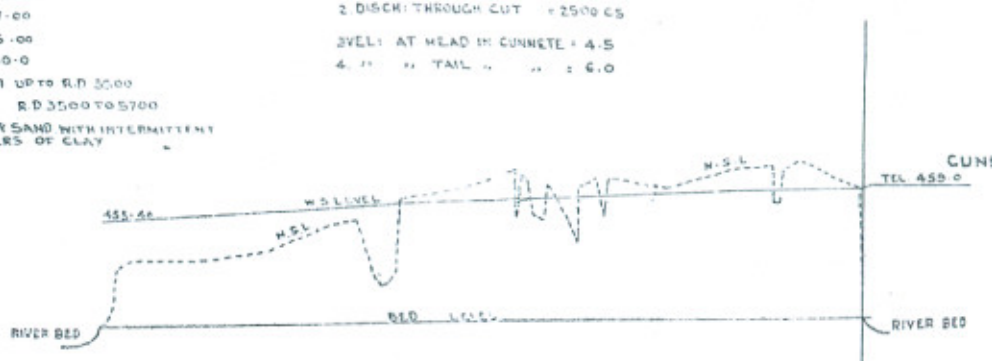
ITEM — RIVER SLOPE 0·5FT/MILE

1. TOTAL WORKING HEAD = 3·5
2. DISCH: THROUGH CUT = 2500 CS
3. VEL: AT HEAD IN CUNNETE = 4·5
4. " " TAIL " " = 6·0

PLATE 9

LONG: SECTION OF CUNNETE AT ISLAM HEAD-WORKS

SCALE { HOR. 8" = 1 MILE
VER. 1/100



DATUM LINE 400·0

5700	4824	3850	2500	744			R.D
46·0	46·16	46·33	46·54	46·87	447·0		BED LEVEL
455·48	456·15	456·83	457·64	458·57	459·52		COMPUTED WATER LEVEL IN CUNNETE

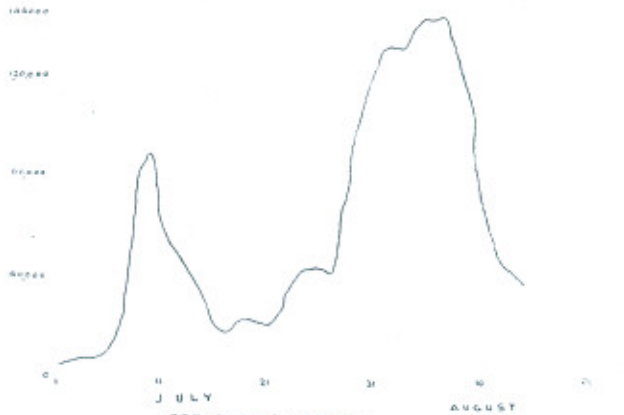
PLATE 10.

DATA PERTAINING TO DEVELOPNE
C THE ARTIFICIAL CUT OFF AT
ISLAM HEADWORKS

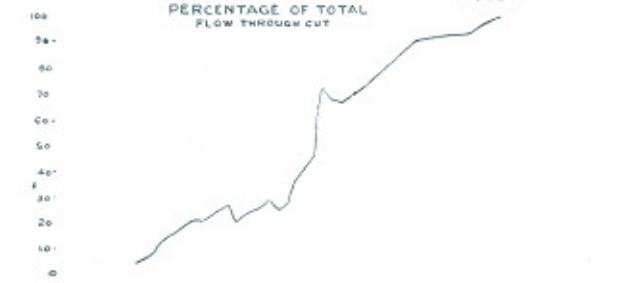
PAPER NO. 352



UPSTREAM RIVER DISCHARGE



PERCENTAGE OF TOTAL
FLOW THROUGH CUT



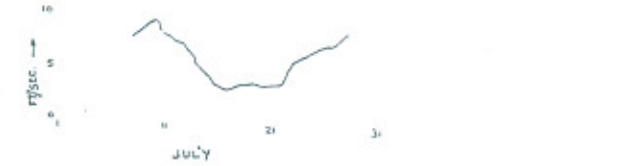
AVERAGE BED @ R.D 2000
CUNNETE

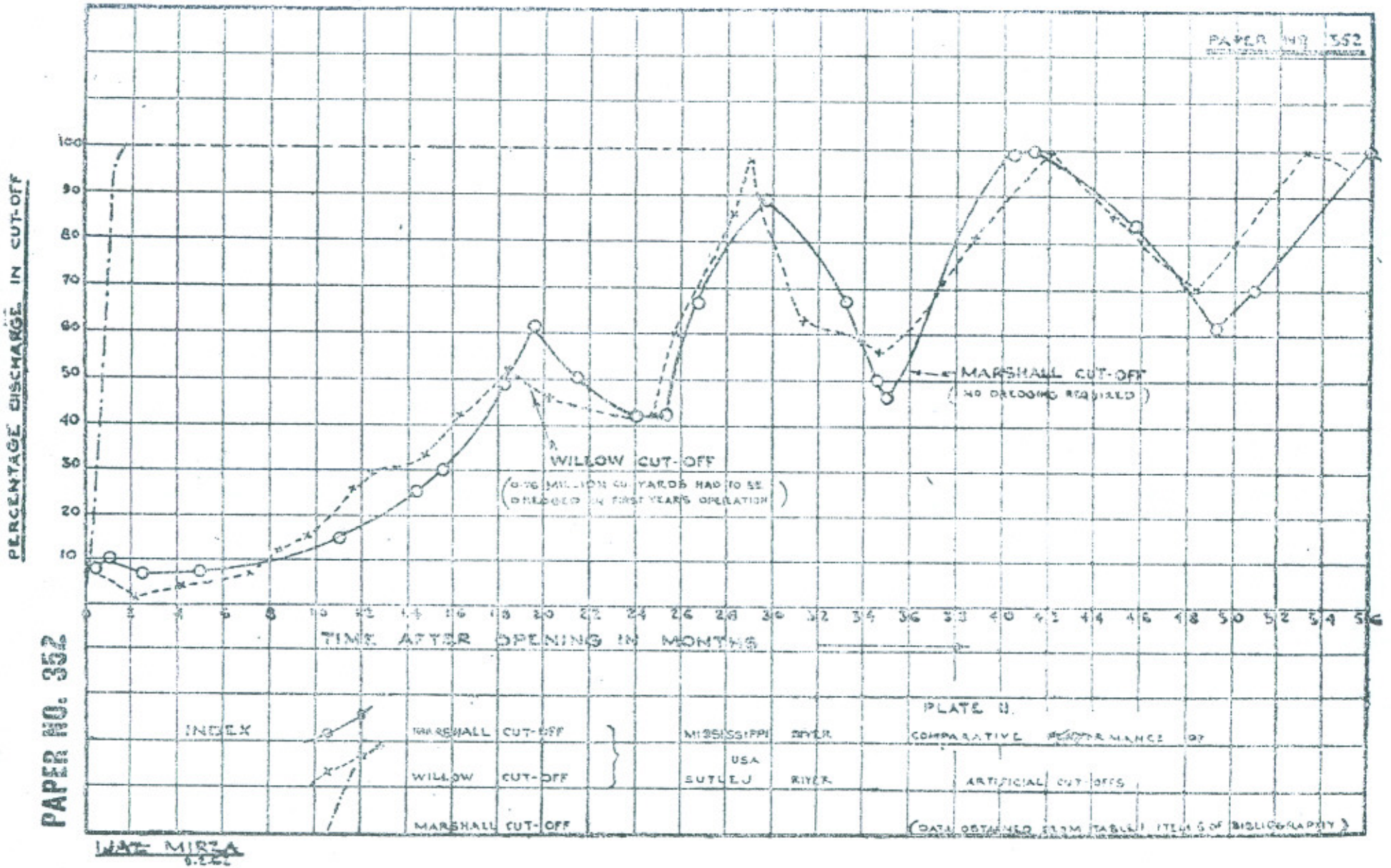


CROSS SECTIONAL AREA
AT R.D 2000 CUNETE



AVERAGE VELOCITY AT R.D 2000
CUNNETE





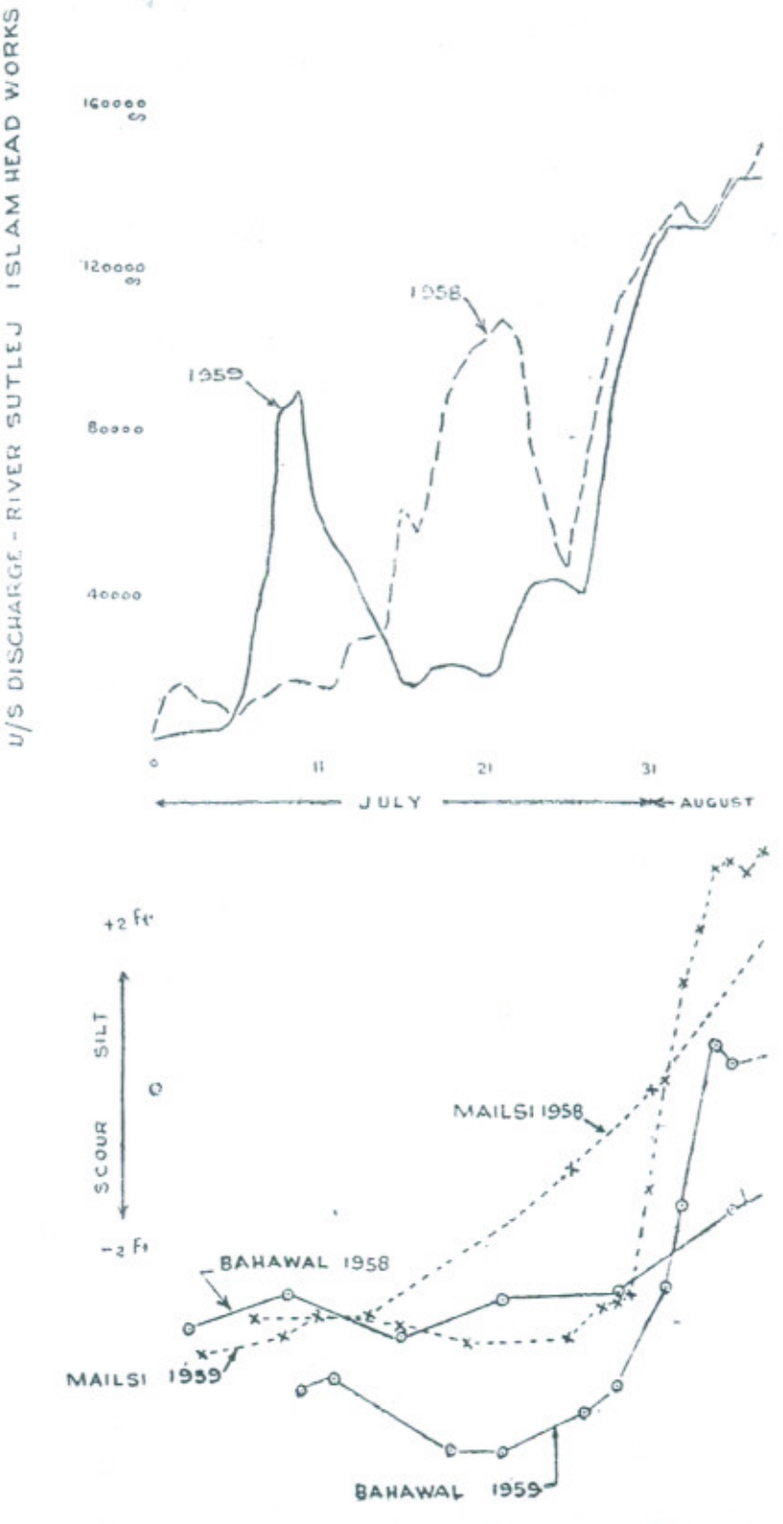
PAPER NO. 352

WAZ MIRZA

PLATE 12

PAPER NO. 352

SILT DEPOSIT IN HEAD REACHES OF MAILSI & BAHAWAL CANALS



PAPER NO. 352

PLATE 13

L-SECTION OF MAILSI CANAL
SHOWING SILTING UP
6 8 59 TO 14 10 59

