A REPORT
ON
DEGRADATION BELOW DAMS.

Written by

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Under the direction of

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For

C.E. 292.

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DEGRADATION BELOW DAMS.

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DEGRATION BELOW DAMS.

I. Introduction-- During the last half a century, a peculiar phenomenon has been observed by many engineers working with hydraulic structures, on alluvial or sandy rivers. Whenever a dam or a weir is constructed across such rivers, the bed downstream of such an obstruction starts lowering and this effect continues for a long time and long distance downstream, depending on factors like discharge, size of the bed material, duration of floods, slope of the river etc. This phenomenon has an important bearing on design of downstream pile line and impervious apron in the case of weirs, and design of turbine draft tubes of power plants downstream of the dams. This is because, as a result of lowering of the bed, water level drops and the foundations of the structures are endangered, while draft tubes which were previously under water are now exposed.

This effect has been observed by many engineers from most of the countries during the last three or four decades, on rivers like Nile in Egypt, Wisconsin, Rio Grande, Arkansas, Sacramento, Yuba, Red, South Canadiaan, Colorado, in the United States; Indus, Sutlej, Chenab in India; and Saalach in Germany.

Lowering of the bed of a stream or river in nature is called by geologists as degradation, and since this phenomenon is the result of the same causes as that which commonly occurs in streams, it can be reffered to as degradation. In some hydraulic literature, the term used is retrogression for the same phenomenon, but as the term degradation is widely used for many years, in the following pages, the term used for this phenomenon is degradation.

Apart from the danger to the hydraulic structures and power plants, degradation also affects, locks in navigable rivers, outlets of the sewers etc. In fact the degradation has become more or less a basic phenomenon in river engineering and it has far reaching effects.

An attempt is made in this paper, to compile various data on degradation and try to analyse it.

2. SCOPE OF STUDY.

Recently attempts are being made to treat this basic phenomenon more or less mathematically, so as to predict the degradation results in future, when the various factors responsible for it are known. But as these treatments are still in primary stage and are not confirmed by degradation results, in this paper, only a mention is made of these methods, avoiding more details.

The various data on different rivers in many countries like America, Egypt, India, is collected and analysed qualitatively. Civil engineers are now a days realising the importance of degradation, because of major failures of weirs etc.- like that of Islam weir-due to lack of proper understanding of these effects. Hence it is hoped, that this paper will give some momentum to the engineers to become more conscious of degradation, while designing hydraulic structures like dams, weirs, Barrages, power plants, navigation locks etc. on alluvial rivers.

3. HISTORY.

The degradation or retrogression of the river bed below the dam in movable bed rivers is not a very recent discovery. The earliest mention of this topic is found in "Irrigation Manual" by Mr. Mullins, published in 1890. While discussing his experience in Madras Province in India, he writes-

"Retrogression of levels in the river bed is a nearly inevitable result of building a weir."

In his book "Irrigation Works in India (1905, pp . 113) Buckley says-

"A weir constructed across a river in which this action is in progress, stops the erosion above the weir by forming the permanent bar at that point. But the cutting action below the weir is not checked, and the bed of the stream is gradually cut away.The action may be slow but by still degrees, the head on the weir is increased and the toe of the tallus of the weir is attacked."

In United States also this phenomenon was noticed as early as in 1917. Mr. Gilbert G. K. in his "Hydraulic Mining in Sierra Nevada" (Ref. NO. I.) Clearly differentiated between scouring and degradation below dams. He says-

"The scour due to falling water is taken care of by the quarry rock inserted as a rip rap at the toe of thedam, while the result of excavation was a general profile with continuous descent downstream from the edge of the barrier. This feature of the descent as well as the fact that, the reduction of the surface below the dam included the whole width of the river bed, leaves no doubt , that the reductionwas caused by the application, to the river bed, of flood discharge that was free from the bottom load and therefore competent to excavate the loose material over which it passed."

A similar reference is found in the "Report For The Failure Of Islam Weir" in Punjab, India written by Islam Inquiry Committee.

4. PHENOMENON

When a dam or a weir is constructed across a river a reservoir is caused by the dam. If the bed of the river is actually moving, in its natural course , when the water from such a reservoir is released ., it starts lowering the bed downstream of the dam, by carrying away the bed material. This action may or may not extend several miles downstream, and may continue for a long time, depending upon the size and gradation of the bed material, and hydraulic properties of the river. The lowering of bed level occurs firstly just downstream of the dam, and it gradually extends downstream to a point where the stream has picked up a capacity load as determined by the prevailing slope and discharge of the regulated flow. This effect is many times dangerous. It is called as degradation.

This phenomenon is entirely different from what is known as scouring and therefore it must be differentiated from the latter.Of course the effect of the two phenomena is the same viz. lowering the bed level of the stream. But the main difference is in causes which produce them. Scouring results from high velocity water passing over the dam and it extends at most only a few hundred feet down stream of the dam. degradation effect is due to disturbance in equilibrium between incoming and out going bed material and it is spread many miles downsream. In the immediate vicinity of the dam both actions may occur.

5. CAUSE OF DEGRADATION.

But in fact, the construction of a barrier is only one of the ways in which the degradation starts. The cause of degradation is more basic. As long as the material coming at a point,is equal to the amount of material going away from that point , there will be a sort of equilibrium and therefore there will be no lowering or degradation at that place. But when the dam or any kind of barrier is constructed across the river, downstream of the dam,the material coming in is stopped and hence the equilibrium is disturbed and therefore there is a general lowering of the river bed.

Generally all of the bed load and a great percentage of the suspended load will be deposited in the reservoir behind the dam,the amount of the latter being dependent on the size if the reservoir. As the solids are removed from the water, equilibrium no longer exists between the bed load, slope, and discharge in part of the river downstream of the dam. The water released from the reservoir will have a tendency to attain the equilibrium by picking up the material from the bed. Hence conditions that will make the stream to pick up high sediment load, will naturally be conducive to higher rates of degradation. The conditions favourable for high sediment loads are--

I. Greater discharge

2. Steep slope of the bed

3. Heavy sediment concentrations

4. Fine non cohesive material in the bed.

In general, the degradation takes place in any reach of the river when more sediment is carried out of a section, than is brought in by the water entering it. The rate of degradation depends on the magnitude of difference of inflowing and outflowing sediment. If under natural conditions , a section of a stream is in a balanced state, with sediment inflow equal to sediment outflow, any cause which will decrease the inflow , without equally decreasing the outflow will cause degradation.

Other causes of degradation--

(A) As an example, the results in Cheery Creek near Denver Colorado (U. S. A.) may be cited. In the bed of this creek, very large pool was formed due to removing of large quantities of sand for building purposes. Hence the sediment load coming from upstream, was all naturally stored in that pool and water passing downstream of the pool was carrying sediment, much less than its capacity to carry load. As a result of this, the degradation started and it resulted in lowering the bed of the creek by a maximum of about I6 feet. The sewer outlets were exposed due to lowering of water level.

(B) In many instances, when rivers are divided into two or more branches, as in the case of deltaic rivers, it is not possible for every branch to maintain a stage of equilibrium in respect of sediment flow. If the sediment load is in excess of transportation capacity of any one of the branches, deposition or aggradation will occur inthat channel, while degradation is bound to occur in the other channel. Even though such cases of aggradation have been reported in the case of Ganges River in India, and Yellow River in China, unfortunately data is not available as regards degradation.

(C) Degradation on tributaries--

With a stream system functioning normally, there is a balance of tendencies between the flow of the main stream, its gradient and the debris carried by it and those similar functions on its tributary. The addition of the tributary brings about a flatter gradient in the main stream, for some distance above the junction, while at and below the junction such steeper slope is established as may be required for the movement of the added debris. The tributary as a rule has a lesser run off and a steeper gradient than the main stream, its characteristics being reflected in its own flood plain, where it has attained the favourable conditions for the transportation of its own debris under its own conditions of flow.

If the flow of the main stream is regulated while the tributary remains unregulated, sooner or later , conditions at the junction of two will become critical because of the absence of flood flow in the main stream, w hich was formerly available for the removal of the sediment and debris from the tributary. The tributary now having to assume the role of main stream cannot cope with with the wider streambed and flatter gradient of the latter. If conditions are favourable degradation in the tributary starts.

Some times the lowering of the levels does not stop at the main tributary but also goes to subtributaries, causing troubles at bridges and road culverts. This has been observed in the case of many streams in Iowa.

If the equilibrium between sediment load and the discharge is destroyed and if the strtch of river has unerodable material--sayrock outcrops etc.--the natural tendency of the river will be to eat away the banks, or if the river is crooked, cutting away the inside of the bends and thus gain sufficient suspended load before it attains equilibrium. This has occured in the case of South Canadian River below Conchas dam. At several locations in the reach where the canyon has given way temporarily to gravelly hills, the river is erodingthe inside of the bends as a result of tendency to straightenthe channel and attain equilibrium. (Ref. No.26.)

6. BED MATERIAL.

The hydraulic properties of the stream determine the competency of the flow to erode and transport the load, whereas resistance offered by the load to the erosive and transport action of the stream is determined by the composition and formation of the bed.

While considering the effect of bed material on degradation of the river, size ofmaterial, gradation, its specific gravity, density, depth of deposition, and extent along the river length are the factors which must be taken into consideration.

The bed material is transported by the stream mainly in two ways viz. as a suspended load which is carried integrally with water and as a bed load which is dragged along the bed with smaller velocities than that of water. This transporting power of the stream depends on the turbulance in the stream itself.

If the bed material is heterogeneous, the maximum size up to which the stream will remove the material, depends upon the discharge, slope, turbulance etc. Material above this size will not be moved. If the requirements of the stream as regards its sediment carrying capacity are not satisfied, the material from farther downstream will be removed. Once the requirements are satisfied, there will be no degradation downstream. As is the case ordinarily, the stream bed is composed of noncohesive material covering all sizes. As said above , since the water can most easily remove small size material, during the process of degradation proportionally greater quantity of smaller sizes are removed than the coarser ones and the material gets coarser. As the material has become coarser in this region, next year, the stream will pick up relatively smallamount of material from this reach of the river, and hence it will cause degradation farther downstream every year. Plate No. I shows size analysis curves of the bed material at various places on Colorado River (U.S.A.) b elow Hoover and Parker dams.They show that the proportion of fine material decreased , with the time after the release of clear water from the reservoir or in other words the material of the bed became coarser.

If on the other handthe bed material is of relatively uniform size, most of the requirements of the stream as regards its capacity to carry the sediment, can and probably will be satisfied within a short distance below the dam or the barrier, and hence the degradation effects will not go farther downstream. If the thickness of this material is limited then a time may come , when the material immediately downstream of the dam will either get coarser or a new and perhaps a hard strata as of rock etc. may be reached. In either of the cases, such a strata will fulfill the requirements of the stream to a smaller extent, and hence degradation will travel downstream with years. If the thickness of the relatively uniform size material is indefinite, the degradation effect will be localized in the immediate downstream vicinity of the dam.In fact this is very dangerous because it will result in lowering of the tail water level and (a) Hydraulic gradient will increase (b)Hydraulic jump will move downstream and there fore the depth of water on the downstream will decrease.As a result of this, the net upward pressure on the apron increases, and there is every possibility of destruction of the apron depending on the value of upward pressure.(c)Foundation of the dam will be exposed rapidly. In the case of Islam Weir on Sutlej River(India),in two years, there was 6.5 feet lowering of the tail water level. (Ref. No. 3.)

The sediment transporting capacity of the stream is satisfied by bed material and by the banks.

It may happen that the bed material is so coarse that the stream cannot carry it either as suspended load or as bed load.In such a case two effects may be observed. (a)As we have seen above, the degradation will move downstream and pick up material available. (b) The stream will have a natural tendency to satisfy its capacity by removing the material from the banks. This results in widening the river bed. If the river is meandering and has bends, the bends may be straightened up. This has been observed in the case of South Canadian River(Ref. No.26.)

But the quality of the bed material is not the only factor controlling the depth to which degradation will occur. If there is any obstruction of an unerodible material such as rock, boulder, heavy clay bottom,lenses of heavy gravel etc. it hinders or stops the degradation, because it controls the water level upstream. This causes the degradation effect to move downstream.

7. SLOPE OF THE STREAM.

As said before, due to the construction of a dam, most of the sediment load of the river is stored in the reservoir, that is caused by the dam. Due to this, depletionof sediment load, the equilibrium between the slope discharge, and the bed load is disturbedin the portion , downstream of the dam. The water flowing over the dam, is is clearer compared to that flowing before the construction of dam. It is necessary to have steeper slope , to carry a mixture of sediment and water than clear water alone.

Therefore, as a result of the flow of clearer water, the river bed has a tendency to readjust its slope, so as to conform with the requirementsof clear water, released from the dam. In this readjustment, the clear water picks up material from the river bed, degradation results, and in the end the profile of the river bed is rotated about some point or control in the river, where the water level is held constant. This control in the river may be a downstream reservoir or a dam,a ground or submerged sill erected expressly for this purpose or a rock ledge in the bed, a lake, gulf,or sea into which the river flows.

Thus on Rio Grande River (U.S.A.), due to the construction of Elephant Butte dam, the slope of the river between Elephant Butte dam and El Paso, changed from 4 feet per mile to I.5 feet per mile.(Ref.No. I9.)

Degradation of the river continues until the reservoirhas aggraded or silted up completely.subsequently the entire sediment load passes over the dam, because it cannot be stored above the dam. Many times as the flow is diverted and only the clear water is taken, for irrigation, even though the flow is reduced, the total sediment load remains the same. Hence the flow downstream, is now not sufficient to carry the same amount of material, and the stream will have the tendency to increase its bed slope, to that required to carry the load with lesser discharge.

In the case of Yuba River(U.S.A.), a barrier was built up across it, to stop the debris from hydraulic mining. The construction of this barrier was complete in I905;the flood of I906 filled the reservoir completely. In I907,the barrier was destroyed and the river regained its original slope. (Ref. No. I.)

8.EFFECTS OF DEGRADATION.

Effects of degradation may be divided in to two main sections, viz.

(a)Effects leading to dam failure.

(b) Other effects.

(a) Effects leading to dam failure.

The greatest disadvantage of degradation is usually that it endangersthe safety of the dam. This can happen in following ways:

(I) In the case of dams where hydraulic jump is used as an energy dissipation device, it is so designed that the elevation of water surface after the jump and tail water elevation are the same. If however, the tail water level for the spillway is reduced due to the reduction of downstream bed level, the jump will move downstream. In the worst case, the jump may be moved off the downstream end of the apron or out of the stilling basin. When , in such a way, the jump forms out of the apron, there is only a thin layer of water on the apron, which has only a small weight to resist the upward pressure beneath the apron. In designing these aprons, the downward pressure of the tail water depth is taken into consideration,in balancing the upward thrust. Hence the reduction of tail water depth over the apron, may result in increasing the net upward lift, and if this upward pressure exceeds the weight of apron and weight due to the depth of water, failure of the apron may occur. Same thing has happened on Wisconsin River(U.S.A.) at Prairie Du Sac. The tail water level started lowering gradually, until a stage reached when the jump would not form on the apron for all the discharges. This lowering of the tail water at Prairie Du Sac was 6feet after which it was rather stabilized and hence it did not endanger the safety of the dam.

(Ref, No.5)

(2) If a concrete or earth dam is constructed on pervious foundation, there is another source of danger. The reduction of tail water increases the effective head which is the difference between head and tail water levels.

Hence, the degradation may bring about an increase in the probability of failure from the piping where the water seeping beneath the structure emerges from the ground. This is because, seepage is directely proportional to the head. Hence the factor of safety against the failure by piping is reduced. Secondly, the lowering of the level at the downstream, of the dam, will reduce the length of the path of seepage,which means that uplift will be increased. Many times the reverse filter provided at the downstream end of the dam is destroyeddue to degradaton. Therefore the protection against piping is removed.Even if the reverse filter is not destroyed, lowering of the bottom close to the dam may cause the position of the exitpoint of the seepage, to change from that point where it passes through the filter to some oter point where no filter exists, and therefore the probability of failure is greater.

(3) It may so increase the drop of water at the downstream edge of the spillway apron, that the apron is undermined and caused to fail and hence the dam may fail. This is probably the reason for the failure of the dam on Yuba River in U.S.A.(Ref. No.I.)

(4) The lowering of the tail water level may so change the action of energy dissipation devices below the spillway of the dam as to greatly increase the scour at the downstream edge of the dam and thus cause the undermining of the dam spillway. The action of most of the devices provided at dams for dissipating the energy

of flowing water, so that it will not produce dangerous scour, is very sensitive to shanges in elevation of the downstream water level.(Ref.No.4.) Therefore as a result of degradation, an energy dissipation device which was functioning normally before degradation, may not work with the same efficiency after degradation. Therefore in the design of spillway,it is necessary to study the action of the proposed devices, under the entire range of tail water levels,which would occur at all discharges upto the maximum, at all stages of degradation from the normal conditions to maximum lowering.

(5) Lowered water levels due to the degradation,by increasing the net head acting on the structure, decreases its factor of safety against sliding and overturning. Except in unusual cases, these effects are not going to be very large and they can be easily allowed for by increasing the factor of safety.

(b) Other effects--

(6) Effects of degradation on power plant--

These effects of degradation on the power plant are both advantageous and disadvantageous. Firstly, when the tail water level is lowered as a result of degradation, the head available is naturally augmented. This means ,greater head is available for power generation. Such an increase in ~~power~~ head, has occurred in the case of power plant at P rairie Du Sac on WisconsinRiver(Ref.No.5), and also at Uppenborn power plant of Munich in Bavaria, Germany on Saalach River(Ref.No.2). In many cases increase in power output results.But untill recently,while designing the power plant, degradation is seldom anticipated or any special provision made for increase in head,in the design of plant. At Junction dam on Mainstee River in Michigan (U.S.A.), when the dam eas constructed in 1917, taking into consideration the previous experience with Croton dam on Muskegon River, the Junction dam draft tubes were placed 10 feet lower than necessary,But even this amount proved to be insufficient,for the draft tubes have been corrected since, and later a weir was built to stabilize the head.(Ref.No.5) If such a provision is not made either intentionally or unintentionally,the increased vaccum at the turbine runner level may cause severe cavitation pitting of the turbine and if the lowering is great enough, the exit end of the draft tubes may be exposed to such an extent that air may enter them and destroy the draft tube action. This will greatly reduce the power output. A power plant designed for this will be more expensive because--

(a) Deeper foundations have to be built,below the water level. Hence excavation and pumping cost increases.

(b)More concrete will be required because height is increased.

(7) Many times lowering of the bed does not stop at the main river, but it may extend to tributaries and subtributaries also.This is because lowering of the water level in the main river increases the velocity of the tributary and therefore its bed is liable to scouring.This has been

observed in some of the streams in iowa.

(8) Lowering of the river bed by degradation increases the capacity of river channel to carry the flood flow. thus it reduces the height of floods.Creating artificial degradation by construction of big reservoirs and thus increasing the capacity of rivers,is a method that has been suggested as a possible solution to the flood problems of Yellow River in China and Kosi River in India. If a reservoir site of sufficient capacity could be found on the Yellow River,at the head of its delta, in which it could deposit part of its silt, the water, after leaving the reservoir,would again take up a load of sediment from the river bottom and carry it to the sea,thus excavating the large quantity of earth from the river bottom and causing a lowering of the bed. The practicability of such a scheme depends on a favourable topograbic condition,and other factors.

(9) Lowering of the water level due to degradation,reduces the height of ground water table in the adjoining fields. This improves the cultivation and facilitates the drainage.

(10)Sewer outlets shall have to be protected against the scour which will result from drop in grade,which will be produced where the sewer joins the stream.Pipe lines and sewers which were buried beneath the stream bottom nay be exposed and threatened with destruction.This has occurred in Cherry-Creek near Denver(Colorado.).

(11)Reduction of tail water may expose to the air,pile foundations of bridges, abutments,and other structures which may lead to the deterioration of piling.

(12)A large reservoir dam may cause degradation below a series of diversion dams,many miles downstream,as in the case of Colorado River.

(13)Degradation may cause the lowering of water level at the existing irrigation intakes and make the diversion for irrigation more difficult.

(14) Degradation may cause substantial powering of navigable depth over the sills of locks in the case of navigable rivers thus lessening the navigable depth. In the extreme case, the lock may be useless. This has happened at many places. Due to degradation,a lock on Wisconsin River was less efficient because ,the navigable depth was reduced. Drisco has reported the construction of a lock and a dam on the Oder River at Ransom,as a result of a reduction of navigable depth and exposure of the pile foundations of a lock at Breslau.Dutch engineers,on Meuse River,were forced to abandon an ambitious channel rectification programme planned for this river,because they found that many stretches would no longer have navigable depths during the low water season.(Ref.No.17.) In one instance,channel improvement for navigation on Upper Missicippi RIver at St.Louis,was followed by channel degrading which lowered the low water level at that city by about 4feet in the course of 10 years.

(9) COMPUTING THE MAGNITUDE OF PROSPECTIVE DEGRADATION.

In recent years, many attempts are being made to treat this phenomenon of degradation, more or less mathematically and come at a figure which will give the degradation effect. The many variables involved in this process make the problem more difficult to have any clearcut procedure. The influencing variables can be summarized as-- (a) Velocity pattern. (b) Discharge pattern. (c) Channel hydraulics, as depth, width, slope etc. (d) Size distribution of the material at various depths. (e) Existence of the downstream controls, such as rock outcrops. (f) Sediment load, transported by the stream; amount of storage behind the dam etc.

In estimating the prospective degradation, because of the many assumptions made, the accuracy of the results is highly questionable. The basic requirements for an accurate degradation estimate will be as follows---

(a) One should have an adequate knowledge of the laws of sediment transportation; the amount of sediment of each size that can be transported by flows of variable depths and slopes with stream beds of various composition, must be known.

(b) Knowledge of the depth of bed material which is stirred up or turned over by the flowing water during the degradation process, is essential. As the water from the dam picks up more of the finer material from the bed and carries it downstream, thus making the bed coarser, the rapidity with which this coarsening action takes place depends upon the depths if the bed material which is worked over,because the deeper this layer is,the greater must be the amount of finer fractions carried away,to produce a given coarsening and thereforegreater the time required to move larger quantity.

(c) Relative frequencyof this turn over,at each depth must also be known.

(d) Knowledge of the length of pick up distance necessary for the water to flow,before itcan pick up the maximum load which it is capable of carrying,is necessary.

(e) In addition to vertical lowering of the bed,we must also consider the lateral scour.It may happen that,after the stream is deepened, the tendency to widen by cutting the banks may continue.

General procedure for such an estimation is given below--

The first step is to collect information,such as bed material size,their depths,slope of the river etc. Several methods are then available,for estimating the transportability of the bed material,for the range of stream discharge. Following are some of them--

(1)Tractive Force--

$$\text{Tractive force} = \gamma \cdot d \cdot s.$$

Where -- $\gamma = 62.5$ lbs/cft.

d = Depth of water.

s = Slope of the stream.

Hence for a certain range of discharge,the tractive force can be computed. From this value,the mean diameter of the particles,that can be moved by this force,can be found out.

(2) Competent bottom velocity--

The size of the bed material, that the stream can transport, is often considered in terms bottom velocity or velocity near the bottom. Curves of competent bottom velocity against diameter of the particles are given in "International Association of Hydraulic Research Journal", Second Meeting, Stockholm, 7-9, vi 1948. The bottom velocity is usually 0.5 to 0.7 times the mean velocity. Former coefficient is suitable for very deep rivers, while the latter for shallow rivers.

(3) Bed load transport--

A rough guess can be obtained if the values of (slope × hyd. radius), for the range of discharge are obtained first and then applied to Einstein's bed load curves to obtain the maximum transportable size.

From these methods, we can know the maximum size that can be transported by a given discharge. As an example, suppose in a certain stream, material greater than about 50 mm. size is unlikely to be transported by a discharge of 100,000 cfs. Now looking at the size analysis curve for the bed material of the stream, we can say, that about 22% of the bed material is larger than 50 mm. size. Hence we have material in the bed that will effectively create an armor for given hydraulic conditions. As a rough rule, a layer of nontransportable size material, equal to the diameter of the largestsize material found in the bed, will create an effective armor. Let us further assume that size analysis and actual observation indicate, that the maximum size of bed material is between 4 and 6 inches. Hence, we need a layer of material 6 inches thick, of material greater than 50 mm. (2inches) to get effective armor.

In 1 ft. depth, we have $12 \times 0.22 = 2.6''$ in depth of material greater than 50 mm. size.

Required thickness of material less than 6" size is 6".

Hence depth of turn over to obtain 6" of material less than 6" size is $6/2.6 = 2.3$ ft.

Material moved out will be $2.3 - 0.5 = 1.8$ ft. in thickness

Hence the degradation will be about 1.8 or 2 ft.

Other factor which must also be found out, is the point downstream of the dam, up to which the degradation will reach. It can be stated that, in general, the amount of volumetric degradation downstream, will be a direct function of the amount of material retained in and above the reservoir area. (Ref.No.27.)

On Saskatchewan River in Canada, a different procedure is followed in arriving at the probable degradation.

Immediately below the stilling basin, the transporting capacity of the stream will have a definite value, because water surface slope has a definite value. As most of the sediment settles upstream of the dam, the water coming down from the dam will have zero sediment load, and hence the erosion will have to be infinitely large, over an infinitely small distance, in order that the capacity of the water is immediately satisfied. How ever, an assumption is made that, the full load is picked over a distance of 1000 ft., and therefore the above difficulty is overcome.

The computational procedure is as follows. The channel is divided into reaches of 1000ft. After the first step,scour has taken place over the first reach only. The back water curve , corresponding to the new situation is computed. From this back water curve, the transporting capacity is determined. It is found that, on the first reach, the capacity is reduced from 100% to 76%. On the second reach, and those following,it is still 100%.During the second step, 76% is eroded on the first reach and 24% on the second reach. During the given time interval of 10 days,this gives a certain amount of erosion. From the new bottom profile,the new back water profile and new transportingcapacities are computed. The first reach has now a capacity of say,62%,the second 98%, and the third and the following reaches 100%. The procedure is repeated untill the desired objective is reached. (Ref.No.28.)

(10) CONTROL OF DEGRADATION.

There is no effective method or way in which degradation can be completely stopped. But it can be controlled in a definite reach to a certain extent.

(a) Progress of degradation is sometimes stopped or hindered by an obstruction of unerodible material, such as rock or mass of boulder, heavy clay bottom, rock reef, lenses of heavy gravel etc. They form the control of water level at that point. Of course, while they limit the lowering of bed at and above that point, they cannot stop degradation downstream of them. Various examples can be cited in support of this statement.

Because of the presence of a large island, immediately downstream of the dam on Wisconsin River at Prairie Du Sac, the lowering of the tail water level, was not appreciable until 1920, when the island was completely removed. From then until 1932, the recession of tail water was more rapid. (Ref.No.5)

In the of Red River below Denison dam(U.S.A.), the minimum tail water level was computed for the diversion structures, on the basis of a rock reef that existed at the location, and in accordance with the present indications, the control appears to be stable. (Ref.No.24)

As an extreme case, the control may extend, some miles along the stream. Hence degradation will start below that control. As an example, just downstream from the recently constructed Boysen dam on the Wind River, in Montana(U.S.A.), is a rocky canyon, where the bed material of the stream,for many miles,is largely very coarse and relatively non movable.No appreciable degradation is to be expected in this section,but degradation is expected , downstream of the canyon,where the stream enters into a wide valley with a bed of movable material.

(b) Constructing a dam or a series of dams, also helps in controlling the degradation.By the construction of a series of dams,the flood flows are equalized. Transporting power of water in a stream,increases at a faster rate than the first power of the discharge,and therefore,a given volume of water will carry more sediment away from the stream bed,downstreamfrom the dam,if the flow is at a high rate,than it will when the flow is low. Equalizing the flow,therefore,makes the transporting power low and thus decreases the sediment transported,and degradation which results from it. Secondly, construction of a dam, also decreases the slope of the river,thereby reducing the velocity and hence capacity of the flow,to pick up the material. This has been actually observed on Colorado River where a series of dams--Hoover,Davis,Parker, and Imperial--is constructed. In the case of Mainstee River, the construction of Junction dam,resulted in lowering of tail water level by 10 ft. To control this and in order to stabilize the bed,another weir had to be constructed downstream.The degradation was temporarily reduced.(Ref.No.5) Another case can be cited on Arkansas River (U.S.A.) A flood that occurred during the construction of John

Martin dam in 1942,deposited about 12,000 acre feet of sediment above the incompleted dam and lowered the river bed at a gage station,several miles downstream by about 3 ft.to rock and gravel. A diversion structure,some 5 miles below the river gage,was built immediately and before the end of summer,the low flow profile at the river gage had reached its former elevation. (Ref,No.24)

In the case of Naga Hamadi Barrage on the Nile River,the amount of fall was 2.3 ft, after 8 years of operation. Actually a subsidary weir has had to be built,below the barrage,to keep the head on it within ptescribed limits during summer.(Ref.No.25)

(c) In such a way,when a series of dams is constructed, the flood is reduced downstream of the dams.Sediment load carried by tributaries enter the stream,in degrading reach. This load may consist of coarse material of sizes,which, the reduced flow in the main stream is incapable of carrying, but which the stream in natural condition moved along during flood periods. Such coarse material will settle in the stream channel and cause an aggrading condition that may offset the degradation or even cause net aggradation.

(d) In many Indian rivers,which are subject to degradation effct,it is found that,after few years of degradation,an aggrading of river channel starts and many times the river bed level goes a little higher than the original. This is found in the case of rivers like Sutlej,Chenab, etc.This is due to many reasons. A common practice on the Indian

Rivers isthat,in summer when the flow is small,occa-sionally the gates of the barrage are opened,so that a large % of sediment collected above the dam,is allowed to go downstream. It is this sediment,that either lessens the degrading effect or actually offsets it. Secondly, the intakes of irrigation works,take clear water,leaving the sediment in the river. This is many times made possible,by the use of raised sills for the intake structures,or by some other devices. As a result of this,the water flowing downstream,contains more sediment load than it can carry. This causes aggradation. Thirdly, when the discharge is low, it carries excessive silt which causes aggradation.

(11) EXAMPLES OF DEGRADATION ON VARIOUS RIVERS.

(a)Rivers in United States ofAmerica.

Colorado River---

In its virgin state before the diversions were made,the Colorado River is estimated to have carried an average of 17,720,000 acrefeet of water annually across the international boundary in to Mexico.Annual flow varied from about 5,000,000 to 25,000,000 acrefeet.The Colorado River carries a tremendous volume of silt and in its virgin state,ranked as one of the greatest in comparison with other major silt carrying streams of the world.

At present,the dams on the portion of the river under consideration,are as follows--

No.	Name.	Miles below Hoover.	Date of closure.
1	Hoover	0	Feb.1,1935. water approached maximum level in 1941.
2.	Davis.	67	Diversion accomplished in June 1948. Spillway closed on Jan 1950
3.	Parker.	142	Storage in dam began on July 1938.
4.	Imperial.	290	

Bed of the River--In the area between Parker and Imperial dams, about 147 miles,the river flows through a wide valley for a considerable part of its length.Much of the portion,is of alluvial type,with a width of 2 to 5 miles.

Erosion and sedimentation-- For many years prior to the construction of Hoover dam,the river carried great quantities of silt brought from the drainage areas during the flood flow.Some of this material,was deposited in the river channel and some was carried to the mouth of the river.During the seasons following the flood flows, pa rt of the sediment was picked up from the river bed and carried further downstream. The net result was the bed elevation of the river started rising gradually.

With the construction of Hoover dam(1935), the complete sediment load of the river was trapped in the Lake Mead (formed by Hoover dam) and clear water was released from the dam.The water being free of sediment load,began to scour the deposit,which had been laid down in earlier years. Following the be gining of storage and partial filling of Lake Mohave (formed by Davis dam),the point of degradation moved downstream of Hoover dam by 67 miles.With the completion of Parker dam and that of Imperial dam(1938), two depositories were formed from the material removed and two other points on the river became subject to degradation.

Bed material size--

Plate 1 shows,the bed material size analysis below Hoover dam and between Parker and Imperial dams at different times.Thus it can be seen that in Feb.1936,i.e. one year after the completion of Hoover dam,50%size of the bed material,40 miles velow Hoover dam was 0.2 mm.,while in Dec. 1941,it coarsened to 0.36 mm. Similarly,12 miles below Parker dam,50 % size of the material,changed from 017 mm.to 8mm.from Aug.1938 to Sept. 1949.

Degradation--

Initial storage above Parker dam took place in June 1938, raising the water level approximately 9 ft. In Jan. 1950, the second stage of storage took place. Following the initial closure of the river, the bed immediately downstream was subjected to renewed degradation. About 60 miles down stream of Parker dam, the average bed dropped 6.5 ft. between Dec. 1947 and June 1949. By Sept. 1951, the total drop since 1947 was 7.8 ft.

With the closure of Parker dam in 1938, and resulting release of clear water, the river bed below the dam started degrading. Materials in amounts up to 41 million tons per year were removed.

Aggradation--

When there is a series of dams like that on the Colorado river, the material degraded below upstream dam, is deposited in lake or reservoir created by the downstream dam. Same thing has happened in this case. By 1946 area above the Imperial dam, was filled with sediment, and almost entire load below Parker dam was carried, over the Imperial dam through California. As a result, the bed below Imperial dam aggraded slightly, during the six years 1946 to 1952.

This is a striking example, where the construction of a dam on alluvial river, has caused deposition, gradually extending farther and farther upstream. This level will tend to approach a slope, equal to that of the river, in its original condition, beginning at the crest of the dam.

The rapidity of this trend,depends largely on the storage volume available,and the rate of sediment supply.This action was rapid in the case of Imperial dam, because the sediment load was great and the storage volume below the crest of the dam was comparatively small.

Some other effects also take place apart from degradation and aggradation,by constructing a dam such as Hoover.Serious consequences may follow,because we are stopping high flood flows,which in the natural state of the river, serve to clean the river bed of accumulated vegetation, and even to scour substantial amount of accumulated sediment of the bed of the stream.This and other causes,brought about by the construction of Hoover dam,added to the delta formation upstream,from the Parker dam reservoir, created serious situation along the river,between the towns of Needles in California,and Topock in Arizona,where a true river bed ceased to exist and water started flowing,through innumerable channels and sloughs creating a virtual swamp.

Similar degradation effects were observed,below Laguna dam on Colorado River, on the border of Arizona and the California state.Laguna dam was completed just before the summer flood of 1909 and it createda reservoir,having a capacity of about 20,000 acre feet. Much of the sediment settled in reservoir. The comparativelyclear water, picked up and carried downstream a large quantity of bed material.

Yuba River---

As a result of hydraulic mining, a large quantity of debris was coming down the Yuba river.The deposit at some places,was found to be as deep as 85 ft. thick.At Marysville(see plate 8.),it was 15 to 25 ft.thick. This material was mostly gravel,sand,silt,etc.

For the control of Yuba river and for impounding a portion of its detrital load,a barrier was constructed, about 14 miles above Marysville,where the flood channel of the river is about 1500 ft.wide.The part of the barrier, about 6 ft, high,was completed in 1904 and the second part of another 8 ft. above the former, was completed in 1905, thus making total height equal to 14 ft. The basin created by the first stage of construction was filled by the river with detritus, chiefly gravel, during the first winter. In order to study this effect, a program was set up. It included two surveys of the bed of the river, above and below the barrier, one before the completion of the second unit and other after the floods of the river had brought down their load of detritus and heavier portions of it had been arrested in the basin.

The barrier was afterwards breached and destroyed by the flood of March 1907, where upon the original profile of the river chanel was immediately restored.

The initial slope of the river bed in the vicinity of the barrier was about 16 ft. to a mile and there was a rapid increase upstream to 22 ft. per mile. At Marysville near the mouth the river, where the chief material is sand, the slope is about 6 ft. per mile and it increases upstream as the material changes successively to coarse sand, fine gravel, and coarse gravel. The erectin of first 6 ft. of the barrier in 1904 caused a filling during the flood stages of the ensuing winter, which extended at least 1½ mile upstream and probably somewhat more, reducing the average slope in that region to about 12 ft, per mile. When the second unit was added to the barrier, increasing its height by 8 ft. deposition again began and flood of January 1906, in filling newly formed basin, extended its deposition upstream about 1.75 miles, reducing the average grade for that distance to about 9 ft. to a mile. The subsequent storms of the same winter, extended the area of the fills, somewhat farther upstream and nearly restored the slope 12 ft. per mile, which had been created by the floods of preceeding winter.

The whole body of the material arrested by the barrier in the winter and the spring of 1906, as computed from the comparision of contour maps made before and after that period, was 1690,000 cubic yds. This material could be classified as ____ 0.6 % less than 80 mesh per in. size; 1.8 % less than 8 mesh per in. size; and remainder ranging up to boulders 1 ft. in diameter, the greater part being relatively fine material.

Maximum discharge between Oct. 1, 1905 and Oct. 1, 1906 as recorded about 5 miles above the barrier was 48000 c.f.s. while the minimum discharge was 5550 c.f.s. At 900 ft. down stream of the barrier the bed was lowered by 18 ft.

At 1600 ft. downstream of the barrier, the bed was lowered by 12 ft. Since these points are relatively at short distance downstream of the barrier, the above effect may be a combination of degradation and scouring. From the pictures given in Ref. No.1, it can be seen that, the top of the apron was about 12 ft, above the bottom of the river bed, though it is not known how high was the apron, above the bed before degradation.

Red River---

The Red River project is mainly, a flood control and power project, located on the Red river on the boundary between Oklahoma to the north and Texas to the south. The dam is a rolled fill structure with length 15200 ft. and maximum height 165 ft. above the normal stream bed elevation.

The Red river rises in the eastern part of Mexico, 562 miles above the Denison dam, while a number of intermitent streams meet it in the semiarid Llano Estacado or staked plains of Texas Panhandle. Then it flows eastward and south easterly about 1313 miles to its junction with Mississippi river. The total drainage area, above the Denison dam is 35291 sq. miles.

The river at the dam site, has a history of heavy sediment loads and studies indicate that, the average rate of sedimentation is about 19600 acre feet per year.

The closure of Denison dam was made on July 27, 1942. Immediately after the closure, thirteen degradation ranges were established within first 17 miles downstream of the dam, in July and August 1942. The spacing of these ranges varied from

½ to 3 miles,increasing progressively downstream.In 1946 the system was extended,approximately 100 miles downstream of the dam.

Repeated surveys,made on these ranges in the first 17 miles below the dam,show the degrading effect of water releases between July1942,the time of closure of Denison dam and Dec. 1945. Significant flows have passed during 1941, 1943, and 1947,all of which have caused a degrading effect on the river bed and tail water level,for a discharge of 5000 c.f.s.(See Plate No.3).Also Plate No.4 shows the progressive measured and estimated tail water levels on the Red river below Denison dam.It will be seen that,at high discharges,there is comparatively less drop in tail water level,than at lower discharges.

From the stream bed profile shown in plate 3,it may be observed that,the river bed at the first bridge, located approximately 2 miles below the dam,has retained its original level.Minimum tail water for the design of diversion outlet works and the power house was computed on the basis of the rock reef,that exists at the location, and in accordance with the indications,the control appears to be stable. At the second bridge however,there has been some degradation and inspection reveals that,there are some rock outcrops.At the third bridge site, approximately 3 miles downstream,there is evidence that some channel degradation has occurred.However,the presence of a fairly stable control for a short distance downstream,is believed to influence the channel stability at that point.In the 17 mile reach below the dam,an estimated quantity of 2900 acre feet of material was removed in a little more than 3 years.

Plate No.4 shows the size analysis curves,for the bed material, below the Denison dam at various miles(Ref,No.24)

Arkansas River---

From the source of Arkansas river to Canon city(Colorado),about 100 miles,the stream is a typical mountain torrent and this section is characterised by a series of narrow valleys,separated by short canyons.Below Canon city,the river emerges in to a portion of great plains for the next 50 miles,up to Pueblo.It is in this portion of the river,that large quantities of sediment are picked up,from the drainage area and river bed. Much of this material is gravel and boulders.Below Pueblo,the Arkansas river is characterised by low banks and broad sandy bed which is subject to considerable meandering.Thereare about 7 or 8 tributaries which join Arkansas river between Pueblo and John Martin dam,in the length of about 110 miles,and they carry large quantities of sediment during the summer months.

The slope of the river,above John Martin dam is about 6 to 8 miles per mile.Between Pueblo and John MArtin dam,and in general in plain areas,the soils are highly variable in origin,depth,and texture,but for the most part they are heavy and easily erodible.

The dam is located on Arkansas river,in Bent County,Colorado, It is a concrete gravity structure ,1644 ft. long,120 ft. high,togather with earth fill structure 2600 ft. long.

Purpose of dam	Flood control and Irrigation
Drainage area above dam	18933 sq.miles.
Spillway capacity	639200 c.f.s.
Closure of dam	Dec. 1942.

Since 1940,ten floods have been recorded on Arkansas river just downstream of John Martin dam,with peak discharges over 6000 c.f.s. The maximum discharge was in April 1942, and it amounted to 23600 c.f.s.

Thirteen degradation ranges were established in the channel of Arkansas river between John Martin dam and Lamar (about 20 miles).The results of degradation range surveys below John Martin dam,indicate that, 223 acre feet of the material was removed from the river channel,between the dam and Lamar,during 1943 to 1951. The movement within this reach was extensive,much of it was widely redeposited.

Degradation occurred between the dam and the range 6 (about 7.5 miles);aggradation took place between range 6 and 8(about 4 miles); degradation between the range 8 and 11 (about 4 miles); and aggradation below range 11. Largest quantity of material removed from this reach of 20 miles, was 175 acre feet,between 1944 survey and April 1945 s urvey.

Wolf Creek---

Wolf Creek is an important tributary of North Canadian River,above Oklahoma city,Oklahoma. The dam structure is of rolled earth fill type,with its length 11325 ft. and maximum height of 81.5 ft.above original level of stream bed.

Purpose	Flood control project
Drainage area above the dam	1735 sq. miles.
Spillway	The capacity is 210000 c.f.s.
Closure	The embankment section of the dam was closed on Jan.11,1941; while normal operation began on June 11, 1942.

Since the Wolf Creek has no important tributaries, the source of its sediment cannot be localised.It is believed that,most of it is furnished by the medium depth heavy plains soil,the shallow plain soil,and the very shallow hilly soil.

In the period of 1941-1949,the reservoir was partially drained three times--(1) In 1942-43 to permit the original survey of sedimentation ranges,below conservation pool elevations. (2) In Oct.1943,the pool was lowered in an attempt to replenish the water supply of Oklahoma city. (3) In 1947, it wasalmost completely drained,for the purpose of planting aquatic vegetation in the conservation lake bed area,to serve as protection and source of food for fish.

Degradation--

Ten degradation ranges were established across the valley of Wolf Creek,between the Fort Supply dam and the confluence of Wolf Creek with the North Canadian river. These were established in Dec.1944 and resurveyed in June 1949.It was found that,in this range of 5 miles,during a period of four and half years, 268 acre feet of material was removed.These ranges are located in an area,where the wind action has a considerable effect upon the valley profile.Hence it is quite difficult to differentiate between profile changes due to releases from the dam,and changes due to wind erosion or deposition.This degradation resulted in a lowering of 8 ft. intail water level for low flows. Plate 5 shows the measured and estimated tail water levels at various discharges below Fort Supply dam on the Wolf Creek.

Rio Grande--

Rio Grande river flows through the central part of Colorado state and central part of New Mexico.Elephant Butte Dam was completed in 1915.Prior to the construction of this dam,the channel was shifting, due to its lengthening during the years of low flood. and due to erosion and change in alignment during high floods. Proir to the construction of dam, the discharge at El Paso (130 miles downstream of the dam) during the spring runoff was about 2000 c.f.s.,while highest discharge passing El Paso was 24000 c.f.s.

Since the storage operation started in 1915, the entire discharge of Rio Grande has been retained in the reservoir, except as released for irrigation use. It must be stated that, in this project, the river channel itself is used as irrigation canal. Highest discharge at El Paso, since the dam was constructed, is 13500 c.f.s.

There are two sources of flow below Elephant Butte dam. One is the regulated discharge for irrigation demand, as released from the reservoir, which varies from 500 to 2500 c.f.s. Other source is the drainage between Elephant Butte dam and El Paso; this was maximum 8000 c.f.s. in 1916. This drainage carries a great amount of sediment with it.

The river carries a heavy sediment load. The average silt content of the river water is 1.65 %, while the maximum is about 10 % by weight. Practically all of the silt is settled out in the reservoir, created by the dam. Soon after the dam was constructed, the clear water started degrading the river bed, immediately below the dam and in a short period degradation downstream of the dam, was 7 to 8 ft., whileat distances 50 to 100 miles, it was between 2 and 1 ft.

In 1917 the river bed slope below the dam, was as follows--

First 100 miles	4 ft. per mile.
Next 30 miles	3.5 ft. per mile.
Between El Paso and 15 miles downstream	2.8 ft. per mile.

The 1932 survey has revealed that,a decrease in gradient has resulted just below the dam,due to heavy detritus from small streams,which the regulated river flow is unable to move.

Due to the regulated flow and a series of dams in the project, maximum flows were reduced more than 50 %; mean annual flows were reduced 30 %.To reduce the maintenance cost, desilting devices were provided to all canals etc. and therefore, all the sediment was retained in the river channel. Due to the consumption of water by irrigation,the channel was almost closed below International dam(143 miles Elephant Butte dam.).The absence of large floods has offered no opportunity,for the scouring action,and the river channel below El Paso,has filled with sand sediment to a point where it is higher in many places, than the adjoining farm areas.This has helped in offsetting the degradation.

However , the character of bed material in the stream bed, has changed below Elephant Butte dam.Since 1915,the material has changed from quick sand to sand,coarse sand, fine gravel, and gravel.

South Canadian River--

General-- The Conchas dam is located on the South Canadian river, in the state of New Mexico(U.S.A.). Conchas reservoir is a dual purpose structure, that is for flood control, as well as for irrigation. Through out entirely 130 miles below the dam, the river is confined to a narrow canyon section, before it emerges in to a reach of low hills. In this canyon section, the river bed occupies the entire floor of the valley and during the low flow periods, the channel consists of a series of shallow meanders. High flows occupy the whole bed and extend up the canyon walls, from 15 to 20 ft.

Slope and bed material--

The slope of the river, just above the dam is about 5.6 ft. per mile. Below the Conchas dam, the slope is 5.1 ft. per mile, levelling some what to 4.1 ft. per mile, 75 miles downstream. The bed material is in the form of, a deposit of sand and gravel, over the original sand stone. Prior to the construction of dam, the river bed at the dam site, consisted of coarse sand blanket of 10 ft. average depth, over lyinga 5 to 6 ft. strata of clay and gravel. The finest material found near the dam, in quantity, was classed as medium to coarse sand, with attaining a prominent portion about 30 or 40 miles downstream.

Discharge and Floods--

Normal flow of South Canadian river, near the dam site, varies from zero to 50 c.f.s. with flashy flood flows even up to 38,000 c.f.s. The following table gives an idea about the flood flows and flood discharge after the dam was constructed.

Date	Flood Discharge c.f.s.	Flood Flow million c.f.s.
May 17,1941.	18,100	1160
June 7,1941.	16250	1170
June 9,1941.	13750	1180
Sept.24,1941.	12500	2600
April 24,1942.	38300	1150
Sept.2,1942.	31000	1140

Since 1939 to 1948,there were four major floods, resulting in spillway discharge,which reached a maximum rate of about 38000 c.f.s.Otherwise there was no flow release,except 5 to 7 c.f.s. from the power house.

Degradation--

This type of flow has brought about a net degradation of 7000 acre feet of material,from the river bed over a distance of 20 miles downstream from the dam.The maximum lowering of the low water profile,10 ft.begins about 1.25 miles below the dam,and continues at this magnitude for 4.5 miles below the dam,decreasing to a negligible value 2o miles below the dam.Beginning at a point about 1 mile below the dam,the river bed has eroded to rock outcrops, forming a seriesof pools,because these outcrops acted as controling points for the water level;These pools can be observed in the first 5 miles.The present bedsurface in the first five mile reach is wholly rock and large gravel and it is apparent that,all the material of the size of medium gravel and smaller has been removed.Small gravel and coarse sand begins to show at about 6 miles downstream. At several locations in the reach,the river has a tendency to erode the inside of the bends, thus straightening the channel and compensating for a change of slope due to degradation. These are the reaches where the canyon gives way temp orarily to gravelly hills.

Wisconsin River---

The Wisconsin River has a bed of sandy material which continuously moves downstream, in a stretch near the Prairie Du Sac dam.The movement of the sand in the form of sand bars ,is evident at the stream gaging station at Muscoda (Wisconsin), many miles downstream of the dam. At this gaging station , which was established,at about the same time,as the Prairie Du Sac dam was constructed,it is a common practice to observe a sand bar,upstream from the gaging station ,during the early part of open water season. As the season progresses,the bars move closer to the station, finally reaching it; and at the same time a normal depth of,from 8 to 9 ft. at the gaging station is replaced by 6" to 1 ft.of water over the surface of bars.

The hydro-electric power plant at Prairie Du Sac (wisconsin),was placed in operation in 1914. The mean flow of the Wisconsin river, as recorded at Muscoda gaging station during 1915- 1942 was about 8816 c.f.s. (Trans.A.S,C.E.1950)

A general lowering of the tail water and of the river bottom downstream from the plant, became obvious, a few years later. The average rate of recession of the monthly tail water levels over 17 year period, 1915--1931 inclusive was 0.43 ft. per year. From 1932 to 1936 it was about 0.1 ft. per year, while the minimum monthly tail water level was practically constant from 1937 to 1944.

Plate 6 shows the variation of 12 monthly mean low tail water level each year with years. From that it can be seen that, during the first few years, these drops in the water levels were more rapid, when the finer material was being removed. After wards the bed material was coarsened, and therefore the bed of the river as well as the above mentioned typical water levels were stabilized to some extent. As a result of degradation, the tail water level dropped to such an extent that, apparently the jump would not form on the apron for all the discharges.

As said on page 14, this movement of the jump in downstream direction, is very dangerous to the structure. Usually there is a considerable difference in water levels before and after the hydraulic jump, and when the jump moves downstream, to such an extent that it would not form on the apron, the depth of the water on the apron is reduced. In normal course, the uplift on the downstream apron, is balanced by the weight of the apron and weight of the water on the apron. Reduction of the depth of water on the apron, there fore, apparently increases the uplift, and if the weight of the tail water depth plus that of the apron is less than the uplift, the apron will burst.

Therefore during 1929,hydraulic model tests were carried out ,to determine a method of reducing excessive erosion of the river bed,immediately downstream of the dam.A temporary and cheap method of wooden baffles was designed andconstructed in 1930.

The river being nominally navigable,a lock was provided, during the construction of dam.This lock is 35 ft. X 170 ft. with its lift that reaches exceptionally high maximum of 34 ft. the sill of the lock was about 6 ft. above the bed.As the degradation in 18 years was of the order of 7.5 ft.,it is clear that the lock must be useless.

Missouri River.--

Fort Peck dam, on Missouri river in north eastern Montana,is the largest earth fill dam in the world. The primary purpose of Fort Peck project,is to improve the navigation in the river below Sioux city,Iowa,w ith the incidental purpose of flood control, prevention of bank erosion,hydro-electric power and irrigation.

Some facts about this dam are as follows--

Length of the dam	21,026 ft.
Max.width at the base	4900 ft.
Maximum height	250 ft.
Area of the reservoir	245,000 acres.
Drainage basin	57,725 Sq. miles.
Mean discharge	6620 c.f.s.
Maximum discharge	25,000 c.f.s.
Spillway capacity	250,000 c.f.s.

All except the last 100 miles of Missouri river,above Fort Peck dam,is considered to be stable ,nonalluvial river. For some distance below the dam,the river has all the characteristics of an alluvial stream. Average slope of the bedof the river is 0.94 ft. per mile.The river at Fort Peck dam was not considered to be a heavy sediment carrier prior to the construction of the dam.

Different degradation ranges were established in May 1936,and measurements have been made at intervals of about six months.Following table gives some degradation results,at different ranges.(The rates and total lowering is for 11.5 years)

Range No.	3	4	5	6	7	8
River milage below dam.	6.8	7.5	9.6	13.8	26.6	46.8
Average lowering of bed. ft./year	0.39	0.08	0.22	0.18	0.05	0.03
total lowering ft.	4.52	0.96	2.59	2.01	0.54	0.30

Data for the mechanical analysis of the bed material for range numbers 2A and 5,showing the changes that have occurred,in the composition of the material in the channel bed,is shown in Plate 9.(Ref.No.24.)

The above table and the mechanical analyses curves,show two things--(1)The material gets coarser as the degradation continues. (2)As the material gets coarser the rate of degradation decreases.

Based on the observation and some basic assumption it is estimated that,5900 acre feet of material has been removed, from the river channel, up to range 8,in these 11.5 years.On the basis of volume,the river bed has been lowered, an average of 1.24 ft, during 11.5 year period of record.

At the end of 1951, a total of 34 permanent and 61 temporary ranges have been establishrd. These ranges cover a reach of approximately 157 river miles, extending from Fort Peck dam downstream to range 16, which is located 26.5 miles upstream of the confluence of Missouri and Yellow stone river.

From the recent survey, it is evident that, at some sections on these ranges, considerable lateral erosion has taken place. Hence degradation is many times represented in terms of the cross sectional area.

Thus, at ranges 5, 6B, and 7C, which are about 9.6, 21, and 38 miles downstream of the dam, the increase in the cross sectional area, between 1948 and 1954 was, 4900, 1850, and 1400 Sq.ft. respectively.

LOwering of water level, for specific discharges was also recorded at various gaging stations. Between 1950-54, this lowering of w.L. for 10,000 c.f.s. discharge was as follows--

NO.	Gaging Station.	Miles below dam.	Lowering in ft.
1.	7.Mile	8.4	1.1
2.	Range 6B.	21	0.65
3.	Frazer	36.2	0.55
4.	Oswego	45.7	0.40
5.	Wolf Point	72.4	0.40

AT Culbertson, 154 miles d.s., there was o.25 ft. rise in 7 rears.

(b) Rivers in India----

Most of the degradation effects in the case of rivers in India,have occurred in northern part of India,where there is a very thick strata of alluvial material.A greater part of it is called Indo-Gangatic plain.

One of the great failures of weirs on alluvial material which occurred on Sutlej river,was that of Islam weir.This is many times called as Islam barrage.Barrage is a gate controlled weir,right across the river with the crest usually at one level. This weir is one of the four similar structures (Ferozepore barrage,Sulemanki barrage,Islam barrage,and Panjnad barrage.),built on Sutlej river in Punjab,as diversion structures for canals of that valley project.

Islam weir is 1621 ft,long with 24 openings of 60 ft. span each. Impervious and broad upstream and downstream aprons,of concrete,were provided for it. The downstream apron slopes down for some distance andthen extends in horizontal direction,ending without a cutoff wall. Down stream of the concrete apron,were concrete blocks and heavy rip rap. The barrage sustained a maximum head of 18 ft. and was put in to service,in the spring of 1927.By November of that year,the bed downstream had dropped 2.3 ft. The bed lowered to 5.5 ft. by December 1928 and it had reached 6.5 ft.by May 1929.At this stage,the water level downstream was 4 ft.below the floor of the weir.The scour resulting from this drop was so severe that, a large portion of the downstream apron was destroyed,and finally six bays of the structure collapsed.

After the reconstruction of the barrage,process of aggradation started,the level reaching its highest value in 1942. The process of aggradation was.however followed by a period of degradation.The lowest levels were reached in 1947,when the downstream levels were 6 ft. lower than those in 1942.This degradation resulted in a loss of control to some extent, at the barrage.For higher discharges,it was found thatthe jump moved downstream.In 1947,model studies were carried out and it was found that,for high discharge intensities,the depth is about 2 ft.too small,to form the jump at the toe of the glacis.Also it was experimently found,two rows of rectangular staggard blocks are a best device for this lowering.These blocks were actually constructed in March 1949,in the depressed bay of the weir. After the floods of 1950,with the rectangular blocks in position,there was silting just downstream of the apron.(Ref.No.6)

Serious degradation has taken place in the case of Ferozepore and sulemanki weirs of this project.At the former the degradation reached a maximum of 5 ft. the same year it was put in to service,but the bottom since then tended to rise.This is no doubt due to the filling of the reservoir upstream andtendency towards the restoration of the normal supply of material from upstream.At sulemanki weir,the degradation was noticed the first year of its service.

It reached a maximum of 6.2 ft.in the second year,but then recovered to 4 ft in the third year. The river bed at all these structures is composed of sand and the river has a slope of about 1.1 ft. per mile.

Thus ,as a result of degradation of the of these rivers,while the low water levels have been found to drop from 4 to 7 ft. the maximum flood levels have not been known to have dropped by more than 1 to 1.5 ft.(Ref No.15)

Similar effects have also been observed on Indus river.Specific discharge curves at Bachalshah were studied from 1923 to 1942, and an average rise of 0.1 ft. per year was found.Bachalshah is 1 mile below Sukkur barrage.The barrage was complete in 1931. From 1931 to 1935,there was heavy degradation and then a steep rise occurred at a rate of four times the average of 0.4 ft. per year.(Ref.No.10.)

On page 53,is given the degradation and aggradation effects on the river beds downstream of some of the weirs in India and Pakistan.

The inspection of this table shows that ,in most of the Rivers in India and Pakistan,in the beginning there is degradation,which is slowly recovered and afterwards there is a net aggradation.As explained some where in this report,this may be due to following causes.

(a) Aggradation of the river occurs,when a large portion of clear water is drawn by an irrigation canal,leaving the sediment load,particularly the coarse material,to be carried by the reduced flow.

(b) When the river discharge is low,it carries down,an excessive silt charge;this checks the degradation of the river bed and the deposition of the silt starts.

(c) At low flows,i.e. usually in summer,it is a common practice on these rivers in India and Pakistan, to open the gates of the weir occassionally,so that the silt stored above the dam is then flushed down.This offsets the degrading effect and some times net aggradation results.

River Weir Opened in	Chenab Khanki 1891	Sutlej Rupar 1882		Jehlum Rasul 1900		Chenab. Marala 1910	
Degradation	4.5 ft.	5.0	Continued	1.0	5.5	Steady degradation	1.0
Period	1891-98	Immediately after Operation	1882-90	1902-12	1912-19	1910-19	1922-27
Rate of Lowering	0.64 ft/year	-	-	0.1	0.79	-	0.2
Recovery ft.	4.5	-	Complete Recovery	—	2.0	1.0	—
Period	1898-1909	-	1890-1917	--	1919-30	1919-22	-
Rate of Recovery ft	0.44	-	-	-	0.18	0.33	-

(c) Degradation on Nile in Egypt--

Bed degradation is revealed by a progressive change in the gage discharge relation,where in the water level at which a certain discharge passes gets lower and lower.This effect has been observed below the present Aswan dam,the Sennar dam, and the Naga Hemadi Barrage on the Nile river.It must also have taken place below the Esna Barrage,but no data is available.

In the case of ASwan dam,the readings of Aswan gage fell by about 1 ft. immediately after the completion of the dam in 1902. The total fall up to 1953 is about 3 ft.This fall has not been regular.In 1925,for example,the gage readings were actually higher than what they were in 1903.

In the case of Sennar dam,a lowering of the gage reading at Makwar(About 5760 ft.downstream),tothe extent of 3.6 ft.was observed after 9 years of operation.This was reported by the Sudan Irrigation Adviser in Feb.1934.In that note it was stated that,bed degradation below the dam,did not reach Wad El Hadded, 23 miles downstream.Inspection of recent reports however shows that,between 1930 and 1950,there is a net fall of 0.49 ft at that gaging station.

In the case of the Naga Hemadi barrage,the amount of lowering was 2.3 ft.after 8 years of operation.Actually a subsidary weir had to be constructed below that barrage,to keep that head on it,during summer within prescribed limit. Recent investigation shows that,the bed degradation below the barrage is still going on.but at a much lower rate.(Ref.No.25)

(d) Degradation on Saalach River in Germany.

An excellent example of degradation and effect of controls, is the profile of the Saalach River, below Reichenhall reservoir, in Bavaria. Here the degradation in eight years was sufficient to endanger seriously the safety of a pier of a rail road bridge 3 miles below the dam. Degradation was also observed at Innworks, Upper Bavaria. As this dam, consisted of gates with sills at river bed level, much of the bed load passed through during floods and the lowering was slight.

AS shown in plate 8, the river bed downstream from the dam receeded almost 10 ft, in a little more than 21 years, or at a rate of 0.5 ft. per year,

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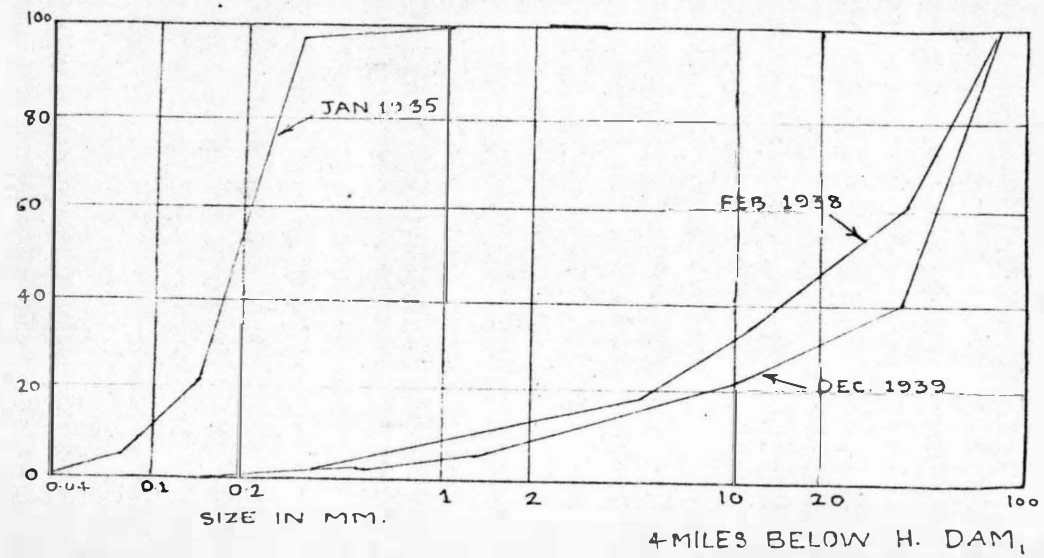
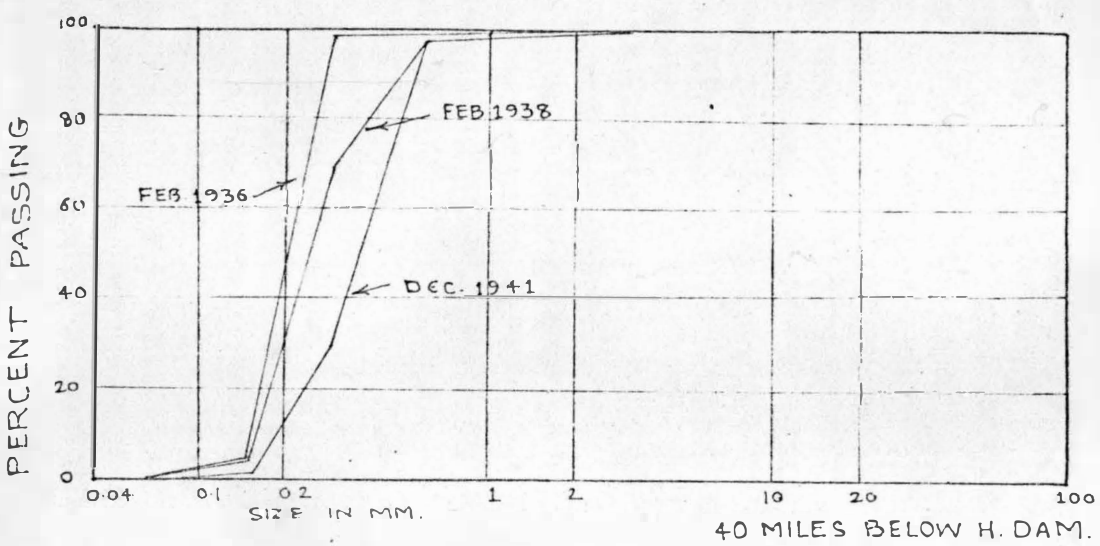
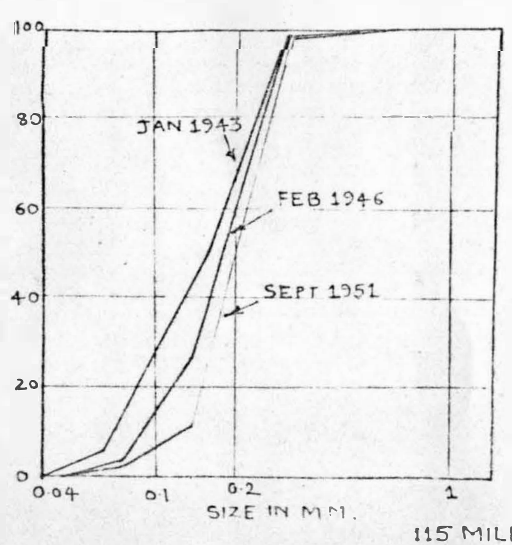
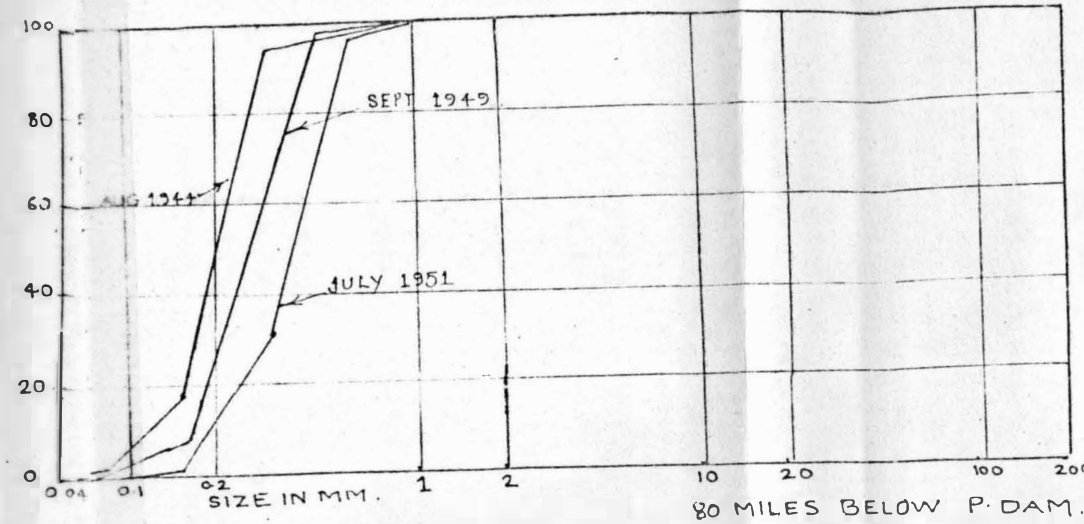
PLATE No. 1

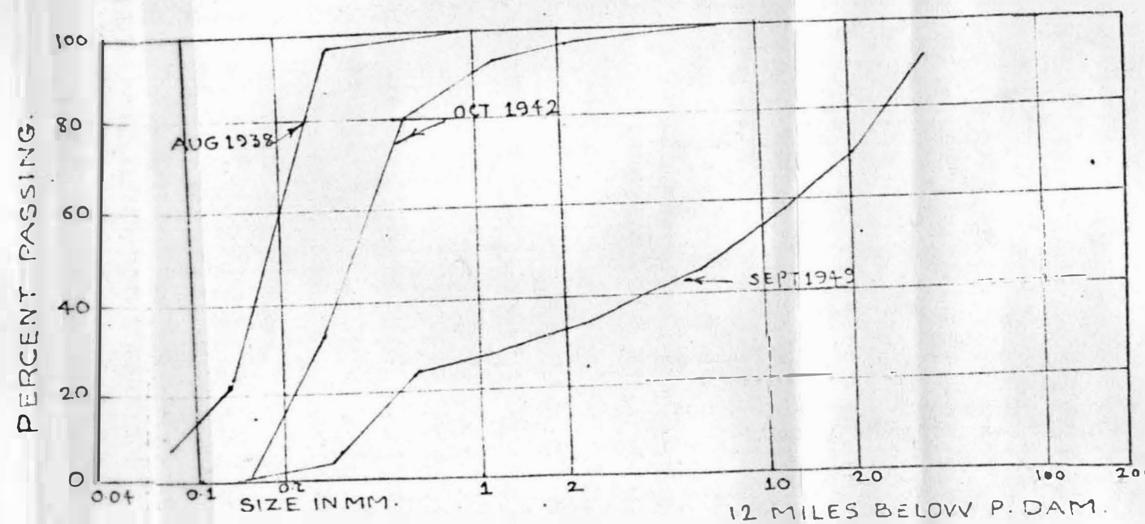


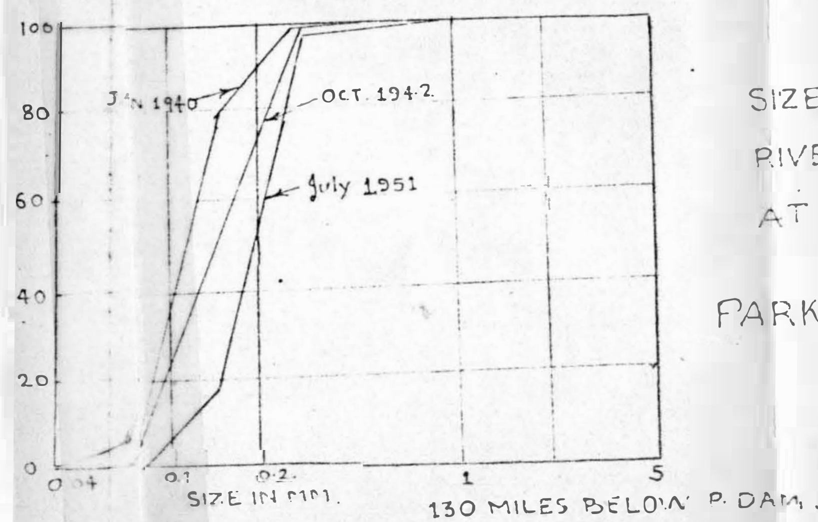




SIZE ANALYSIS OF
RIVER BED MATERIAL
AT TYPICAL SECTIONS
BELOW
HOOVER DAM.

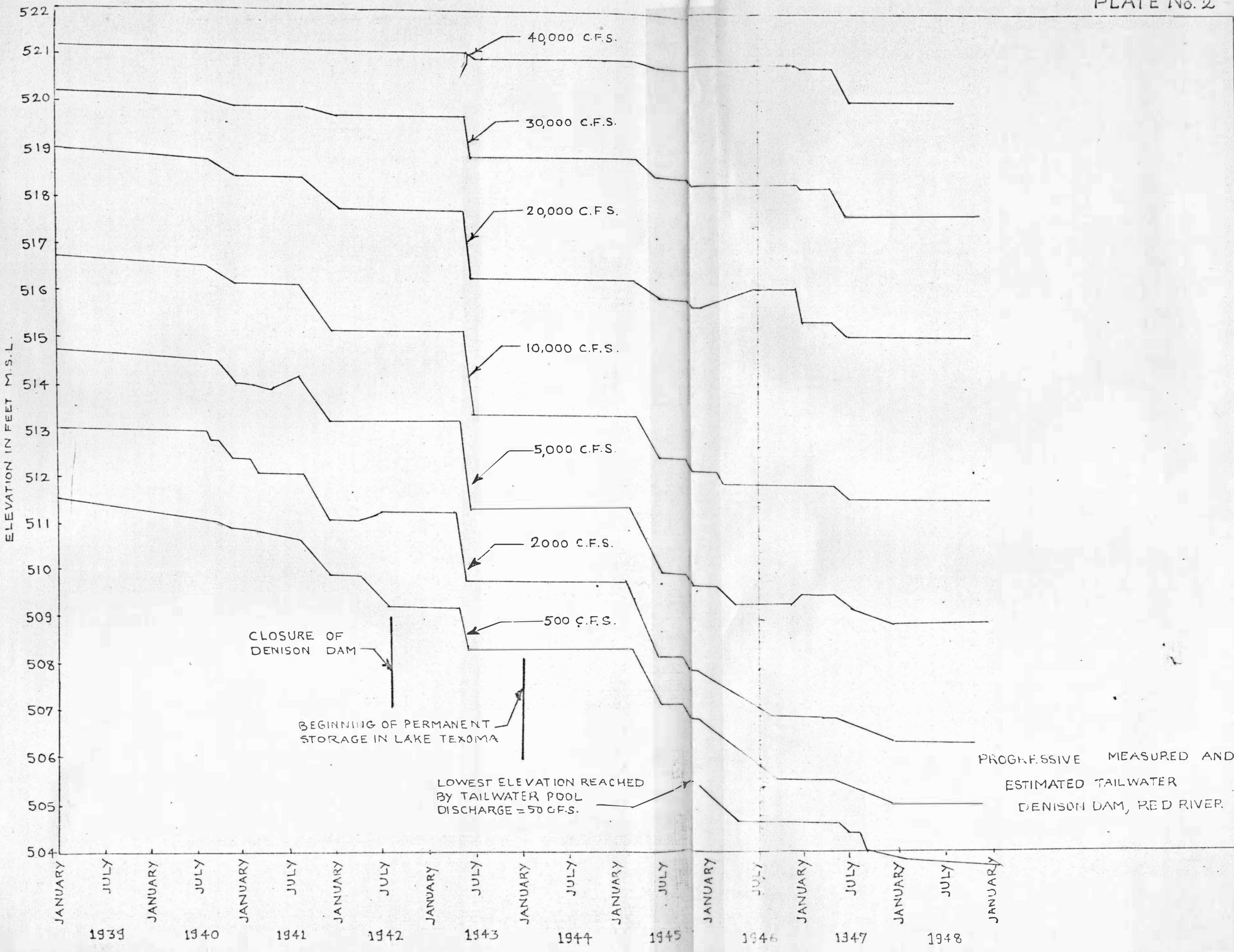






SIZE ANALYSIS OF
RIVER BED MATERIAL
AT TYPICAL SECTIONS
BETWEEN
PARKER AND IMPERIAL
DAMS

PLATE No. 2



PROGRESSIVE MEASURED AND ESTIMATED TAILWATER DENISON DAM, RED RIVER

PLATE No.3

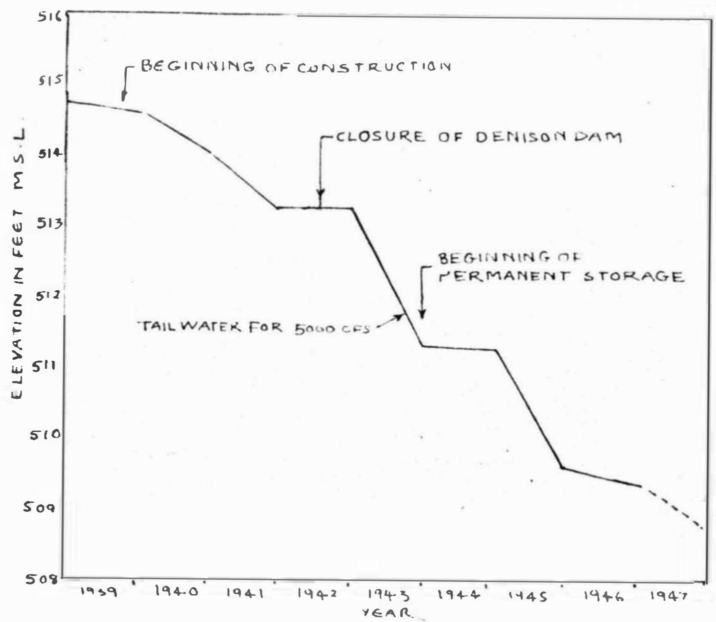


Fig. CHANGE IN TAILWATER ELEVATION
DENISON DAM RED RIVER, U.S.A.

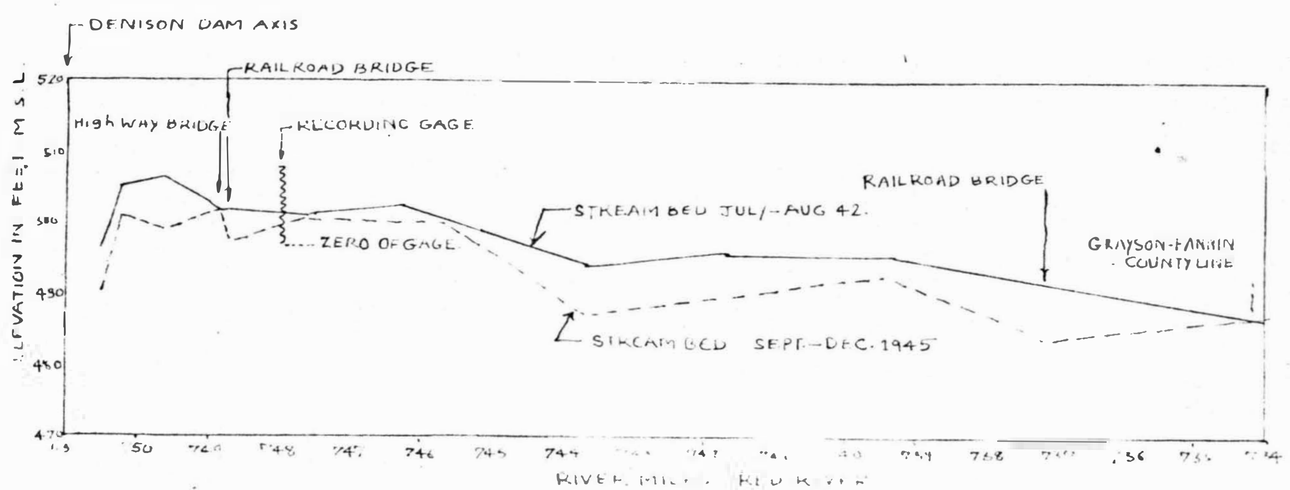
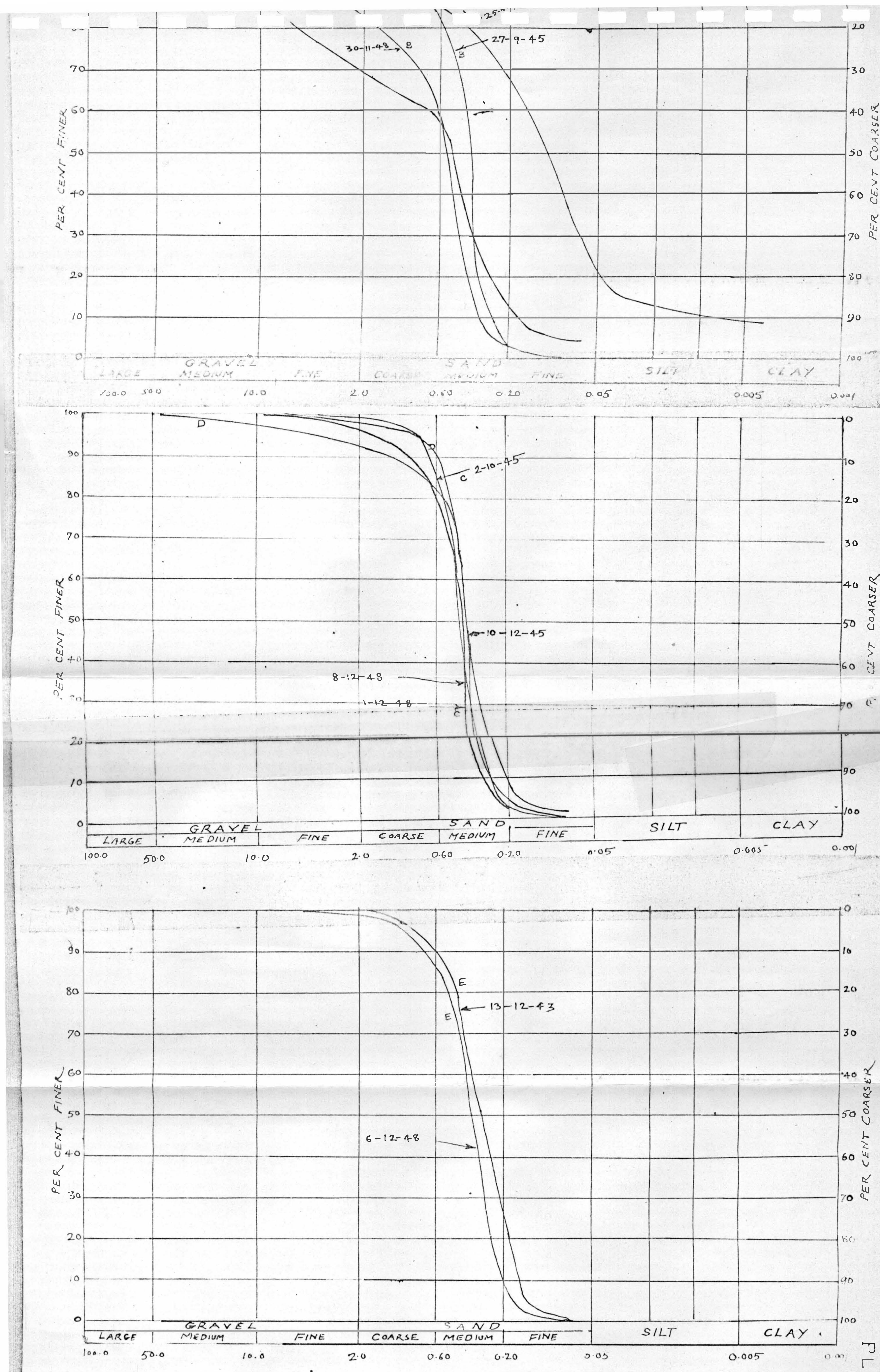


FIG. —STREAM BED PROFILES BELOW DENISON DAM
RED RIVER, U.S.A.



RED RIVER BELOW DENISON DAM
MECHANICAL ANALYSIS CURVES

A — 1/2
B — 7
C — 8
D — 10
E — 18
→ MILES BELOW DAM.

PLATE No 4

PLATE No. 5

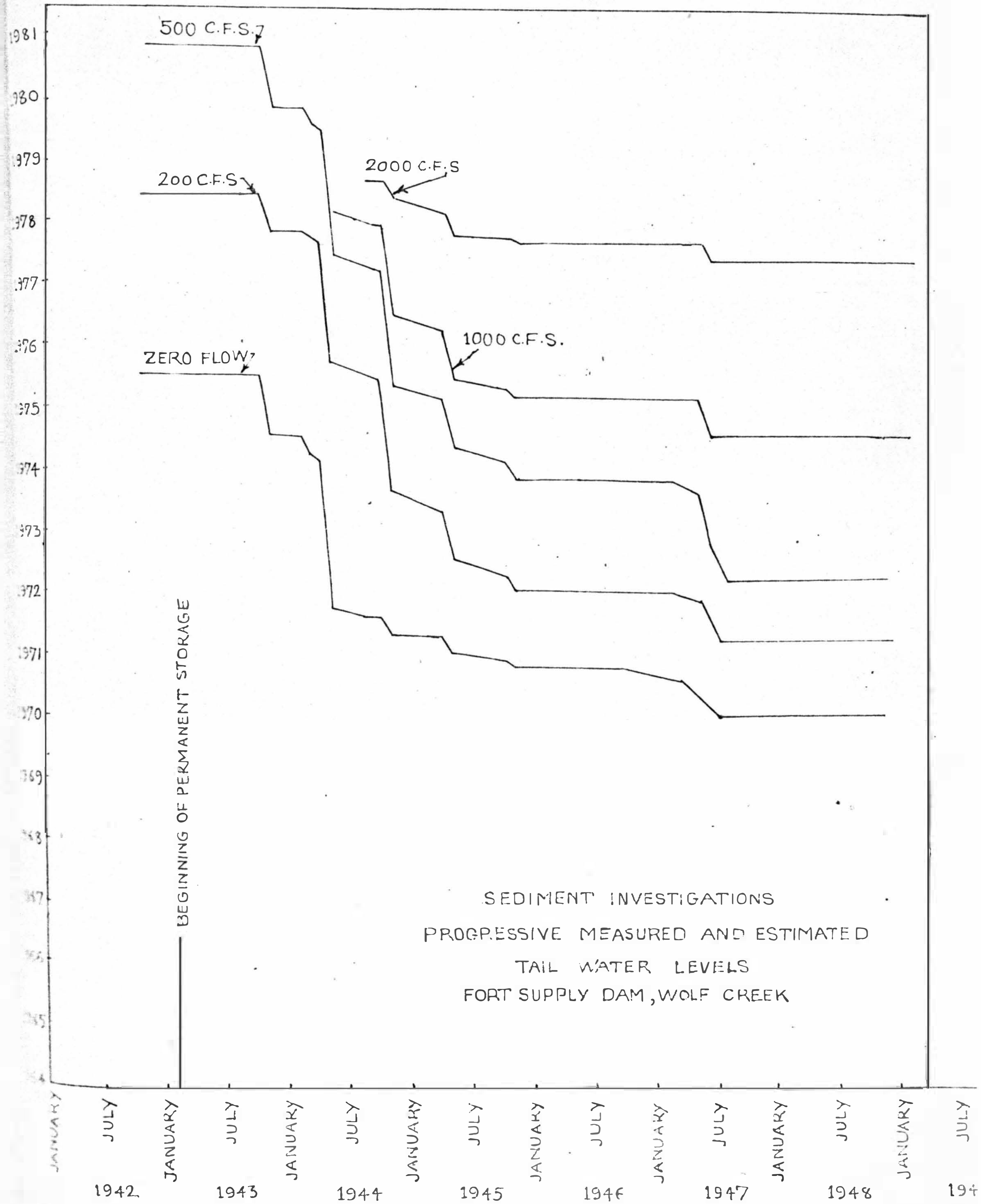
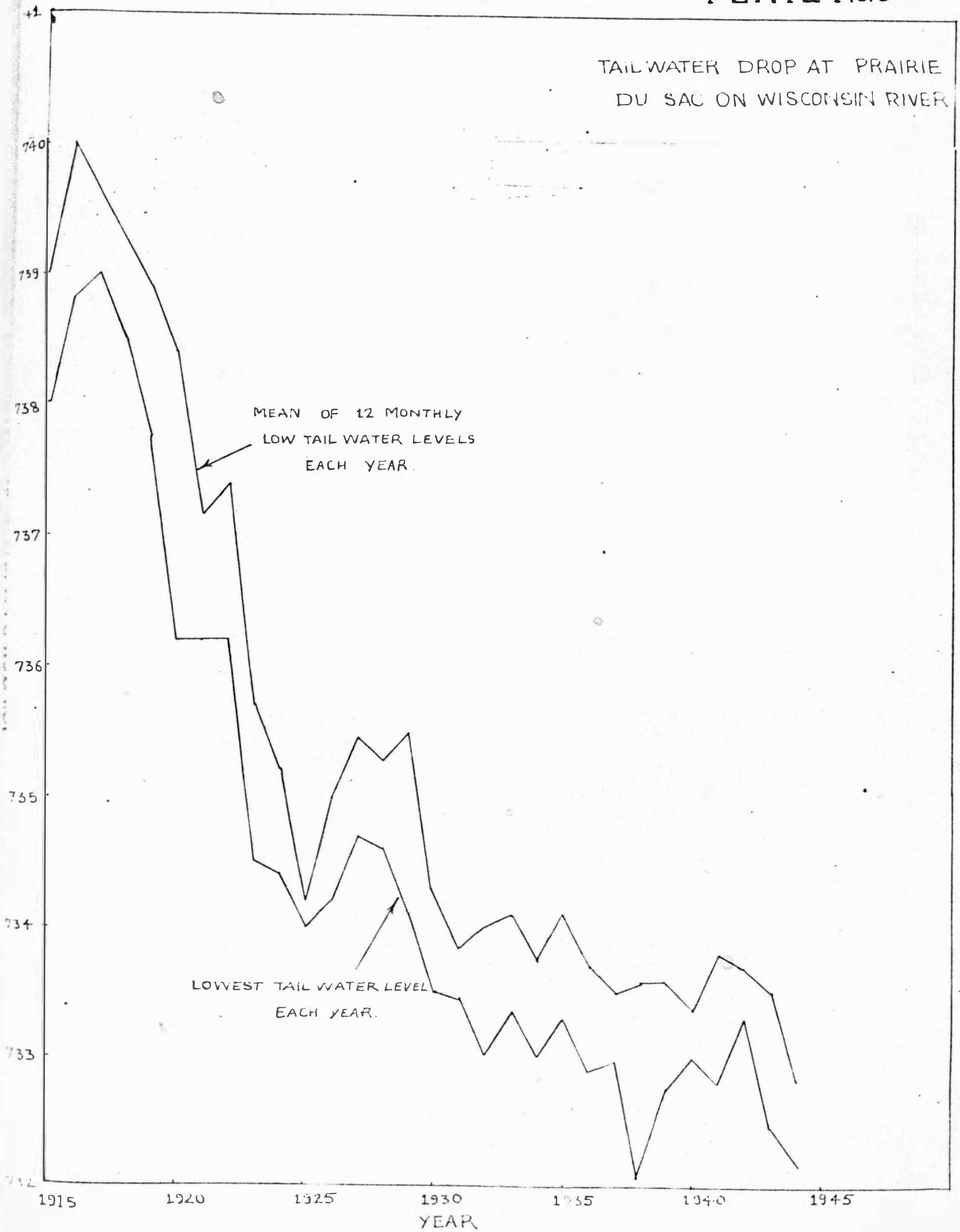
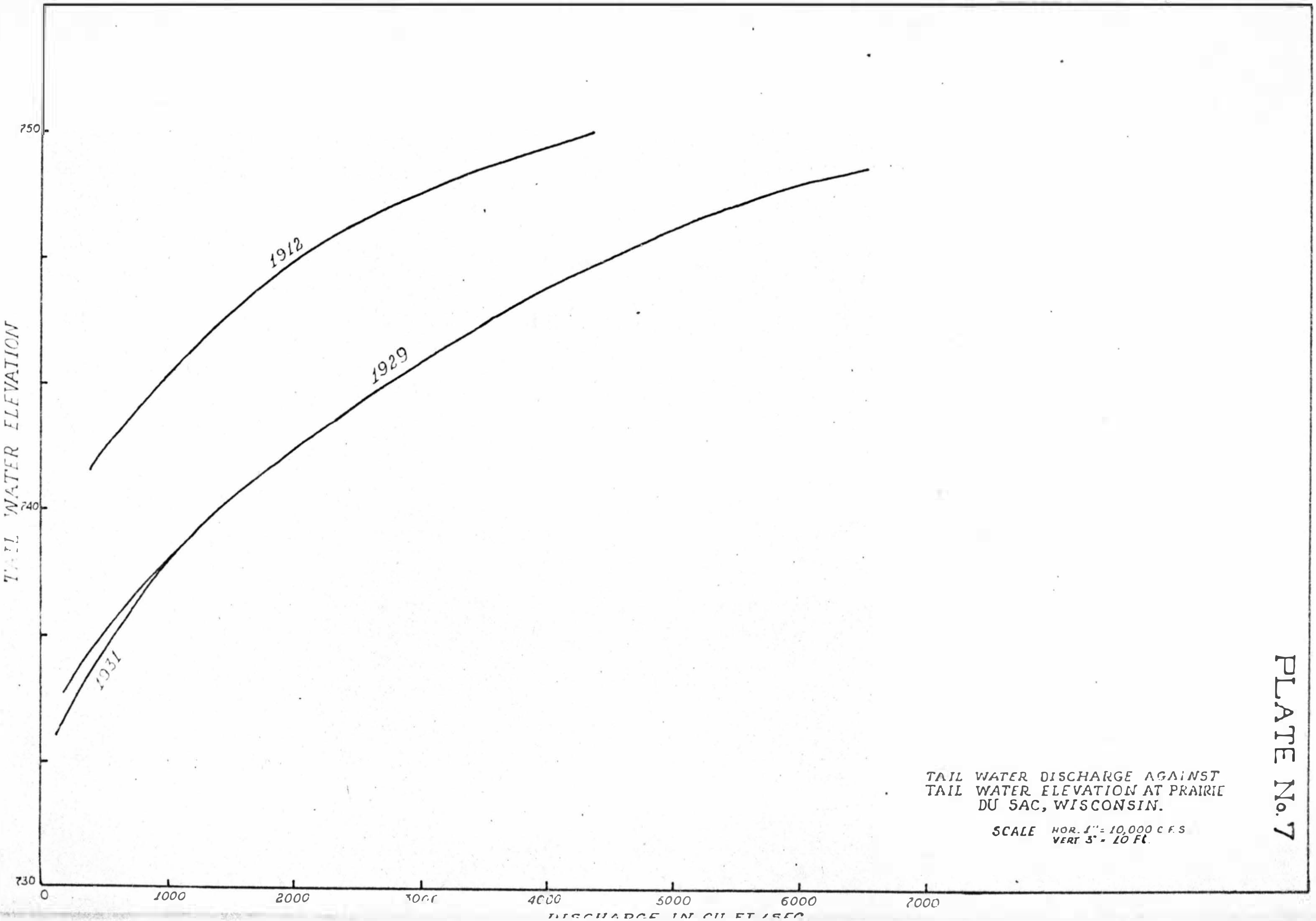

500 C.F.S.
2000 C.F.S
200 C.F.S
1000 C.F.S.
ZERO FLOW
BEGINNING OF PERMANENT STORAGE
1981
1980
1979
1978
1977
1976
1975
1974
1973
1972
1971
1970
1969
JANUARY
JULY
1942
1943
1944
1945
1946
1947
1948
SEDIMENT INVESTIGATIONS
PROGRESSIVE MEASURED AND ESTIMATED
TAIL WATER LEVELS
FORT SUPPLY DAM, WOLF CREEK

PLATE No.6

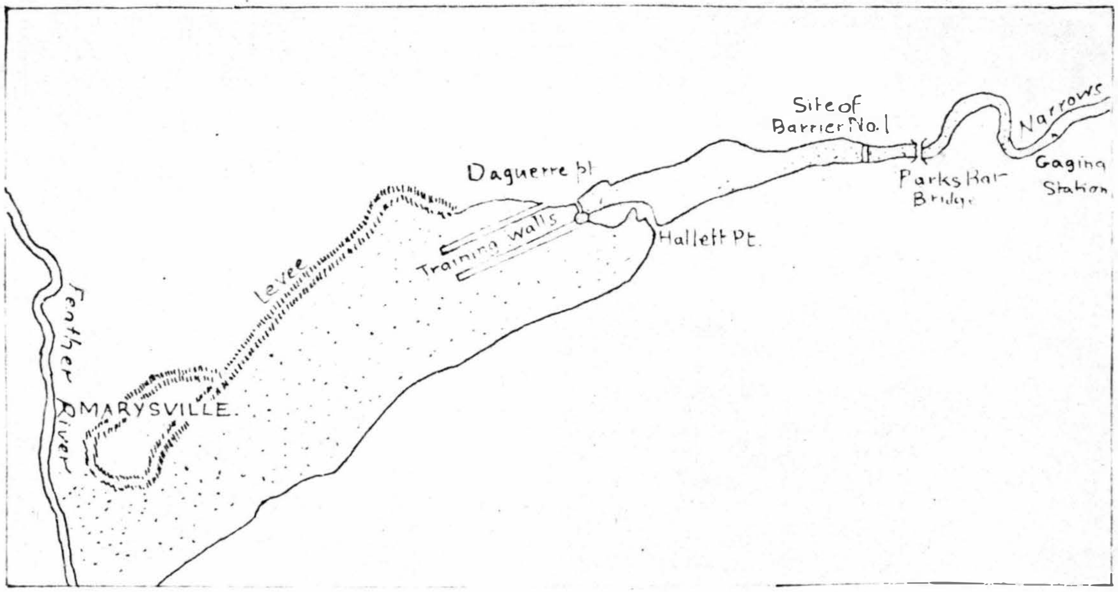

TAIL WATER DROP AT PRAIRIE
DU SAC ON WISCONSIN RIVER
MEAN OF 12 MONTHLY
LOW TAIL WATER LEVELS
EACH YEAR.
LOWEST TAIL WATER LEVEL
EACH YEAR.
740
739
738
737
736
735
734
733
1915
1920
1925
1930
1940
1945
YEAR



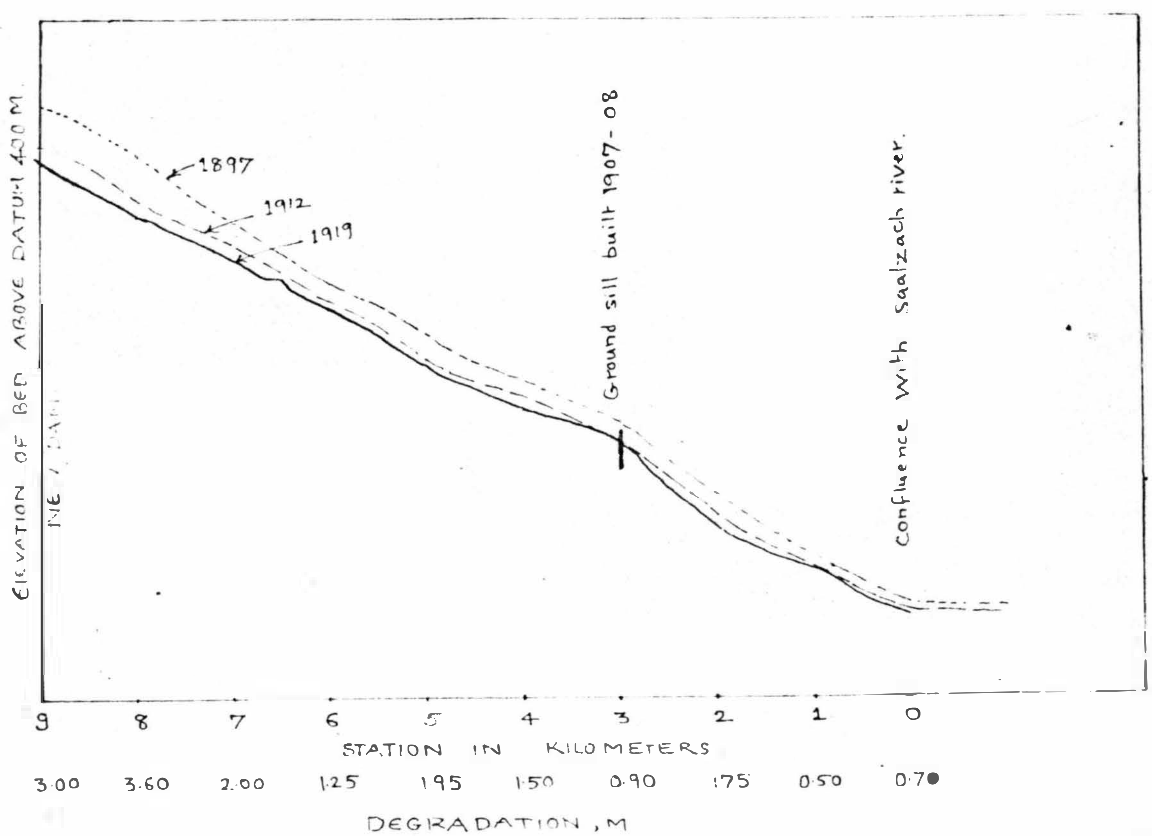
TAIL WATER DISCHARGE AGAINST TAIL WATER ELEVATION AT PRAIRIE DU SAC, WISCONSIN.

PLATE No. 7

PLATE No.8



OUTLINE MAP OF PIEDMONT DEPOSIT OF YUBA RIVER



DEGRADATION OF THE BED OF SAALACH RIVER

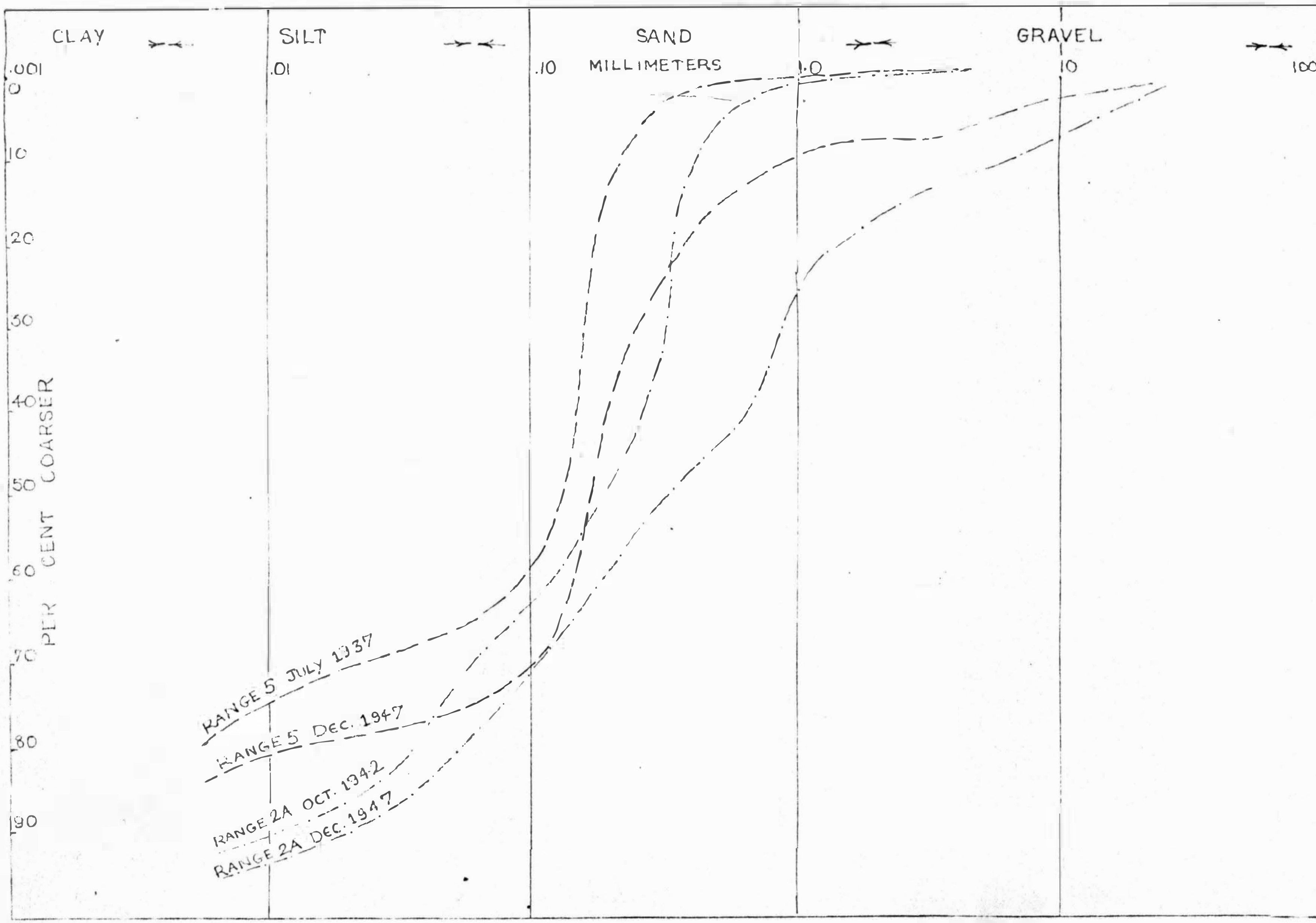


FIG. — MECHANICAL ANALYSIS OF BED SAMPLES
MISSOURI RIVER BELOW FORT PECK DAM, U.S.A.

PLATE No. 9