

Engineering Laboratories Division
Hydraulic Laboratory Branch

Schroeder

MASTER
FILE COPY

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

BUREAU OF RECLAMATION
HYDRAULIC LABORATORY
NOT TO BE REMOVED FROM FILES

HYD 372

THE IMPORTANCE OF FLUVIAL MORPHOLOGY
IN HYDRAULIC ENGINEERING

Hydraulic Laboratory Report No. 372

ENGINEERING LABORATORIES



COMMISSIONER'S OFFICE
DENVER, COLORADO

December 1954

CONTENTS

	<u>Page</u>
Introduction	1
Early History	1
Nomenclature of the Geomorphologists	2
The Geomorphological Approach	2
Characteristics of the Various Ages of Rivers	3
Base Level	5
Equilibrium in Natural Streams	5
Changes of the Profile of Natural Streams	7
Classes of Stream Profile Changes	7
Examples of Class 1	8
Examples of Class 2	9
Examples of Class 3	11
Examples of Class 4	12
Examples of Classes 5 and 6	12
Conclusion	13

FIGURES

	<u>Number</u>
Class 1--Stream Profile	1-a
Class 2--Stream Profile	1-b
Class 3--Stream Profile	1-c
Class 4--Stream Profile	1-d
Class 5--Stream Profile	1-e
Class 6--Stream Profile	1-f
Roof of Powerplant Buried by Rise of Bed of Mu Kwa River in Formosa	2
Degradation Below Fort Sumner Dam on Pecos River in New Mexico	3
Waterfall on Five Mile Creek, Wyoming	4
Bed Lowering in Cherry Creek, Denver, Colorado	5

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Office of the Assistant Commissioner and Chief Engineer
Denver, Colorado
December 1954

Laboratory Report No. Hyd-372
Hydraulic Laboratory
Compiled by: E. W. Lane
Reviewed by: E. J. Carlson

Subject: The importance of fluvial morphology in hydraulic engineering

INTRODUCTION

Morphology is defined as "the science of structure or form" and fluvial is defined as "produced by river action." Since rivers can hardly be said to have structure, fluvial morphology is therefore the science of the form of rivers as produced by river action. It is a branch of geomorphology, the science of the form of the earth's surface. Geomorphology has also been called physiography.

Fluvial morphology is particularly important to the hydraulic engineer as many of his greatest problems arise because of the form of streams brought about by the transportation and deposition of sediment by them. For the proper solution of these problems, a knowledge of the principles of fluvial morphology is often necessary. Among the problems in which fluvial morphology is a very important factor are many of those dealing with water resources development and include some of the most important river problems in the world. Examples of these are flood control on the Lower Mississippi and on the Lower Colorado Rivers, the development of the hydraulic resources of the Missouri and Arkansas Rivers, the Yellow and Huai River flood problems in China, the Kosi River floods in India. As streams become more highly developed, and changes in sediment movement due to stream developments slowly become evident, the importance of the morphological aspect of river control problems will be increasingly appreciated.

EARLY HISTORY

The science of fluvial morphology has developed from 2 roots which have been largely independent of each other. The most vigorous root is in the science of geomorphology where the principal originators were the geologists, J. W. Powell,^{1/} G. K. Gilbert,^{2/} and W. M. Davis,^{3/} who worked in the latter part of the past century and early part of the present one. The work of these men dealt chiefly with the form of the surface of the earth and the importance of flowing water in causing

^{1/} The numbers refer to references in the bibliography at the end of the paper.

the present shape, but Gilbert also made extensive investigations into the quantitative aspects of sediment transportation. The other root is in engineering and goes back much further to Dominique Guglielmini, 4/ about 1697, who was probably the first writer on fluvial morphology. As early as 1750, engineers 5/ were arguing about the advantages and disadvantages, from the standpoint of navigation, of dividing the Rhine into several channels and were constructing hydraulic models to prove their contentions. Very complete histories of the developments of this science in the field of engineering can be found in the summaries of Hooker 6/ and Mavis 7/. Unfortunately for both engineering and geology, these 2 roots, except for the work of Gilbert, have remained largely separate down to the present time; but it seems probable that in the future a closer coordination of the two fields will exist to the advantage of both.

NOMENCLATURE OF THE GEOMORPHOLOGISTS

One of the best contributions made by the geomorphologists to the science of fluvial morphology is the nomenclature which they have introduced. Rivers have been classified by them on 2 bases: (1) on the basis of the method of formation, i. e., whether the position of the river is a consequence of the initial slope of the land area or a result of other factors (8/ p. 171) and (2) on the basis of the age of the stream. From the standpoint of the approach of this report, the first of these methods of classification has little usefulness; but classification on the basis of age introduces ideas of major value. A number of their descriptive terms for rivers, such as meandering and braided, have been generally adopted. The conception of "base level" and of a "graded river" are also very useful, as are also the terms "aggrading" for the change of the level of a river whose bed is rising and "degrading" for change downward.

THE GEOMORPHOLOGICAL APPROACH

As previously mentioned, the geomorphologist is interested in fluvial morphology principally as a tool in explaining the origin of the present form of the surface of the earth. The science appears to be of comparatively recent origin. Although many able men contributed to its early development, the outstanding work is that of W. M. Davis. 3/ According to the Davis conception, the primary action in the formation of the earth by moving water is the geographical or geomorphic cycle which is a cycle of erosion passing through several stages. It starts with a nearly flat land surface which is gradually warped by movements of the earth's crust. This gives rise to increased erosive and transporting power of the water flowing from the land, the water beginning to carve the landscape into various forms. As time goes on, the forms of the land surface change, the various types of topography being characteristic of the various length of time during which the water has acted. Material is constantly being carried away from the land

surface and deposited (usually in the sea); and the elevation of the land surface is gradually lowered and flattened until, after a very long period of time, the end of the cycle is reached when the whole surface has been reduced to a very gently sloping plain called a peneplain, and thus comes back to the condition in which the cycle started.

The various stages in the cycle are described in terms of age, beginning at the start of the cycle with youth which passes into maturity and then into old age. The topographic forms typical of the first stage are spoken of as young or youthful, later ones as mature, and those of the last stage as old, with further subdivisions when desirable such as, for example, early and late maturity.

The same set of terms are used to designate the age of streams, and certain characteristics are typical of rivers of these various ages. Although the age of the stream usually corresponds with that of the surrounding topography, this is not necessarily the case.

Fluvial morphology as developed by the geomorphologists is largely a qualitative or descriptive science and suffers somewhat from a lack of quantitative relations, but many keen minds have contributed to it. It is not the intention in this report to present in detail the geomorphological approach to this subject but rather to present geomorphology from an engineering viewpoint in order that the engineer may have the advantage of the extensive work of the geomorphologist, and that the latter may possibly gain something from the engineering viewpoint. An engineer who wishes to become a specialist in this field of fluvial morphology should thoroughly study the numerous good books and original sources of this part of the science. 8/, 24/, 25/, 26/

CHARACTERISTICS OF THE VARIOUS AGES OF RIVERS

In the same way that a person rapidly forms an opinion of the age of another person from the presence or absence of certain features which are characteristic of the various ages, a geomorphologist forms his opinion of the age of a river from the presence or absence of certain conditions which are characteristic of the various river ages. According to the classical conception, young rivers are characterized by their ability to cut their stream beds downward with considerable rapidity; and the characteristic features are those which result from this action. The valleys of young streams are usually V-shaped or are deep gorges or canyons. Waterfalls or rapids often exist in these streams because sufficient time has not passed since they were uplifted for the stream to cut down and thus eliminate them. There are frequent changes of the grade of the stream caused by the hardness of the strata over which the stream flows, and pot holes are sometimes found. Because the valleys are steep sided and narrow, there is very little flat land in their bottoms; and highway and railroad construction along them is accomplished with difficulty. Douglas Johnson 26/ suggests that early youth ends when lakes are eliminated, and middle youth ends when falls and rapids are eliminated.

Late youth ends and early maturity begins in a stream bed when the stream ceases to cut down rapidly but continues to widen the bottom of the valley. This occurs in any stretch of the river when the sediment supplied by the river upstream, the tributaries within the stretch, and the erosion of the banks and valley sides is equal to the transportation capacity of the river. It then ceases its rapid cutting down, but the valley widens as the material from the banks and valley sides continues to be carried away. Normally, the river would continue to lower its bed as the whole drainage area is lowered; but this is a very much slower rate than the lowering in a youthful stream. Early maturity ends and late maturity begins when the valley width equals the width of the belt covered by meanders of the stream. Late maturity ends and early old age begins when the valley width reaches several times the meander belt width.

The features usually associated with maturity in streams are flood plains, often with natural levees; no rapids or falls; and meanders with oxbow lakes, but not other kinds of lakes. There are no sharp divisions between the various stages, nor is there general agreement as to when the various stages end. For example, an old river is sometimes considered to be one in which all of whose tributaries have reached maturity. Also some consider that when the flood plain widens to the width occupied by the stream's meanders so that these can move unrestrained by the valley walls, the end of the maturity stage is reached; and when the flood plain is wider than this, the river is old. These limits differ from those previously stated.

An entire river need not be of the same age throughout. A part of it may be young and another part mature or old, and the young portion may be downstream from the mature or old portion.

The foregoing classification represents the views of the classical or Davis school of geomorphologists; but recently this classification has been questioned, largely by those dealing with the Lower Mississippi River who believe that the classical viewpoint puts too much emphasis on erosion and the formation of erosional peneplains and not enough on the depositional aspects. According to their view, the Lower Mississippi River with its meanders, oxbow lakes, and natural levees, and with a flood plain several times the meander belt width is still a comparatively young stream since it is building up the land along its course. There seems to be some justification for this new viewpoint. Obviously when an uplift occurs and streams start to cut down, there must soon be a part of their length, even though a relatively short one, along which at least part of the eroded material is deposited. This part of the stream is thus building up, and this process is as characteristic of a stream in the early part of the geographic cycle as is the cutting down of the highlands. It will thus be seen that the classical classification of age of a stream may be inexactly related to chronological age and there is room for further work in classification to bring about a more logical system.

BASE LEVEL

Another of the concepts of the geomorphologist which is very useful to the engineer is that of base level. If the quantity of water in the ocean remained the same and no moving of the earth's crust took place, the dry surface of the earth would eventually be reduced to sea level. Sea level is thus the ultimate base level toward which all streams tend to cut their beds. There are often certain local levels which are temporarily elevations toward which streams tend to cut their beds. Lakes, for example, for the period of their existence, control the level of streams entering them and thus form local or temporary base levels for such streams. Waterfalls and rapids often form local base levels. The bed of a large stream usually forms the temporary base level for its tributaries. There are here also borderline cases where it is difficult to establish the existence of a local or temporary base level, but usually they are quite evident.

EQUILIBRIUM IN NATURAL STREAMS

The concept of equilibrium in streams as developed by the geomorphologist is also a very useful one. A variety of terminology has been used to express this condition. A stream in equilibrium is said to be a graded stream, a poised or balanced stream, or to be a regime stream or a stream in regime. Makin (25/ p. 471) has given the following definition:

"A graded stream is one in which, over a period of years, the slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium."

When a stream is capable of carrying more sediment than is supplied to it, it carries away material from its bed and thus tends to lower the bed. This cutting down increases the slope of the tributary streams which causes them to bring down more material to the main stream. The more the stream cuts down into the surrounding land, the greater becomes the load supplied to it. Since most streams eventually reach either the ocean or some other base level as they cut down their beds, their slopes decrease; and therefore their ability to carry away the sediment brought to them is diminished. With the amount of material brought down to the stream increasing and the stream's ability to carry it away decreasing, a point is eventually reached where the rate at which sediment is brought to the stream becomes substantially equal to the rate at which it is carried away by the stream and a condition of equilibrium is reached. Under these conditions the stream neither cuts down nor fills up the bed.

Ordinarily in natural streams the discharge of water is not constant but continually varies, the ratio of the high flows frequently

being a hundred or more times the low flows. Although a stream tends to pick up or deposit bed material until its load equals its capacity to transport the load, a condition of equilibrium in which the load exactly equals the capacity of the stream to transport rarely exists except momentarily because of the variations of flow and sediment supply. Since the tendency of streams is to wear the land surface down to sea level and hence to lower their beds, considering a long geological period, the tendency is for more sediment to be removed from a section of a stream than is supplied to it; and, therefore, when long periods are considered, natural streams are rarely in equilibrium. Normally, therefore, neither in very short or very long periods may natural streams be considered to be in equilibrium.

Over long historical periods, however, it is true that the beds of a large number of streams, for most practical engineering purposes, are substantially in equilibrium; and accurate conclusions for many purposes may be reached by assuming equilibrium to exist. In some streams their beds may be slightly lowered in floods but fill back to their former level as the flood recedes and, except during floods, be at practically the same elevation even at the end of a long period of years as at the beginning of it. Although exact equilibrium is only momentarily obtained and, a stream may be slowly degrading or aggrading, for practical purposes it may be considered to be in equilibrium. The term equilibrium in this case may be likened to the term sea level, which for practical purposes is considered to be a fixed level, although the surface of the sea is constantly fluctuating above and below this level due to waves and tides; and, over very long periods of time, the sea level may rise or fall scores of feet due to more or less water being stored on the land surface in the form of glaciers.

For engineering purposes a section of a stream may, therefore, be said to be in equilibrium, even though it may continually fluctuate between aggradation and degradation, and over a long period of years, the net amount of change is not sufficiently large to be detected by quantitative measurements. It is believed that most alluvial streams, where not affected by the works of man, may thus be said to be in this equilibrium or graded condition.

In a reach of a river where equilibrium exists, a change of one condition at a single cross section which would upset the equilibrium at this section would, if no other factors changed, eventually upset the conditions of equilibrium throughout the entire reach and bring about a new condition of equilibrium in this reach. Except in short reaches, however, other changes probably occur before the readjustment to any one change is complete; and in most streams on which man has built hydraulic works, several changes are going on at the same time. Not infrequently, however, one change is so large compared with the others that it overshadows the minor ones and appears as a single change.

CHANGES OF THE PROFILE OF NATURAL STREAMS

As the science of sediment transportation and deposition develops, it will be possible to predict more and more closely the morphological changes which will take place in a river due to any set of conditions and the rate at which they will occur. In the future the necessity of making such predictions is likely to increase. Such quantitative predictions can often be made by means of the knowledge of sediment transportation now available if all of the factors are known with sufficient accuracy. Usually, however, the data is not sufficient for quantitative estimates; and only qualitative estimates are possible.

The following very general expression will be found useful in analyzing qualitatively many problems of stream morphology:

$$Q_s d \propto Q_w S$$

Here Q_s is the quantity of sediment, d is the particle diameter or size of the sediment, Q_w is the water discharge, and S is the slope of the stream. This is an equation of equilibrium and if any of the four variables is altered, it indicates the changes which are necessary in one or more of the others to restore equilibrium. For example, if a stream with its sediment load is flowing in a condition of equilibrium and its sediment load is decreased, equilibrium can be restored if the water discharge or the slope are decreased sufficiently or if the size of the sediment is increased the proper amount. This equation is not an exact mathematical equation as it will not give the quantitative values of the variables involved which bring about equilibrium, but it is helpful to indicate qualitatively the changes which will take place in a stream when a change of any one of the variables occurs.

The sediment discharge, Q_s , in this equation is the coarser part of the sediment load or more exactly the bed material load,* since this is the part of the load which largely molds the bed formation. In most cases, the quantity of the fine load of silt and clay sizes can change almost indefinitely without materially affecting the river profile. In the following discussions of profile changes, changes of sediment load will be considered to mean changes of bed material load.

CLASSES OF STREAM PROFILE CHANGES

The changes which take place in the profile of a graded stream in equilibrium, due to a change of one or more of the factors controlling equilibrium, usually fall into one of six classes. One of the most common classes (Class 1) is the change that takes place in a stream with an equilibrium Grade BA, as shown on Figure 1-a, which reaches a base

*Bed material load is sediment in transport of sizes readily available in considerable quantities in the stream bed.

level at A, due to a change of conditions in the channel. Suppose the change of conditions is an increase in the sediment load Q_s beginning at C without changing the size of the sediment diameter d or the water discharge Q . To re-establish equilibrium the slope S must be increased. Ordinarily after such a change of conditions a new equilibrium tends gradually to be established as follows: When the change of conditions first occurs, the stream between C and A cannot carry the increased load of sediment, and some of it is deposited on the bed downstream from C causing the bed to rise or aggrade to C'. At first this deposit may not extend down to base level but may end at E. As the deposit continues, the bed level may be increased to C'', and the rise or aggradation may extend all the way to A. If the new condition continued a long enough time, a new equilibrium Grade C'''A would eventually be established; and no further rise or aggradation in the grade would take place.

The same changes would take place in Figure 1-a if instead of the sediment discharge Q_s increasing at C, the size of the sediment d was increased at C, leaving the sediment discharge Q_s and water discharge Q the same. A decrease of the water discharge Q leaving Q_s and d the same would produce the same result.

The foregoing changes also would cause a change of grade above the point C. The raising of the bed to C' would cause a decrease in the slope S upstream from the point C. The stream could not transport the sediment brought down on this flattened slope; and some of it would be deposited upstream from C, aggrading the stream bed. As the stream bed below C aggraded, the stream bed above C would also rise, approaching a final equilibrium Grade C'''B''' parallel to the original equilibrium Grade CB. The height of C'''B''' above CB would depend on the magnitude of the change of conditions which brought it about. The raising of the grade of the main stream in this way would also usually cause a rise in the grade of the tributaries entering the raised section, extending up the tributary a greater or less distance depending on the conditions in its bed.

EXAMPLES OF CLASS 1

One of the common causes of a change in stream profile as in Class 1 is the decreasing of Q by taking the water out of the stream for irrigation, desilting the water, and returning the sediment to the river again, thus decreasing Q without changing Q_s or d . In the Rio Grande and in the Arkansas River, this has resulted in a rise in level of the river bed which causes many difficulties. A rise of the Yuba river bed in northern California, of about 20 feet started about 1850 due to the increase in the sediment load Q_s resulting from the discharge into the streams of large quantities of gravel wasted in the hydraulic mining of gold.^{22/} After hydraulic mining activity was greatly reduced, the height of this deposit gradually decreased, tending to restore the former levels. A similar case is the Serendah River in Malaya,

where the river bed rose 21 feet in the years 1922-1933 due to the addition of sediment from the hydraulic mining of tin.^{32/} A very striking example is the Mu Kwa River in Formosa, the bed of which raised about 40 feet in 3 years due to the addition of sediment to the river from landslides. A two-story hydro-electric powerhouse along the side of the river was completely buried, Figure 2.

A rise of the stream bed may also occur due to the increase in sediment load brought into the stream by a tributary. The slope of the Missouri River for some distance upstream from the mouth of the Platte River is flatter; and below the mouth it is steeper than the slope of the remainder of the river in this vicinity, which is said to be due to the large quantity of coarse sediment brought in by the Platte River. The deposits brought in by a tributary may cause the bed, downstream from the mouth of the tributary, to build up so rapidly that the deposit upstream may not be rapid enough to keep the bed level upstream higher than that downstream. The deposits downstream then form a sort of dam which causes a lake to form upstream from the tributary mouth. An example of this condition is found at Lake Pepin which has been formed in the Upper Mississippi River by the great load of sand brought into it by the Chippewa River. Matthes reports that the sediment brought down the Yuba River previously mentioned temporarily formed a dam in the Feather River, into which the Yuba discharged, which caused a lake 10 miles or more long; and later the sediment coming down the Feather River formed another temporary dam in the Sacramento River into which the Feather River discharged which also produced a lake. Farther down the Sacramento River at the city of Sacramento, California, the low water stage was raised 10-1/2 feet by the deposits. This maximum stage was reached in 1890. The discharge of gravel into the streams was prohibited by law and the deposits decreased, restoring the original stage at Sacramento by 1920.

EXAMPLES OF CLASS 2

Class 2 is similar to Class 1 but results in a lowering or degrading of the profile of the stream due to a decrease in the sediment load or its particle size or an increase in the water discharge. A reduction of the sediment load Q_s of the stream at point C (Figure 1-b) is brought into balance by a reduction of slope S from point C to the base level at A, and upstream from C the bottom is lowered but retains the same slope as before. In this case, tributaries entering the stream usually have their beds lowered also.

A very common cause of such a lowering is the removal of part or all of the sediment load from a stream by its deposit in the quiet water upstream from a dam. Downstream from the dam the river bed is often considerably degraded because of the sediment carried away from the bed by the clarified water. This action caused the failure of an important dam in India. Many other changes of Class 2 have been observed on the Indus River.^{29/, 30/, 31/} A stream profile change of Class 2

necessitated the complete reconstruction of Fort Sumner Dam on the Pecos River in New Mexico. The extent of the degradation below this dam is shown in Figure 3. Stream profile changes of Class 2 have affected in some cases beneficially and other cases detrimentally a large number of hydro powerplants. A knowledge of the magnitude of this action is an important factor in the design of the spillways of many dams, since failure to correctly estimate the lowering may in some cases cause failure of the spillway or even of the dam itself. A number of cases of degradation below dams have been described in technical literature. 13/, 27/

The increase of the flow Q_w has the same effect as a lowering of the quantity of sediment Q_s . A very striking case of stream bed lowering due to an increase in the flow has occurred in Five Mile Creek in Wyoming. The added flow is due to the waste water of an irrigation project constructed in the valley of this stream. Here the stream bed has degraded until it has uncovered rock ledges which were below bed level and produced waterfalls and rapids where the water flows over these ledges as shown in Figure 4. This degradation removed about 1,000 acre feet of sediment in a year from the stream bed and banks and which is depositing in Boysen reservoir a short distance downstream.

An interesting example of stream bed lowering due to a reduction of the quantity of sediment Q_s has occurred in Cherry Creek in Denver, Colorado. Large quantities of sand have been removed from the stream for building construction; and downstream from the point of removal, the bed degradation has extended to the mouth, a distance of about 5 miles. Figure 5 shows the magnitude of the lowering which took place at one point in about 2 years. The construction of a number of check dams was necessitated to hold up the bed level and prevent the undermining of walls, bridges, and sewers along this creek. A similar degrading has resulted on the Loup River near Bolus, Nebraska. A canal for hydroelectric power was constructed from one branch of the stream to a powerplant on another branch. The increased flow in the branch below the powerplant caused a lowering of the grade of the river which extended downstream 1-1/2 miles to the junction of the two streams below which the discharge is unchanged. The effect was beneficial to the power development as it increased the fall available for producing power by about 5 feet, but it caused damage to the foundations of bridges over this portion of the stream.

Usually the changes involved go on quite slowly but under certain conditions changes of surprising magnitude and rapidity can take place. Todd and Eliassen (11/ p. 376) report that in a 30-mile stretch in the Yellow River, the bed was deepened an average of 15 feet. At Langmen within the stretch, the bed was lowered approximately 30 feet over a width of 3,000 feet. The depth tapered off upstream and downstream removing an estimated quantity of 9,000,000 cubic yards in not more than 12 hours. The cause of this phenomenon is not indicated; but

it was probably due to an increase in discharge, perhaps of less heavily sediment laden water.

EXAMPLES OF CLASS 3

Class 3 changes of stream bed profile are those which occur when the grade of the stream is suddenly raised at one point. The most common cause of such a rise is the construction of a dam; but such changes also occur from natural causes, such as the damming of rivers by landslides, mud flows, lava flows, or the advance of a glacier. This class is represented by Figure 1-c which shows the changes which occur in the bed of a stream in equilibrium when the grade at one point is suddenly raised.

If the stream grade is raised suddenly enough, a lake is formed upstream from the point of rise; and this lake is then gradually filled with sediment brought down by the stream. The conditions during the filling period are represented by the profile ending at C' on Figure 1-c. The unusual shape of the stream profile is due to the coarse sediment being deposited at the upper end of the reservoir and the fine material being carried farther into the lake or flowing down the lake bottom as a density current. The reservoir is filled when the stream bottom is raised to point C'', and part of the sediment load passes over the obstruction. The grade continues to rise upstream from the dam and approaches a final equilibrium grade which is parallel to that before the grade was raised. This was probably first pointed out by Harris 28/ over a half century ago. The changes discussed under Class 1, where lakes were formed on main stream channels upstream from the mouths of tributaries, are also occurrences of Class 3.

The time of the lake filling stage in this class depends largely on the volume of the lake and the rate at which sediment is brought down by the stream. When the reservoir volume is small and the rate at which sediment is brought down is great, the time of the filling period is short and the effects upstream from the lake may develop very rapidly. For example, the deposits above the Imperial Dam on the Lower Colorado River within 7 years were causing a rise of the stream bed 55 miles upstream from the dam, whereas the level pool above the dam originally extended only 15 miles upstream. The profile of the river upstream from the dam had already reached a gradient of three-fourths that of the original slope which was probably very close to the equilibrium grade. The bed 55 miles upstream would have continued to rise and the effect would have extended much farther upstream had it not been for the degradation effect, as discussed under Class 2, from another dam built farther upstream about the same time.

Another interesting example of similar action was observed on the Nan-shik-chi River in Formosa. This stream had a slope of about 1:120. A dam about 13 meters high was constructed on this stream 1.3 km below a hydroelectric powerplant. In 7-8 years the lake above the

dam was filled and the slope of the river bed extended upstream from the crest of the dam on a slope of 1:250, or about half that of the original river bed. This raised the river level so much at the hydroelectric plant that it was threatened with flooding, and it was necessary to blast off the top of the dam downstream to prevent it.

Extensive changes of level above dams have been investigated in India in connection with the great irrigation works in the Indus River basin. 29/, 30/, 31/

EXAMPLES OF CLASS 4

Class 4 profile changes (Figure 1-d) result from the lowering of the temporary base level of the stream and causes effects somewhat similar to those upstream from point C in Class 2. This case often occurs when a reservoir, which is usually held at a constant level, is drawn down. The Salton Sea in California, U.S.A., was at one time filled to an elevation of 40 feet above sea level and the Whitewater River (12/ p. 320) built a grade adjusted to this level. The sea has been cut off from the ocean and lowered by evaporation to 250 feet below sea level, and the Whitewater River is slowly adjusting itself to this new base level. The flow in the river is ordinarily very small so that the adjustment is slow; but in the rare large floods, scour proceeds rapidly upstream in a series of cataracts. Another example is the Mojave River which flowed into ancient Lake Manix. This lake drained itself by cutting through a barrier, and the stream is now adjusting itself to the new level. Over a long period of time such changes have taken place in many large rivers.

It is known that the level of the ocean during glacial times rose and fell several times as more or less ice was imprisoned on the earth surface in the form of glaciers. The lowerings reached as much as 325 feet below the present level. During these glacial changes, the beds of all of the streams which flowed in erodible deposits and entered the sea were probably adjusted to the lower level as they are now adjusted to the present level. Recent geological investigation 9/ has shown that the Mississippi River was so adjusted.

EXAMPLES OF CLASSES 5 AND 6

Classes 5 and 6 (Figures 1-e and 1-f) result from the base level moving up or down the stream without a change of elevation. Illustrating Class 5 is the following set of circumstances: A railroad runs up the valley of the Missouri River, and small tributaries of the river pass under the railroad in culverts. When the railroad was built, the river flowed along the side of the valley near the railroad and the culvert for one of the tributaries was set to conform to the grade established by this situation. The Missouri River shifted to the other side of the valley and the distance from the culvert to base level in the river increased. This caused a raising of the grade of the tributary to such an extent that it was necessary to raise the grade of the railroad where it crossed the

tributary. An illustration of Class 6 has occurred in the lower Mississippi Valley.^{8/} Here the Mississippi River has shifted from the west to the east side of the valley; and streams entering the Mississippi from the east, which were adjusted to the former position, have cut down their beds to the altered position of the base level.

CONCLUSION

As the rapid pace of water resources development continues throughout the world, many changes brought about by these works will cause changes in the profiles of the rivers. Some of these may be beneficial and some detrimental, but a knowledge of fluvial morphology will enable the hydraulic engineer to predict the changes and to reduce the detrimental effects to a minimum and take advantage of the favorable effects.

BIBLIOGRAPHY

1. Powell, J. W. ; 1875; Exploration of the Colorado River of the West.
2. Gilbert, G. K. ; 1887; Report on the Geology of the Henry Mountains--
U. S. Geographical and Geological Survey of the Rocky Mountain
Region.
3. Davis, W. M. ; 1909; Geographical Essays; Ginn and Company.
4. Guglielmini, Dominique; 1697; Della natura di flumi trattato fisico
matematico.
5. Frizi, Paul; 1762; Treatise on Rivers and Torrents with Methods of
Regulating their Courses and Channels (In Italian); Translated by
Gen. Garatin; London; 1818.
6. Hooker, E. H. ; 1896; The Suspension of Solids in Flowing Water;
Trans. A.S.C.E. ; Vol. 36; 1896; pp. 239-340.
7. Mavis, F. T. ; 1935; An Investigation of the Transportation of Bed
Load by Flowing Water; Thesis at the University of Illinois.
8. Lobeck, A. L. ; 1939; Geomorphology; McGraw-Hill Book Company.
9. Russell, R. J. ; Quarternary History of Louisiana; Bulletin of the
Geological Society of America; Vol. 51; August 1, 1940; pp. 1199-
1234.
10. Dowd, M. J. ; 1939; Silt Problems of Imperial Irrigation District as
Affected by Completion of Boulder Dam; Civil Engineering; Vol. 9;
October 1939; pp. 609-611.
11. Todd, O. J. and Eliassen, S. ; 1940; The Yellow River Problem;
Trans. A.S.C.E. ; Vol. 105; pp. 346-453.
12. Soderegger, A. L. ; 1935; Modifying the Physiographical Balance by
Conservation Measures; Trans. A.S.C.E. 1935; Vol. 100; pp. 284-
346.
13. Lane, E. W. ; 1934; Retrogression of Levels in River Beds Below
Dams; Engineering News Record; Vol. 112; June 28; p. 836.
14. Shulits, S. ; 1934; Experience with Bed Degradation Below Dams on
European Rivers; Engineering News Record; Vol. 112; June 28; p.
838.
15. Corey, H. T. ; 1913; Irrigation and River Control in the Colorado
River Delta; Trans. A.S.C.E. ; Vol. 76; pp. 1204-1571.
16. Matthes, G. H. ; 1941; Basic Aspects of Stream-Meanders; Trans.
American Geophysical Union; Part III; p. 632.

17. Central Board of Irrigation of India; 1939-1940; Annual Report (Technical).
18. Schoklitsch, A. ; 1937; Hydraulic Structures; American Society of Mechanical Engineers.
19. Jefferson, M. S. ; 1902; Limiting Width of Meander Belts; Nat. Geo. Mag. Vol. 13, pp. 373-384.
20. Bates, Robert E. ; 1939; Geomorphic History of the Kickapoo Region, Wisconsin; Bull. Geol. Soc. Am. Vol. 50; pp. 819-880.
21. Kesseli, J. E. ; 1941; The Concept of the Graded River; Journal of Geology; Vol. 49; August, September 1941; pp. 561-588.
22. Gilbert, G. K. ; 1917; Hydraulic-Mining Debris in the Sierra Nevada; U. S. Geological Survey; Professional Paper No. 105.
23. Stabler, Herman; 1925; Does Desilting Affect Cutting Power of Streams; Eng. News Rec. Vol. 95; December 10; p. 969.
24. Worcester, P. G. ; 1939; A Textbook of Geomorphology; D. Van Nostrand Company.
25. Mackin, J. Hoover; 1948; Concept of the Graded River; Bulletin of the Geological Society of America; Vol. 59; May 1948, pp. 463-512.
26. Johnson, Douglas; 1932; Streams and Their Significance; Journal of Geology; Vol. 40; August, September 1932; pp. 481-497.
27. Hathaway, G. A. ; Observations on Channel Changes, Degradation, and Scour Below Dams; Report of the Second Meeting of the International Association of Hydraulic Research; 1948; pp. 297-307.
28. Harris, E. G. ; Effect of Dams and Like Obstructions in Silt Bearing Streams; Engineering News; Vol. 46; August 15, 1901; pp. 110-111.
29. Foy, T.A.W. ; Regime Level Changes on the Indus System; Punjab Irrigation Branch Paper No. 16.
30. Malhotra, S. L. ; Effect of Barrages and Weirs on the Regime of Rivers; International Association for Hydraulic Research; Bombay, 1951;
31. Joglekar, D. V. and Wadekar, G. T. ; The Effect of Weirs and Dams on the Regime of Rivers; International Association of Hydraulic Research; Bombay; 1951.
32. Dobby, E. H. G. ; Southeast Asia; pp. 59-60.

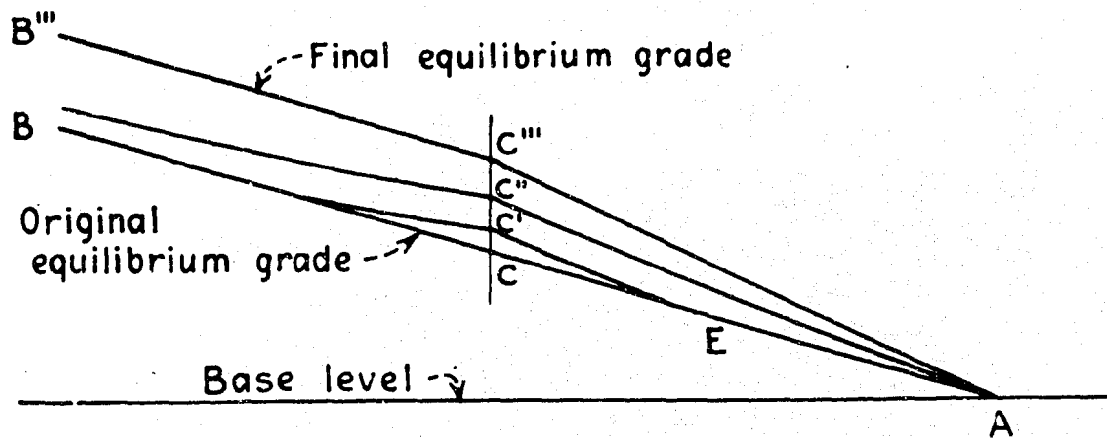


FIGURE 1-a CLASS 1

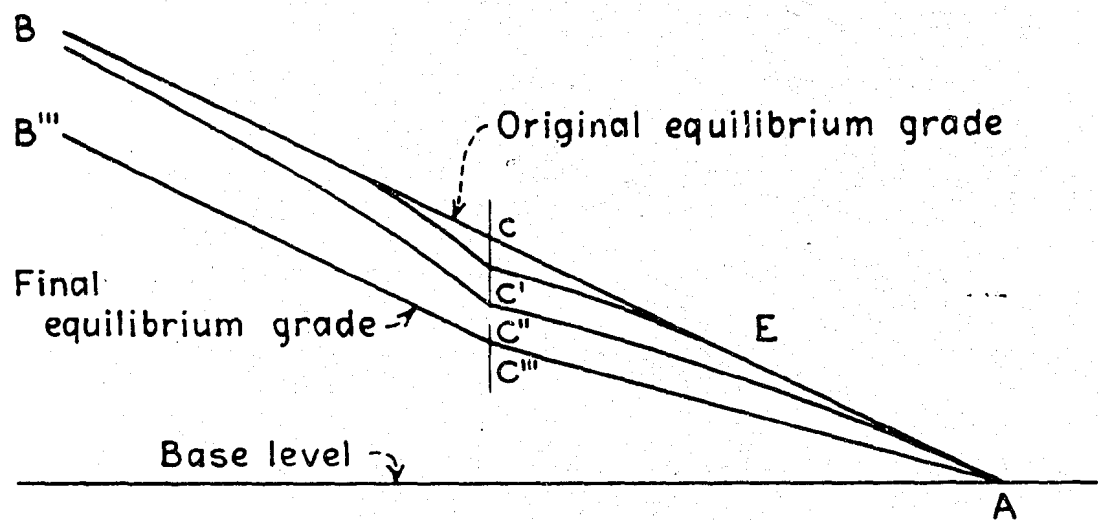


FIGURE 1-b CLASS 2

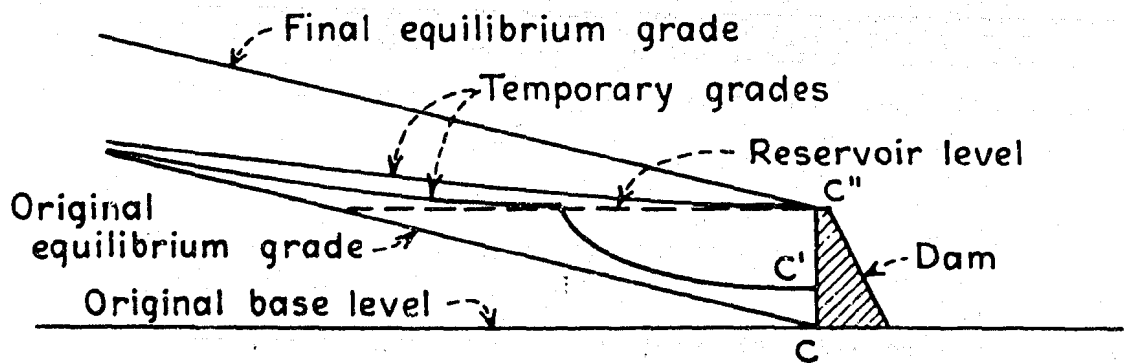


FIGURE 1-c CLASS 3

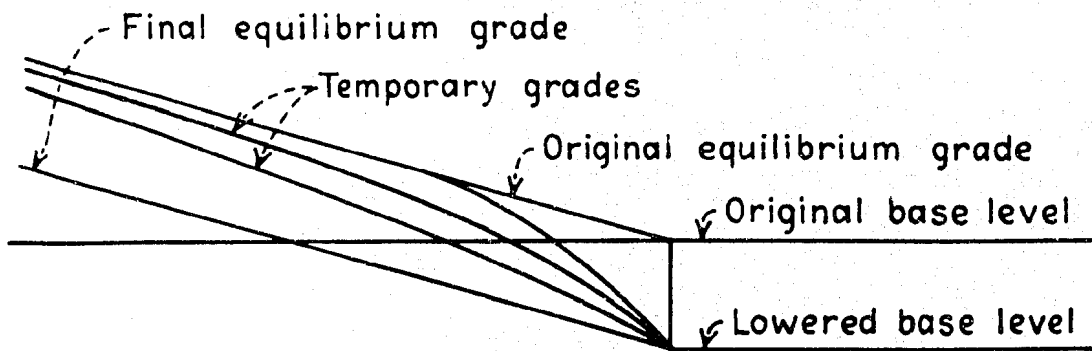


FIGURE 1-d CLASS 4

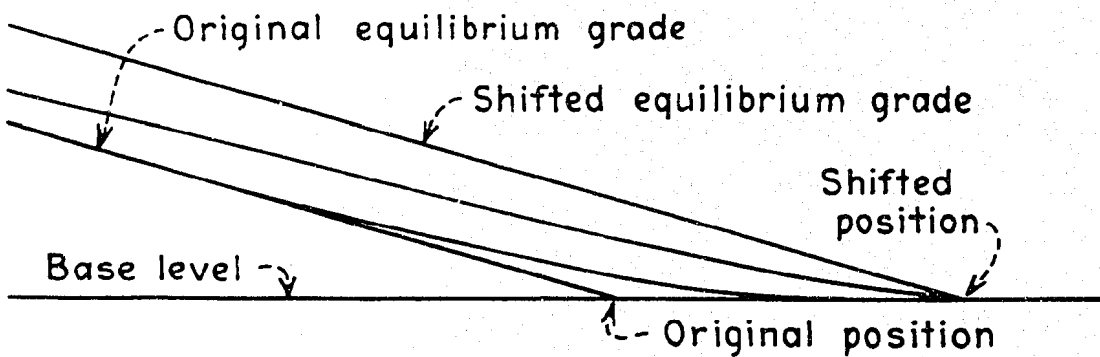


FIGURE 1-e CLASS 5

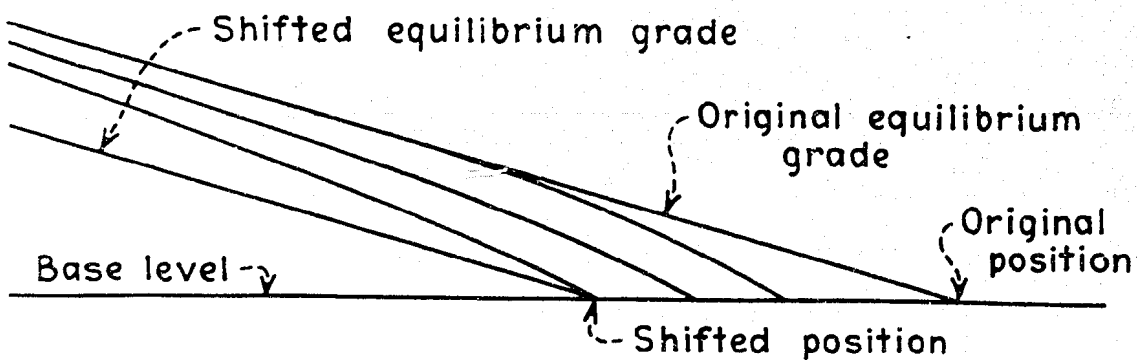


FIGURE 1-f CLASS 6

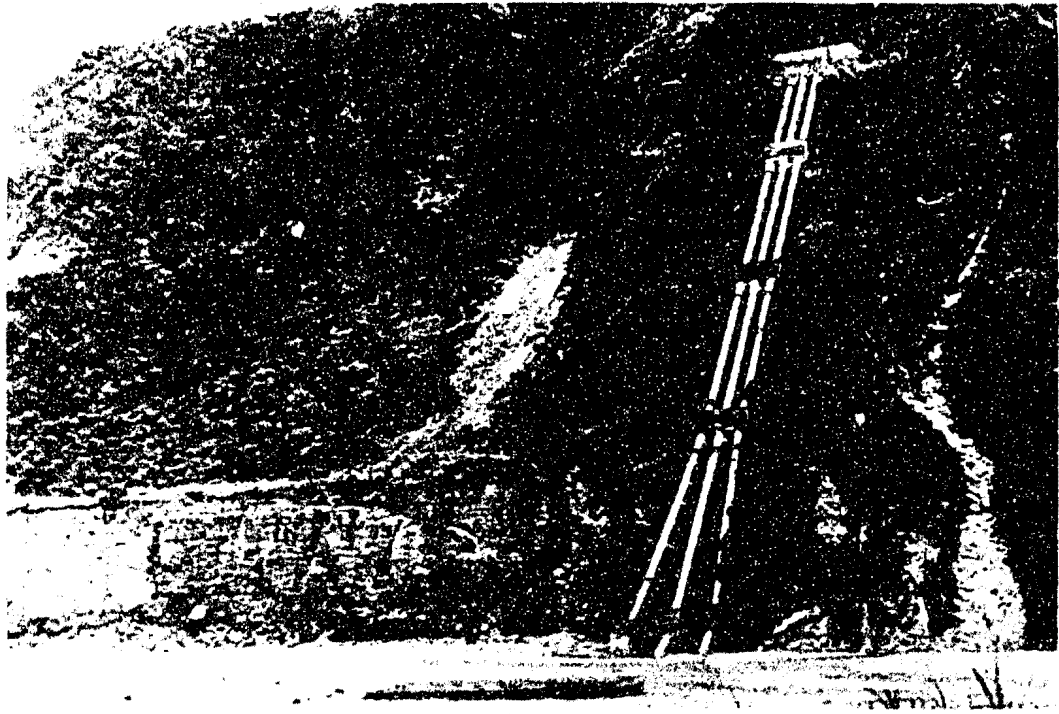


Figure 2. Roof of Powerplant
Buried by Rise of Bed of the
Mu Kwa River in Formosa

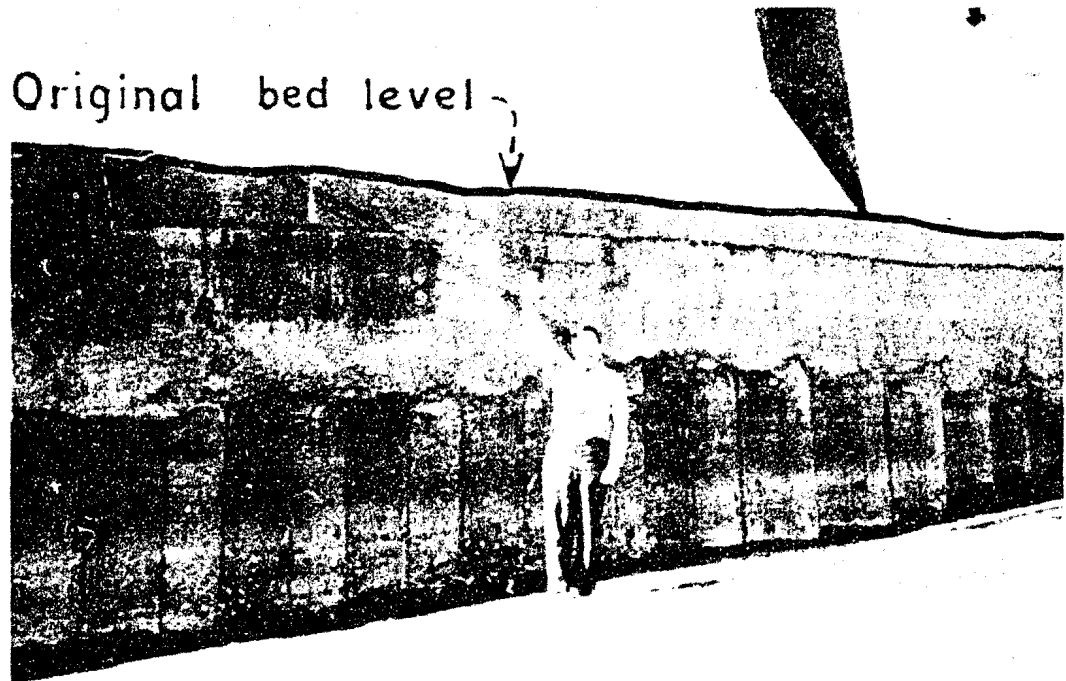


Figure 3. Degradation below
Ft. Sumner Dam on Pecos
River in New Mexico



Figure 4. Waterfall on Five Mile Creek, Wyoming, Resulting from Grade Reduction Caused by Increase in Discharge



Figure 5. Bed Lowering in Cherry Creek, Denver, Colorado, Caused by Reduction of Sediment Load