Sediment Movement in Bear River, Utah

Calvin Geary Clyde

Utah State University

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Sediment Movement in Bear River, Utah

By

Calvin Geary Clyde
B.S. (University of Utah) 1951
M.S. (University of California) 1952

THESIS

Submitted in partial satisfaction of the requirements for the

DEGREE OF CIVIL ENGINEER

in the

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of the

UNIVERSITY OF CALIFORNIA

Approved:

[Signature]

Associate Professor H. A. Einstein
Professor J. W. Johnson
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Committee in Charge

Berkeley, California
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Part I
INTRODUCTION

In the northern part of Cache Valley, Utah, accelerated erosion in recent decades has cut deep gullies of impressive size into the flat, irrigated bench land along the Bear River. Millions of tons of fine sediment have been washed into the river and great amounts have been deposited in the river bed. The resulting flooding and high water-table have caused much damage to the land near the river.

In addition to summarizing much of what has already been written concerning the problem, this thesis traces the development of the present day conditions and gives a detailed description of the Bear River in Cache Valley. The possible effects of the fluctuating river discharge (caused by the operation of upstream power plants) upon the sedimentation of the stream and the resulting flooding is discussed. The effect of the backwater of a downstream reservoir upon the deposits in the river bed is also described and some general conclusions concerning the future condition of the river are made. Some of the methods which might be used to control the erosion in the gullies are suggested and measures for the rehabilitation of the damaged lands by proper river management are set forth.

In recent years much progress has been made, principally by means of flume studies, in developing a theory by which the amount of bed-material transported by a stream can be predicted. Comparison of the calculated transport rates with field
measurements of the bed-load is of great value in testing the usefulness and accuracy of the theory. Field measurements of the bed-load are especially needed in streams such as the Bear River which have a flat slope and small bed-material grain size. Previous measurements in similar rivers have shown that the present theory gives unsatisfactory answers in some cases.

The ready accessibility of the Bear River and the wealth of hydrologic and hydraulic information available for the stream make it ideal for such investigations. The instrumentation and technique of bed-load sampling as used on the Bear River is described herein. A method is developed by which bed-load measurements are utilized to test the findings of flume experiments and to indicate the modifications of the present theory which may be necessary in its application to streams similar in character to the Bear River.
Part II

HISTORY OF THE DEVELOPMENT OF PRESENT DAY CONDITIONS
ALONG THE BEAR RIVER.

Bear River is the largest stream which flows into the Great Salt Lake. It has a drainage area of about 6,000 square miles in northeast Utah, southeast Idaho, and southwest Wyoming. From headwaters in the high mountain area of Utah and Wyoming, the river flows first northward across a broad plain to a point near Soda Springs, Idaho and thence southward thru a long broad valley and two narrow, rocky canyons and out onto the flat, entrenched plain in northern Cache Valley. At Logan, in the southern end of Cache Valley, the stream turns westward thru a short, but steep, canyon into the Great Salt Lake Valley and thence southerly to enter the Great Salt Lake near Ogden, Utah.

Only the reach of the river in Cache Valley is to be considered in this report. In this area the tributaries of interest pertaining to sediment supply to the river are Battle Creek, Deep Creek, and Five Mile (Dayton) Creek.

Geologic History of the River Valley near Preston

In a report \(^1\) in 1947, William Peterson described in detail the geologic history of the Bear River and its tributaries in Cache Valley. The summary given here is based principally upon his report and upon the original Bonneville report by Gilbert.\(^2\)

Prior to the time of Lake Bonneville, the Bear River established its course thru the mountainous area into

\(^*\) Numbers refer to references listed at the end of the report.
Cache Valley and probably eroded its bed to about the present level. During the Pleistocene, or glacial, epoch the precipitation was much greater than in recent times. The flow of the bear River and of all other streams emptying into the Great Basin was greatly increased. The water level in the basin rose until, at its highest point, the great Lake Bonneville with a total area of 19,750 square miles and a maximum depth of 1080 feet was formed. The basin filled to a maximum elevation of 5150 feet above sea level and remained near that elevation for many thousands of years as indicated by the extensive wave-cut terraces. Cache Valley was a bay in this great lake and connected with the main part of Lake Bonneville over Beaver Dam as well as the Bear River narrows.

Gilbert estimated that approximately half of the water flowing into Lake Bonneville came in from the Bear River drainage. This enlarged river carried a greatly increased sediment load which was deposited where the river met the still waters of the lake. By the end of the Bonneville period, the Bear River appears to have completely filled with sediment its course thru the mountains from Grace, Idaho to at least a point three miles below the confluence of Mink Creek and the Bear River. Remnants of the sediments and terraces of the Bonneville level can be traced throughout this distance. Great sediment deposits were made in what is now called Gentile Valley. To understand better the extent and depth of the Bonneville sediments, it might be well to note that the Oneida Reservoir has an elevation of 4800 feet, which is 350 feet below the old Bonneville level.
Ordinarily a river will deposit coarse gravels and sands in the mouth of its delta with the finer sands and silts being carried further into the lake before being deposited. The old or Bonneville delta of the Logan River is shown by its remnants to be of this type. The sediments laid down by the Bear River in Lake Bonneville were unusual in that little or no coarse particles were present. The reason for this is that the Bear River flowed thru Bear Lake, which was at that time some 40 miles in length. The coarse debris was deposited in Bear Lake and the sediments carried on into Cache Valley consisted of the finer particles that could be carried thru the lake plus any sediment eroded from the stream course between Bear Lake and Cache Valley.

Until the end of the long Bonneville period, the lake had no outlet to the sea. Then the level of the lake rose a little, overflowed the Red Rock pass into a branch of the Portneuf River and flowed on to the Pacific Ocean thru the Snake and Columbia Rivers. After the outlet was established, the water flowed rapidly and during an unknown but geologically short period of time, the water cut the Red Rock pass down until the lake level was 4,770 feet. The lake remained at this lower or Provo stage for thousands of years and had during this period a total area of 13,000 square miles.

As soon as the lake began to drop, the loose, unconsolidated sediments in the river channel were eroded, carried into the new lake, and redeposited to form a broad, extensive delta which eventually covered the northern part of Cache Valley. These redeposited and unconsolidated materials,
which are known as the Provo deposits, are 200 or more feet thick and consist of layers of fine sands, silts, and clays. The Provo deposits now appear as the flat, fertile, irrigated benches on both sides of the river valley in northern Cache Valley. (See Fig. 1)

The rate of deposition in this period was probably rapid since the stream was carrying the loose debris of the Bonneville period and redepositing it in the Provo stage in addition to bringing down its normal sediment supply from Bear Lake. All the tributary streams in Cache Valley went thru a similar process of washing and redepositing sediment that had accumulated in the Bonneville period.

During the Provo stage the precipitation was probably about the same as for the Bonneville period. The excess waters flowed out over Red Rock pass. Cache Bay, at this time, was connected to the main lake only thru the Bear River narrows.

From deposits of travertine along the Provo shoreline of the large lake it is known that the water was saturated with calcium carbonate. Since no such deposits are found in Cache Valley, there must have been no such concentration there. This indicates that the Bear River contributed not only all the excess water that flowed over the Red Rock pass but also, at times, flowed into the main lake in quantities great enough to prevent concentration of carbonates in the Cache Bay waters.

Towards the end of the Provo period, the climate began to change. Eventually evaporation in the lake exceeded the rate
of inflow of water and the lake level dropped below its outlet. The waters continued to recede until the major remnant of the once great Lake Bonneville became the modern day, briny Great Salt Lake.

As the lake fell below the Provo level, the Bear River cut into the Provo deposits to dig its present valley which is approximately 180 feet deep in the unconsolidated sediments and averages about 1600 feet in width. The valley is very young and in many places its sides stand at an angle steeper than the normal angle of repose for such sediments. When the material becomes excessively wet it can no longer stand at such a steep angle and slides out. As can be seen in the aerial photographs (See Fig. 2) there are numerous slide areas along the stream valley, especially on the east side between Preston and Riverdale in Idaho. While these slides have forced the relocation of canals in some places, they do not contribute much volume of sediment to the river.

The main stream, at present, runs crystal clear over a gravel bed as far as Preston, Idaho, at the upper end of Cache Valley. (See Fig. 2) There is no evidence that the river carries any fine sediments at Riverdale except during large floods. Between Riverdale and Preston, tiny sand bars along the banks (visible only at low water) indicate that a small amount of fine sediment enters the river from slides and from minor gulleys along this reach. The river meanders extensively in its valley but appears to be quite stable in its course.

Near Preston in the short distance of less than three
miles, three tributaries enter the Bear River from the west bench. From this point on, the character of the stream changes abruptly. (See Figs. 3 and 5) The water is cloudy and the channel so choked with sediment that the stream has only a shallow channel and must flood adjacent lands even with a moderate discharge. Obviously tremendous amounts of sediments enter the river from these tributaries, Battle Creek, Deep Creek, and Five Mile (Dayton) Creek. Some estimates run as high as 20,000,000 tons in the past thirty years.

**Conditions in the Tributaries**

As the waters of the Provo period of Lake Bonneville receded, the tributaries also cut their way down thru the loose strata until their gradients met the Bear River. This erosion by surface waters made relatively narrow valleys with steep sides which were quite stable until recent years. The greatly accelerated erosion in the tributaries is an event that has occurred within the memory of the older residents of the area.

The stratified deposits of the ancient lake contain mostly layers of fine sands and silts, but there are also several layers of tight clays at various elevations. All the strata appear to slope gently downward toward the river valley.

Water from rainfall and from irrigation percolates downward until it reaches a layer of clay. Unable to penetrate this, the water flows laterally until it reaches the gorge of the tributary or the river, there to manifest itself as a seep. If the flow of water becomes great enough, some of the
and is washed out with the water leaving the material above unsupported. Then the bank above will cave and slip into the seep. Enough water is usually present to wet the whole mass which then slides and flows into the bottom of the stream where it can be carried away by the running water.

This type of accelerated erosion by ground waters is present in all tributaries and along the main river valley. It is characterized by a typical circular shape of the head of the gulley (See Fig. 6) as contrasted with the pointed V-shaped head of a gulley cut by surface waters alone. The ground water erosion areas vary in size from a few feet high and wide to great chasms over a hundred feet deep and several hundred feet in width and length. These gulleys can grow with alarming speed for a time or can remain quite static until another cycle of erosion begins. Examples of this type of erosion may be seen in all the tributaries that cut thru the Provo sediments.

Rawlins Wash. Rawlins Wash, located on the east side of the Bear River valley near Preston, (See Fig. 6) was non-existent in 1946. By 1949 it extended 1000 feet into good farmland, was 800 feet wide and 150 feet in maximum depth. The gulley consumed over fifteen acres of highly productive irrigated land in four years and forced the relocation of an irrigation canal. Since 1949 the wash has ceased its rapid growth. It is highly probable that the canal relocation, by decreasing the ground water flow, was responsible for stopping the gulley's growth. One should remember, however, that the destructive erosion can begin again any time the ground-water flow increases.
**Battle Creek.** Battle Creek is a small tributary some twenty miles in length. The upper end of the stream is in older formations and shows no sign of accelerated erosion. However, in its lower course the stream cuts into the Provo deposits and particularly in the four miles just before the stream meets the Bear River, the characteristic seeps and caving banks have developed, especially on the west side. In one spot a bank several feet high and a quarter of a mile long has developed. There is little doubt that the seeping ground water seen in so many places comes from the irrigated fields on the bench just west of the stream. Grass and willows appear to have held the erosion quite well in check so far, but a faster rate of erosion could start almost any time should the ground water flow be increased by greater rainfall or excessive irrigation or should a flash flood of surface waters occur.

**Deep Creek.** For the first twelve miles of its twenty mile length, Deep Creek flows over the flat area that once led to the outlet of the ancient lake. Along this part, the stream flows slowly, has cut only a shallow valley and carries very little sediment. In the lower few miles the stream has cut a deep valley in the Provo sediments. In recent times the characteristic seeps and caving banks have developed in some places.

The condition on Bien's farm well illustrates the destructiveness and rapid growth of these gulleys. In 1947 William Peterson described this gulley as follows: "More water is flowing out of a newly developed seep, and the incoherent lake debris is now constantly caving, leaving a bank 20 to 30 feet high, standing vertical. This disturbance is in a tributary
extending from the main stream at a point about 1000 feet to the west."

In early spring 1952 a vastly increased cycle of erosion began. By August 1952 the vertical banks were over 60 feet high at the head and the gulley was over 100 feet deep. (See Fig. 8) The circular gulley was over 300 feet wide and had swallowed a good part of a large level field. One can plainly see even in the picture that no surface waters at all have flowed over the lip of the chasm. The clay layer upon which the ground water seeps out is plainly indicated in the picture by the band of wet material around the bottom of the gulley. The flow of water appeared in August 1952 to be about six to eight cubic feet per second. It carries so much sediment into Deep Creek that the stream is periodically dammed by the muddy flow. (See Fig. 9) When this mud dam is overtopped, a large mass of mud and water rushes down the stream into the Bear River. One such flow took out a bridge over the Deep Creek.

The river seems able to move most of the sediment entering from Battle and Deep Creeks. The normal gravel bed of the river is visible below their junctions, but large sand bars and sand islands in the channel indicate that large amounts of sediment come into the stream at this point.

Five Mile Creek. The largest part of the fine sediment dumped into the river appears to have come from Five Mile Creek. Einstein estimated in 1951 on the basis of surveys made by the Utah Power and Light Company that in the preceding 37 years approximately 16,000,000 tons of material had been moved out
80% of the total sediment washed into the stream, a value which seems reasonable to this author.

Five Mile Creek originates from the surface waters of Dayton Creek, a small stream that flows from the mountains to the west of the river. In times remembered by residents of the area, the gulley was much smaller than it is now. One of the older farmers told the author that he remembers a time when he was a boy that his father drove a grain reaper across the then small watercourse to get to his other fields. In the same spot the gulley is now over 100 feet deep and 300 feet wide with 30 or 40 degree slopes.

Judging from visible remains of old terraces along the gorge, Five Mile Creek was stabilized at least two and possibly more times in recent decades. (See Figs. 10 & 11) One terrace is 40 feet below the top and another 70 feet down. Present depth of the gulley is over 100 feet in many places with a bottom width from 40 to 100 feet and a top width of from 200 to 500 feet.

According to the Soil Conservation Service, the gulley now extends three and a half miles and includes 290 acres within its rim with accelerated erosion occurring on 170 of these acres. (See Fig. 4)

The erosion in Five Mile Creek appears to result from both surface and sub-surface waters. Surface water flow is small during most of the year, but cloudbursts and snow melt have produced, at times, considerable discharges. The Soil Conservation Service reports a cloudburst in July 1951 which had a runoff estimated at 375 cubic feet per second which appeared to be 50% solid matter. The mud flow formed a dam across the
Bear River which flooded the lowlands. A similar flood occurred in 1943 and the wave that went down the valley when the mud dam washed out destroyed the Preston City park and the Preston Country and Golf Club.

The head of the main gulley advances with alarming rapidity during such flows. The author was told by one resident that during the spring runoff in 1952, the head of the gulley advanced upstream 30 feet in one 24 hour period. The gulley now threatens a major canal and the railroad and highway. Rock has been dumped in the head of the gulley but other measures will probably be necessary to stop the upstream march of the gulley.

In all the tributary fingers and along the main gulley, seepage of ground waters is visible. The typical caving banks and rounded gulley heads are noticed in many places. Very little, if any, surface waters ever enter the tributary fingers. The erosion in the fingers of the gulley is due primarily to ground water.

The clay layers are neither continuous nor uniform, but where they appear, there is usually seepage above them. In some places the clay layers coincide with the levels of previous stabilization of the stream bed.

The origin of the ground water is without doubt the irrigation water and rainfall on the bench above, but to locate its zones of percolation more exactly would require extensive underground exploration that apparently is not justified. Some of the water could have come a considerable distance from the west, northwest, or southwest.
**Estimate of Losses Due to Erosion and Sedimentation**

Considerable losses have occurred along the valley because of the erosion and the sedimentation in the Bear River and its tributaries. The Soil Conservation Service\(^3\) roughly estimated that in the past 25 years, losses from damage and lost production for all concerned might exceed $500,000. These losses might be broken down as follows:

**Erosion.** Considerable land has actually been lost to the gulleys and slides by erosion. Additional acreage along the gulley rims is no longer tilled for fear that irrigation waters might get away and cause still more erosion. The total acreage thus lost would probably be measured in the hundreds.

**Flooding.** The lands in the bottom of the gorge that have been rendered unuseable or on which production has been seriously impaired amount to about 3,000 acres according to the Soil Conservation Service.\(^3\)

**Canal Relocation.** The relocation of canals has been necessary in the past because of gulleys and slides. More canals, a railroad, roads and bridges, and farm buildings are now threatened.

**Maintenance Costs.** The Cub River Irrigation Company and others pumping from the river must bear higher maintenance and operative costs because of the sediment in the water.

**Destruction by Floods.** The Preston City Park and the Preston Golf and Country Club were destroyed in 1943. Their estimated value at that time was $30,000.

**Reservoir Sedimentation.** Cutler reservoir has been partly filled with sediment. Complete measurements of the amount of sedimentation have not been made, but the amount can easily be
estimated. Of the 20,000,000 tons that have gone into the
river, about 10,000,000 tons have been deposited in the channel
above Cutler reservoir. Some of the remainder has been de­
posited in the bottom lands during floods, some is fine enough
to be carried thru the reservoir, while the rest, perhaps
6,000,000 tons or more has been dropped in the reservoir. Great
bars of the newly deposited light colored sediments are visible
from the air all along the reservoir even to a point below
the Cache Junction bridge. The storage capacity of the reser­
voir has been substantially decreased and will diminish further
in the future. At some future date facilities will have to be
built by the power company to remove the sand from the water
before it enters the turbines.
Stream Bed and Water Surface Profiles

From surveys and probings made by the Utah Power and Light Company, Einstein in 1951 prepared a chart showing the profiles of the water surface and the stream beds, past and present, of part of the Bear River. This chart tells much about the condition of the stream bed and is included in this report as Fig. 12.

Between 1910 and 1950 (the dates of the two surveys) the bed of the river was raised six feet or more by deposition of sediments throughout the 50 mile reach shown. This estimated 10,000,000 ton deposit of sand is laid down upon entirely different material. In the upper 20 miles coarse gravel underlies the sand while in the lower 30 miles, the underlying material is hard clay. The slopes of these dis-similar materials are 0.0004 and 0.00009 respectively.

No detailed survey has been made for the river further upstream from the bridge west of Preston where the stream still flows over its gravel bed, but it appears that the slope is nearly the same or only a little steeper up as far as the canyon mouth at Riverdale.

This continuous gravel bed is what one might call the "normal" condition of the river in this reach. If the sediment supply to the stream from the tributaries and gulleys had not been so great in recent years, the stream would still flow over its gravel bed for a considerably greater distance.

The presence of similar gravel deposits under the clay layer not far upstream from the old Whelon Dam shows that the
FIG. 12
PROFILE OF WATER SURFACE AND STREAM BED
BEAR RIVER, UTAH
Gravel bed may be continuous to Whelon. The clay layer was probably laid down during a period of low flow in the backwater caused by the rock ledge upon which the old Whelon Dam was founded.

**General Appearance of the Stream**

Throughout its length in Cache Valley, the river meanders extensively in its valley. Many oxbow lakes and areas of dead water and marsh have been formed. Although in many ways similar throughout its length, the character of the stream does change noticeably. Three distinctive reaches of the river are noted.

**Riverdale to Five Mile Creek.** In this reach the river flows clear over its gravel bed. Although the banks are low, the mean water level in the stream is low enough so that the land along the river is cultivated. There are some willows and brush along the banks which are not thick or continuous. (See aerial photograph, Fig. 2).

**Five Mile Creek to the Cornish Bridge.** The river water becomes muddy at the point where Five Mile joins the stream. (See Fig. 3) The gravel bottom can be seen for a short distance further (See Fig. 13) and then disappears under the light colored sand deposits. The old gravel bed is, however, exposed now and then in the shallow crossovers between bends as far downstream as section 4. (Location of sections given in Fig. 12)

In this reach, the river had a shallow channel even before deposition of sand began. What little channel was available is now almost filled with sediment. (See Figs. 14 & 15) In some places clearly visible in aerial photographs the water is no
longer confined to one definite channel but makes its way thru several braided shallow branches. (See Fig. 5) Sand bars are everywhere in the channel. Between the Preston and Weston Bridges, the stream valley is somewhat narrower and the bottom land is mostly under water. What land one sees above water is so water-logged as to be useful only for limited grazing. There are scattered willows and brush along the banks. The peak daily flows caused by power plant operations upstream are sufficient even in the summer time to force the stream over its banks in some places. The stream flows slower with a velocity for a moderate flow of about $2\frac{1}{2}$ to 3 feet per second.

**Cornish Bridge to Cutler Reservoir.** Along this reach the depth of the river valley decreases until it practically disappears. The channel is deeper and more stable with less evidence of deposition visible above water. The old clay bottom is buried under the light colored silt. Much of the land immediately on each side of the stream is high enough above the water so it has not been damaged. The water is deeper and flows still slower than in the reach above. Thick brush and willows line one or both banks in many places. (See Fig. 18) The stream carries much organic matter such as moss and twigs as well as a great deal of fine sediment in suspension.

**The Rise in the River Bed at Weston Bridge**

For many years (1913 to 1950) the Utah Power and Light Company maintained a gaging station at the Weston Bridge. The records from this station give interesting information about the variation of the stream bed elevation. (See Fig. 19) The continuously rising bed has made frequent gaging of the stream necessary.
to establish rating curves. Since 1951 the station has not been maintained continuously, although the recorder operates on a part-time basis.

Prior to 1920 the river bed elevation was constant at the level of the underlying gravel deposit. In 1920 the bed began to rise and continued upward at an even rate until 1940. At that time the rate of deposition increased significantly coincident with a serious breakout of Five Mile Creek. The rapid rise continued until 1949 after which an abrupt, but temporary, drop occurred. By summer 1952 the bed had more than regained its previous elevation. The large runoff in Five Mile Creek in the spring of 1952 and the breakout of the gulley on Bien's farm at the same time on Deep Creek account for the resumption of deposition.

It is important to note that the bed elevation has at times dropped rapidly. This indicates that if the sediment supply could be cut off entirely, the river itself would degrade its bed and may return in time to its old profile on the gravel deposit.

Since the river flow for 1950 was also lower than in 1949, the lowered bed could not be attributed to a greater stream flow.

Fluctuating Flow

Because the Utah Power and Light Company operates hydro-electric plants at Bear Lake, Soda Springs, Oneida, and at the Cutler Dam, the flow in Bear River is closely controlled at all times except during flood stages. The Oneida plant controls the flow thru Cache Valley down to Cutler Reservoir. In
FIG. 19
TOTAL ANNUAL FLOW RATES
AND
BED ELEVATIONS
AT WESTON BRIDGE

- - DISCHARGE
- - BED ELEVATION

YEAR
1910 1920 1930 1940 1950

HEIGHT
0 1 2 3 4 5 6 7 8 9 10
the summer months this installation is operated as a peaking plant, and water is released thru the turbines only during periods of high power demand. Immediately below the Oneida plant the rate of flow varies from as low as 200 to a maximum of 3000 cubic feet per second — often going from the lowest to the highest stage in less than an hour. This greatly varied flow is an important characteristic of the Bear River in Cache Valley.

Some of the local residents have come to believe that the fluctuating flow has an adverse effect upon the flooding of the bottom lands. This question is discussed in detail on page 75.

Although the fluctuation at Oneida is extreme, the effect of channel storage along the river is to smooth out the irregular flow. Whereas daily stage changes at Weston are still appreciable, at Amalga they are no longer so important.

Figure 20 is reproduced here by permission of the Utah Power and Light Company. It shows the hourly discharge at Oneida and simultaneous gage height records from near Weston, Trenton, and Amalga. This record was made some time prior to the other measurements in this thesis, but is still indicative of the conditions in August 1952. Whereas maximum stage variation at Weston was 3$\frac{1}{2}$ feet, at Trenton it was 2 feet and at Amalga only 1$\frac{1}{2}$ feet.

**Composition of the Stream Bed**

**Method of Taking Bed Samples.** The capacity of a stream to carry sediment depends upon both the sediment size and the flow condition. The discharge and velocity can easily be measured or predicted from the hydraulics of the channel, but the composition of the bed is more difficult to determine. The question
FIG. 20, Reproduced by Permission of the Utah Power & Light Co.
immediately arises as to where and how the samples should be taken.

When material is in suspension in a stream, the larger particles, on the average, settle out first as the velocity and accompanying turbulence decrease. For this reason the particles in the bed of the stream would be expected to decrease in size downstream if the slope were flatter and the velocity smaller as in the Bear River. Segregation of the material should also be expected on bends, since the flow velocity is lowered on the inside of the curve. Local differences in flow conditions such as pools and crossovers and shallows also cause different sizes to settle in different places.

Obviously one single sample cannot be expected to adequately represent the average bed of a stream. There has been much discussion concerning the proper method of obtaining a representative bed sample. Certainly the purpose of the sample should be kept in mind as it is taken. The sample should also be easily obtainable in the field.

If a sample of the exposed bed for only one flow condition and one rate of transport is desired, then only the topmost layer of the bed should be taken. Practically a sample of this layer is difficult to obtain in a river, and it still may not represent an average condition for the stream at that point.

In order for the sample to represent the average of many flow conditions and sediment transport rates and to be quite easily obtainable in the field, the bed should be sampled in depth -- in fact, down as deep as the bed is scoured during the largest floods. To average the possible differences along
and across the stream, many small samples in depth should be taken over an area of the stream of such extent as to yield a representative sample for the whole section. The small samples should be combined and thoroughly mixed to obtain an average sample which then can be analyzed.

Depending upon the type of bed material, different methods must be used for the sampling in depth. A small diameter tube driven into the deposit and then withdrawn full of sediment is effective along the Bear River. If the tube is transparent, any stratification of the deposit can easily be seen. Many of the samples by the Utah Power and Light Company in 1950 were made in this manner.

Lacking a boat and the equipment and assistance necessary to sample the bed in the best manner, the author used the only method at hand. During low-water stages, many small samples were taken from the surface of the bed deposit (never deeper than the top six inches) with an open can. The samples were combined into an average sample which was kept for analysis.

This procedure was easily followed in water up to 4 feet in depth. In deeper water it was necessary to swim out into the stream, dive down to the bottom, scoop up the sample, and then swim back to shore while holding one hand over the open end of the can. Needless to say, a small amount of the finer material was undoubtedly washed out of the samples during such a process.

Samples were taken every few thousand yards along the stream from Preston down to the Cutler Reservoir backwater at Amalga. Where marked segregation of material was evident (such as at bends or in shallow water) samples of each different deposit
were taken and the width of deposit noted. An approximate composite sample for the entire cross section could be made up later by combining the samples roughly proportional to the widths of the separate deposits.

Analysis and Meaning of the Bed Samples. The composition of the samples was determined by sieve analysis using the Tyler Sieve series and a Ro-Tap machine. Such a small percentage of the samples was finer than the No. 250 sieve that no hydrometer analysis of the finer material was considered necessary.

The typical grain size distributions of the bed materials at Weston Bridge and at Trenton Bridge are shown in Figs. 21a and 22a. Samples made by the Utah Power and Light Company in 1950 at the same locations are also shown on the same figures and are seen to be of similar composition.

As was expected, the bed material becomes progressively finer as one goes downstream. This changing composition is shown by Fig. 23.

Obviously, the method of sampling leaves much to be desired, although it is good enough to show the general nature of the change in bed composition. A larger number of samples taken in greater depth would establish the local bed composition with greater accuracy, but the general variation of bed material particle size distribution along the river would probably not be greatly different than that shown in Fig. 23.

It should be noted in Fig. 23 that most of the high points on the chart (local average coarseness of the bed material) occur at bridges. This is readily explained because bridges
FIG. 21 B
GRAIN SIZE DISTRIBUTION
OF THE
BED MATERIAL
SHOWING LOCAL SORTING AT WESTON BR.

GRAIN SIZE IN MILLIMETERS

GRAIN SIZE IN MILLIMETERS

PERCENT FINER

SIEVE NUMBER

O = SAMPLES FROM DEEP WATER
O = SAMPLES FROM SHALLOW WATER
O = SAMPLES FROM SAND BAR ALONG BANK
FIG. 22 A

GRAIN SIZE DISTRIBUTION
OF THE
BED MATERIAL
AT TRENTON BRIDGE

- = SAMPLES TAKEN IN AUGUST 1952
O = SAMPLES BY UTAH POWER & LIGHT CO., 1950
FIG. 22 B

GRAIN SIZE DISTRIBUTION
OF THE
BED MATERIAL
SHOWING LOCAL SORTING ON A BEND
NEAR TRENTON BRIDGE

○ = SAMPLES FROM DEEP WATER IN MID-STREAM
□ = SAMPLES FROM OVER-BANK DEPOSITS
· = SAMPLES FROM SHALLOW WATER ON THE
INSIDE OF THE BEND

PERCENT FINER

GRAIN SIZE IN MILLIMETERS

SIEVE NUMBER
FIG 23

CHANGING COMPOSITION of the BED MATERIAL
ALONG THE BEAR RIVER

DISTANCE FROM CUTLER DAM IN THOUSANDS OF FEET
are almost always built at a narrow location in the channel. Being the narrowest section, the bridge is a controlling point in the river. In flood stages, the increased volume of water cannot spread out so it scour deeper. When lower water again comes, the deep hole at the bridge is quickly filled with sediment. Thus, the bridge section with its narrow section and high velocities is probably not representative of the average bed in other parts of the stream above and below the bridge site. The river adjusts itself to carry its sediment load, but at narrow sections the grains that can settle out are of different size distribution than at other localities because of the different section geometry and different velocity.
Part IV

FIELD MEASUREMENT OF SEDIMENT TRANSPORT RATES IN BEAR RIVER

Sediment is transported by streams in two different manners: either the particles are carried in suspension supported by the turbulence of the surrounding water and rarely, if ever, settling to the bottom, or the particles are rolled and pushed along the stream bed in a sliding and bouncing motion, sometimes going into suspension for a short time but always returning to the bed. This latter type of motion is generally referred to as the "bed-load" in contrast with the former which is known as "suspended load."

In the reach of Bear River under discussion most of the total sediment transported is moved in suspension. However, a significant amount of the total moves as bed-load. Certainly, for the Bear River, a knowledge of the manner and magnitude of bed-load movement would be important because of the large amount of sediment that has been deposited in the bed of the stream.

In determining the sediment transport rates, two approaches are possible: the suspended load and bed-load rates can be directly measured, or the transport rates can be determined analytically. The direct measurement method is discussed in this section, and the analytical approach is discussed in the section following.

Types of Sampling Devices

"Suspended-sediment samplers" have been developed, are widely accepted, and have been used on many streams. These instruments take samples of the water from different points...
in the stream cross section. The concentration of sediment in the water can be determined from the samples. The rate of transport of particles in suspension at the sampled point equals the product of the concentration and the corresponding water discharge -- the assumption being made that the average horizontal velocity of the sediment particles is the same as that of the surrounding water.

Near the bed this assumption breaks down, since the velocity and concentration gradients become too large and the solid particles cease to travel at the velocity of the water. A different type of device is required to measure directly the rate at which sediment is moved near the bed. Such an instrument is called a "bed-load sampler."

The Dutch-Type Bed-Load Sampler

Different kinds of bed-load samplers, both permanently installed and portable, have been used successfully and are described by Einstein and others. For this investigation of the Bear River, a box-type sampler was used which was designed originally by Dutch engineers for use on the lower Rhine River where the maximum grain size is 1 millimeter. With a similar sediment size and flow velocities in the Bear River as in the Rhine, the Dutch type sampler was found to work satisfactorily.

The sampler was built from somewhat modified Dutch specifications by the Soil Conservation Service Field Laboratory in Greenville, South Carolina in 1940. It was used by the Soil Conservation Service on several eastern streams before being brought West. The sampler is shown in Figs. 24 and 25.

The box-type sampler depends for its operation upon the
**FIG. 24**

DUTCH-TYPE BED-LOAD SAMPLER
following principle: Water and sediment enter the trap together thru the rectangular mouth. Inside the body of the sampler, the flow velocity is reduced, allowing the sediment to be deposited, while the water flows out the rear. The downstream end of the original Dutch trap was made of screen which aided in retaining the sediment in the trap. In streams such as Bear River which carry much fine, floating organic matter, the screens quickly plugged up and prevented the operation of the sampler. For use in such streams the open-end type of box sampler was designed which has no screens and depends solely upon velocity reduction to retain the sediment in the trap.

A device of the size of such a sampler offers considerable resistance to the flow. This change in the flow pattern tends to produce a pressure increase at the upstream end of the sampler. The slow moving particles near the bed are especially sensitive to such a pressure increase. Calibration tests have shown that a 10% velocity reduction in the entrance produces as much as 50% difference in the measured bed-load rate. For this reason the mouth of the Dutch sampler was extended ahead of the body and the shape of the sampler was made such as to draw water thru the mouth at the same velocity as the undisturbed flow.

Calibration of the flow thru the sampler used in this investigation was done by the author at the University of California (See Appendix I). It was found that for a flow velocity of one foot per second, the efficiency of the empty trap was 102% (i.e., the velocity in the mouth was 102% of the velocity in the undisturbed
flow). The 2% error in efficiency is thought to be considerably less than errors in the measured bed-load rate arising from other factors. For best results the sampler should also have been calibrated with sediment of size similar to the Bear River bed-material.

Filling bed-load samplers up to about 30% of volume has been found to have little effect upon their efficiency, but if filled beyond this amount, the sampler's efficiency drops considerably. Because results would become inconsistent, care should be taken not to overfill the sampler.

For use in a river, the sampler-box is suspended from a steel pipe framework (See Fig. 25) which has a fin to keep the device headed upstream whenever under water. Suspension of the trap is such that when lowered to the bottom, the tail hits first followed by the metal frame with the body of the sampler held lightly in place on the bottom. Finally the mouth of the sampler reaches the bed and is held firmly on the bed by flexible arms of spring steel. This firm contact of the mouth with the bed is essential to prevent any part of the sediment from finding its way under the sampler instead of into it. Some designs of box-type bed-load samplers have been very inefficient due to a lack of some such provision for positive contact with the bottom.

For the velocities for which it was designed, the weight of the device is sufficient to hold it firmly in place on the bed without anchorage. When the sampler is raised, the mouth is lifted first, then the metal frame with the box. When suspended free of the bottom, the box assumes a tilted position with the
mouth of the sampler upward so none of the catch can escape. A cork is provided in the bottom near the downstream end for washing out the catch after the sampling period. The top of the sampler can be removed for cleaning and inspection.

**Technique of Use of the Dutch Bed-Load Sampler**

The size and weight of the sampler is such that it cannot be raised and lowered by hand. A small hand operated crane with a long swinging boom was built at the University of California and was mounted on the right rear corner of the bed of a small truck as shown in Fig. 26. With the truck near the side of a bridge, the sampler could be raised and lowered with ease. Such a crane also could be mounted on a boat for use on other sections of a river.

Before beginning the sampling operation, some preliminary observations should be made, such as the cross-section of the stream at the sampling location, the river stage, a sketch of the stream course above and below the location, water temperature, weather conditions, date, time of day, and any other information that might influence the measurement. Unless an automatic recorder is installed nearby, it is essential that the stream be gaged at the same time the sediment movement is being measured. Any fall or rise in stage during the period of sampling also should be noted.

One possible error in the use of the Dutch type sampler arises from sediment particles that are collected while the device is being lowered to and raised from the bed. This occurs when particles present in the bed are being transported in appreciable quantities in suspension and tends to increase
the measured rate. To minimize this error, the sampler should be lowered and raised quickly.

The sampler should be lowered until the fin is under water with the sampler mouth still in the air as in Fig. 27. Once the sampler is headed upstream and is steady, it can be quickly lowered all the way to the stream bed. The time of sampling should be measured from the instant the sampler rests upon the bed. By trial-and-error a sampling period should be selected to give a substantial catch and still not overfill the sampler. A period of from 3 to 5 minutes usually gave the best results on the Bear River.

Since any moss and sticks caught on the mouth or inside the sampler tend to decrease the efficiency, measurements should be repeated if the sampler comes up partially plugged with organic matter. About a fourth of the measurements on the Bear River had to be repeated because of this reason.

One difficulty in the use of this type of sampling device is the irregularity of sediment transport. If the sampler touches the bed just upstream from a sand ripple, the catch may be only a few score cubic centimeters, whereas in the same amount of time the sampler may come up with a few hundred cubic centimeters if it touches bottom just downstream from a ripple. For this reason, the sampling process must be repeated several times in the same spot until a reliable average value of transport has been obtained.

After the filled sampler has been raised from the bottom, the catch should be carefully washed out of the box into a graduated cylinder. Care should be taken not to lose fine
particles by letting the graduated cylinder overflow. After the particles settle to the bottom, the excess water can be poured off. The cumulative volume of sediment in cubic centimeters as well as the time of sampling should be recorded after each catch is emptied into the graduated cylinder. When a reasonable average of the transport appears to have been obtained, the total volume of catch and the total time should be recorded. The sediment should then be washed out of the cylinder into containers (milk bottles are handy for this purpose) and kept for later sieve analysis.

Since the transport of material near the bed varies greatly from point to point across the stream, the sampling process must be repeated at frequent intervals across the river. The more such measurements are made, the more accurate is the final determination of the bed-load transport rate.

Two persons are required to operate the sampler -- one to maneuver the sampler with the hand crane, the other to remove the catch from the sampler and record the data. At the same time a third person may gage the stream and establish the shape of the cross-section. On the Bear River three to four hours were required for one series of measurements. On larger streams the process may require a whole day.

The time required to make a measurement limits the use of the Dutch type bed-load sampler to streams in which the discharge is essentially constant during the period of sampling. This limitation made the use of the sampler difficult on the Bear River because of the fluctuating river stage previously described. It was desirable to make the bed-load measurements
as near as possible to a maximum river stage, thereby reducing as much as possible the change in discharge during the sampling time.

Peak discharges from the Oneida power plant do not always occur at the same time each day. Rough calculations indicated a time lag of approximately 12 hours between the release of water at Oneida and its arrival at Weston Bridge. Upon learning each day the time of release at Oneida, ample time was still available to reach the location and prepare to begin the sampling process somewhere near the desired time.

**Computation of the Measured Rate of Bed-Load Movement from the Sampler Data**

The data obtained from the bed-load measurements can be conveniently presented by drawing a line representing the mean water surface and plotting the river depth below the line and the corresponding rate of bed-load transport above the line. The area inside the transport curve represents for the existing discharge the total bed-load transport in the 2 inches above the bed. (The trap height was 2 inches.) Figures 31, 32, and 33 represent the three measurements which were complete enough to be worth keeping. Another measurement was begun at Trenton bridge on August 22 but was not finished because of a falling stage and a lack of time.

**Measurement at Weston Bridge, Aug. 21, 1952 (Fig. 31).**
The total measured bed-load rate was 21.7 tons per day at the average discharge of 1050 cubic feet per second. During the measurement the river stage rose from 10.5 to 11.4 or a total
FIG. 31
MEASURED BED LOAD TRANSPORT
AND
RIVER CROSS-SECTION
WESTON BRIDGE     AUGUST 21, 1962

DISCHARGE = 1050 CFS.
TOTAL BED LOAD TRANSPORT = 9,111 \frac{\text{CC}}{\text{MIN}} = 217 TONS PER DAY
WATER TEMPERATURE = 72^\circ \text{F}
Fig. 32
MEASURED
BED LOAD TRANSPORT
AND
RIVER CROSS-SECTION
WESTON BRIDGE
AUGUST 22, 1952

TRANSPORT

MEAN WATER SURFACE DURING MEASUREMENT

DISCHARGE = 1020 CFS.
TOTAL BED LOAD TRANSPORT = 14,000 C.C. = 33.3 TONS PER DAY
WATER TEMPERATURE = 72°F
of 0.9 ft. in the 3½ hour sampling period (4:00 to 7:30 p.m.). This rise represents an estimated 250 cfs. or 25% change in discharge and an even larger change in the rate of bed-load movement. The sampling process was begun on the right (east or shallow) side of the stream and as the sampling progressed, the stage increased. One would expect that the samples taken early in the period would indicate a lower rate, whereas later samples would indicate a higher rate than the value for the average stage. Comparison of figures 31 and 32 appears to substantiate this supposition.

Although the rise in stage alone would probably not account for all the difference in bed-load transport as measured on the different days, figures 31 and 32 illustrate the importance of having a relatively constant stage during the sampling period.

Other factors contributing to the unreliability of the Aug. 21 measurement are: the stream was not gaged or the cross-section accurately determined during the measurement; this being the first measurement made, the sampling procedure had not been worked out as efficiently as in later measurements; a local difference in the flow condition due to the presence of a sand wave could have affected the transport. For these reasons this measurement is not used in later calculations.

Measurement at Weston Bridge, Aug. 22, 1952 (Fig. 32). The total measured bed-load rate was 33.3 tons per day at the average discharge of 1020 cfs. The stage rose from 10.9 to 11.0 ft. during the 3 hour sampling period (5:30 to 8:30 p.m.). The stream was gaged during this measurement and the cross section accurately determined.
Measurement at Trenton Bridge, Aug. 27, 1952 (Fig. 33). The total measured bed-load rate was 13.5 tons per day at a discharge of 1350 cfs. The stage rose 0.2 ft. in 4 hours (10:30 to 2:30 p.m.) and the stream was gaged during the sampling period.

**Grain Size Distribution of the Total Measured Bed-Load Rate**

Each sample of the bed-load caught by the sediment trap represents the transported material only in the neighborhood of the point in the cross-section at which the sample was taken. To produce a single sample which would represent all the transport in the whole section, the percentage of the total transport contributed by each sample was determined from the transport curves (Figs. 31, 32, 32) and composite samples were made accordingly for each series of measurements. Figs. 34 and 35 show the grain size distributions of the composite samples.

**Suspended Load Samples**

To determine approximately the suspended sediment concentration, a few depth-integrated suspended-load samples were taken at each bridge using a primitive Einstein-Anderson type suspended load sampler. The samples were integrated from the water surface down to approximately 1 ft. above the bed, thus leaving unsampled by either device the fluid between 2 inches and 12 inches above the bed.

For purposes of roughly determining the suspended-load transport, the samples taken were assumed to represent the average sediment concentration of the entire flow. Upon this basis the following results were obtained:
FIG. 33
MEASURED BED LOAD TRANSPORT
AND
RIVER CROSS-SECTION
TRENTON BRIDGE  AUGUST 27, 1952

DISCHARGE = 1350 CFS.
TOTAL BED LOAD TRANSPORT = 5,690 C.C. = 13.5 TONS
MIN. = 13.5 TONS
DAY
WATER TEMPERATURE = 70° F.
FIG. 34
GRAIN SIZE DISTRIBUTION
OF THE
MEASURED BED LOAD
AT WESTON BRIDGE

GRAIN SIZE IN MILLIMETERS

SIEVE NUMBER

PERCENT FINER

O = AUGUST 21, 1952
• = AUGUST 22, 1952
FIG. 35
GRAIN SIZE DISTRIBUTION
OF THE
MEASURED BED LOAD
AT TRENTON BRIDGE

GRAIN SIZE IN MILLIMETERS

SIEVE NUMBER

PERCENT FINER

O = AUGUST 27, 1952
<table>
<thead>
<tr>
<th>Bridge</th>
<th>Date</th>
<th>Concentration ppm (Avg.)</th>
<th>Discharge cfs</th>
<th>Suspended Load Tons/Day (Dry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weston</td>
<td>Aug. 26</td>
<td>1500</td>
<td>1300</td>
<td>4,120</td>
</tr>
<tr>
<td>Trenton</td>
<td>Aug. 27</td>
<td>400</td>
<td>1350</td>
<td>1,460</td>
</tr>
</tbody>
</table>

The grain size distribution of the suspended load was not determined.

It is greatly regretted that time was not available to make more measurements. Although those taken were as accurate as can be expected with the available equipment, a series of several complete measurements at each bridge would have made the results even more reliable.
Analytical Determination of Sediment Transport Rates

Each particle that is transported by the moving water in a stream must satisfy two basic conditions: First, the particle must have been eroded from the watershed upstream from the reach and thus made available to be transported; and second, the stream must be able to somehow move the particle down to and thru the reach. The rate at which particles of any size or kind are moved can be limited by either condition.

Einstein, Anderson and Johnson were first to formally propose that the total sediment load carried by a stream be divided into two parts, each governed by a different condition. As a result of their suggestion, the term "wash load" is used to describe the finer particles whose transport rate is governed by erosion in the watershed, while "bed-material load" refers to the coarser particles whose movement is determined by the capacity of the stream to transport the particles.

Since the "wash load" by definition depends only upon the availability of the particles in the watershed, it cannot be related to the flow condition of the stream. Because the supply of "wash load" never exceeds the capacity of the channel to transport it, the particles are for the most part washed thru the reach and are deposited in the bed only in very small amounts. Although the "wash load" usually accounts for a large part of the total load, it has no significance in determining channel stability.
The "bed-material load," on the other hand, depends upon the capacity of the stream to transport it. If, for a given flow, too much or too little bed-material is supplied by the watershed, the stream will either deposit the excess or scour the needed particles from the stream bed. "Bed-material load" is always transported to capacity. Thus if the discharge changes, the "bed-material load" also changes.

It should be emphasized that the "bed-material load" includes not only the particles sliding and rolling along inside the bed layer (which we have called the "bed-load") but also many particles of bed material which are being moved in suspension above the bed layer.

Many attempts have been made to describe the bed-load movement and to determine just how it is related to the flow condition. Most investigators have expressed the rate of bed-load movement as a function of the "tractive force" or shear developed by the water flowing over the bed. The important formulas of this type have been summarized by Vanoni.12

The approach of Einstein to the problem of relating the bed-load movement to the flow condition was different in that the concept of a shear or tractive force was not used directly. As summarized by Einstein and Chien, the basic steps in the development of the so called bed-load function are as follows:

"It was first concluded on the basis of special experiments that a given particle size moves in a series of steps of a constant average length, and that it is periodically deposited in the bed after performing such..."
a step. The number of particles deposited per unit time in the unit of bed area may be expressed in terms of the rate of transport and the size and weight of the particle. The rate at which sediment particles of a certain size are eroded from the bed is proportional to the number of particles in the surface of the bed area and to the probability that such a particle in the bed surface is eroded during the unit time. This probability may be expressed also as the probability of the ratio of dynamic lift on the particle to the weight of the particle under water to be larger than unity. The equilibrium rate of bed material transportation is then obtained by equating the number of particles deposited on and eroded from the unit bed area per unit time; and this leads to the final bed-load equation as follows:

\[ 1 - \frac{1}{\sqrt{\pi}} \int_{-B \psi_* - \frac{1}{\eta_0}}^{B \psi_* - \frac{1}{\eta_0}} e^{-t^2} dt = \frac{A_* \phi_*}{1 - A_* \phi_*} \]

in which \( \eta_0 \), \( A_* \) and \( B_* \) are universal constants. The equation is represented graphically by a single curve between the flow intensity \( \psi_* \) and the intensity of bed-load transport \( \phi_* \), in which

\[ \phi_* = i_B \phi = \frac{i_B}{i_b} \frac{g_b}{g_s} \left( \frac{S_f}{S_s - S_f} \right)^{\frac{1}{2}} \left( \frac{1}{g D^3} \right)^{\frac{1}{2}} \]

\[ \psi_* = \frac{5}{5} Y \left( \frac{B}{\beta_x} \right)^2 \gamma = \frac{5}{5} Y \left( \frac{\log_{10} 10.6}{\log_{10} 10.6 X} \right)^2 \left( \frac{S_s - S_f}{S_f} \right) \frac{D}{R S_e} \]
In 1950 Einstein extended his theory to make possible the calculation of the equilibrium rate at which the entire bed-material load will be transported by various discharges. Briefly, this is done as follows:

The existing suspended load theory as summarized by Vanoni determines the sediment concentrations at any point above the bed layer if the concentration at any one point is known. By using the bed-load function to calculate the sediment concentration at the upper edge of the bed layer, the concentration at all points in the flow can be determined. By a process of integration, the total bed-material load in the whole section then can be calculated. Since the thickness of the bed layer depends upon the particle size, the load must be divided into fractions for each grain size, the transport of each fraction must be determined separately, and the total transport arrived at by summation. This rather complicated procedure of calculation is described in detail in the reference cited.
All necessary tables, charts, and curves are also given therein. The definitions and symbols used in the calculations made for this thesis are the same as those used by Einstein. Many of the graphs contained in his report are necessary for the calculations made herein.

**Results of Recent Experiments**

The original bed-load function as given by equations 1 to 3 was developed from experiments with uniform sediment. The correction factors $Y$ and $g$ are introduced only for non-uniform materials.

The "hiding factor" $\frac{\xi}{\rho}$, which is a function of $D/X$, is introduced "to account for the consequence of the mutual interference between bed particles of different sizes i.e., particles of a certain size in a mixture are not subjected to the same flow velocities as they are in the case where the entire bed is composed of material its own size."$^5$

The original $D/X - \frac{\xi}{\rho}$ curve was based on experiments made by Einstein in 1944-46 in which sand mixtures with a small range of grain sizes were used. The question later arose as to what would happen to the curve if the bed material included a very large range of grain sizes. Would the "hiding factor" correction still be the same? To answer this and other questions another series of experiments were completed recently at the University of California.$^5$ Some of the findings of this investigation are summarized as follows:

"With a large spread of grain size in a mixture, the bed material has a tendency to segregate" (that is, to become
stratified with a fine layer on the surface of the bed underlain by a coarser material). "Because of the surface segregation of the bed material, the $D/X - S_0$ curve retains its original shape but may shift its relative position. The degree of shifting can be correlated by a dimensionless parameter $\frac{D_{90} \left( \frac{f_r - f_f}{S_o} \right)}{y}$."

$D_{90}$ = sieve size of the grains of which 90% by weight are finer

$D_{75}$ = sieve size of the grains of which 75% by weight are finer

$D_{25}$ = sieve size of the grains of which 25% by weight are finer

$S_o$ = sorting coefficient $= \sqrt{\frac{D_{25}}{D_{75}}}$

$y = y \left( \frac{\beta}{\beta_x} \right)^2$

Choice of the Means of Comparison

The final test of the usefulness of any method for calculating sediment transport is its application to a natural stream. If a formula is accurate for the flume conditions from which it was developed, but gives a false result in a natural stream, it has little practical value.

One purpose of this investigation is to check the Einstein method by river measurements to see how closely it can predict the equilibrium rate of bed-material movement in Bear River. It was originally intended to compare directly the measured bed-load movement with the total calculated bed-material load. If this were done, each set of measurements would check
but a single point on the discharge vs. transport curve shown in Appendix II. So that each time consuming measurement would yield as much information as possible, another means of comparison has been derived as follows:

(1) It will be shown later that almost half of the bed-material load at Weston bridge moves in suspension above the 2 inch layer caught by the bed-load sampler. Therefore comparison must be made only with the calculated bed-material rate for the 2 inches above the bed. The integration process for the suspended load must be carried out from the bed layer up to a depth of 2 inches instead of from the bed layer all the way up to the water surface.

(2) Instead of using the new \(D/X - \frac{6}{3}\) curve (See Fig. 36) in computing the bed-material transport, the measured bed-load rate (along with other necessary data) was used to compute the actual \(D/X - \frac{6}{3}\) curve for the stream.

By this inverse calculation the behavior of each grain size fraction can be observed better and the presence and amount of the shift of the \(D/X - \frac{6}{3}\) curve can be easily seen.

**Method of Calculation**

Chien\(^{15}\) in describing the efficiency of depth-integrating suspended-sediment sampling has shown that the portion of the total suspended-sediment load which moves above any chosen elevation \(\Delta\) above the bed can be expressed as follows for each grain size fraction:

\[
\frac{i_{3d} \theta_{3d}}{i_T \theta_T} = \frac{(2D/d)^{2-1} (d-d_1)^{2} (PI_{1d} + I_2)}{1 + PI_1 + I_2}
\]  

(4)
in which

\( i_{s0} \) = the fraction of suspension in a given grain size \( D \) moving above the elevation \( \lambda \).

\( i_T \) = fraction of total load in a given grain size.

\( q_{s0} \) = the suspended-load rate (above elevation \( \lambda \)) in weight per unit of time and width.

\( q_T \) = corresponding total load rate.

\( \lambda \) = arbitrary height above the bed (in this case, the height of the bed-load sampler mouth, or 2 inches).

\( d \) = average depth of flow.

\( z \) = Exponent of suspended distribution.

\( P \) = Parameter of total transport.

\( I_{1d} \) and \( I_{2d} \) are integral values which can be evaluated from the same graphs used to determine \( I_1 \) and \( I_2 \) provided that

\( A_d = \frac{d}{d_0} \) is used in place of \( A = \frac{2D}{d} \).

The portion of the total bed-material which moves below the elevation \( \lambda \) above the bed is for each grain size fraction

\[
\frac{i_{d} q_{d}}{i_{T} q_{T}} = 1 - \frac{i_{s0} q_{s0}}{i_{T} q_{T}} = 1 - \frac{(\frac{2D}{d})^z - (\frac{d-d}{d-2D})^z (PI_{1d} + I_{2d})}{1 + PI_{1} + I_{2}} \tag{5}
\]

in which

\( i_{d} \) = the fraction of the total load in a given grain size \( D \) moving below the elevation \( \lambda \).

\( q_{d} \) = the transport rate of all particles below elevation \( \lambda \) (as measured by the bed-load sampler).

Thus

\[
\frac{i_{d} q_{d}}{i_{b}} = \left[ 1 - \frac{(\frac{2D}{d})^z - (\frac{d-d}{d-2D})^z (PI_{1d} + I_{2d})}{1 + PI_{1} + I_{2}} \right] \frac{i_{T} q_{T}}{i_{b}} \tag{6}
\]
and since \( \phi_* = \frac{i_B}{i_b} \phi \), \( i_T g_T = i_B g_B (1 + PI_1 + I_2) \),
and
\[
i_B g_B = \phi_* \frac{i_B}{i_b} \rho g 3/2 D^{3/2} (S_s - 1) 1/2
\]
in which \( S_s \) is the specific gravity of the solids,
then by substitution
\[
\frac{i_d g_d}{i_b} = \left[ \frac{1 - \left( \frac{2D}{d} \right)^{3/2} (1 - d) (2D - d) \left( PI_1 + I_2 \right)} {1 + PI_1 + I_2} \right] (1 + PI_1 + I_2) \left[ \rho g^{3/2} D^{3/2} (S_s - 1) 1/2 \right] \phi_*
\]

The final form of the above equation for convenient use in the calculations that follow is
\[
\phi_* = \frac{i_d g_d}{i_b} \left[ \frac{1}{(1 + PI_1 + I_2) - \left( \frac{2D}{d} \right)^{3/2} (1 - d) (2D - d) \left( PI_1 + I_2 \right)} \right] \left[ \rho g^{3/2} D^{3/2} (S_s - 1) 1/2 \right]
\]

Once the intensity of bed-load transport \( \phi_* \) is known, \( \psi_* \) is given by the bed-load function. Then
\[
\psi_* = \frac{\rho g}{\left( \frac{B}{\beta_x} \right)^2 \psi} = \frac{\rho g}{\left( \log_{10} \frac{10.6}{\log_{10} 10.6 X} \right)^2} \left( \frac{S_s - S_F}{S_F} \right) \frac{D}{R^1 S_e}
\]
from which the \( D/X - \frac{\psi}{\psi_*} \) curve can be plotted.

**Data Necessary for Computing the D/X - \( \frac{\psi}{\psi_*} \) Curve**

The data necessary for computing the curve is as follows:

1. The grain size distribution of the bed material (from sieve analysis of local samples (Figs. 21 and 22) or from the chart of grain size distribution along the stream (Fig. 23).

2. The grain size distribution of the measured bed-load (Figs. 34 & 35).

3. The measured rate of bed-load movement (for a known discharge) per unit of time and distance (Figs. 31, 32 & 33).
4. The description of the hydraulics of the average channel of the reach under consideration. (See Appendix II)

All the necessary data were available for the calculations for Weston bridge. At Trenton bridge no description of the hydraulics of the average channel was available. However, such a description was obtained from the Utah Power and Light report for Reach 1 which is just 5 miles downstream. Because the slopes at both locations are the same and the depth, width, and appearance of the stream very similar, the curves describing the area, wetted perimeter and the hydraulic radius at Reach 1 were assumed to apply also at Trenton Bridge.

The Meaning of the Calculated D/X - Curves

The D/X - curves were calculated for the measurements made at Weston and Trenton bridges and are shown in Fig. 36. From them two conclusions may be drawn:

1. For the smaller grain sizes which make up about half of the total transport, the shift of the D/X - curve and the correlation of the shift with the parameter

\[
\frac{D_{90}}{S_{0}R_{f}^{1}} \frac{\Delta \phi}{\phi_{f}} \frac{y}{S_{0}}
\]

are affirmed.

2. While for the grains smaller than about 0.2 millimeters, the measured and the theoretical transport rates (considering the D/X - curve shift) are the same, for the particles larger than about 0.2 millimeters, the theory gives a larger value for the transport rate than does the measurement.

Petrographic examination of the grains of the transported material indicated there was no significant difference in the density of the large and small grains. The larger grains did appear to be more angular than the smaller particles, but this
FIG. 36

\[ \frac{D}{X} = \frac{2}{\phi} \]

CURVES

FOR VALUES OF THE PARAMETER \( \frac{R_b}{S_e} \),\( \frac{R_b}{S_e} \), \( \frac{R_b}{S_e} \) = \( \phi \)

POINTS COMPUTED FROM RIVER MEASUREMENTS:

○ = WESTON BRIDGE, AUG. 22
△ = WAAL RIVER
● = TRENTON BRIDGE, AUG. 27
X = MIDDLE LOUP R.

AT WESTON BR., \( \phi = 3.00 \)
AT TRENTON BR., \( \phi = 2.32 \)
difference in shape would not, alone, account for the difference in measured and calculated rates for the large grains. It is thought, rather, that the apparent difference in the behavior of large and small grains can be at least partly attributed to the relative efficiency of the bed-load sampler for the large and the small grains. That is, as the sampler fills or when the sampler is partly plugged with organic matter, a slight pressure increase builds up in the sampler mouth and the larger particles, being concentrated nearer the bottom and moving more slowly, are more sensitive to such a pressure increase than the small and are less likely to be caught by the sampler. It is therefore recommended that if future measurements are made on the Bear River, special care should be taken not to overfill the sampler and to repeat all measurements during which the sampler becomes at all plugged with organic matter. It would be desirable also to make a thorough calibration of the sampler with sediment from the Bear River to see what the actual relative efficiency is for the large and small grains when the sampler is overfilled or partially plugged.

The D/X - $\delta$ curve was calculated several times for the Weston bridge measurement, each time using some different assumptions. For one calculation the bed composition from local samples was used and for another, the bed composition from Fig. 23. The shape of the curves was identical for both these methods with an insignificant shift of the calculated points.

One critical part of the calculations is the division, for the reach, of the total friction among the channel irregularities (the sandbars), the grains, and the banks.
This was done as outlined by Einstein by breaking the total hydraulic radius \( R_T \) into parts contributed by each agent producing friction i.e., the bars \( R'' \), the grains \( R' \) and the banks \( R_w \). For the August 22 measurement at Weston bridge \( R' = 0.7 \) Ft. and \( R'' = 2.8 \) Ft. with no bank friction considered so that \( R_T = 4.5 \) Ft.

To see if the apparent behavior of the larger particles was a result of error in the division of \( R_T \), various assumptions were made and their effect upon the calculated \( D/X - \phi \) curve was observed. For one calculation \( R' \) was assumed to be 0.5 Ft. and \( R'' \) equal to 3.0 Ft. This sizeable reduction in \( R' \) did not change the shape of the \( D/X - \phi \) curve at all, but only shifted the whole curve somewhat. Calculations made considering bank friction gave similar results. It was therefore concluded that the peculiar shape of the \( D/X - \phi \) curve could not be explained by an error in the assumptions made concerning the bed, grain and bank friction.

The \( D/X - \phi \) curves for both points of measurement are almost identical in spite of the difference in slope and sediment size at Weston and Trenton bridges.

There appear to be two explanations for the apparently abnormal behavior of the grains larger than about 0.2 millimeters:

1. The measurements could be in error. This cannot, in the author's opinion, fully account for the shape of the \( D/X - \phi \) curve. The fact that the small grains are transported in the amounts expected seems to indicate that the sampler was operating satisfactorily.
2. Some factor, not yet considered, which is operative in the Bear River (and in similar streams of flat slope and small bed-material grain size) makes the $D/X - \xi$ curve actually change its shape.

Data from some other rivers also produce $D/X - \xi$ curves of shape similar, in part, to the Bear River. Two such examples (the Waal River in the Netherlands and the Middle Loup River in Nebraska) as analyzed by Chien\textsuperscript{16} are shown in Fig. 36. The slope of the $D/X - \xi$ curves for these streams is the same as for the larger grains in the Bear River, but the curves are shifted considerably toward smaller $\xi$ values and therefore agree better with data from flume studies than do the Bear River data.

As previously defined, $\xi$ is a "hiding factor" which expresses the mutual interference or interaction of the particles of different sizes. A change in the $D/X - \xi$ curve would apparently indicate a change in the mutual interference between particles. Actually a change in the $D/X - \xi$ curve can mean something else also. The nature of the calculation of the curve is such that any and all factors not specifically taken into account in some other manner are lumped together in the one $\xi$ factor.

As already stated, Chien\textsuperscript{5} has shown that segregation of the bed occurs for mixtures of bed material with large range of grain sizes which in turn causes the $D/X - \xi$ curve to shift. Another observable phenomenon which might also affect the $D/X - \xi$ curve is local sorting of the bed deposits at bends and at shallow crossovers. Such sorting is especially
noticeable in the Bear River (See Figs. 21b and 22b).

It has been pointed out previously that the existing sediment transport theory has been developed mostly from laboratory flume experiments. Such flumes are straight and usually quite narrow. The flow condition is essentially two dimensional rather than the three dimensional flow as in rivers. The local sorting such as that which occurs at bends in natural streams cannot be reproduced for study in such a flume and is, therefore, not taken into account in the present theory.

Flumes are also limited by practical and economic considerations to relatively small depths (when compared to large rivers) and steep slopes. Under such conditions fine sediment cannot be used to study the bed-load since it will not be carried mostly in suspension. Thus, the ratio of depth of flow to the bed-material grain size must be small in a flume. In nature this corresponds to a steep stream, with a shallow water depth, transporting large particles. Deep rivers with small bed-material grain size and flat slopes simply cannot be duplicated easily for study in a laboratory.

It appears from this investigation that the Einstein method for calculating the equilibrium rate of bed material transport, while essentially correct, must be modified in some details when it is applied to flat streams with small sediment sizes. What is now needed is a series of bed-load measurements under widely varying conditions of flow. A method has been pointed out in this thesis whereby such measurements can be used to indicate the modifications necessary to make the present theory governing bed-material transport
just as applicable to flat streams with fine sediment as it now
is for steeper streams with coarser particles.

The Total Transport Rate of the Bed-Material

By performing the integration process (for the suspended
bed-material) from the bed layer up to the water surface
(instead of just 2 inches above the bed layer as in the previous
calculations) the total transport rate of the bed-material
during the measurements was calculated. These computations
are included in Appendix III.

At Weston bridge the total bed-material transport rate
on August 22 was approximately 60 tons per day compared to
the 33 tons per day caught by the bed-load sampler. Thus
almost half of the bed-material at Weston bridge moves in
suspension above the 2 inch layer.

At Trenton bridge on August 27 the total transport rate
of bed-material was 24.8 tons per day compared to 13.5 tons per
day caught by the sampler.

The above figures indicate how important it is to realize
that not all the bed-material transported always moves near
the bed.
Part VI

FACTORS AFFECTING THE CHANNEL SEDIMENTATION AND THE FUTURE CONDITION OF THE BEAR RIVER

In previous sections a description of the Bear River between Preston, Idaho and Cutler Dam has been given and the transport of sediment by the stream has been discussed. Some general conclusions regarding the behavior of the stream now can be made and some measures for improving the unsatisfactory conditions can be suggested.

Extent and Effect of Backwater from Cutler Reservoir

The location and shape of deposits in the bed of a stream depend upon the cause of the deposition. If, for example, the bed-material is supplied to the stream in amounts no greater than can be transported, deposition will occur principally in the delta of the stream. As the river meets the backwater of the lake or ocean, the velocity of flow is reduced and some of the sediment is deposited in the channel while the remainder of the load is carried into the still body of water. The sediment deposited in the channel produces an additional backwater effect which extends still further upstream. In this manner the deposit in the channel tends to grow in the upstream direction and assumes a wedge shape, being thickest at the lake and decreasing in depth upstream.

In streams where the bed-material is supplied at rates greater than can be transported, deposition must take place in the channel beginning at the place where the sediment enters the river. In this case the deposit of sediment will grow downstream with the thickest part of the wedge shaped deposit
at the upstream end.

The recent deposits in the Bear River channel (laid down since the survey in 1910) are almost uniform in depth or even deeper at the upstream end than downstream. This suggests that both types of deposition are occurring with wedge shaped deposits growing from each end of the reach toward the middle. From Fig. 12 it appears doubtful that the backwater effect of Cutler Reservoir extends upstream much beyond the Amalga bridge. Between Five Mile Creek and the Cub River pumping plant, where the damage by flooding is the greatest, the backwater of Cutler Reservoir obviously has no effect. In this reach the deposition occurs because the supply of sediment exceeds the transporting capacity of the stream.

Possible Condition of the River in the Future

The extensive overbank and sand bar deposits seen in the reach above the Cub River pumping plant are not as numerous downstream from that point. On-the-spot observation seems to suggest that a plug of sediment is moving down the valley and at present has reached a point just downstream from the Cub River pumping plant.

The field measurements of the bed-load indicated that for a discharge of approximately 1000 cubic feet per second, less than half as much bed-material is transported at Trenton bridge as at Weston bridge. The difference in the amount transported is deposited some place between the two sections. As the larger particles now in the upper reaches of the river (Fig. 23) are gradually moved downstream, the bed-material
transporting capacity in the lower reaches will decrease still more--thus causing greater deposition. Even should the supply of sediment be stopped entirely, flooding conditions downstream from the Cub River pumping plant could be expected to increase for a time before any improvement would be evident.

Effect of the Fluctuating Flow upon the Transport of Sediment

Einstein in 1951 reported that the Utah Power and Light Company had reconstructed from records of stream flow and the changes in reservoir storage the "natural" flow of the Bear River from 1913 to 1949. Duration curves were then prepared for both the "natural" and the actual regulated flows in the river. These curves were each used separately to integrate the Discharge-Transport Curve (Fig. C, Appendix II) over the stated period. By this method Einstein found that at both Reach 1 and Reach 2 the total bed-load transport over the 36 year period would have been essentially the same for the "natural" flow as for the actual flow. On this basis he concluded that the "deposition of sediment in the river channel is not materially affected by the three upstream power plants." None of the results from this investigation would greatly effect this conclusion.

Effect of Fluctuating Flow upon Flooding and Land Use

Some of the land owners along the river believe they have suffered damage from the regulated flow of the river. They point out that the daily inundation which occurs in the summer-time makes the water table so high as to prevent use of the land for anything but limited grazing. They claim that if the river were unregulated, they would suffer but one big flood in
the spring followed by a dry summer during which the bottom-lands along the river could be cultivated irrespective of the extensive sediment deposits in the stream bed.

In the author's opinion, such reasoning is not justified in the light of the following:

1. The reconstructed "natural" flow of the Bear River shows that from 1913 to 1949 the Bear River at Weston bridge would have been dry only one year in three. Normally the period of zero flow would only be two months or less. With no flow in the river, seepage from the valley sides would probably be sufficient to maintain the high water table on some of the bottom-land unless a drainage system were constructed.

2. With uncontrolled spring floods occurring from April thru June, little time would be left for growing season after the land had been dried out and planted. With the channel filled, as it is, with sediment, a small flow in the river is sufficient to hold the water table at a high level. It appears that cultivation would be only possible in the driest years.

3. With the channel filled with sediment the flood damage each spring could be expected to be greater for the "natural" flow than it now is for the regulated stream.

As long as extensive sedimentation prevents the stream from acting as a drain, little use could be expected from the land even with the "natural" river flow. What is needed is a river channel deep enough to drain the land even during higher flows. In the author's opinion, the flooding damage and the water-logging of the land occurs more because the deep channel that once existed is now filled with sediment
than because of the fluctuating flow.

**Possible Effect of the Removal of Cutler Dam**

Some land owners are of the opinion that if Cutler Dam were removed, the river would "wash all the sand thru the narrows into the Great Salt Lake." That this hope is not justified is easily demonstrated from Fig. 12. A dotted line has been drawn tangent to the present stream bed profile and passing thru the rock ledge upon which the old Whelon Dam was built. From this it is seen that if both Whelon and Cutler Dams were removed, the slope of the river could not be steeper than the present gradient at Reach 1. The condition of the stream would be unaffected upstream from that point.

**Reclamation of the Damaged Lands**

**River Management.** Proper management of the river could do much to improve the condition of the bottom-lands. The dredging of a deeper, straighter, more efficient channel would enable the river to carry a greater sediment load and would provide better land drainage. Artificial spreading of the water over the river valley by means of low dikes would deposit the sediment upon the land and would fill up the low spots and the ox-bow lakes. The "built up" land would be available for cultivation in later years after the spreading area had been moved downstream. Such measures of river management, although effective in reclaiming the land, are so expensive that their application to the Bear River is probably not justified by the potential worth of the land along the river. Even should such methods be economically possible, the above
measures would do nothing to halt the loss of the bench-land to erosion.

Control of Erosion. Control of excessive erosion in the tributaries and along the river valley so as to prevent the entrance of sediment into the stream is the only means by which most of the problems along the river can be permanently solved. In the past some effort has been made in this direction, but the work done has been mostly sporadic, "last-ditch," desperation measures undertaken only when a new and spectacular threat of erosion has developed. A program of erosion control, if it is to be either successful or economically feasible, must be well planned and carefully carried out over a period of years. Some work must be done every year regardless of the apparent conditions at the time. The next outbreak of a gulley or the next cycle of erosion can be prevented only by work done now.

An effective program for controlling erosion and for keeping the sediment out of the river should include such measures as the following:

1. Surface runoff should be kept out of the gulleys as much as possible. The water from Dayton Creek should, for example, be diverted from Five Mile Creek to flow down Nash Hollow (which should in turn be protected from future erosion).

2. Where surface runoff from local rainstorms cannot be diverted, a structure should be built at the head of the gulley to drop the water safely down into the gulley bottom. Such structures should be placed on many of the fingers of the main gulleys.
3. Wherever water is seeping out of the ground or wherever dampness indicates that a destructive seep might develop, steps should be taken to drain the ground water out of the local strata in such a way that no sand and silt will be washed out with the water. This has been attempted crudely in the past by dumping rock on the area of seepage. To be effective, such a filter would have to be carefully graded with coarse sand next to the bank followed by pea gravel, coarse gravel and finally rock with the whole filter covered by earth.

In the author's opinion, a better solution would be to drive a few perforated and gravel packed relief wells or drains horizontally into the face of the seepage area. Such wells would remove the ground water without piping of the silt. The wells could be driven a few at a time wherever the danger of an outbreak might appear. The cost would thus be distributed over a number of years.

4. The hydraulic fill dam constructed in Five Mile gulley in 1952 will be useful in catching some of the sediment, but might have been more effective if it had been built further downstream nearer the mouth of the gulley. The height of the dam and the lack of an adequately protected spillway appears to the author to endanger the whole structure should a flash flood occur before all surface waters are diverted from Five Mile Creek. Impounding water above the dam for any length of time will force the water to seep around the sides producing seepage that may become dangerous in the future. A series of lower dams with drop structures would, it appears, be
just as effective in catching sediment but would be less
dangerous.

5. The planting of willows in the gulley bottom is an
important step in the right direction and should be continued.
Willows (and possibly other water loving shrubs) should be
planted all the way across the gully bottom rather than just
along each side of a narrow channel.

6. The sides of the gullies should be planted to grass
wherever the slopes are stable enough for it to grow.

7. The irrigation efficiency should be increased on the
bench-lands. No more water should be used for irrigation
than is necessary for good crop production.

8. All irrigation canals on the bench-lands should be
lined.

9. Drop structures should be built in the gullies and
tributaries wherever necessary to stabilize the channels.

Difficulties Encountered in Doing Something About the Situation

Pointing out past errors is usually easier than avoiding
future mistakes or correcting present evils. For this reason
people sometimes tend to belittle criticism of the past. Still
an analysis of all the kinds of factors which have compounded
the difficulties along the Bear River will aid not only in
seeing what must now be done but also in suggesting the kind
of organization necessary to cope with the problem.

Lack of Recognition of the Problem in Its Early Stages.

If the first farmer to notice the beginning of a seep or the
growth of a gulley had appreciated the danger and had immediately
done something about it (in those days when a reaper could still be driven across the Five Mile Creek) the control of erosion would have been tremendously easier than it is at present. But the farmers on the bench lands only lost a little bit of their lands to the gulleys each year. Viewed year by year it probably didn't seem to be much. Surely when seen over a lifetime, however, the losses have indeed been great to those farms being literally swallowed by the gulleys.

It is unfortunate that someone in those bygone days did not understand the danger, for a few men with a few days work could then have done more to stop the destructive erosion than many men working together for many months can now do. Unfortunately the problems can only get worse if remedial action is longer delayed. Surely it would be foolish to take no action upon the Deep Creek and Battle Creek tributaries until those streams have cut gorges the size of Five Mile.

**Location of Damaged Areas.** Because Cache Valley straddles the Utah-Idaho state line, no existing agency has jurisdiction over all of the problem area. The main source of sediment from erosion is in Idaho while much of the area damaged by sediment deposition and flooding is in Utah. Different field offices of interested government agencies have jurisdiction on each side of the state line. Various individual landowners, irrigation and canal companies, corporations (such as the Utah Power and Light Company), and groups (such as Water Users Associations and Farmers Cooperatives) are interested in the problem. Any agency to best be able to cope with this problem must have inter-state authority as well as
to be able to represent and unit these other groups.

**Difficulty of Fixing Responsibility.** A basic principle of justice in this country, well established by court precedent, is that if one's property is damaged by another's, the damaged party is entitled to compensation for the damage done. If, for example, a car goes out of control and smashes a fence, the car owner must repair or pay for the fence.

There is no doubt, in this case, that the landowners along the river bottom have been damaged by the deposition of sediment and the resulting flooding. But who is to be held responsible? The power company that regulates the river flow will point out that they have nothing to do with the entrance of sediment into the stream. Shall we, then, penalize further the man from whose land the sediment came? If so, who is to say which grain of sand came from which field? The farmer whose land was washed away will certainly point out that his land would never have disappeared were it not for the ground water underneath it that caused the erosion. And the ground water? Well, it came from his neighbor's irrigation water or from a canal or from last winter's snow. What court would ever try to fix responsibility under such conditions?

It is only natural for those who have suffered damage to try and find a scapegoat -- someone to take all the blame and pay all the claims. In this case, the only party that appeared able to pay anything was the power company -- hence the attempt of some people to fix blame for the flooding of the bottom-lands upon the power company.
In the author's opinion, the problem has developed as a result of the very character and origin of the area, from the cultivation and irrigation of the land, and from the use and development of the stream. Should not all who have shared in the benefits from the cultivation, use, and development now assume their just portion of the expenses of solving the problem? Surely it is to the advantage of all to work together in the matter and not waste time and energy trying to fix blame where blame cannot be fixed.
Part VII
SUMMARY OF CONCLUSIONS

Excessive amounts of sediment supplied to the Bear River in recent decades by rapid erosion of gullies has raised the river bed and flooded the bottom lands. The rapid erosion cannot be traced to any one cause but was made possible by the character and origin of the valley and was started by the interference of man with the natural conditions on the bench lands. The problem has been aggravated by irrigation of the land, by a lack of appreciation of the seriousness of the problem in its early stages, and by disunity among all the parties being damaged by the erosion and subsequent flooding.

Cutler Dam has not caused the deposition of sediment in all the river but has only modified the deposit in the vicinity of the reservoir.

The fluctuating discharge resulting from the operation of the upstream power plants has not greatly affected the deposition of sediment in the channel.

Flooding of the bottom-lands probably would be just as severe even if the discharge of the river were not regulated.

Conditions downstream from the Cub River pumping plant can be expected to get progressively worse as the larger particles in the bed are gradually moved down the river into the section with a lower slope and smaller bed-material transport capacity.

A program for the control of erosion is the best, and the only permanent solution, to the problem. The river
will scour an adequate channel if the supply of sediment can be stopped.

Only thru the cooperative action of all who have suffered losses or who will benefit from corrective measures can a program of erosion control and river management be formulated and carried out.

The Dutch-type bed-load sampler appeared to operate satisfactorily in the Bear River. For accurate results, care must be taken not to overfill the sampler and measurements during which the sampler becomes partly plugged with organic matter should be repeated. For the most reliable results the sampler should be calibrated with sediment from the river in which the measurements are to be made.

The bed-load measurements made in the Bear River during this investigation were used to compute the actual $D/X - \frac{\kappa}{\phi}$ curve of the river for comparison with the theoretical curve as developed from flume studies. From this analysis the following conclusions were made:

1. For the grain sizes smaller than about 0.2 millimeters, the shift of the $D/X - \frac{\kappa}{\phi}$ curve and the correlation of the shift with the parameter $\frac{D_{90}}{S_{eR}} \frac{f^2 - f_f}{f_f^2} \frac{y}{S_0}$ are affirmed.

2. For the grain sizes larger than about 0.2 millimeters, the theoretical transport rates are larger than indicated by the measurements.

This apparent change of shape of the $D/X - \frac{\kappa}{\phi}$ curve is thought to indicate that either some additional factor not now included in the sediment transport theory must be considered...
for streams of flat slope and small bed-material grain size or a different interpretation must be given some factor already considered.

What is now needed is a series of bed-load measurements under widely varying conditions of flow. A method has been pointed out in this thesis whereby such measurements can be used to indicate the modifications necessary to make the present theory governing bed-material transport just as applicable to flat streams with fine sediment as it now is for steeper streams with coarser particles.
LIST OF REFERENCES


2. GILBERT, Grove Karl, "Lake Bonneville," U.S.G.S. Monograph No. 1, 1890.


16. CHIEN, N., From unpublished analysis of data of the Waal and Middle Loup rivers.
APPENDIX I

Calibration of the Bed-Load Sampler
CALIBRATION OF THE BED-LOAD SAMPLER

To insure the most accurate field measurements possible, bed load samplers should be calibrated with sediment similar to the bed material of the river in which the sampler will be used. The purpose of such a calibration is to determine for various known rates of bed load movement the actual amount of bed-material caught by the sampler.

With neither the facilities nor the time available for sediment rate calibration of the sampler, the author checked its performance by calibrating the velocity of flow in the sampler mouth. If the velocity of flow in the sampler mouth were found to be very nearly the same as the velocity in the flume, then no pressure gradient would build up at the sampler mouth to interfere with the sediment movement and the sediment caught by the sampler should be a reasonable measure of the actual bed-load movement.

The calibration of velocity in the sampler mouth was performed as follows:

1. The Dutch-type bed-load sampler was mounted with the sampler mouth 1 3/4 inches above the bottom of a 3 ft. wide flume (as shown in Fig. A).

2. The special pitot tube shown below was made to measure the velocities just inside the sampler mouth and flush with the upstream edge. Inside diameter of the tube was 1/16 inch.

---

**Diagram:** Pitot Tube inside of Sampler Mouth
The pitot tube was connected to one side of a differential manometer. With the other side connected to an opening in the side of the flume, the manometer (using kerosene as the fluid) measured the velocity head.

3. The pitot tube was mounted on a point gage so that the position of the pitot tube could be accurately determined.

4. With a water depth of 9 1/2 inches and a flow velocity of about 1 ft./sec. a series of manometer readings were made with the pitot tube at different points in the sampler mouth.

5. Finally, with the sampler removed from the flume and with the same discharge flowing, manometer readings were made again with the pitot tube at the same positions as before.

The average of the 37 readings made inside the 2 x 4 inch sampler mouth was 0.0693 ft. of kerosene. The average of the 16 readings taken at the same points in the undisturbed flow was 0.0664 ft. of kerosene.

Since the velocity of flow is proportional to the square root of the velocity head, the velocity inside the sampler mouth = \[ \sqrt{\frac{0.0693}{0.0664}} = 1.022 \] times the velocity in the undisturbed flow. Thus, the efficiency of flow thru the sampler is 102.2% for a flow velocity of about 1 ft./sec.

No further check was made on the sampler efficiency at other velocities of flow.
APPENDIX II

Curves taken from the calculations made by Einstein in preparing his report to the Utah Power and Light Company
AVERAGE HYDRAULICS of BEAR RIVER

WETTED AREA (SQ. FT.)

SURFACE WIDTH & WETTED PERIMETER (FT.)

HYDRAULIC RADIUS (FT.)

REACH 1

REACH 2

SURFACE WIDTH & WETTED PERIMETER (FT.)

WETTED AREA (SQ. FT.)

ELEVATION (FT.), REACH 1, AT CABLE

ELEVATION (FT.), REACH 2, SEC. 6
RATING CURVES OF BEAR RIVER

DISCHARGE (CFS.)

ELEVATION (FT.), REACH 2

DISCHARGE (CFS.)

ELEVATION (FT.), AT CABLE

REACH 2

SECTION 6

REACH 1

AT CABLE

MAIN CHANNEL ONLY

WITH FLOOD-PLAIN FLOW

WITH FLOOD-PLAIN FLOW

MAIN CHANNEL
SEDIMENT TRANSPORT RATE IN TONS PER DAY

BEAR RIVER
DISCHARGE - TRANSPORT CURVE
APPENDIX III

Sample Calculations
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$$\frac{(d-d)}{d-2D} = \frac{(d-d)}{d-2D}$$

$$\frac{1280}{1380} = \frac{220}{280}$$

$$\frac{300}{380} = \frac{240}{280}$$

**TRANSPORT WESTON BRIDGE**

**AUG, 22, 1952**

**CALCULATION OF S VALUES & TRANSPORT**

**WESTON BRIDGE**

**AUG, 22, 1952**

**BED COMPOSITION FROM LOCAL SAMPLE**
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Calculation of \( g \) values & transport

Trenton Bridge

Aug. 27, 1952

Bed composition from Fig. 23
Excessive amounts of sediment supplied to the Bear River during recent decades by erosion of gullies has raised the river bed and flooded the bottom lands. Comparison of field measurements of the bed-load movement with the calculated transport rates indicates that the present theory, while essentially correct, must be modified in some details when applied to streams with flat slopes and small sediment size.

This thesis traces the development of the present day conditions and gives a detailed description of the Bear River in Cache Valley. The possible effects of the fluctuating river discharge (caused by the operation of upstream power plants) upon the sedimentation of the stream and the resulting flooding is discussed. The effect of the backwater of a downstream reservoir upon the deposits in the river bed is also described and some general conclusions concerning the future condition of the river are made.

The Dutch-type bed-load sampler appeared to operate satisfactorily in the Bear River. The bed-load measurements were used to compute the actual $D/X - \phi$ curve of the river for comparison with the theoretical curve as developed from flume studies. From this analysis the following conclusions were made: 1, for the grain sizes smaller than about 0.2 mm., the shift of the $D/X - \phi$ curve and the correlation of the shift with the parameter $\phi'$ were affirmed; and 2, for the larger grain sizes, the theoretical transport rates were larger than indicated by the measurements. This is thought to indicate that either some additional factor not now included in the sediment transport theory must be considered for streams of flat slope and small bed-material grain size or a different interpretation must be given some factor already considered.