DEPOSITION AT THE HEADS OF RESERVOIRS

By

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INTRODUCTION

Scope

Experience has shown that there are two characteristic types of sediment deposits in reservoirs along alluvial rivers: (1) those occurring generally over the reservoir bottom, mostly composed of the finer fractions of the river sediment load — the silts and clays; and (2) those occurring in a characteristic delta formation at the head of the reservoir, including all the coarser fractions of the river sediment load — the sands and gravels — but which may also include large quantities of the silts and clays. This paper will be limited to a discussion of the headwater delta deposits, with some reference to deposits which have occurred upstream of reservoirs, but are not necessarily associated with them.

Purpose

The analytical procedure for predicting delta formation will be discussed in a general way and some conclusions which have resulted from observations at the heads of existing reservoirs will be offered. It is the purpose of this paper to suggest some of the factors which must be taken into account in an engineering estimate of future deposition at the heads of existing or proposed reservoirs, so that action for the control or alleviation of problems which could arise therefrom can be planned before the problems become serious.

The Engineer’s Interest in the Problem

It is well known that delta deposits can progress in two directions. They build downstream into the reservoir and, unless the river bed is degrading, as it would below a dam, they extend themselves upstream, progressively aggrading the river channel above the limit of reservoir backwater. Upstream aggradation of the river channel
could under some circumstances cause the reservoir backwater effect to progress upstream, increasing flood heights. The growth of the delta into the reservoir lessens the reservoir capacity, affecting its economic life. In Lake Texoma above Denison Dam [1], 49.5% of the deposition between 1940 and 1948 occurred in the delta area, large portions of which were silt and clay. Consideration of downstream delta building is also important when allocating areas for docks and recreation on a new reservoir. An example is a privately owned fishing camp located on the upper end of Possum Kingdom Reservoir in Texas. When the pool was filled in 1941, there was deep water at the camp. By 1951, a delta had progressed downstream past the camp, creating a two-foot muddy channel, and endangering the camp-owner’s livelihood.

Corps of Engineers Delta Inspection

Many of the comments presented herein are the results of observations by the writer who, in the company of other Corps of Engineers personnel, inspected thirteen western reservoirs during October and November 1951. Inspection of the delta areas of these reservoirs was facilitated by the fact that the pools were drawn down considerably below normal following a long drought in the West. These reservoirs are listed in Table I.

**TABLE I**

Reservoirs Inspected by Corps of Engineers Personnel in October and November 1951

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>River</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denison (Lake Texoma)</td>
<td>Red and Washita</td>
<td>Oklahoma-Texas</td>
</tr>
<tr>
<td>Possum Kingdom</td>
<td>Brazos</td>
<td>Texas</td>
</tr>
<tr>
<td>Altus</td>
<td>Red</td>
<td>Oklahoma</td>
</tr>
<tr>
<td>Conchas</td>
<td>South Canadian &amp; Conchas</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Alamogordo</td>
<td>Pecos</td>
<td>New Mexico</td>
</tr>
<tr>
<td>McMillan</td>
<td>Pecos</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Avalon</td>
<td>Pecos</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Caballo</td>
<td>Rio Grande</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Elephant Butte</td>
<td>Rio Grande</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Jemez</td>
<td>Jemez</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Lake Havasu (Parker Dam)</td>
<td>Colorado</td>
<td>California</td>
</tr>
<tr>
<td>Lake Mead (Hoover Dam)</td>
<td>Colorado</td>
<td>Nevada-Arizona</td>
</tr>
<tr>
<td>Gibraltar</td>
<td>Santa Ynez</td>
<td>California</td>
</tr>
</tbody>
</table>
GENERAL ASPECTS OF DELTA FORMATION

Bed-Material Load and Wash Load

The sediment load of an alluvial stream is usually divided into two classifications, *bed-material load* and *wash load*. Bed-material load consists of those grain sizes which are found in significant quantities in the river bed, including sands, gravels, and, in some cases, certain silt fractions. Wash load is silt and clay, not generally found in significant quantities in a river bed. It often comprises the major portion of the total sediment load. The rate of transport of bed-material load is a function of the hydraulic properties of the flow and the bed composition; hence a change in the movement of bed-material load through a reach while the discharge remains constant can effect significant changes in the bed elevation and the bed composition. Though changing within wide limits, the movement of wash load through a reach will not alter the bed significantly. For a given bed and a given flow there is a definite rate of bed-material transport that can be maintained, while the rate of wash load transported seems to be governed mainly by its supply. During high stages, bed-material transport is confined mainly to the sandy river channel, while wash load is transported throughout the entire valley cross section.

Deposition of Bed-Material Load

When a sediment-laden river enters a reservoir, the pattern of deposition of the bed-material load differs from that of the wash load. Bed-material load begins to deposit at the section in the river channel where the backwater from the reservoir first decreases the water-surface slope and increases the water depth, lowering both the ve-

![Fig. 1. Idealized Reservoir Delta Profile.](http://ir.uiowa.edu/uisie/34)
locity and the transporting capacity. Deposition continues over a channel reach which extends into the reservoir, to a section where the velocity becomes too small to support transport. The result is a headwater delta deposit having a schematic profile illustrated in Fig. 1. If the bed-material load is made up of a range of grain sizes, the larger grains will deposit more readily than the smaller as the velocity decreases; therefore, the reach over which the fine materials deposit will extend farther downstream on the delta than will that of the coarse. The result is a gradation of the bed composition on the delta, the bed mixture at the upper end being coarser than at the lower end. Figure 1 illustrates the delta profile at a particular time. Continual deposition occurs along the entire delta profile. Deposition at the upper backwater limit causes a flattening of the bed at that point, moving the limit of backwater upstream. Deposition near the foot of the delta decreases the water depth, increasing the velocity and increasing the capacity of the flow to carry bed-

![Delta Profile Diagram](http://ir.uiowa.edu/uisie/34)

**Fig. 2. Progressive Growth of Idealized Reservoir Delta.**

material load farther into the reservoir. The foot of the delta thus moves progressively down into the reservoir. Figure 2 illustrates this upstream and downstream delta growth under idealized conditions.

Deposition of Wash Load

In contrast to the bed-material load, the wash load usually deposits more generally throughout the reservoir, but its distribution can be very complex. Some of the silts may deposit on the delta in the slack water adjacent to the channel, the rest being carried into the reservoir for a distance which depends on the velocity of flow through the reservoir. Silts will deposit farther downstream in nar-
row reservoirs than in wide reservoirs. Very slow-settling discrete clay particles may become generally distributed throughout the pool during a period of inflow and may settle to form a uniform deposit throughout the reservoir area during a subsequent period of still water. On the other hand, density currents may carry the clays and perhaps the fine silts down into the reservoir, where their deposits will be concentrated in the reservoir thalweg and in a sediment "pool" immediately upstream from the dam. It is often the case that some of the incoming clay load will consist of flocs or groups of several discrete particles bonded together. The clay flocs, having settling velocities larger than those of discrete particles, may settle out on the delta along with the coarser silts. It is also often true that the reservoir water is of a different quality than the inflow. The change in the chemical content, brought about by intermixing of the inflow and the reservoir water, may cause colloidal clay transported by the inflow to flocculate and settle out rapidly at the head of the pool. If a river carries much clay load, this effect can result in deep clay deposits, as has been found in the downstream ends of the deltas in both Possum Kingdom and Denison Reservoirs. It was observed that a pole could be shoved easily four or five feet into the underlying soft clay deposit in the Red River delta of Denison Reservoir (Fig. 3). About fifty percent of the total deposition in the Red River arm of Denison Reservoir is found in the delta; therefore, since the major portion of the incoming sediment is wash load, a substantial portion of this load has deposited in the delta. Although the characteristic form and nature of the growth of a delta is usually governed by the deposition of

Fig. 3. Lake Texoma — Red River Arm, Showing Sun-Baked Crust at Surface of Deposits near Lower End of Delta. Mud on Stick Marks Depth to Which Stick was Shoved Easily Into Underlying Soft Clay.
bed load, it is apparent that significant deposits of wash load can occur in reservoir headwaters and greatly augment the volume of the delta.

**General Observations of Existing Deltas**

**Concentration of Flow**

There is evidence that the main thread of flow tends to remain concentrated on the delta at high discharges even though the water depths on the delta are large and the water surface is valley wide. In Lake Texoma, where the deltas in both arms are in wide valleys, the delta surface adjacent to the river channel seems to be as much as ten feet higher than the surface a little distance to the side. Inspection of the surface material on a cross section showed sand in and adjacent to the channel with a lateral grain-size gradation down to clay away from the channel. This concentration of sand marked the location of the channel bed at the end of the last period of substantial inflow. In the Washita Arm of Lake Texoma, the delta is building out into the wide Cumberland Pool and the sandy channel bed has the appearance of a long, narrow finger extending out into the pool on top of previously deposited delta material. In Fig. 4, the same long, narrow deposit of bed material on a much smaller scale is shown in the case of a small tributary which has pushed a delta into Lake Mead. Observations in a number of reservoirs seem to indicate that a substantial part of the bed-material load is deposited in a definite channel wherein the flow tends to be concentrated for the entire length of the delta during discharges that bring in important amounts of sediment.

**Channel Alignment**

Though at a given time the flow is concentrated in a definite channel, the channel will shift to a succession of locations on the delta. The shifting probably is not gradual but rather takes the form of a series of channel avulsions. The channel remains in one place until its aggrading bed is somewhat higher than the surrounding delta and then breaks over suddenly to form a new channel in a lower place.

Observations indicate that a sinuous channel tends to straighten under aggrading conditions. This effect is particularly marked on the Washita delta of Lake Texoma where the alluvial river channel, originally quite sinuous, has straightened since aggradation began and now more or less follows the valley alignment for most of the
distance below the head of the delta. There is evidently a tendency for the river to adjust to a certain regime which is consistent with open-river conditions, and one of the adjustments the river makes in doing this is to maintain its bed slope at some optimum value. The adjustment of bed slope in this case is probably a function of the energy slope, the composition of the bed, the composition of the banks, and the bed-material load transport. As the original bed aggrades, its slope decreases, and the channel must become progressively straighter to maintain the desired optimum slope. When the

![Image](http://ir.uiowa.edu/uisie/34)

Fig. 4. Lower End of Colorado River Delta in Lake Mead. Delta of Small Tributary Deposited on Colorado River Delta when Lake Mead was Higher.

channel alignment becomes parallel to the valley alignment, the channel has reached its minimum length; and the bed slope will decrease from the optimum as aggradation progresses further. For this reason, an aggrading channel on a reservoir delta probably can be expected to follow the valley alignment once appreciable deposition has occurred.

If the reservoir is drawn down far enough, unless scour is inhibited by erosion-resistant clay deposits, the channel will be able to degrade and increase its bed slope to the optimum value. If the drop is too great for the channel to have a straight alignment while maintaining the optimum slope, the channel may begin to meander. Such an occurrence has taken place in the sandy Pecos River delta upstream of the lowered pool of Alamogordo Reservoir.

Resistance to Erosion of Clay Deposits

It was observed that deposits of clay or silty clay, once consoli-
dated, were extremely resistant to erosion. Figure 5 is a photograph of the South Canadian River channel which has cut ten feet into the predominantly sandy Conchas delta, exposing an old clay layer. It appeared that the layer has resisted further cutting even though the cobbles seen in the photograph must have been carried in and deposited when velocities on the layer were quite high. It is signifi-

![Image](https://example.com/image.png)

**Fig. 5. Conchas Reservoir — South Canadian River Arm, Showing Exposed Clay Layer near Lower End of Delta.**

cant that a small layer of clay can retard degradation on a delta which is predominantly easily eroded sand. Figure 6 is a photograph of the Brazos River channel on the Possum Kingdom delta. The delta is predominantly clay in this location, and there was little evidence of cutting even though the pool was drawn down. Possum Kingdom was, at the time of observation, typical of other reservoirs with drawn-down pools and deltas, the lower ends of which contained extensive deposits of consolidated clay. Instead of losing elevation through channel degradation along the length of the delta, the water surface on erosion-resistant deltas fell to the lowered pool elevation in a series of short rapids near the foot of the delta as illustrated in Fig. 7, a photograph taken near the lower end of the Washita delta in Lake Texoma. A major portion of the erosion is concentrated at these rapids, which move slowly upstream. Even over a period of years, however, the scouring of material from the delta, and its movement farther into the reservoir, probably will be negligible.
Vertical Distribution of Deposits

Figure 8, a photograph of a vertical section exposed where the Pecos River has cut into the Alamogordo delta, reveals alternate strata of sand and silt clay, and occasional thin layers of hard clay. The shifting sandy channel with silt and clay depositing in the slack water to the side resulted in the alternate layers of sand and silty clay, while periods of slack water and high pool elevations resulted in the deposition of thin clay layers over the submerged portion of the delta. This stratification of deposits was typical of nearly every reservoir delta where channel cutting had exposed a vertical section. One exception was Gibraltar Reservoir, where the deposition was almost entirely sand. Stratification probably is not very pronounced at the lower ends of deltas where there are found deep clay deposits, resulting, perhaps, from rapid flocculation upon
entering the reservoir as suggested in the discussion of washload deposition. These deep clay deposits appeared to be present at the foot of the Colorado delta in Lake Mead, in a substantial reach at the lower end of the Brazos delta in Possum Kingdom Reservoir, and at the lower ends of the Washita and Red River deltas in Lake Texoma.

**Analytical Approach**

**Basic Relationships**

If the variation in the rate of sediment transport along a river reach at a given time can be determined, the rate of aggradation or the rate of degradation at all sections in the reach can also be evaluated. Assume that the bed profile and the water-surface profile of an alluvial river entering a reservoir pool are as shown in Fig. 9a at a given time. For the moment, consider only bed load, for which, as already explained, there is a unique rate of transport for any given hydraulic flow conditions and bed-surface composition. Because of the reservoir backwater, the rate of transport will decrease, as shown in Fig. 9b, from the open-river rate at the upper limit of backwater to zero at some point in the reservoir where the velocity and the energy gradient are small. The average depth of deposition between two sections, 1 and 2, after a short time period $\Delta t$ is given by

$$\Delta h = \frac{(q_1 - q_2)\Delta t}{\Delta L b \gamma_s}$$

in which $\Delta h =$ the average depth of deposition in a short reach

$\Delta t =$ the time period over which deposition took place

$\Delta L =$ the distance between Sections 1 and 2

$b =$ the width on which deposition occurred

$\gamma_s =$ the unit weight of deposited sediment in place (weight per unit volume)
The rate of transport at Section 1 (weight per unit time)

\[ q_1 = \text{the rate of transport at Section 1 (weight per unit time)} \]

\[ q_2 = \text{the rate of transport at Section 2 (weight per unit time)} \]

If the ratio of finite increments \( (q_1 - q_2)/\Delta L \) is replaced by the differential expression \( \delta q/\delta L \), and if the change in rate of this trans-
port gradient with time is neglected, the finite depth of deposition at a section during a short time period is given by

$$\Delta h = \frac{1}{b \gamma_s} \frac{\delta q}{\delta L} \Delta t$$

(2)

the bar having been removed from $\Delta h$ because it is no longer averaged over a reach of finite length. Equation (2) shows that the depth of deposition after the time period $\Delta t$ is proportional to the gradient in the transport rate. The transport rates at each section actually will change during $\Delta t$, but it will be assumed that $\Delta t$ is short enough that the initial transport rates can be taken as constant during the period without introducing a serious error. By taking the slope $\delta q/\delta L$ at several points on the curve in Fig. 9b and assuming $b$ and $\gamma_s$ to be known, depths of deposition during a time $\Delta t$ can be computed from Eq. (2) and plotted as in Fig. 9c. Equation (2) is a basic relationship for determining the increment of deposition at a section during a short time period. Equation (1) can be used if it is more convenient to deal with the average deposition in a short reach.

Calculating Progressive Delta Formation

Since the initial bed in Fig. 9a is the original river bed, Fig. 9c is actually the delta profile after the first increment of time in which aggradation occurs. The new water-surface profile resulting from the new delta profile can be calculated and is shown in Fig. 9d. Transport rates along the delta now vary as shown in Fig. 9e. From Eq. (2), the increments of deposition during a second time period $\Delta t$ can be calculated and added to the previous profile to give a second delta profile as shown in Fig. 9f. The procedure can be repeated until an entire succession of delta profiles are plotted.

Because the water depth increases rapidly over a short distance downstream from the foot of the delta as shown in Fig. 9d, the transport rate will go to zero rapidly over the same distance as shown in Fig. 9e. The result will be a large amount of deposition immediately downstream of the delta foot and, if the depths of deposition are computed from Eq. (2), a disproportionate piling up of material to an elevation above the delta foot may be indicated. Practically speaking, a river must push this material downstream in front of the delta. This results in the characteristic downstream building of the delta. For this reason it is felt that Eq. (2) should not be used downstream of the delta foot which exists at the begin-
ning of the time period \( \Delta t \). Instead, the volume of sediments which passed the delta foot during \( \Delta t \) should be distributed as indicated in Fig. 9f. This volume equals \( q_f \Delta t / \gamma_s \) in which \( q_f \) is the transport rate at the delta foot at the beginning of the time interval. The top boundary of this distributed volume logically can be the downstream extension of the delta surface occurring at the end of \( \Delta t \). Choice of the foreset slope can be based on the results of measurements in existing reservoirs. The writer has no reliable data on foreset slopes for presentation, but values ranging from 0.005 to 0.01 are suggested.

A procedure for calculating progressive delta development can now be outlined.

1. Determine an initial discharge, an initial reservoir pool elevation, and an initial bed profile.
2. From backwater calculations, determine the initial water-surface profile.
3. Calculate the varying rates of sediment transport along the river reach affected by backwater.
4. Assume a short time period \( \Delta t \) and assume that the transport rates remain constant at the initial values during this period.
5. Calculate the depths of deposition during \( \Delta t \) from Eq. (2). (Equation (1) can be used if it is preferred to divide the river into short reaches and compute the average depth of deposition in each reach.)
6. Add the depths of deposition to the initial bed profile to give the delta profile at the end of \( \Delta t \).
7. If the initial profile is a delta profile, calculate the volume of transport past the foot of the delta during \( \Delta t \) as \( q_f \Delta t / \gamma_s \) and distribute this volume downstream as suggested above.
8. Assume a pool elevation and a discharge at the beginning of the next time period \( \Delta t \), and calculate a new water surface based on the new delta profile.
9. Repeat the procedure until the calculated delta development is projected as far into the future as desired.

Determination of Variables

Prior to conducting the foregoing basic procedures, the engineer who sets out to make a calculation will be confronted immediately with a number of preliminary problems which must be solved before
a final solution can be obtained. These are discussed in the following paragraphs:

1. **Channel cross section.** The cross section of the channel in the delta is expected to vary with the channel bed composition and the slope of the delta. Until more is known about this variation, however, it is suggested that the cross section along the entire delta be assumed to be the same as the normal river cross section.

2. **Channel alignment.** It is necessary to assign a channel alignment on the delta in order to determine the channel bed slope. Although at present there is no way of determining analytically the optimum slope, the assumption is that it is the same as the normal river slope. This leads to a suggestion for determining the channel bed slopes to be used in hydraulic and transport calculations. If the computed bed plotted along the valley alignment has a slope less than the normal river slope, assume that the channel alignment is parallel to the valley, and use the bed slope equal to that of the profile. If the computed bed plotted along the valley has a slope larger than the normal river slope, assume that the channel meanders, thereby increasing its length so that the true bed slope equals the normal river slope.

3. **Channel roughness.** It is well known that the hydraulic roughness of an alluvial river channel varies considerably with flow conditions. For example, for the Missouri River at Fort Randall, South Dakota, the value of Manning’s $n$ varies from 0.014 to 0.045 as the discharge varies from 145,000 cfs to 5,200 cfs. There is a large range of velocities and water depths along a reach affected by reservoir backwater, and so it is reasonable to expect a considerable range in channel roughness conditions.

Einstein and Barbarossa [2] have presented a method, based on actual river measurements, of separating river-bed roughness into two components, the *granular roughness* of the bed material and *extra roughness* due to sand bars and to meandering of low flows within the channel. The extra roughness disappears for high flows, resulting in lower $n$ values. The extra roughness effect is evaluated from an empirical plot in which one dimensionless parameter, expressing the extra roughness effect, is found to be a function of another dimensionless parameter $\psi_1$ expressing the transport capacity of the flow. The parameter $\psi_1$ is a function of the velocity of flow, the energy slope, and the properties of the river-bed material.

Although this method was developed for uniform flow conditions,
the writer believes it can be used in the case of a channel affected by backwater. Holding the discharge constant and using the methods described in [2], the variation of Manning’s $n$ with water depth can be computed and plotted. Using this curve to vary the channel $n$ value with water depth, the water-surface profile on the delta for the given discharge can be computed by any standard backwater method. There is one reservation. The $n$ value should not become larger than that obtained when the $\psi_1$ parameter equals 4. The writer believes that the empirical curve which gives the extra roughness reflects the meandering of low flows within the channel for values of $\psi_1$ larger than about 4. The greater-than-normal depths for a reservoir backwater curve will prevent this sort of meandering from occurring in most cases. Therefore, extra roughness from this source will not materialize.

4. Computation of bed material transport rates. There are a number of formulae for computing rates of bed material transport, including those of Straub [3], Lane [4], Kalinske [4, 5] and Einstein [6], in which the rate of transport is a function of the average velocity, the water depth, the energy slope, and the bed-surface mixture. The velocity, depth, and slope are known for each delta channel cross section as soon as the water-surface profile is computed. Where no deposition has taken place, the bed surface mixture is that of the open river; where previous deposition has taken place, the mixture is that which has resulted from calculation of the previous increment of delta formation.

The existing transport formulae have been developed for equilibrium river conditions, but it is assumed here that they can be applied to the condition of an aggrading bed. This assumption may have to be revised when the results of studies of transport on an aggrading bed, now under way at the University of California, become available.

The writer suggests use of the Einstein [6] relationship because it presents a rational tie-in between the bed-material load transported as bed load and bed-material load transported as suspended load, it allows computation of load by individual grain-size fractions, and it corrects for the fact that a given grain size behaves differently in a bed mixture than in a uniform bed. At present there does not seem to be another theory as complete as that of Einstein. At first glance the computation method seems complicated, but working curves can be prepared which will facilitate its use.
The bed-surface composition at a cross section on the delta will change continually because the various grain sizes have different rates of deposition. These changes can be evaluated. If the initial bed-surface composition is assumed to be known, the transport rate of each grain-size fraction can be computed for various sections along the delta and plotted as in Fig. 10. The summation of the transport rates of each fraction gives the total rate of bed-material transport as shown in Fig. 10. From Eq. (3), a depth of deposition at a given section in a given time period can be computed for each grain-size fraction. Assuming the unit weight of deposited material is the same for each fraction, the depths deposited are proportional to the weights deposited. Therefore, the depths for each fraction computed from Eq. (2) can be combined to obtain an average mechanical analysis of the material deposited at a section during the time period. This mechanical analysis can be taken as that of the new bed surface.

5. Volume of wash-load deposition. There does not seem to be a functional relationship between discharge and the transport rate of wash load. The amounts which will enter the reservoir can best be estimated from the results of sediment concentration measurements over a number of years. These data will yield an average production rate in terms of weight per unit time which can be used to estimate the wash load inflow during a time period $\Delta t$. The records may show that there is a basis for varying the rate according to the time of year in which $\Delta t$ is taken, provided $\Delta t$ is some fraction of a year.

![Fig. 10. Rates of Transport for Various Grain Sizes Along an Idealized Delta.](http://ir.uiowa.edu/uisie/34)
What portion of the wash load will deposit in the delta along with
the bed-material load is a difficult question to answer. One approach
is to assign a percentage based on the results of surveys of existing
reservoirs for which the shape of the valley, the quality of the reser­
voir water, the quality of the inflow, and the nature of the clay load
are similar. Naturally this percentage must increase with the prog­
ress of delta formation because the longer the backwater area, the
greater the expected entrapment of silt and clay. In general, the
narrower the river valley the less the wash load that is expected
to deposit in the delta area, because substantial velocities across the
entire cross section will carry the material into the reservoir. The
possibility of rapid flocculation and deposition of the clays as al­
ready described should be considered.

6. Distributing deposits. The longitudinal distribution of bed-
material load deposition on the delta comes directly from the trans­
port calculations, but its lateral distribution must be assumed. As
long as the original channel has not filled up, the flow and the bed-
material load deposition probably is confined to that location. How­
ever, after the original channel has filled, the shifting of the chan­
nel probably will, in time, distribute the deposition fairly evenly
across the delta. Accordingly, it is suggested that the bed-material
load deposition be distributed within the channel until the original
channel fills up, and over the entire delta thereafter. This is equiva­
lent to using the channel width for $b$ in Eq. (2) before the original
channel fills, and using the delta width afterwards. It is assumed,
as an approximation, that the delta width may be taken as the aver­
age width of the meander pattern of the normal river. This width
may be maintained for analytical purposes where the delta builds
out into a wide pool.

The distribution of the wash load that deposits on the delta dur­
ing a short period of time $\Delta t$ must be assumed. Observation shows
that these deposits are far more predominant near the foot of the
delta where velocities are small and water depths are large than
they are near the head of the delta where conditions approach those
of the normal river. Outside of this general observation and the
other comments already made, the writer can offer no suggestion
for detailed distribution of the wash load deposition in a computa­
tion. This must be a matter of individual judgment. The sum of the
depths of wash-load deposition and bed-material load deposition
during $\Delta t$, added to the initial delta profile, will give the new delta profile.

7. Reservoir elevations and inflows. The sequence of pool elevations and inflows seems to be the most important factor influencing the ultimate shape of the delta profile. In contrast to the idealized delta shown in Fig. 1, actual deltas will have very complex profiles resulting from a succession of deposits upstream, downstream, and on top of one another, depending on the sequence of pool elevations and inflows. Estimates of future reservoir elevations and the corresponding inflows can best be obtained from the reservoir operation studies. On the other hand, it often will be found, especially in cases of reservoirs operated to meet power commitments as well as to provide flood control, that the pool elevation will fluctuate over a relatively short range much of the time, or is likely to be between certain set limits at the time of year when major inflows occur. In these cases, it seems just as well to assume, for the purposes of an aggradation study, an average pool elevation which remains constant.

If a constant pool elevation is used, the assumption of a constant average inflow may also be justified. In this case, a sediment mean discharge should be used rather than a temporal mean discharge. This is necessary because the higher discharges transport disproportionately high sediment loads, and the average discharge for a period will usually fall far short of transporting the average sediment load. The sediment mean discharge is found as follows:

a. Obtain a discharge frequency curve showing the percent of the time the inflow will exceed a given discharge.

b. Calculate a bed-material load rating curve for the normal river, plotting the rate of bed-material load transport against the river discharge.

c. Divide the range of discharges under the discharge frequency curve into a series of short increments. Then

$$\text{Sediment mean discharge} = \frac{1}{100} \sum (i_2 q_2)$$

in which $i_2$ is the percent of the time the discharge is in the narrow discharge range $Q_1$ to $Q_2$ (from discharge frequency curve), and $q_2$ is the average between the transport rate at $Q_1$, and the transport rate at $Q_2$ (from the bed-material load rating curve).

8. Degradation in the delta. If a reservoir is drawn down appre-
ciably from the pool elevations at which most of the delta formation occurred, the water-surface profile may be as in Fig. 11a with increased water-surface slopes at the downstream end of the delta. The computed bed-material load transport rates may increase in the direction of flow as in Fig. 11b, which means that the channel will degrade. Equation (2) can be used to compute the depth of degradation at a section. Using positive values of the gradient $\Delta q/\Delta L$, negative values of $\Delta h$ will be obtained, indicating the depths of degradation at each section as in Fig. 11c. The transport that passes the foot of the delta during the time period $\Delta t$ can be distributed
downstream as already indicated. Material scoured from the degrading channel bed is thus reworked downstream into the reservoir when the pool is drawn down. If it is expected that a reservoir will be operated so that the pool will be drawn down for any appreciable portion of the time, the possibility of reworking should be considered.

On account of the erosion-resistant qualities of consolidated clay deposits it can be assumed that reworking will be negligible in deltas which contain moderate quantities of clay. The deltas in Denison and Possum Kingdom Reservoirs fall in this category. Limited reworking of deposits can be expected in deltas such as those in Lake Mead, Conchas Reservoir, and Altus Reservoir, which contain smaller but significant quantities of clay. Only in deltas which are almost entirely sand, Gibraltar Reservoir for example, will the inflow have complete freedom to rework deposits farther into the reservoir when the pool is drawn down.

If channel degradation and reworking is expected to occur, the computation is made as described above. A section of the Conchas River channel is cutting into the Conchas Reservoir delta. This section, typical of degrading sections which were observed in sandy deltas, is a little wider than the normal river channel and seems to be widening very slowly by bank caving. In a number of years it may widen naturally the entire width of the delta; however, it is reasonable to assume that the reservoir pool will rise, putting an end to this condition, before the widening becomes extensive. Accordingly, it is suggested that the width of the degrading section be assumed equal to the channel width in using Eq. (2). In assigning a bed composition for use in computing transport rates at a section on the degrading bed, it is suggested that the aggradation computations be referred to and the composition of the material deposited at the same elevation during aggradation be used. The computed depths of degradation, based on bed-material load computations, should be augmented by the percent of wash load which deposited previously with the bed-material load.

Simplifying Assumptions

In view of the extreme uncertainty associated with some phases of the computation discussed above, particularly the volume and the distribution of the deposited wash load, certain simplifying as-
sumptions in connection with other phases seem warranted. These simplifying assumptions include:

1. Use of a constant channel alignment and cross section.

2. Use of a constant value of Manning's $n$ based on normal river conditions.

3. Assumption of a uniform bed mixture in sediment computations. (This is particularly applicable for rivers in which most of the bed mixture is concentrated in two or three sieve fractions. The size in a mixture at which thirty-five percent by weight is smaller is suggested as the effective sediment size.)

4. Use of a constant sediment mean inflow and a constant pool elevation.

**IMPORTANT EXTRANEOUS EFFECTS**

A number of phenomena associated with aggrading river channels may influence deposition to a far greater degree than reservoir backwater alone. Special problems associated with aggrading channels have occurred in three widely publicized cases, including the Middle Rio Grande near San Marcial, the Lower Colorado River near Needles, and the Pecos River upstream of Lake McMillan. Even though the problem in each of these areas occurred above a reservoir and may have been aggravated eventually by reservoir backwater effects, it should be pointed out that, in each case, the condition began before the reservoir backwater effect was felt and probably would have developed if a downstream reservoir had not been in existence. Since the phenomena are associated with aggrading channels, however, it seems pertinent to describe these cases in order to differentiate between normal reservoir phenomena and those which may be anticipated only under certain special conditions.

Since before the beginning of the century, the Middle Rio Grande in New Mexico has been an aggrading stream due to the fact that irrigation depletions have reduced the clear snow melt flows while the heavy sediment contributions from the tributaries have remained the same or have increased. Near the town of San Marcial, aggradation may have been accelerated in 1890 when the Santa Fe Railroad constructed a fill diagonally across the valley and contracted the channel into an 800-foot bridge opening. Aggradation continued until the channel bed was considerably higher than the adjacent valley; and in the flood of 1929 the river broke out of its channel, flowed into the lower part of the valley, and buried the
town of San Marcial with a deep deposit of sand. In the meantime, a high water table and the pooling of floodwaters adjacent to the perched channel promoted the growth of salt cedars and tules in the valley. This vegetative screen, in turn, promoted further deposition, and today the San Marcial area is a wide, swampy wasteland with a deep alluvial fill over what was once a prosperous agricultural valley. Although Elephant Butte Dam, 43 miles downstream, began to store water in 1915, the developments which led to the channel avulsion and extensive deposition in the valley were well under way before the reservoir backwater reached as far upstream as San Marcial.

A similar situation developed near Needles, California, where the Lower Colorado River had aggraded until the channel bed was higher than the valley floor. The aggrading condition started some time before 1900 and might have been aggravated by an impediment to the flow caused by a sediment “plug” deposited in the valley from Sacramento Wash, which joins the Colorado 13 miles downstream of Needles. In 1935, Hoover Dam, upstream of Needles, began storing water. For five years, during the filling of Lake Mead, the releases were restricted to minimum demand with the result that a dense growth of tules took over the unused portion of the channel downstream. In 1941, Hoover Dam releases were increased. The increased discharge could not be carried by the overgrown channel and the flow broke over into the valley, creating a vast swamp in which an almost impenetrable screen of tules soon developed. By 1944, the swamp was valley wide at Needles and extended 13 miles downstream to the town of Topock. All semblance of a river channel had been choked out by tules, and greatly increased flood heights presented the town with a severe flood threat which was alleviated in 1951 when a new channel was dredged through the swamp area (see complete description by Vetter). In 1937, Parker Dam was closed, filling Lake Havasu, the headwaters of which are near Topock. There will always be some doubt, but it is not probable that the backwater from Havasu had progressed far enough upstream by 1941 to aggravate the situation at Needles itself, although it probably did aggravate the situation downstream.

Prior to 1912 the Pecos Valley above Lake McMillan was practically void of vegetation except for low-growing salt cedars which had been introduced from abroad as an ornamental shrub. In 1915, volunteer seedlings of salt cedar appeared and began to multiply
at the head of the reservoir as well as along the river far above the reservoir. Evidently, climatic and soil conditions were especially conducive to salt cedar growth because the vegetation has become very dense at the head of the reservoir and for 200 miles upstream (see Fig. 12). This vegetative screen has induced overland deposition of sediment far up the valley, resulting in a swampy condition and high ground-water levels in adjacent fields. Overbank deposition upstream probably was increased by contractions at the Dayton and Artesia Bridges which are 9 and 17 miles, respectively, upstream of McMillan Dam. Although the reservoir undoubtedly aggravated the condition as far upstream as the Dayton Bridge, the backwater effects never extended far enough to affect the spread of vegetation and the deposition which occurred upstream of the Artesia Bridge.

The foregoing case histories point to two factors which should be considered in predicting delta development, because they may, un-der certain conditions, alter radically the deposition pattern in and adjacent to the aggrading channel at the head of a delta.

1. Vegetation. The overbank sediment deposits and the high water table which accompany channel aggradation in some cases might promote the spread of phreatophytes, or water-loving plants, such as salt cedars, tules, willows, and cottonwoods. This vegetative screen may promote accelerated upstream deposition by reducing
the overbank velocities during floods. The engineer should consult the agronomist in deciding whether climatic and soil conditions might be conducive to rapid phreatophytic growth.

2. **Contractions.** The cases of the Santa Fe Railroad Bridge near San Marcial and the Artesia Bridge above Lake McMillan indicate that such contractions may cause backwater effects which will promote deposition of sediment upstream. There is evidence to show that "The Narrows" in the Rio Grande Valley at the head of Elephant Butte Reservoir and the Granite Bridge, which crosses the head of Altus Reservoir, have created secondary backwater effects which promote deposition on the delta of sediment which otherwise might have been carried farther into the reservoir. The relative effect of contractions can be evaluated by making backwater computations.

Consideration of these extraneous effects points to the possibility of controlling reservoir sedimentation by inducing upstream deposition deliberately. The Bureau of Reclamation estimates that the vegetative screen above Lake McMillan intercepts over eighty percent of the sediment inflow, prolonging the useful life of the reservoir for many years. Naturally, if upstream valley lands are well developed, the prevention of extra upstream deposition is the problem; and the remedy is to maintain a clear channel through the length of the delta, to eliminate any man-made local contractions, and to keep the channel free of encroaching vegetation if possible.

**Conclusions**

A search for information through a great number of reservoir surveys reveals that reliable information on the delta portion of reservoirs is sparse. (Notable exceptions are Conchas Reservoir, Lake Texoma, and Lake Mead.) Because most surveys were conducted primarily for the determination of storage loss, only the portion of the reservoir below the spillway crest was considered, and reservoir effects upstream to the limit of backwater were not taken into account. If there is to be a better understanding of the way a delta is formed, the following information should be obtained from some reservoirs:

1. Water-surface profiles along the delta, during both high and low discharges.

2. Bed-surface samples taken along the channel from the head to the foot of the delta, during high discharges if possible.
3. Borings to determine the distribution of material within the delta.
4. Cross sections of the delta surface.
5. Surveys or aerial photographs of the channel alignment.
6. Reconnaissance of the delta after major inflows to note general disposition of new deposits on the delta surface.

This discussion of the various factors which must be considered in predicting future delta formation has pointed to the need for more information on some of the basic phenomena involved. In the opinion of the writer, the analytical tools which will enable predominantly sand deltas to be computed are on hand or are being developed; but for deltas which contain large amounts of clay the problem is still indeterminant because of the lack of knowledge of the criteria for deposition of fine materials. A computation of delta formation due to reservoir backwater is, in itself, inadequate as an engineering estimate in many cases. Consideration must be given to the possibility of vegetation and other extraneous effects altering the deposition pattern.

DISCUSSION

Mr. Lane, discussing Mr. Harrison's paper, commented that engineers dealing with sediment problems have in recent years become aware that the position at which the sediment coming into a reservoir deposits is very important. Some years ago, a common assumption was that the sediment deposited in the lowest part of the reservoir, with a level upper surface. It is now widely known that this does not occur and under the large range of conditions which is found in reservoirs, it is difficult to predict just what will occur. Mr. Harrison's paper is very valuable as an aid in such a prediction.

Probably the best way to visualize what will take place during the period of the filling of a reservoir, he said, is to realize that a delta will form. The deposition of sediment in an artificial reservoir is exactly the same as would take place if the same stream were to flow into a natural lake or other body of water with the same shape and water-level fluctuations. For this reason a study of natural deltas will throw a great deal of light on the deposition of sediment in reservoirs.

From the engineering standpoint, Mr. Lane continued, one of the most important aspects of reservoir sedimentation is the filling which takes place above the water level, as this has in some instances
resulted in considerable damage as in the abandonment of the town of San Marcial on the Rio Grande, already cited, which was about 18 feet above the highest water level reached in the reservoir. The effect was not entirely due to the dam, but was partly caused by a general aggradation of the stream. On the Colorado River the deposits above the Imperial Dam have in only 7 years reached upstream a distance several times as far as the length of the level pool above the dam, and this deposition would have continued to extend upstream had not the construction of another dam above caused a degradation which limited the filling. In regions where the supply is inadequate, the water used by the extensive vegetation growths represents a serious loss. The water use by the vegetation above Elephant Butte Reservoir is estimated at about 140,000 acre feet per year, and is largely responsible for the serious shortage of water which has recently occurred in the area served by that reservoir.

Mr. Bondurant reemphasized the point brought out in Mr. Vetter's discussion of problems along the Colorado River, that it was probably an aggrading stream along portions of its reach, even before construction was begun. The same thing was probably true along parts of the Rio Grande and that difficulty was to be expected sooner or later. The Rio Grande in the valley in the vicinity of San Marcial probably had gone through several avulsions prior to completion of Elephant Butte Reservoir, and the flooding of San Marcial might not have been entirely due to the construction of that reservoir.

Mr. Vetter expressed his appreciation of the presentation, which contained several observations which coincided with those that have been made along the Colorado River. He was a little pessimistic regarding the computation of delta formation in an artificial reservoir used for power generation, as the fluctuations are so great and rapid that conditions of equilibrium are probably never approximated. Lake Mead does not function as a natural lake would, for there are fluctuations of over 80 feet from season to season. With immersion of a delta formed during low reservoir, fine sediments are deposited on it, which are not susceptible to analysis for rate or time of deposition. When the lake is low and spring floods come, the flow over the delta is very violent, waves from 5 to 6 feet high have been observed and the delta is being rapidly and violently channelized.
REFERENCES
