CONSERVATION IMPACTS AND PRACTICES OF SAND
REMOVAL FROM DRY BED OKLAHOMA RIVERS

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ABSTRACT

An analysis of the response of a river system to sand mining requires establishing the morphology and hydraulics of the system prior to man's activities. The complexity of alluvial channel flow and the dynamic nature of river systems are reflected in the large number of interrelated variables necessary to describe natural streams. A number of interdependent factors responsible for changes in channel characteristics are discussed. As a general effect, sand mining decreases the local flow velocity with an attendant increase in flow capacity and more water storage becomes available. The long-term impact depends on the rates of sand removal and natural supply. Overmining results in lowering the base level for upper reaches and tributaries. The reduction of bedload will induce the downstream tendency to decrease the channel width-to-depth ratio and increase the sinuosity. An understanding of the meandering process reveals the best location and time for mining sand. Not all sand removal activities are detrimental. In fact, if under proper guidance, sand mining can act as a flood plain management factor and produce overall benefits. A set of guidelines for prudent sand mining is presented.

CHAPTER I

INTRODUCTION

GENERAL

Alluvial rivers have been a source of sand and gravel for many decades, but the physical impacts on river morphology have only recently been recognized. The usual rivers in Oklahoma and neighboring Western States are essentially wide braided streams with broad areas of exposed dry beds. This permits an easy access to a needed and desired economic commodity, namely, sand. This available resource has opened the door to an entire industry. River sand now is an important natural resource which has wide uses ranging from fill material applications to the whole of the industrial and construction industry in the State.

Apparently, no guidelines or rules have been set out by any governmental agencies that apply to sand mining operations. Fill activities in rivers have come under federal regulations in recent years; however, removal activity impacts are yet to be researched. Although not generally applied on the same scale as river maintenance or dredging, sand mining, which removes material from normally dry areas, can produce a significant influence on a river system. Nevertheless, not all sand removal operations are detrimental. A systematic and organized removal plan to mine sand from appropriate reaches is deemed to be essential in light of the latest environmental and conservation practices. Improper operations may well lead to bank erosion, meandering, scour, and increased flood hazards.

It is important to determine whether current modes of mining are adversely affecting the environment, and to identify the extent to which sand mining in natural rivers has a positive or negative net effect on the streambed.

A river system, when viewed from the geologic time span, is an open system undergoing continuous change, and there are no constant relations between the

dependent and independent variables as it changes with time. So this study was limited in scope and in geographical extent and its effort is only aimed at the qualitative of river regime to change over a relatively short geologic span of time.

PURPOSE

The sediment in a stream and the removal of that sediment have an important effecr on the stream's hydraulic geometry and environment. The intent of this study is to explore the effects of one particular form of sediment removal: the mining of sand from rivers.

The study will determine and assess the changes that sand mining causes in natural rivers and reveal some guidelines for prudent sand mining operations.

SCOPE

This study deals specifically with the physical changes that occur in a stream as a result of mining sand from that stream. Its intent is to provide a description of the various parameters affected (cross-section, velocity, etc.) and to determine the correlation between and among these variables. The study is limited, however, to the physical effects of sand mining. Other changes - for example, chemical effects and the impacts on a stream's biota - are beyond the scope of this study.

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CHAPTER II

LITERATURE SURVEY

All rivers possess a common nature of self-adjustment. This nature can be clearly drawn from the concept of grade or steady state proposed by Morisawa (1968). He stated:

> "A graded system, therefore, is one in which a steady state has been reached such that, over a period of time, the discharge and load entering the system are balanced by the discharge and load leaving the system. The steady state is achieved and maintained by mutual interaction of channel characteristics...any change in the controlling factors will cause a displacement in a direction that will tend to absorb the effect of the change."

A river is self-regulatory and for any change in hydraulic or hydrologic conditions, it will adjust to the new conditions by changing its slope, cross section, bed roughness, length, or the pattern of its channel. It may change any one or a combination of these characteristics, whichever it can, in order to maintain the balance between its ability to transport sediment and the sediment load carried.

The list of factors that influence alluvial channel flow should include:

$$F \ (V, D, S, \rho, u, g, d, \sigma, \rho_s, \ S_p, \ S_r, \ S_c, \ f_s, \ C_t, \ C_f, \ w) \ = \ 0 \tag{1}$$

in which

v = velocity

D = depth

S = slope of energy line

ρ = density of water-sediment mixture

g = gravitational constant

d = representative fall diameter of the bed material

σ = gradation of bed material

ρ_s = density of sediment

S_p = shape factor of the particles

S_r = shape factor of the reach of the stream

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S_c = shape factor of the cross section of the stream

f_s = seepage force in the bed of the stream

C_t = concentration of bed-material discharge

C_f = fine material concentration

w = particle terminal full velocity

In general ρ_s and g are usually taken as constant.

Applying techniques of dimensional analysis to this list of factors, with V,D, and ρ selected as repeating variables, yields:

$$F_1 \left(S, \frac{VD\rho}{u}, \frac{d}{D}, \sigma, \frac{\rho s}{\rho}, S_p, S_r, S_c, \frac{fs}{\rho V^2}, C_t, \frac{w}{V}\right) = 0 \qquad (2)$$

This equation provides a list of nondimensional parameters which are important in a study of alluvial channel characteristics. These include the Froude number ($V/\sqrt{gD}$), the Reynolds number ($VD\rho/u$) and a relative roughness parameters (d/D). The problems presented by the interdependency of these variables become apparent when an attempt is made to differentiate between depdendent and independent variables. They are all interrelated, and whenever one hydromechanic variable is changed, there is a compensatory change in other variables as well. For example, if one attempts to evaluate the effect of increasing channel depth by sand mining on average velocity, additional variables such as the bed roughness, cross sections shape, sediment discharge quantity, and the shape and position of bars also respond to the changing depth. It is therefore impossible to isolate and study the role of an individual variable.

The response to natural and imposed environmental changes of river channels was investigated by Lane (1955), Leopold and Maddick (1953), and Schumm (1971). These studies support the following general relationships:

(1) Channel width (W) is directly proportional to both water discharge and sediment discharge (Q_s)

(2) Depth of flow (D) is directly proportional to water discharge (Q) and inversely proportional to sediment discharge (Q_s).

(3) Channel shape, expressed as width to depth (W/D) ratio is directly related to sediment discharge (Q_s).

(4) Channel slope (S) is inversely proportional to water discharge (Q) and directly proportional to both sediment discharge (Q_s) and grain size (d_{50}).

(5) Sinuosity (S) is directly proportional to valley slope (S) and inversely proportional to sediment discharge (Q_s).

(6) Transport of bed material (Q_s) is directly related to stream power ($T_o V$) and concentration of fine material (C_f), and inversely related to the fall diameter of the bed material (d_{50}).

Then, a very useful relation for predicting system response can be developed by establishing a proportionality between bed material transport and several related variables.

$$Q_s \sim \frac{(T_o V) \; WC_f}{d_{50}} \tag{3}$$

where: T_o = bed shear

V = cross-sectional average velocity

C_f = concentration of fine material load

equation (3) can be modified by substituting rDS for T_o, and:

$$Q = AV = WDV \tag{4}$$

from continuity, yielding

$$Q_s \sim \frac{(rDS) \; WV}{d_{50}/C_f} = \frac{rQS}{d_{50}/ \; C_f} \tag{5}$$

If specific weight, r, is assumed constant and the concentration of fine material C_f, is incorporated in the full diameter, this relation can be expressed simply as

$$Q_s d_{50} \sim QS \tag{6}$$

Equation (6) is essentially the relation proposed by Lane (1955). He concluded that a channel could be maintained in dynamic equilibrium by balancing changes in sediment load and sediment size by compensating changes in water discharge and river gradient.

Equation (6) is most useful for qualitative prediction of channel response to natural or imposed changes in a river system.

CHAPTER III

RESPONSE OF LOCAL CHANNEL CHARACTERISTICS

INTRODUCTION

Mining of sand changes the local channel configuration and hence changes the flow characteristics. How the river responses to the change of channel shape and to what extent the removed material will be re-supplied are of primary concern. If the rate of mining exceeds the natural rate of supply, detrimental changes in the river result. Due to the complex interrelations between channel variables, each case needs individual analysis to predict the channel response to mining operations. Periodic surveys are essential to identify the trends of change of channel characteristics.

Although quantitative response cannot be precisely predicted, some general conceprs are helpful to analyze the qualitative trends. One idea is that all attempts to change the local configuration of the channel without changing the forces that have produced the configuration can be expected to prevail against the dominant forces of the system for only a limited period of time. For example, one might be skeptical about a oermanent lowering of the water surface profile by channel enlargement due to sand mining.

A. CHANNEL CONFIGURATION

When sand is removed from a river, the channel's cross section increases as defined by Manning's n equation:

$$Q = \frac{1}{n} \; A \; R^{2/3} \; S^{1/2}$$

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where

Q = flow

n = manning's n

R = hydraulic radius

S = slope

The change in turn affects other physical properties. Each of these is discussed below.

VELOCITY

Velocity has an inverse relationship with cross section: i.e., as one increases, the other decreases. In this case, because the cross section has been increased by the removal of sand, there will be a decrease in the velocity of the river's flow. Further impacts resulting from changes in velocity - including the effects on the rates of erosion and sedimentation - are discussed below in Section B.

DEPTH

Increasing the cross section also affects the depth of the water in the river. Since flow is assumed to remain constant, its depth in the broadened channel will naturally be less than it was in the original, narrower channel.

Manning's n

Removing sand and the accompanying change in channel configuration will cause the value of Manning's n to change. This, in turn, will have an effect on velocity, although the nature of that effect - i.e., whether velocity will be increased or decreased - depends on the type of soil underlying the sand removed.

Other Variables

Other variables that are affected, to either a major or minor degree, by an increase in cross section are channel gradient, energy gradient, and critical depth. Channel gradient will be increased and, as a result, change velocity. On the other hand, energy gradient and critical depth will both decrease because the water elevation (depth) is lower.

B. VELOCITY

The speed with which water flows through a channel has a very important effect on the physical, chemical, and biological characteristics of a stream. Even a slight change in velocity can produce changes in other hydromechanic variables, especially in the rates of erosion and sedimentation and in channel gradient.

EROSION RATE

Velocity has a direct relationship with the rate of erosion: increased velocity means more erosion; decreased velocity means less. As mentioned above, removing snd from a stream increases cross section, thereby decreasing velocity. (A change in the value of Manning's n may make velocity decrease even further, although this will depend on thr type of soil underneath the sand.) Since velocity has been decreased, eroision will then be decreased as well.

Sedimentation Rate

Under certain conditions, waterbone material is allowed to settle in a streambed. One of the factors that determines whether and how fast sedimentation occurs is velocity. Unlike erosion, sedimentation has an inverse relationship with velocity. Thus when velocity decreases - as it will when sand is removed from the stream segment being suited - the rate of sedimentation will increase. The larger objects carried by the water will settle first, with smaller particles then being deposited further downstream.

Channel Gradient

As mentioned in Section A, the decline in velocity will make the channel gradient steeper. However, this change will be partially offset by the increased rate of sedimentation. That is, the additional settling of waterborne material will help fill in areas of the streambed from which sand has been removed. The rate of recovery in channel gradient will vary, of course, depending on how much rhe sedimentation rate has been increased. However, the recovery rate will still remain far lower than the rate of excavation.

C. FLOW REGIME

Stream flow can have four different regimes:

1. subcritical laminar: Froud's number (F) is less than 1.0; Reynolds' number (R) is in the laminar range

2. supercritical laminar: F is greater thatn 1.0; R is in the laminar range.

3. subcritical turbulent: F is less than 1.0; R is in the turbulent range.

4. supercritical turbulent: F is greater than 1.0; R is in the turbulent range.

Figure 1 shows the relationship between depth and velocity in these four regimes.
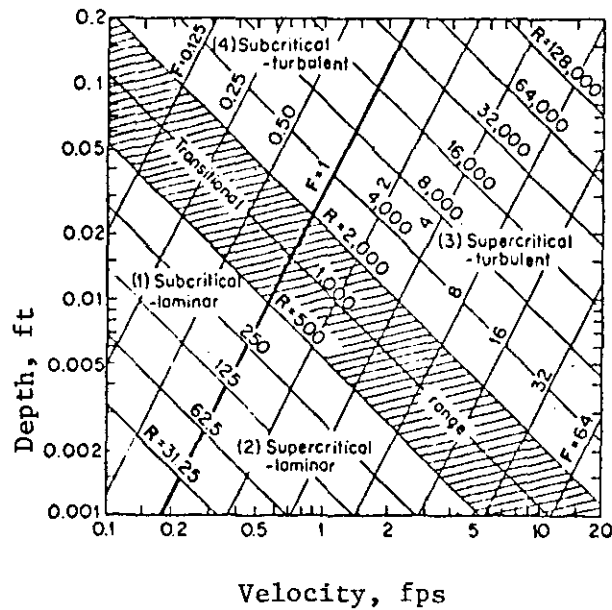

Velocity, fps

FIGURE 1

DEPTH–VELOCITY RELATIONSHIPS FOR FOUR REGIMES
OF OPEN–CHANNEL FLOW

To determine Froud's number, the following formula is used:

$$F = \frac{v}{\sqrt{gL}}$$

where

v = mean velocity

g = acceleration of gravity

L = characteristic length of the channel

If $\sqrt{gL}$ is assumed to remain constant, then since the removal od sand causes the value of v to decrease, it will also mean a decrease in the value of F.

Reynolds' number is determined by this formula:

$$R = \frac{vL}{\upsilon}$$

where

v = mean velocity

L = characteristic length of the channel

υ = kinematic viscosity of the water

If $\frac{L}{\upsilon}$ is assumed to stay constant, then the predicted decrease in velocity means that Reynolds' number, like Froud's will also decrease.

The removal of sand from the river therefore means that, with decreasing values for F and R, the flow regime will tend to be subcritical turbulent.

D. GROUND WATER

Removing sand from a river may have a significant impact on the ground water resources beneath the streambed since changes in the river can affect its ability to recharge these resources. Among the variables that must be examined to determine the effects on the stream's recharge potential are:

1. the depth of the excavation made for sand removal both above and below the water table

2. the slopes and elevations of the streambed, the water surface, and the stream gradient

3. the rate at which water infiltrates through the channel bed to the water table: i.e., the rate at which the stream is able to replenish ground water supplies

E. EROSION

Studies and observations of a number of channelization projects have demonstrated that moderate velocity can be an important factor in causing erosion. A higher velocity will have an even greater impact, leading not only to erosion of the streambed but also to sloughing off of the channel's banks.

Several things can help minimize erosion, including careful design by those involved in sand mining. Limiting the amount of sand removed from a stream will reduce the danger of erosion, as will ensuring that the channel gradient after excavation remains slight (i.e., not too steep) and the side slopes of the channel banks, moderate. Another factor inhibiting erosion is the stability of the streambed, which is determined – at least in part – by the texture of its soils. Once exposed by excavation, some soils resist erosion better than others. Table 1 lists various soil types that may be encountered when sand is being mined from a stream and ranks them in order of their resistance to erosion (i.e., from the most resistant to the least)
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TABLE 1

RANK	EROSION RESISTANCE
1	Gravels and gravelly sands
2	Clayey gravels and gravel–sand–clay mixtures
3	Silty gravels and gravel–sand–clay mixtures
4	Clayey sands and sand–clay mixtures
5	Well- to poorly-graded sands with gravel
6	Silty sands with gravel
7	Inorganic clays of low plasticity
8	Inorganic clays of high plasticity
9	Peat and other organic soils

SOURCE: U.S. Department of Agriculture, Soil Conservation Service, Engineer-
ing Field Manual for Conservation Practices, 1973, pages 4 – 18

As the table shows, gravels and gravelly sands offer the best protection against erosion. Surface excavation of sand mining can destroy this protection and open up the area for possible erosion. The impact of removal of surface cover is closely related to the role played by the coarser fraction of the bed material in controlling and stabilizing channel patterns and bed forms. This coarser fraction has a tendency, through hydraulic sorting, to armor the bed; thereby retarding or arresting excessive scour, stablizing banks and bars, and preventing excessive sediment movement. Formation of a gravel armor layer will tend to retard degradation of a riverbed and thus limit the depth of scour. Armor on the upstream nose of a point bar will resist formation of a chute channel and the development of a divided reach. Gravel armored sandbars can serve as channel controls that define river form. Removal of the coarser fraction from such features can lead to erosion and loss of this contro. As a possible result, meandering reaches may tend toward a braided character, velocity and bed-material transport may increase, and localized changes may contribute to the deterioration of adjacent reaches.

F. SEDIMENTATION

A stream contains two kinds of sediment: that which is carried by the water (suspended load) and that which has settled in the streambed (bed load). The relative amounts of each kind of sediment present in the stream will depend on flow conditions; thus sediment may at one time be part of the bed load and yet at another belong to the suspended load.

With regard to the suspended load, a stream's capacity sediment of one size is at least partially independent of its capacity to carry sediment of a different size. The total amount of sediment that a stream is able to carry depends on a number of factors, but one of the most important is discharge (flow). The correlation between suspended load and discharge is typically

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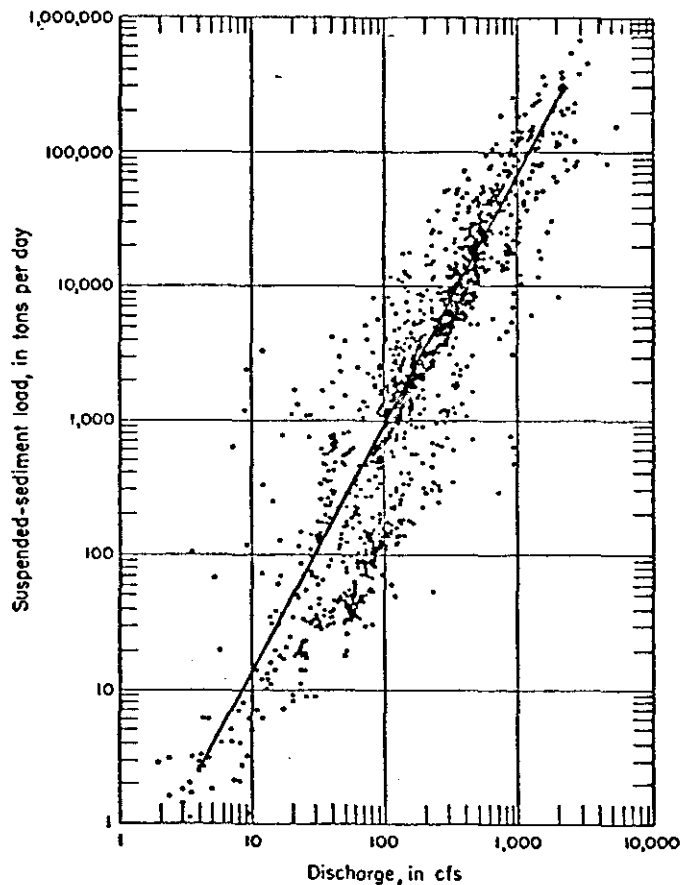
FIGURE 2

RELATION OF SUSPENDED SEDIMENT LOAD TO DISCHARGE
Powder River at Arvada, Wyoming

After Leopold et al. (1953)

shown by a sediment rating curve in which the suspended sediment in units of

weight per unit of time is plotted against the discharge of the water-sediment

mixture. Data obtained from daily, weekly, or other periodic samplings at

sediment gauging stations (which are being installed and mointored in increasing

numbers on American streams by state and federal agencies) are used to plot

such curves. The relationship between the suspended load and discharge at a

particular gauging station on a typical river is shown in Figure 2. The curve

in this figure contains a wide scatter of points, which indicates that for a given discharge rate, the amount of suspended sediment may vary considerably, depending on other factors such as velocity.

If, however it is assumed that there is a straight-line relationship between the amount of suspended sediment in a stream and the discharge rate, then this relationship can be expressed by the following formula:

$Z = pQ^j$

where

z = sediment load in tons per day

p = 2

Q = flow

J = 2

According to thei formula, since p and j are both numerical constants, suspended sediment at any given point in a stream increases faster than the discharge at that point, with the difference between the two becoming more and more pronounces as Z and Q increase. Thus a large increase in flow – for example during a flood – will produce an even more dramatic increase in the amount of sediment carried by the stream.

As mentioned above (see Section B), the rate of sedimentation will determine how much of an excavated area will be refilled, and how quickly. The sedimentation rate in turn depends on how much sediment the stream id able to carry. Thus, to prevent irreversible changes in a river's hydro-mechanic properties, the sediment in both the bed and suspended loads must be adequate to maintain the river's physical equilibrium once sand is removed.

G. MEANDERING

A stream's movement is not only longitudinal but also transverse, which means that no stream travels in a perfectly straight line. Basically, there are three different kinds of channel patterns: sinuous, meandering, and braided. Sinuous and meandering patters are similar, except that in a meandering river thr curvature is more pronounced. The difference between the two is defined by the ratio of channel length (thalwag, or the actual length of the channel as measured along its lowets curve between two points) to valley length (or axial length, as measured in a straight line between the same two points):

$$\text{Sinuosity (or Tortuosity) Ratio:} \quad \frac{\text{Length of thalweg}}{\text{Axial length}}$$

If this ratio is less than 1.5, the river (or the segment in question) is sinuous; if equal to or greater than 1.5, it is meandering. Both sinuous and meandering rivers flow in channels that are generally well defined. A braided river, on the other hand, is quite different. It does not have a single channel, much less a well-defined one; rather, it consists of a network of several interlacing streams.

Meandering rivers are important to the sand minig industry, for the meandering process creates rich deposits of sand. Moreover,if the sand is removed properly (i.e., from the rights parts of the stream at the right times, as discussed below), the potential for irreversible damage to the stream is kept to a minimum, even while sand retrieval is maximized.

A meander in a river may be defined as a full S-curve in the river's path that begins at the apex of one bend, passes completely through a second bend, and ends at the apex of a third bend. In a meander, the flow changes direction (o.e., from clockwise to counterclockwise, or vice versa) two times, thus beginning and ending by flowing in the same direction.

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A typical meander is shown in Figure 3.

L_M	Axial length of meander	W_M	Width of meander
----	Thalweg (channel length)	B	Width of channel
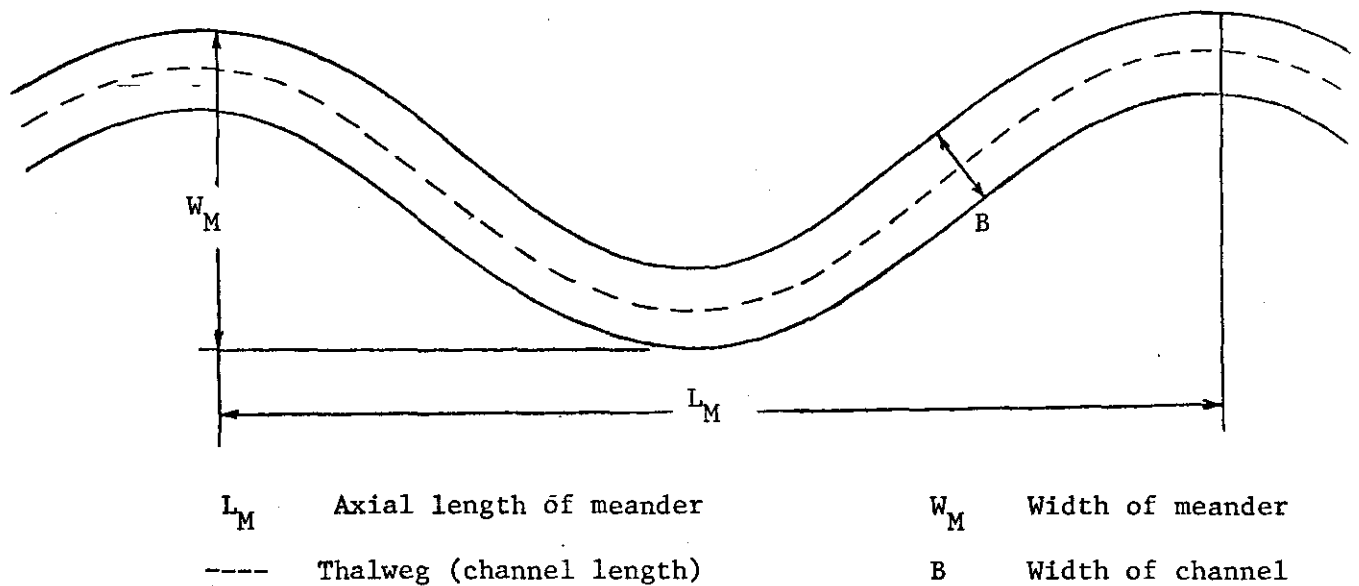
FIGURE 3

TYPICAL MEANDER

As a result of regime studies on rivers in India, Sir Claude Inglis postulated a simple empirical formula for determining the length of a stream's meander:

$$L_M = C_L (Q_{max})^{1/2}$$

where

L_M = mean length of the meander (as measured along a straight line between two corresponding points on successive meander loops)

Q_{max} = peak river flood (100-year frequency)

C_L = constant (range: 18 to 42)

With rather less confidence, Inglis proposed a similar equation for determining a meander's width (W_M) as measured between the outside banks:

$$W_M = \tfrac{1}{2}C_L(Q_{max})^{\tfrac{1}{2}}$$

A number of more recent studies, however, indicate that a meander's length and width — as well as the radius of its curvature (R) — are instead dependent on the square root, not of the peak discharge, but of the dominant discharge (Q). The length, width, and radius also have a direct relationship with the stream's width (B). These relationships can be expressed by the following equations, in which typical constants are used*:

$$L_M = 30\ Q^{\tfrac{1}{2}} = 12\ B$$

$$W_M = 15\ Q^{\tfrac{1}{2}} = 6\ B$$

$$R = 6\ Q^{\tfrac{1}{2}} = 2.4\ B$$

The higher the ratio, the more pronounced the meander: i.e., the sharper the bends (or turns) in the river's channel.

The general phenomena associated with meandering are fairly well known because of observations on many rivers throughout the world. The characteristic patterns of meandering can best be seen on rivers that flow through alluvial valleys since these represent the most recent geological formations and the meandering patterns are thus less influenced and obscured by other geological and topographical forces.

Sinuous and meandering rivers develop dynamic patterns that never quite stabilize but are always in the process of changing. This is reflected in the fact that a meander's width is always less than the width of the river's meander belt, or that part of the floodplain over which meanders have extended throughout the river's geomorphic history.

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*The values, though typical, are naturally imprecise. When applying these equations to a given meander whose particular characteristics are known, they should, of course, be replaced with actual values.

A number of factors affect a river's meandering patterns, among which is the movement of currents from reaches and crossings. A reach is a fairly straight strecth of the river between teo bends; a crossing is similar but limited to the area where the flow is changing direction (clockwise to counterclockwise, or vice versa). The currents from reaches and crossings are directed towards the concave bank at the next bend. This in turn erodes the bank, in effect digging a cave into it that subsequently causes the top of the bank to collapse. This has several effects. First, the bend is made deeper, or is elongated in the sense that its actual length is increased. In additon, the material eroded from the concave bank tends to settle in the next crossing, with the result that the channel tends to become deeper on the concave side of the bend but shallower in the crossing. Eroded material is also deposited on the opposite side of the bend (i.e., the convex side), thus building the channel further and further out towards the middle of the bend. This transverse movement of both the convex and concave sides of the bend continues until a certain limiting point is reached. At this point, chutes tend to develop across ths shoals on the convex bank. These direct the flow towards the downstream end of the concvae bank, thus causing the bend to move gradually downstream.

The transverse and longitudinal movements of a typical bend are shown in Figure 4.
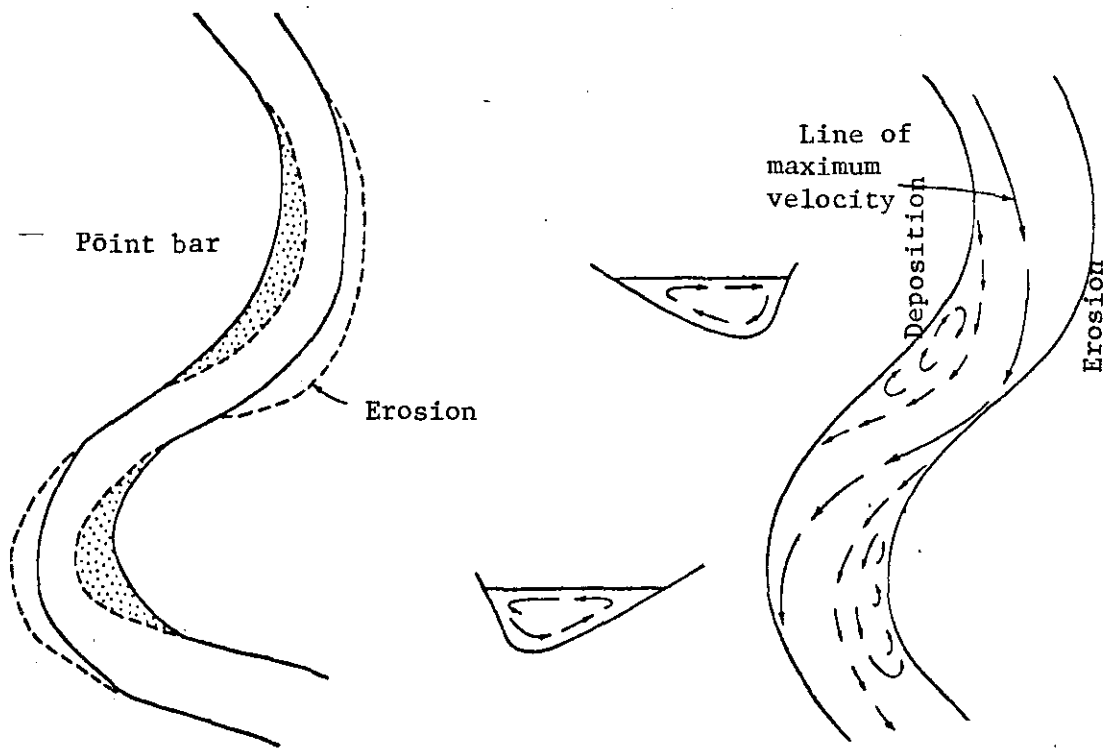
FIGURE 4

TYPICAL MOVEMENT OF A MEANDER

This typical development, of course, is subject to many variations, depending on local conditions. For example, if the downstream banks of a bend are particularly resistant to erosion, the tendency of the bend to migrate downstram is inhibited. Moreover, evn though this migration is slowed, the bend continues to be increasingly elongated until it reaches maximum curvature; at this point, the pressure of the flow may cause the stream to break through the neck of the bend, creating a new channel and abandoning the old one (which then forms an oxbow lake).

One of the advantages of mining sand from rivers is that it can prevent this phenomenon: removing sand deposited along the convex side of a bend - especially at the downstream end - relieves the pressure of the flow

so that the natural tendency of the bend to move downstream is encouraged, thus avoiding the creation of a new channel.

As we mentioned above, meandering rivers provide rich deposits of sand becausr the meandering process increases sedimentation in crossings and along the convex sides of bends. However, when removing sand from these areas, it is preferrable that sand be minded after flooding occurs. The reason for this is that low flows tend to cause scouring of the crossings and to deposit the scoured material into the deep pools near a bend's concave banks. During flood stages, on the other hand, the main thrust of the flow tends to shift away from the low-water channel towards the general axis and slope of the valley, thus increasing the scouring of the concvae banks and in consequence, the deposition of eroded material in crossings and along the bend's convex banks. This deposition reaches its maximum as the flood stages recede. Therefore, the best time to mine sand from a meandering river is immediately after this occurs.

CHAPTER IV

RESPONSE OF ADJACENT REACHES

UPSTREAM IMPACT

A wave of erosion or headcutting will move upstream to the mining area as a result of streambed lowering. Although the bed of mining area will be somewhat filled back to its former level as floods recede, the effect of over-mining is clearly pointed out. It will lower the upstream bed and causes possib;e detrimental effects on the foundations of nearby structures. In this case, tributaries entering this area will have their beds lowered too as they adjust to the new base level. It indicated that a safety distance should be kept from the mining area to structures such as bridges and a controlled rate of mining to ensure that overmining does not happen.

DOWNSTREAM IMPACT

As a result of sand removal and the consequent sedi mentation after floods, the mining area acts as a sink and traps for sediment material, that is, Q_s will be reduced to $\bar{Q_s}$ downstream at high stages. Assuming grain size remains constant as water discharge, slope must decrease downstream of the mining area to balance the proportionality of equation (6) as mentioned in Chapter II.

$$Q_s \ d_{50}{}^{0} \sim Q\,\bar{S}$$

This indicates sand mining would induce a tendency of degradation down-stream. A dam, from which degradation is usually predominant, is a typical example to illustrate the effect of sediment reduction. However, the effect of sand mining is quite different from that of a reservoir. It only reduce sediment load at high stages and the amount of reduction is also not signifi-cant. The downstream response of channel adjustment may be very sloe and needs long time to detect the effect.

The foregoing discussion has assumed that the stream on which the changes occurred was in equilibrium before the mining operations. In applying the

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reasoning developed to the case of any particular river, it is necessary to know whether or not that the mining reach is in equilibrium. For example, a change in the condition on a stream in equilibrium which would produce an aggrading profile might produce in a degrading stream only a slowing down of the rate of degrading. Similarly a change of conditions that would produce degradation in a stream in equilibrium might, in a stream which was aggrading, produce only a slowing down of the aggradation, unless the degrading effect of the change was greater than the present aggradation. So, it is important to identify what kind of state the mining reache was in before the assessment of erosion or deposition induced by the mining operations.

As a decrease in slope, there will be a corresponding change on channel patterns. Lane (1957) investigated the relationship among slope (S), discharge (Q), and channel pattern in meandering and braided streams, and observed that an equation of the form $SQ^{1/4} = K$ fits a large amount of data from meandering sand streams. He found when $SQ^{1/4} \lesssim .0017$ a sand bed channel will tend toward a meandering pattern. Similarly, when $SQ^{1/4} \geq 0.01$ a river tends toward a braided pattern. Slope for these two extremes differ by a factor of almost 6. The region between these values of $SQ^{1/4}$ can be considered a transitional range where streams are classified as intermediate category. If a river is braiding, but with a discharge and slope that borders on transitional, a relatively downstream decrease in slope caused by sand mining could initiate a tendency toward a transitional or more stable meandering pattern.

IMPACT OF TRIBUTARIES

Effects of sand mining on the stream bed profile can be influenced by the impact of tributaries also. Tributaries fall into two classes (Thomas, 1977): (1) those transporting sediment that is finer than the bed load of the main stem, and (2) those having bed material equal to or coarser than that of the main stem. The first type will assist the main stem in transporting bed

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material, resulting in channel degradation and a decrease in slope downstream from the confluence. The second type will exhibit the opposite trend with the confluence area serving as a sink for deposition of bed load until a flood on the main stream removes it. This implies that a mining operation conducted at the confluence area of the second type may produce positive effects on the main stream, or at least it can reduce the undesitable deposition by tubitraries to some extent.

EFFECTS ON FLOODING

Due to a change in flow characteristics, there must be a corresponding change in hydrograph. Considering what happens on a single channel rather than an entire basin, we can expect that more water storage become available after the enlargement of channel and therefore the local flooding is reduced.

Also, systematic removal of sand leads to a reduction in roughness and an attendant increase in flow capacity at the same elevation. This might cause a slight downstream flooding as a result of increased flow capacity of the mining reach.

Anything that happens to change the upstream hydrology must affect downstream processes. However the variety of responses and possible inter-actions are complex. Sand mining in upstream tributaries might slightly increase the flood hazard downstream as the effects of the channel modifications is to move more storm water downstream than the lower reach can discharge it. On the other hand, it might actually reduce downstream flooding if the flood peak from a modified tributary moves out of the basin prior to the arrival of flood peak from other tributary channels.

It is emphasized that each stream must be evaluated independently and a basin-wide analysis is necessary if accurate prediction of downstream flooding is to be achieved. Generalizations remain dangerous.

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CHAPTER V

SAND MINING AS A MORPHOLOGY AGENT

It is obvious that sand mining is neither river development or maintenance oriented, nevertheless they can be incorporated together to produce a type of mutual beneficial influence. The mining of sand can be controlled by the agencies responsible for flood control, navigation, and river stability. Sand will be removed from the river only after due consideration is given to possible adverse effects.

As discussed previously, the reduction of bedload will cause a decrease in channel width-depth ratio and an increase in sinuosity. The eventual result is a more stable channel. In this case, sand mining can play a positive role. Many of the wide, sandy, unstable rivers could be transformed to stable channels partially through reducing of bedload transport. This can be done either by controlling the main stream or tributaries. Where high discharges are required to clear a channel of sediment contributed from tributaries, serious aggradation with accompanying flood problems may arise if periodic flushing of the sediment from the channel does not occur. The aggradation area of main stream or the draining areas of those tributaries are sources of sand and gravel. Hence, mining at these areas does provide a solution to some extent.

Constraining the natural tendency of the channel to meander impacts on the behavior and sediment transport capacity of the river. When the freedom of shifting is taken away because of bank stabilization, the coarser sand deposit on the stream bed, rather than point bars. The resulting aggradation trend makes one consider the consequence of having to raise the levee at some future time to just maintain the capacity to pass the design flood. In this case, when undesired increase in height of stream bed is induced by the fixation of channel location, sand mining shows another benefit in flood control.

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Mining sand from tributaries upstream to reservoirs can reduce sedimentation problems and prolong the life of the project. It can also be related to river dredging as to solve the disposal problem of dredged material.

Whenever sand mining acts as a morphologic agent in support of river development programs, improvement of the reach must be the primary consideration and the obtaining of sand only a secondary benefit.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Sand removal from rivers has been oriented towards "business" wherein the mined sand constitutes selective material used by the construction industry. Not all sand removal operations are detrimental. Unfortunately most mining operators simply remove the most accessible sand and stockpile it at the most convenient place with no regard to the possible damage to the stream. Since no guidelines or rules have been set out by any governmental agencies that apply to this problem, it is anticipated that increasing environmental concern will result in significant controls on sand mining operations. Solution to the dilemma of expanding commercial needs and growing constraints requires a fundamental understanding of the geomorphic and hydraulic response of a river system to the mining operations.

The complexity of alluvial channel flow and the dynamic nature of river systems are reflected in the large number of interrelated variables. Furthermore, the difference in character, meander system, and geometric parameters between the low-stage and high-stage river reveals that an alluvial river is really two rivers flowing in the same bed and adds to the complexity of river systems. Due to this reason, an accurate assessment of quantitative impacts of sand mining is not always available. Where quantitative data is not available for detailed long-term analysis, qualitative analysis constitutes an essential first-step in the analysis by establishing the general trends to be anticipated. As is more often the case, when time or data limitations preclude a detailed quantitative analysis, the indicators provided by qualitative relationships are even more valuable.

From the previous study, several conclusions are drawn as follows:

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1. Removing sand from a stream causes an increase in cross section in the area being excavated. Increaed cross section in turn leads to a reduction in velocity.

2. Decreasing velocity lessens erosion, though the degree to which erosion is reduced depends on the texture of the soils exposed after excavation since some soils resist erosion better than others. As a guide to erosion prevention, Table II lists the maximum velocities acceptable for various soil types.

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TABLE II

Soil Texture	Mean Water Velocity (Feet/Second)
Light, loose sand	1.25
Coarse, clean sand or lightly sandy soil	1.75
Sandy loam	2.50
Silt loam, alluvial soil, average loam	3.00
Clay loam	3.75
Stiff clay, fine gravel, gravelly soil	4.50
Graded silt to cobbles	5.50
Shale, coarse gravel	6.00

SOURCE: U.S. Department of Agriculture, Soil Conservation Service, Engineering Field Manual for Conservation Practices, 1973, pages 4 - 24.

. . . .

3. An increase in sedimentation occurs both when velocity decreases and when flow increases. The former is an automatic results of sand mining since excavation causes a reduction in velocity. However, the increased sedimentation that results will be far less than necessary to fill in excavated areas. Therefore, to increase sedimentation still further and help replenish excavated areas more quickly, sand mining operations should take advantage of periods of increased flow. That is, a desirable time to remove sand from a stream is after a heavy rain, for the rain itself and the resulting runoff upstream will accelerate the rate of sedimentation.

4. The convex sides of bends in meandering rivers offer some of the most attractive sites for sand mining because of their rich sand deposits. It is best that such areas be mined after flooding has taken place and flood stages are receding, both because of the general affect on sedimentation rates described above and because of the impact high flows have on flow patterns in meandering rivers: i.e., after flooding, the sediment carried by the river is not only increased but also far more likely to be deposited in the very areas from which sand is being taken.

5. As mentioned above, increasing cross section reduces velocity. Downstream, however, if the channel has not been altered by excavation, the velocity will resume a faster rate.

6. Systematic removal of sand leads to a reduction in roughness and an attendant increase in flow capacity. The local flooding is reduced, but the net effect on flooding needs a basin-wide analysis.

7. Changing the depth of the water flowing in a stream can have serious consequences, though these are mainly biological and chemical effects beyond the scope of this study. Nevertheless, care should be exercised to ensure that there are no radical changes in water depth resulting from the mining of sand.

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8. From the perspective of this study, the depth of excavation is of critical importance. It is vital that sand be removed at a uniform rate so that the stream's relative slope is unchanged. Otherwise, the entire character of the stream may eventually be altered.

9. Sand should not be removed from all streams. In particular, excavation for sand removal is harmful to streams with low flows and thus should be scrupulously avoided.

10. Wide braided or meandered reaches, where aggradation often involves a shoaling and widening of the channel, are usually good sources for sand. Sand mining on these areas acts as a sink and traps sediment load. The reduction of sediment discharge, especially bed load, can result in a more stable channel. This will be a long-term impact and depend on the initial state of quasi-equilibrium of the river. If well planned, sand mining can act as a flood plain management factor and produce overall beneficial effects, the most obvious being a no-cost maintenance of the river channel.

RECOMMENDATIONS

A long-term post-mining survey program and documentation effort would provide the data base for a thorough examination of the effects of depth, width, alignment and channel stability under a wide variety of hydraulic and geomorphic conditions. In order to attain benefits certain critical elements of the sand mining operation should be considered. These can be formulated into the following guidelines:

1. Sand should be mined only where and when conditions encourage maximum sedimentation to replenish sand losses from the stream.

2. Sand should be removed at a uniform rate and extent wherever it is mined.

3. Sand should be removed only between the left and right overbank stations.

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4.   Sand should not be mined from small flowing streams or from any stream at high flow.

5.   Sand should not be mined near piers and bridges.

6.   A material control process should be implemented so that periodic surveys can ensure that overmining does not take place.

7.   The gravel-armored portions of sand bars should not be removed.

8.   The oresent gradient of the stream should be maintained the same as possible; any abrupt change in profile should be avoided.

9.   Stockpiling should be performed only in parrallel rows to the river and removed before floods.

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