EROSION AND SEDIMENT TRANSPORT
IN THE
SACRAMENTO - SAN JOAQUIN DELTA CHANNELS
STUDY PLAN

to

State of California
The Resources Agency
Department of Water Resources
Central District

by

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1. INTRODUCTION

The Central Valley Basin of California is drained by two major river systems, the Sacramento in the north and the San Joaquin in the south. These river systems produce roughly 40 percent of the annual runoff of the state and converge in the Sacramento-San Joaquin Delta ("Delta") which encompasses 737,000 acres interlaced with some 700 miles of meandering channels. A map of the Delta is shown in Figure 1. The Delta receives freshwater discharges from the rivers, local runoff, and return flows of man's activities upstream. These flows interact with the tides and are modified in quantity and quality as they pass through the Carquinez Straits, San Francisco Bay, and finally, the Golden Gate into the Pacific Ocean.

Man's modification of the Bay-Delta system, and continuing activities have resulted in significant changes in the hydrodynamic, sedimentological, and water quality aspects of the system. Land reclamation, and accelerated shoaling caused by the inflow of hydraulic mining debris, are said to have reduced the area of San Francisco Bay by some 37% in the last 100 years (1,2). Diking of lands within the Delta for agricultural use has reduced the inundated area to a small fraction of the original extent.

As a result of the state's enormous requirements for water, primarily for agricultural use, reservoirs, pumping facilities, and conveyance systems to redistribute water from areas of surplus in the north to areas of demand in the south have been constructed in recent years. The U.S. Bureau of Reclamation's Central Valley Project which went into operation in the mid-40's and the California State Water Project implemented in the 60's, are outstanding examples of engineering works designed to manage the state's water resources. Together these two systems possess an active storage capacity of about 16 million acre feet and conveyance facilities capable of transporting some 12 million acre feet of the estimated 33 million acre feet of runoff at the Delta.

Great quantities of sediment are transported by the rivers into the Bay and Delta and move primarily as suspended load. Of the estimated 5 million tons per annum of sediment inflow to the Delta (3), about 80% originate from the Sacramento-San Joaquin River drainage while the remainder is contributed by local streams. Estimates of the fraction of sediment deposited in the Delta vary from 15% (4), to 30% (5), while the balance moves into the San Francisco Bay system. Sediment circulations within the Bay-Delta system are complex due to the presence of numerous interconnected channels, tidal flats and bays within which the interaction of freshwater flows, tides, and winds produce an ever changing motion of sediments.

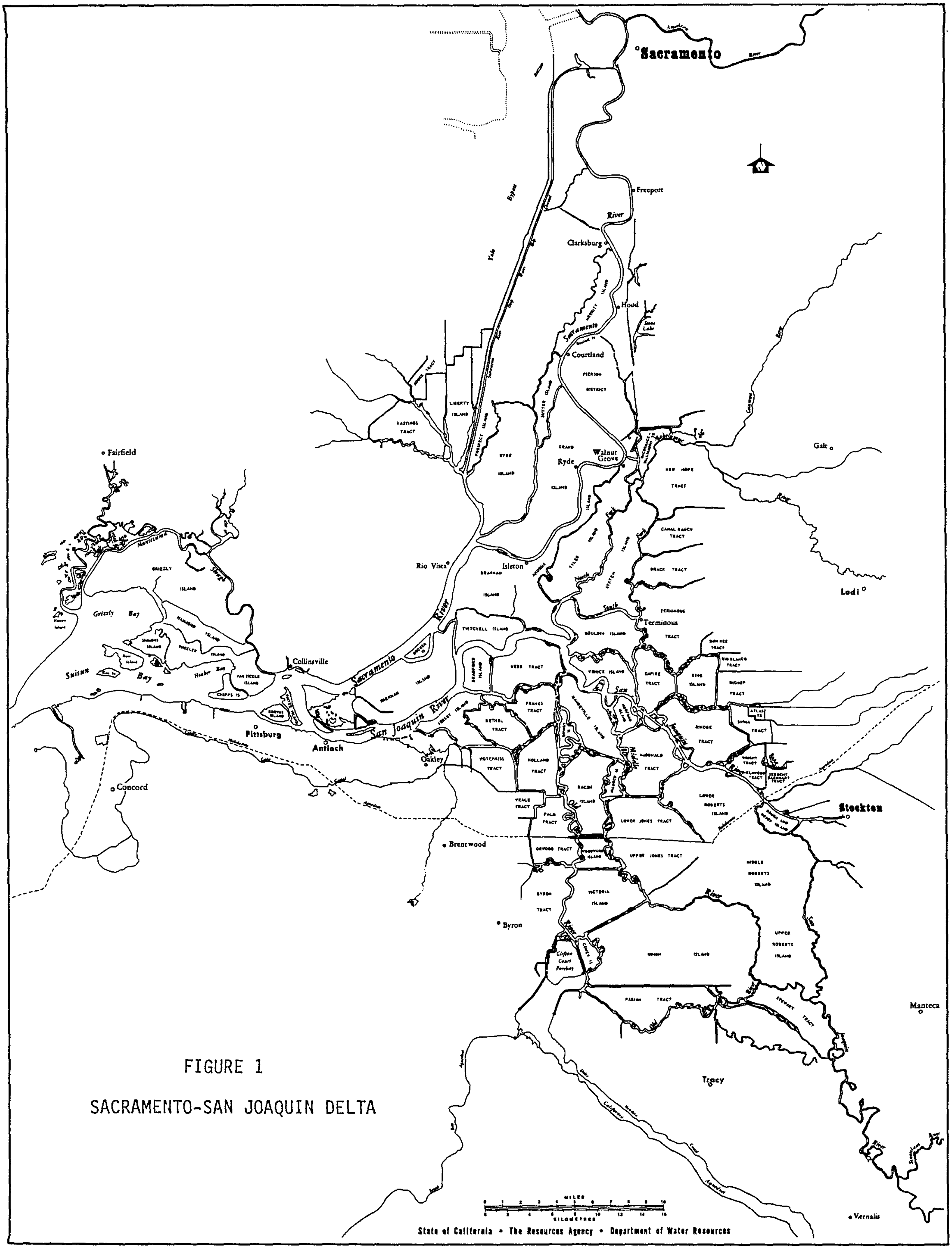

FIGURE 1

SACRAMENTO-SAN JOAQUIN DELTA

About 90% of the sediment that enters the Delta is suspended sediment (5), composed primarily (80-97%) of lithogenous particulates and, the remainder, living and detrital biogenous matter. These suspended sediments are very fine particles of clay and silt capable of forming aggregates when the salinity of the suspending waters is increased. These aggregates settle much more rapidly than the individual sediment particle and, therefore, increasing salinity and reduction in flow velocity enhance shoaling.

Riverborne suspended sediments enter the Delta (more than 80% of the load in the winter months) and a portion of the load is deposited on the channel beds and open water areas. Subsequently, more intense flows caused by higher tides and wind generated waves, resuspend part of this deposited material and move the same to other areas in the Delta and Bay. Pumping at the State and Federal projects alters this circulation of sediments within the system. In addition, higher flow velocities induced in channels due to the pumping, may cause scouring of the bed and banks.

With the view of assessing the impacts of the State and Federal water projects on erosion, deposition, and sediment transport within the Delta, the California Department of Water Resources (DWR) commissioned the study reported herein. The purpose of the study was to develop a detailed work plan that includes a program for collection of additional field data and laboratory analysis if necessary, and describes methods of analysis that could be utilized. In particular, DWR posed the following questions that were to be addressed in the development of the study plan.

1. Will erosion, deposition, and/or sediment transport take place in Delta channels as a result of operation of the State and Federal projects?

2. What information is needed to answer question 1?

3. If the study develops an affirmative answer to question 1, what is the best way to predict:

   a. Where erosion, deposition, and sediment transport will take place?

   b. What channels in the Delta will be subject to:
      (1) Erosion
      (2) Deposition
      (3) Sediment transport?

   c. What will cause such erosion, deposition, and sediment transport?

   d. What quantities and sizes of sediments will be moved?

2. SEDIMENT TRANSPORT MECHANICS

It is important to be aware of the presence of cohesive sediments when attempting the study of sediment transport. Cohesive sediments are very fine particles of clay, organic material, fine silts, and certain industrial and mining wastes that exhibit colloidal properties. The surface charge present on these particles can cause them under certain physical and chemical conditions in the suspending water, to form flocs that settle out much faster than the individual particles. Higher salt content and pH in the suspending waters promote flocculation. Cohesive sediments resist erosion due to the interparticle bond which is a force usually much larger than the weight of the particle. A soil with only 5% clay may exhibit properties similar to that of the pure clay rather than the 95% non-cohesive material it is composed of. Cohesive sediment properties and the study and quantification of transport processes have only been undertaken in recent years. Detailed descriptions of cohesive sediment transport are presented in references 6 through 12.

The effects of sediments on water quality for aquatic biota include limitation of the penetration of sunlight and the sorption and exchange of ions from solution. Cohesive sediments provide a large assimilative capacity for heavy metals, pesticides, and nutrients discharged to the waters in wastes. The process of sorption may be followed by exchange of some of the ions in a saline environment and subsequent deposition so that it is necessary to quantify the transport of cohesive sediments when studying water quality.

The mechanisms of erosion, transport, and deposition of noncohesive sands on the other hand, are quite different from those for cohesive sediments. Resistance to scour of noncohesive sediments is due only to the weight of the particle. During transport, sands usually move in layers near the bed and due to the fact that they are chemically inert, do not flocculate or exhibit ion exchange properties. Unlike clays that consolidate under overburden pressure, sands maintain a relatively uniform density in deposits.

In the sections that follow, the mechanisms of scour, transport, and deposition are described. It is important to note the different criteria and quantitative relationships for cohesive and noncohesive sediments where such differences exist.

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2.1 Critical Shear Stress for Scour

When the hydraulic shear stress at the bed exceeds the resistance of the bed material to such shear, erosion (scour) occurs. The shear stress at the bed that is produced by flowing water is primarily dependent on the average velocity of flow, the depth, and roughness of the bed. The bed shear increases approximately as the square of the average flow velocity. The resistance of a sand bed to erosion depends on the particle size, density, and shape. The larger the particle size and density the greater the resistance to scour.

The resistance to shear of cohesive sediments on the other hand, is dependent on the electro-chemical bond between particles. Before detachment of cohesive materials can take place these interparticle bonds must be broken. The net interparticle attraction depends on:

(i) The surface charge density, which is a property of the clay mineral.

(ii) The salt concentration of the surrounding water, attraction increasing with increasing concentration.

(iii) The valence of the cations in solution, attraction increasing markedly with increasing valency.

(iv) The temperature, attraction decreasing with increasing temperature.

(v) The separation, attraction decreasing very rapidly with increasing distance.

(vi) The pH of the surrounding water.

(vii) The kind of anions in solution.

2.1.1 Critical Shear Stress for Cohesive Sediments

The resistance of a cohesive bed to erosion is usually estimated in terms of gross parameters that characterize the sediment and the surrounding water. One of these parameters is a measure of the clay's capacity to exchange cations, cation exchange capacity (CEC), is usually expressed as the milli-equivalents (me) of exchangeable cations held by 100 g of dry mineral. CEC is an effective measure of the activity of a clay, i.e., the extent to which it possesses colloidal properties, and depends on the surface charge density and the surface area per unit weight of dry mineral. Values of CEC of common clay minerals are typically montmorillonite, 50 to 150 me/100 g; illite, 10 to 40 me/100 g; kaolinite, 1 to 15 me/100 g. The total salt concentration and pH of

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the pore fluid have a strong influence on the mutual attraction between particles and are easily measured from an extract. The other parameter is the sodium adsorption ratio (SAR) which is an equilibrium constant given by:

$$SAR = \frac{[Na^+]}{\sqrt{\tfrac{1}{2}([Ca^{++}] + [Mg^{++}])}} \qquad 2.1$$

where the quantities on the right hand side are concentrations of sodium, calcium, and magnesium in the water.

Together the CEC of the clay, the total salt concentration, SAR, and pH of the suspending water predominate in determining cohesion. The critical concentrations and corresponding salinities of diluted seawater at which kaolinite, illite, and montmorillonite become cohesive as reported in reference (12) are reproduced in Table 2.1.

Table 2.1

Critical Cation Concentrations and Corresponding Salinity for Potential Aggregation in Seawater (Ref. 12)

Clay Type	Total Cation Concentration me/ℓ	Salinity g/ℓ
Kaolinite	1.0	0.6
Illite	2.0	1.1
Montmorillonite	4.3	2.4

Empirical relationships between the critical shear stress for erosion of cohesive beds and the above mentioned parameters have been developed as a result of extensive laboratory and field testing (6,9,10,11). The critical shear stress for erosion of a particular sediment can therefore be estimated by using these relationships provided that the CEC, total salts, SAR and pH are known.

Direct measurement of the critical shear stress for erosion is a somewhat more tedious procedure. Laboratory measurements in recirculating flumes (6), rotating cylinder apparatus (11), or annular rotating flumes (13), can be used to measure erodibility of cohesive and noncohesive soils. Undisturbed or remodeled samples are used for these tests which yield both the critical shear stress and the rate of erosion. Typically, a plot of erosion rate vs. mean hydraulic shear stress such as that shown in Figure 2, is made.

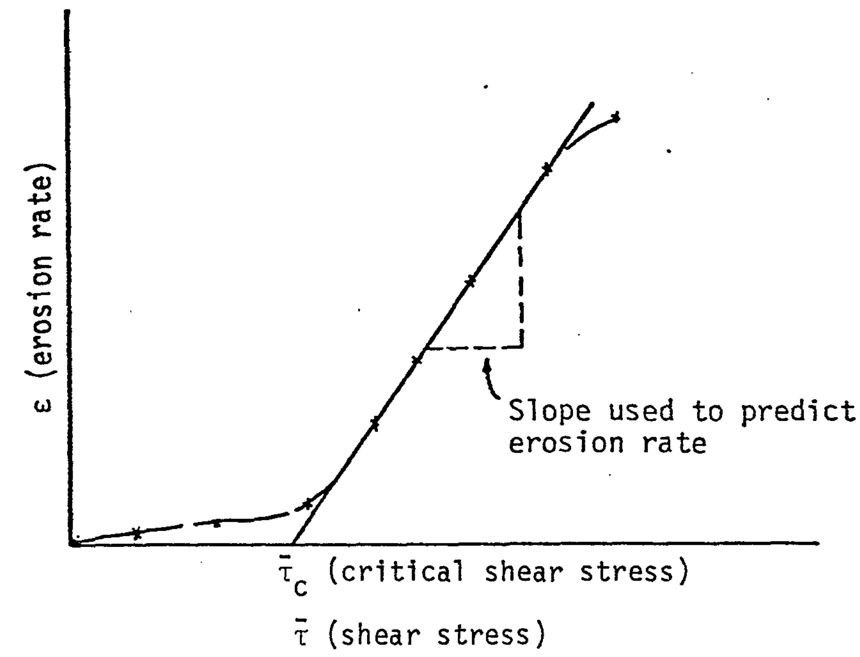

Figure 2

Measurement of Critical Shear Stress

The idealization shown above is usually adequate for practical problems where the sediment is of uniform size or cohesive in nature. It is not valid for a mixture of different particle sizes.

At bed shear stress just above critical value, erosion occurs particle by particle; this process is called surface erosion. At higher levels of stress, however, the bulk shear strength of the bed may be exceeded. The portion of a bed in such a state is susceptible to mass erosion, i.e., as the bed shear exceeds the critical shear stress of that portion of the bed, it fails totally and is instantly suspended.

To model the transport process, it is necessary to know the critical shear stress of each stratum of the bed and also the erosion rate if the erosive mechanism is surface erosion. At present, laboratory measurements must be made to obtain these parameters. The critical shear stress for scour and rates of erosion may be measured in a flume for beds of relatively low strength. Stronger beds may be tested in the rotating cylinder apparatus by the method described in reference (11), although this method is not suitable for thin layers.

The erosion rate for particle erosion is given:

$$(dm/dt)_e = M\,(\tau_b/\tau_{ce} - 1) \qquad 2.2$$

$$\tau_b \geq \tau_{ce}$$

where $(dm/dt)_e$ = mass rate of erosion per unit area

τ_b = bed shear stress

τ_{ce} = critical shear stress for erosion

M = erodibility constant

If d is the local depth of flow:

$$(dC/dt)_e = (dm/dt)_e/d \qquad 2.3$$

is the rate of change of concentration of the suspension due to erosion of the bed.

When mass erosion occurs:

$$(dC/dt)_e = (\Delta m/\Delta t)/d \qquad 2.4$$

where Δm = mass eroded per unit bed area

Δt = a characteristic time in which erosion occurs.

2.1.2 Shields Diagram for Critical Shear Stress of Noncohesive Sediments

Shield's Diagram (Figure 3) for the critical shear stress for scour is based on experimental data. Shields used the dimensionless shear or boundary Reynolds number $u_* d_s/\nu$ and the dimensionless shear stress $\tau_0/(\gamma_s-\gamma)d_s$ to develop a curve of critical values for scour.

Here u_* = friction or shear velocity

d_s = mean sediment diameter

γ_s = specific gravity of sediment

γ = specific gravity of suspending water

τ_0 = shear stress at the bed

and ν = kinematic viscosity

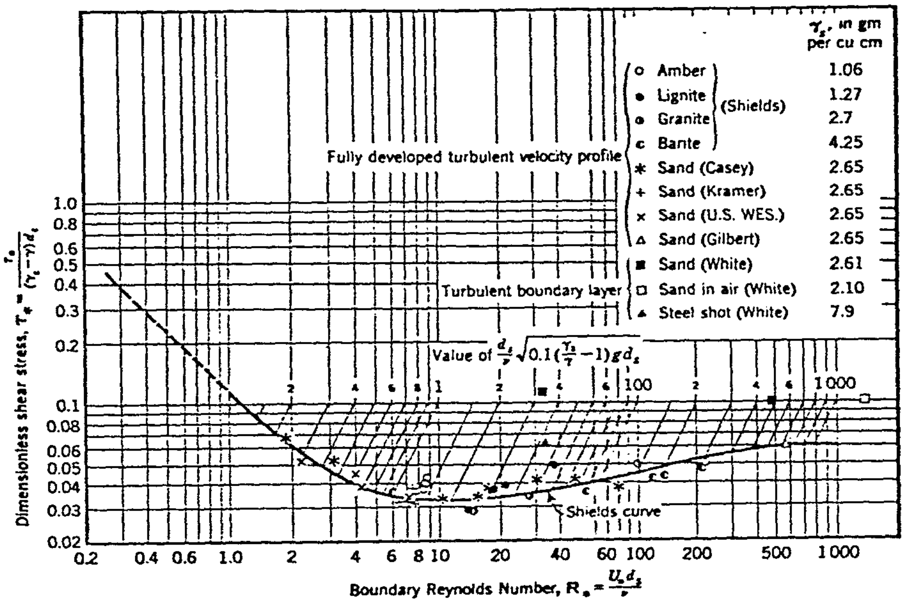

Figure 3

Shield's Diagram

If it is assumed that the initiation of motion is determined by the critical shear stress τ_c, $(\gamma_s-\gamma)$, d and the kinematic viscosity ν, dimensionless analysis yields:

$$\frac{\tau_c}{(\gamma_s-\gamma)d_s} = f\left(\frac{u_{*c}\, d_s}{\nu}\right)$$

where $u_{*c} = \sqrt{\frac{\tau_c}{\rho}}$

The above is the basis for Shield's diagram which usually yields good results except in cases where cohesive sediments are present. Shield's diagram must not be used for cohesive sediments.

2.2 Transport

Sediments are transported as suspended load where the downward fall velocity of the particles is balanced by the upward mixing caused by turbulence, and as bed load. The bed load is carried in a thin layer close to the bed within which particles slide, roll, and saltate (jump) with periods of intermittent rest on the bed.

Einstein in developing his bed-load function made the following definitions:

Bed load: Bed particles moving in the bed layer. This motion occurs by rolling, sliding, and sometimes, by jumping.

Suspended load: Particles moving outside the bed layer. The weight of suspended particles is continuously supported by the fluid.

Bed layer: A flow layer, 2 grain diameters thicks, immediately above the bed. The thickness of the bed layer varies with the particle size.

Bed material: The sediment mixture of which the moving bed is composed.

Wash load: That part of the sediment load which consists of grain sizes finer than those of the bed.

Bed-material load: That part of the sediment load which consists of grain sizes represented in the bed.

Bed-load function: The rates at which various discharges will transport the different grain sizes of the bed material in a given channel.

Bed-load equation: The general relationship between bed-load rate, flow condition, and composition of the bed material.

The total sediment load is composed of the bed load, suspended load, and the wash load. The sediment sizes that comprise each of these loads depends on the intensity of flow. At higher velocities the flow is capable of moving larger sized sediment in suspension. The vertical distribution of sediment for various diameters d at two shear velocities (U_*) are shown in Figure 4. The smaller diameter particles are more or less uniformly distributed in the water column whereas the heavier particles are concentrated near the bed. Clays and silts are assumed to move entirely as suspended load whereas sands may move as suspended load and bed load.

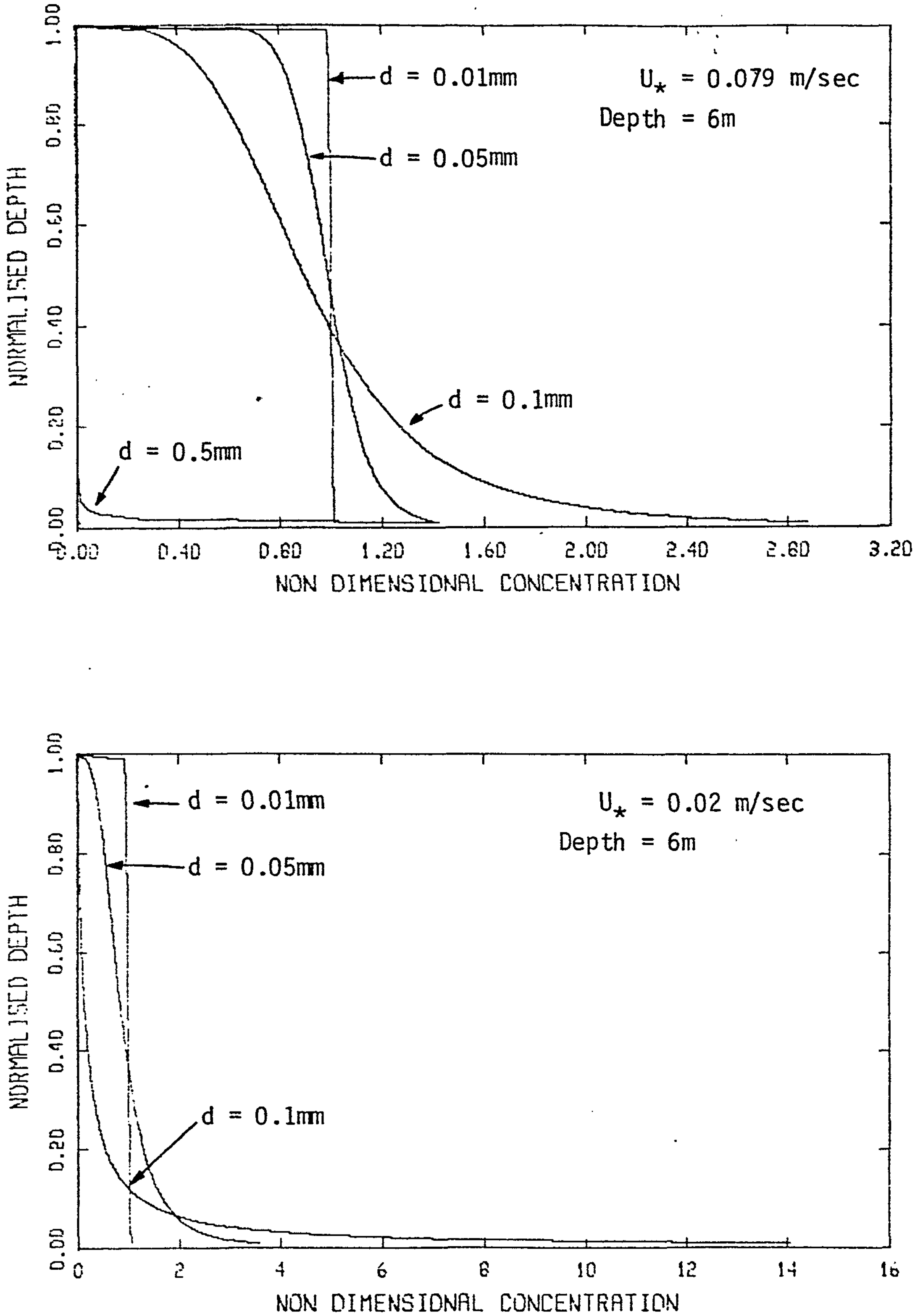

FIGURE 4

Vertical Sediment Distribution
for Various Sizes

The rate of sediment transport (Q_s) for suspended sediments is given by:

$$Q_S = VC \quad \text{mass/unit area/unit time}$$

where V = velocity of the suspension

C = concentration of sediment

For fine sediments in a stream or channel the average flow velocity and concentration can be used to compute the transport rate. Given the flow field the concentration of the suspension is the only unknown. The concentration is usually calculated from a mass balance including scour and deposition.

In the case of noncohesive sediments, total load sediment transport functions such as that proposed by Einstein (14) can be used to determine the load Q directly provided that the flow is steady state. For unsteady flows it is important to estimate the sediment velocity which is different from that of the average flow velocity, see Ariathurai (15). Then:

$$Q_s = V_s C$$

where V_s = sediment velocity

Sediment transport equations for noncohesive sediments are procedures to calculate the capacity of a particular flow to carry a particular sediment. If the amount of sediment in the water is less than this capacity bed material is scoured to make up the shortfall if such material is available on the bed. If there is more sediment in the water than it is capable of moving, as may be the case if there is a reduction in the flow velocity, deposition of the excess occurs.

2.3 Deposition

When the shear stress on the bed is not sufficient to resuspend particles that contact and bond with the bed, deposition occurs. The shear stress at which there is an incipient net rate of deposition is termed the critical shear stress for deposition. This value may be the same or less than the critical shear stress for erosion, depending on the history of the bed surface. As a result of extensive laboratory studies, Krone (6,7) described the depositional dehavior of cohesive sediments in the following manner.

The probability P of particles sticking to the bed increases linearly with a decrease in the bed shear and is given by:

$$P = 1 - \tau_b/\tau_{cd}$$

where τ_{cd} = critical shear stress for deposition. In the absence of continuing aggregation of the transported aggregates, the rate of loss from suspension is:

$$\left.\frac{dC}{dt}\right|_d = -\frac{PV_sC}{d}$$

where d = average depth through which the particles settle.

In the case of noncohesive sediments the amount deposited is usually calculated as that amount in excess of capacity carried by the flow. A sandy bed does not show significant change in density with increasing overburden pressure. Cohesive beds on the other hand, consolidate as the overburden increases and, as a consequence, increase in density and resistance to scour (16).

3. SEDIMENT TRANSPORT IN THE DELTA

The sediment inflow into the Delta and sediment transport pattens have changed over time due to man's activities. Hydraulic mining for gold began about 1850 and up to about 1914 resulted in a doubling of the sediment brought into the Delta. Since then, the construction of dams has further reduced the sediment load. The existing sediment transport conditions in the Delta as indicated by available data are described in this chapter.

3.1. Sediment Inflows

The sources of sediment to the Delta are as follows:

(i) Sacramento River

(ii) San Joaquin River

(iii) Lesser streams and local drainage

(iv) Return from the Bay with the tides

Sediment is lost from the Delta via the following sinks:

(i) Flows into the San Francisco Bay

(ii) Sediments pumped with the exports and local uses

(iii) Removal by dredging

Imbalances between inflow and ouflow result in shoaling or scour within the system. Since the Delta is a net depositional environment, the sediment inflow is greater than the loss during the majority of the time.

3.1.1 Sacramento River

Suspended sediment measurements in the Sacramento River at Sacramento and Freeport have been made by the USGS from 1956 to date. The data collection procedure and analysis is performed as described below by the GS:

"In general, suspended-sediment samples were collected daily with depth-integrating samplers (U.S. Interagency, 1963). At some stations, samples were collected at a fixed sampling point at one vertical in the cross section. Depth-integrated samples were collected periodically at three or more verticals in the cross section to determine the cross-sectional distribution of the concentration of suspended sediment with respect to that at the daily sampling vertical. In streams where transverse distribution of sediment concentration ranged widely, samples were taken at two or more verticals to define more accurately the average concentration of the cross section. During periods of high or rapidly changing flow, samples generally were taken several times a day and, in some instances, hourly.

Sediment concentrations were determined by filtration-evaporation method. At many stations the daily mean concentration for some days was obtained by plotting the velocity-weighted instantaneous concentrations on the gage-height chart. The plotted concentrations, adjusted if necessary, for cross-sectional distribution were connected or averaged by continuous curves to obtain a concentration graph. This graph represented the estimated velocity-weighted concentration at any time, and for most periods daily mean concentrations were determined from the graph. The days were divided into shorter intervals when the concentration or water discharge were changing rapidly. During some periods of minor variation in concentration, the average concentration of the samples was used as the daily mean concentration. During extended periods of relatively uniform concentration and flow, samples for a number of days were composited to obtain average concentrations and average daily loads for each period.

For periods when no samples were collected, daily loads of suspended sediment were estimated on the basis of water discharge, sediment concentrations observed immediately before and after the periods, and suspended-sediment loads for other periods of similar discharge."

A plot of the monthly sediment discharges at Sacramento for the water years 1957-1965 is shown in Figure 5. Annual loads presented in Table 3.1 indicate an average suspended sediment load in the Sacramento River to be 2,770,000 tons/year during this period. A log-log plot of mean daily discharge versus measured suspended sediment load for the period 1956-1963 is presented in Figure 6. The plot of silt and clay fraction versus river discharge shown in Figure 7 was developed from particle size analyses of suspended sediment samples. This plot indicates that most of the time a majority of the suspended sediment is silt and clay (< 0.062 mm), the balance being mostly fine sand.

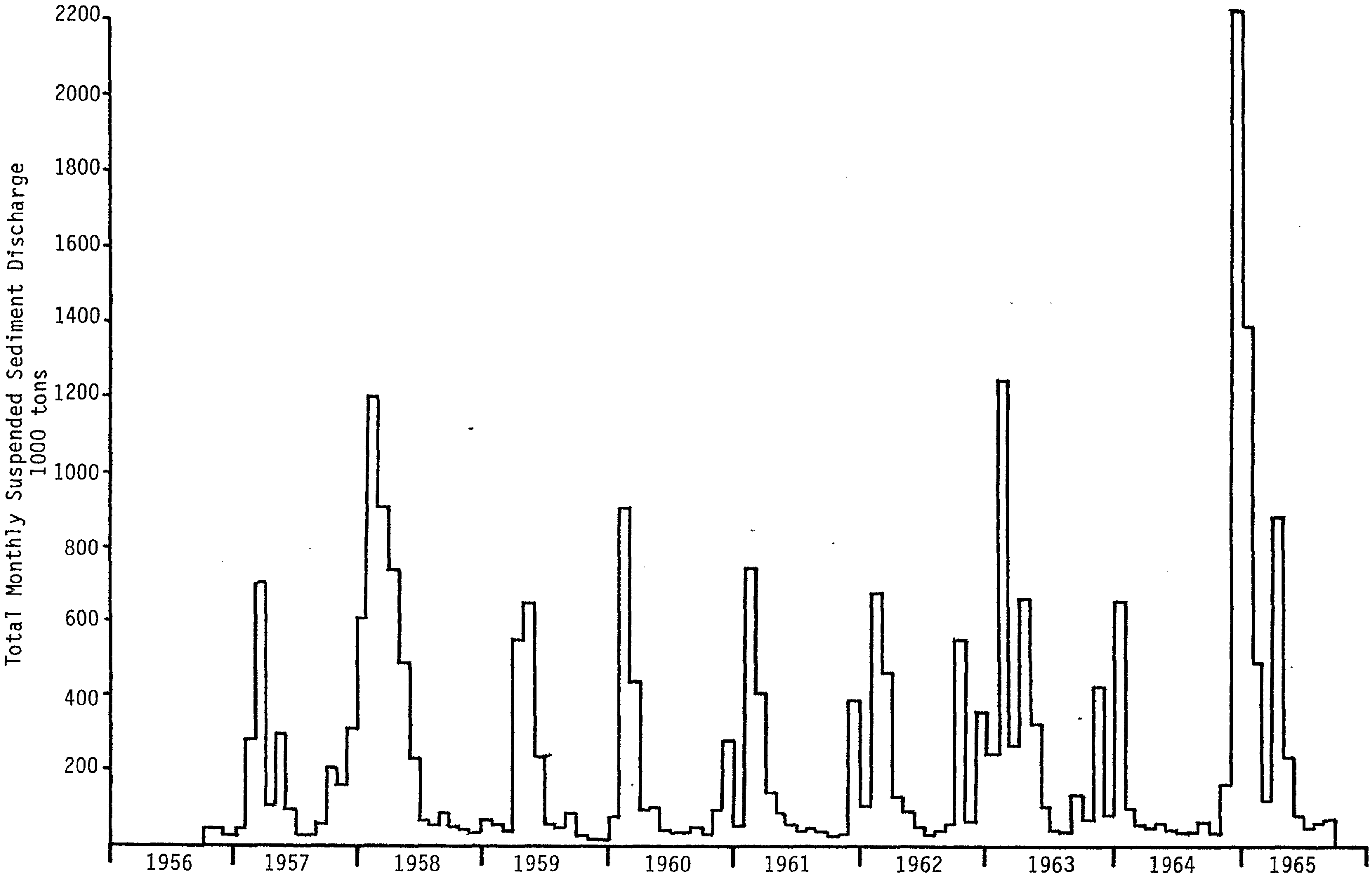

FIGURE 5

SUSPENDED SEDIMENT OF SACRAMENTO RIVER
AT SACRAMENTO, CALIFORNIA
October 1956 - September 1965

TABLE 3.1

SUSPENDED SEDIMENT LOAD
SACRAMENTO RIVER (AT SACRAMENTO)

WATER YEAR	DISCHARGE (CFS-DAY)	SEDIMENT (TONS)
1957	6,649,450	1,688,788
1958	13,049,100	5,000,360
1959	6,038,310	1,856,820
1960	5,423,940	1,765,829
1961	5,745,260	1,943,177
1962	6,544,200	2,006,347
1963	10,227,330	3,946,188
1964	5,862,430	1,069,009
1965	--	5,660,000
Average 2,770,000 tons/yr		

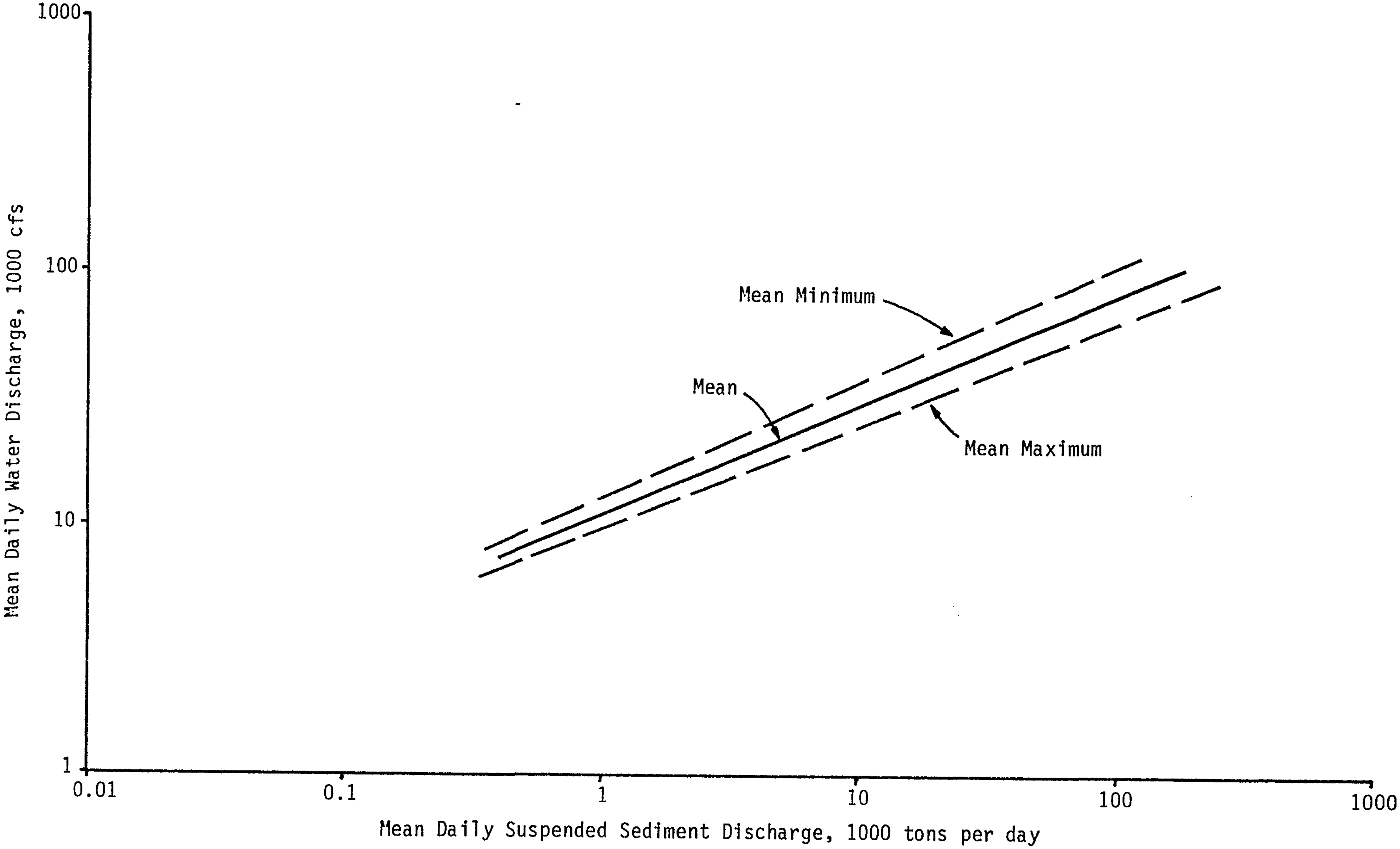

FIGURE 6

SUSPENDED SEDIMENT OF SACRAMENTO RIVER
AT SACRAMENTO, CALIFORNIA
October 1956 - September 1963

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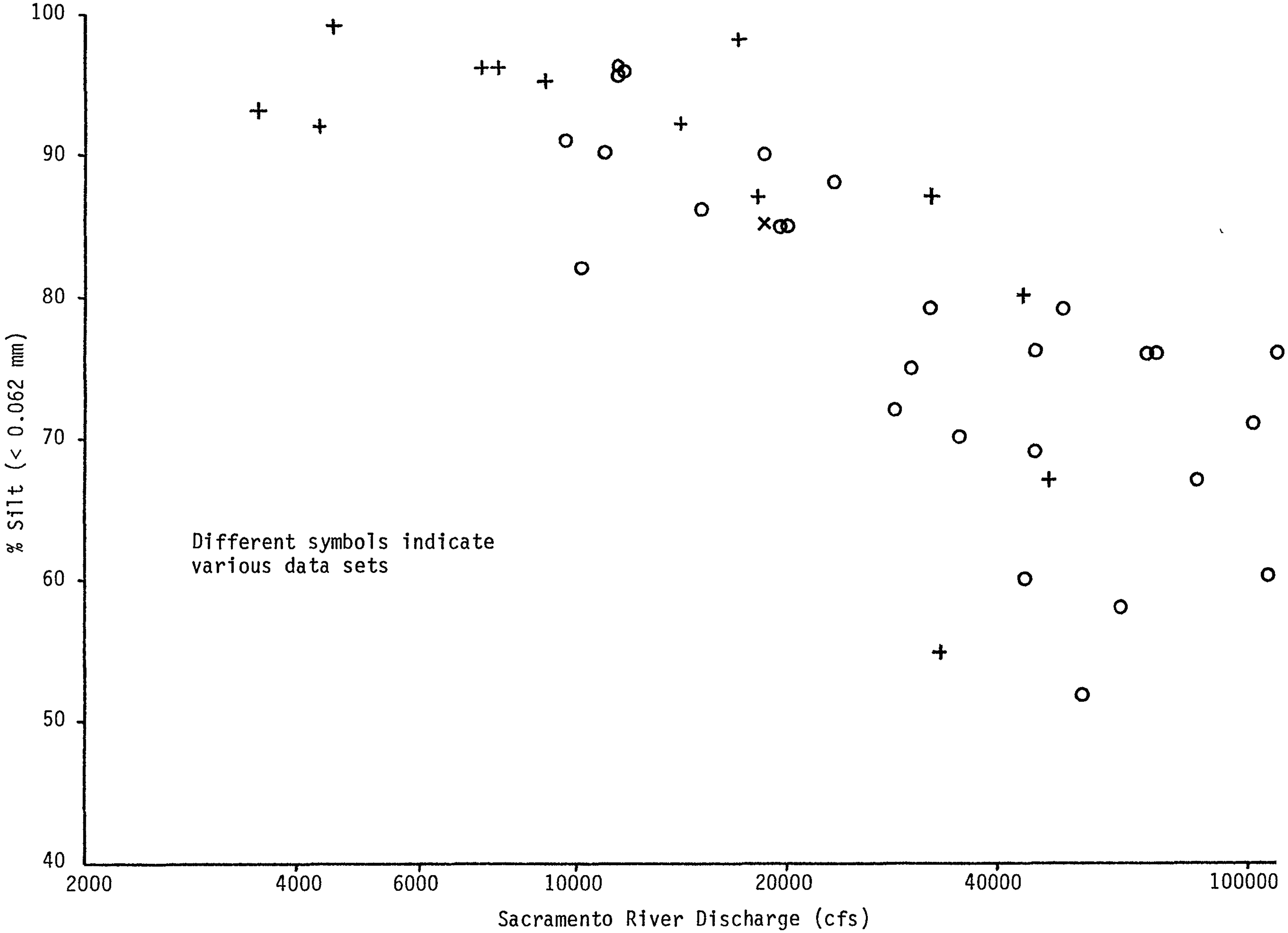

FIGURE 7

DISCHARGE VERSUS SILT FRACTION
SACRAMENTO RIVER

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In addition to the suspended load, it is estimated (4,5) that about 15% as much bed load, composed primarily of medium sand, is transported by the river. The total average annual sediment load of the Sacramento river is therefore, roughly 3,200,000 tons.

The bed material in the Sacramento River near Sacramento is composed of medium sand, coarse sand, and fine sand in order of occurrence. Progressing downstream, the fraction of fine sand increases with a decrease in the amount of coarse sand.

3.1.2 Other Inflows

The San Joaquin River is the second largest source of sediment to the Delta. Suspended sediment sampling in the San Joaquin River has been conducted from 1956-date at Vernalis by the USGS. Local drainage and direct runoff into channels provide the rest of the sediment inflow.

The sediment material derived from these sources is finer than that brought in by the Sacramento River. Estimates of the total sediment inflow to the Delta vary from 4.5 to 5.2 million tons per year so that sources other than the Sacramento River account for between 1.3 to 2.0 million tons of sediment per year.

Flood tides from the San Francisco Bay resuspend part of the sediment deposited downstream of this study area and transport the material into the Delta. Subsequent ebb flows return a part of this sediment back to the Bay. The net seaward mass transferred by such back and forth movement of sediment depends on the tide and the superimposed freshwater flows. Recently, synoptic measurements of suspended sediment concentrations at a number of stations in and close to the Carquinez Straits were made by the Army Corps and the USGS. The data however, has not been processed to date.

3.2 Surficial Sediments

Grab samples obtained by DWR from some of the channels in the system, and observations by other investigators indicate that the surficial sediments in the Delta channels are composed primarily of silt, silty sand, and in areas of lower flow intensity, clayey silt. The lower reaches of the main stem of the Sacramento River contain medium and fine sands. The embayments, sloughs and backwater areas in the western Delta contain more clay due to the fact that the salinity in this area reaches the flocculating concentration of 1-2 gm/ℓ.

The distribution of bottom sediments as evidenced by size distribution analysis of grab samples is shown in Plate 1 (attached to this report).

3.3 Sediment Outflow

The data obtained in the Carquinez Straits area will again be useful in determining the total load carried into San Francisco Bay. Estimates from previous studies indicate that about 70-80% of the sediment that enters the Delta is transported into the Bay (4,5). Dredging of channels in the Delta and exports are other mechanisms by which sediment material is removed from the system.

Suspended sediment measurements in the exports have been made by DWR and the U.S. Bureau of Reclamation (1973-74), see Arthur and Cederquist (17). Rough calculations based on the USBR measurements indicate that 200,000-300,000 tons of fine sediments were exported together with the 4 million acre feet of water in the water year 1973-74 by both the State and Federal water projects. The study showed that sediments deposited in channels during the winter months were resuspended, at least in part, during the summer months of high export.

3.4 Historical Shoaling and Scour

Scour and deposition are natural occurrences in the Delta channel system. Morphological changes in the channels are determined by the flows and associated sediment loads. A rough sediment balance (5) indicates that 1.5 million tons of sediment are deposited in the Delta channels every year.

The Department of Water Resources has conducted a scour monitoring program (18) in the channels in the vicinity of Clifton Court Forebay since 1969. Some 40 cross-sections shown in Figure 8, have been resurveyed at least once a year. Based on the plots made in the report (18), the observations presented in Table 3.2 can be made with respect to the thalweg elevation, average width and total cross-sectional area. No definite pattern of section change seems to have occurred in the few channels surveyed.

3.5 Summary of Transport Processes in the Delta

The local velocity plots shown in Plate 2 (attached) show the variation in velocity in various Delta channels during a mean tide with summertime inflows from the Sacramento and San Joaquin Rivers and pumping at the State and Federal projects. The velocities shown were

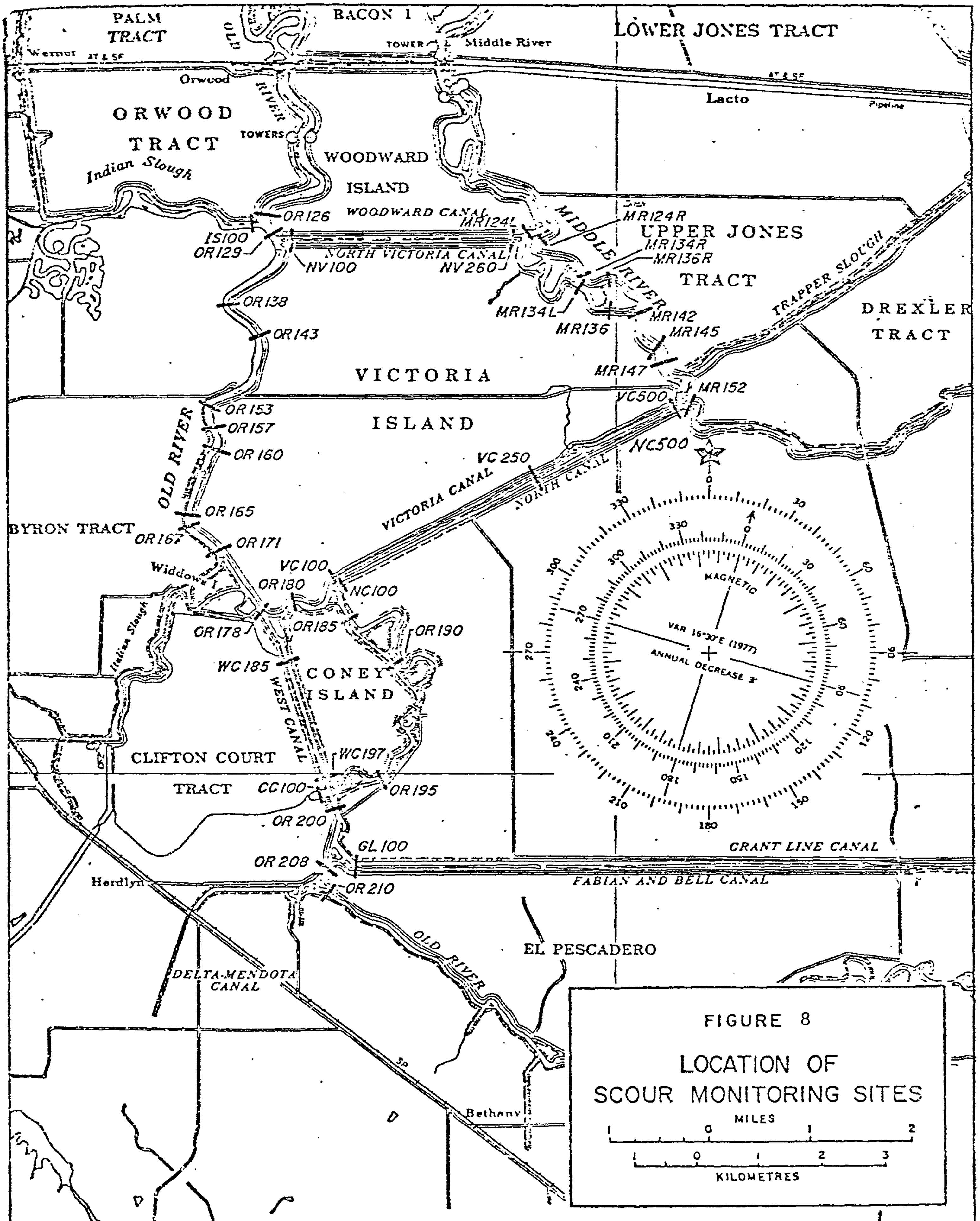

FIGURE 8

LOCATION OF SCOUR MONITORING SITES

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TABLE 3.2

CHANGES IN CERTAIN DELTA CHANNELS

CHANNEL ID	THALWEG	WIDTH	AREA
OR 143	Shallower	Wider	NC
OR 153	Deeper	Narrower	Smaller
OR 157	Shallower	Wider	NC
OR 160	Deeper	Narrower	NC
OR 165	Shallower	Wider	Greater
OR 171	Shallower	Wider	S. Greater
OR 178	--	--	Greater
OR 195	Shallower	Wider	Greater
OR 200	S. Deeper	Narrower	Smaller
OR 208	NC	NC	NC
MR 124L	NC	S. Narrower	S. Smaller
MR 134R	Shallower	Narrower	Smaller
MR 134L	Shallower	NC	Smaller
MR 142	NC	NC	NC
MR 145	Shallower	Wider	Greater
MR 147	NC	NC	NC
WC 197	Deeper	S. Narrower	Greater
VC 100	Shallower	NC	Smaller
VC 500	NC	Wider	Greater
NC 500	Shallower	NC	Smaller
GL 100	NC	NC	NC

S. = Slightly

obtained from a link-node mathematical model simulation (19). A similar run of the model was made for a wintertime condition during which the discharge in the Sacramento River was 100,000 cfs.

These model simulations show that the presence of the cross delta canal near Walnut Grove causes the diversion of a significant quantity of water, and of course, associated sediment into the channels in the northern part of the Delta. Due to the sill level of the inlet control structure being at a higher elevation than the bottom of the Sacramento River nearby, there is selective withdrawal of sediment into the cross delta canal. That is, the coarser bedload continues on down the Sacramento River while the suspended sediments at and above the sill level are diverted. If the sediment load in the Sacramento River is at capacity, the reduction in the flow caused by diversion through the canal can cause deposition downstream.

The waters that flow through the cross delta canal with their predominantly silt and clay load of sediment move down the Mokelumne River channels in which the flow is primarily unidirectional and the average flow velocities such that they provide a depositional environment. The waters then reach the San Joaquin River at which point reversed flows occur due to the tides, the network of channels becomes complex, and the flows and sediment loads are augmented by discharge from the San Joaquin River.

The discharges and velocities in the channels south of the San Joaquin River are influenced significantly by the exports at the State and Federal projects. Sediment deposition and gain from local drainage alter the amount and composition of the sediment transported in the channels. The sediment transport in the channels in the South Delta seem to vary seasonally, deposition occurring in the wintertime and resuspension of part of this deposited material occurring in the summer. In addition, degradation and widening of certain channels may be occurring due to the higher velocities caused by pumping.

Finally, waters carrying suspended sediment enter Clifton Court Forebay within which a portion of this material is deposited (17). The balance is pumped via the aqueduct. In the case of the Federal project all of the suspended sediments enter the intakes and are pumped south.

The operational practice adopted at the cross delta channel gates and the Clifton Court Forebay will affect the sediment transport in the system.

4. STUDY PLAN

The study plan described here will enable DWR to answer the questions posed in Chapter 1 relating to erosion and deposition in the Delta. The general study plan is developed in this chapter and the technical approach to accomplish the work is presented in the next.

4.1 Benefits of Conducting Study

Adoption of the scope and schedule of work suggested herein will result in the accrual of benefits to DWR including the following:

(i) Provide detailed, quantitative data on erosion, deposition, and sediment transport under existing and projected conditions so that DWR will be able to evaluate alternative designs and operational strategies with respect to sedimentation.

(ii) Assist in the design and evaluation of mitigative measures for sediment related problems.

(iii) Provide basis for water quality assessment where water quality is affected by sediment transport such as in turbidity generation, associated toxicant and nutrient transport, and in habitat modification.

(iv) Provide reliable quantitative information to address the claims of landowners, harbor and navigational facility operators, and other agencies that operate within the system.

(v) Enable the planning of dredging where necessary.

Generally, an understanding of the sediment transport processes within the Delta will enable optimal management and design of new facilities within the system.

4.2 Potential Sediment Related Problems

The export of water from the Delta and the modifications to the system to facilitate such exports such as diversions, channel improvements, may cause certain effects with respect to scour, deposition, and sediment transport. These consequences may be detrimental to some in certain instances and beneficial in other cases.

Possible effects are considered under the headings of scour, deposition, and sediment transport in the sections that follow.

4.2.1 Scour

When the velocity of flow in a channel is increased, or when the sediment inflow to a channel in equilibrium is reduced, or when predominance of flow in one direction is altered in a channel that experiences reversed flows, scour may occur. The rate of scouring depends on the composition of the material on the bed and banks and the amount of change in the factors listed before. Scour in the channels may cause:

(i) bank or levee instabilities;

(ii) a drop in water surface elevation which may affect the pumping head and the tidal prism;

(iii) addition of suspended sediments to the waters thereby increasing turbidity and causing accelerated deposition downstream;

(iv) flow changes in other channels by diverting more water.

The increased hydraulic capacity of a scoured channel on the other hand, may be a benefit by allowing the transport of more water through it.

4.2.2 Deposition

Deposition is caused by effects that are exactly opposite to those listed for scour. The rate of deposition depends on the type and amount of sediment in suspension, the salinity, and the extent to which the transport capacity of the channel has been changed by reduction in flow velocity etc. Deposition related problems may be caused by:

(i) Reduction in capacity to transport water which in turn may result in levee instability and flooding.

(ii) Clarification of waters and increased light penetration which may cause more rapid growth of algae.

(iii) Flow diversions and altered tidal incursions.

(iv) Reduced capacity in forebays.

(v) Increased costs for dredging in boat harbors etc.

4.2.3 Sediment Transport

Increased sediment concentrations in the waters may:

(i) Affect water quality by altering the nutrient and toxicant levels in the water and by reducing the penetration of sunlight. These effects may be beneficial or detrimental depending on the changes.

(ii) Increase the amount of sediments in the water exported as a consequence of which problems may be caused in the aqueducts and points of water release.

Incidentally, increases in pump efficiency can be produced by increased levels of suspended fines in the water.

4.3 Available Methods

The approaches that can be used to quantify erosion, deposition, and sediment transport and the feasibility and utility of each are discussed below.

Hydrodynamics. The time-varying stages and velocities in the channels must be known before sediment transport computations can be made. The DWR link node model and Fischer's model provide dynamic cross-section averaged velocities in the various channels given the boundary conditions. Any one of these models will be quite adequate to provide the flow field for sediment transport computations. Therefore, the rest of this discussion will be restricted to sediment transport only.

Direct Measurement. Direct measurement of suspended sediment transport and bed changes with the complex geometry and highly time varying flows in the Delta is utterly impractical. In special situations at one or two places in the system, localized effects may be measured and extrapolations made to predict changes. Direct measurement cannot be used for predicting the effects of altered geometry or flows.

Channel by Channel Computation. Given the time dependent sediment concentrations and compositions at either end of a channel reach in which reversed flow occurs, and the surficial sediment composition on the bed, hand or computer calculations can be made to determine the sediment transport and bed profile changes. The accuracy of the computation will depend on the sediment transport equations used for the particular modes of transport. It is unnecessary to go into the merits of the various methods of computing sediment transport at this point because the boundary conditions for such calculations require about the same effort to obtain, i.e., measurements or modeling, as the answer to the problem.

This method is useful for unidirectional, gradually varying flow which is not the case in the Delta channels.

Physical Modeling. Although physical modeling of flows has proved to be successful, the inability to maintain dynamic similarity for sediments between prototype and model makes it difficult to model sediment transport in a physical model although attempts have been made using walnut shells and crushed coal to model sediment. However, it is not possible to model cohesive sediment transport in a physical model.

Mathematical Modeling. Mathematical modeling of sediment transport in the system is certainly the best approach based on accuracy, cost, and predictive capability. Multi-dimensional suspended sediment transport models have been applied successfully to a number of riverine, estuarial, and reservoir sediment transport problems in the recent past. The features that are necessary in a mathematical model to be applied in the Delta to address the problem of sediment transport in general, and answer DWR's questions in particular are:

(i) The model must be capable of handling a network of interconnected channels within which the cross-sectionally averaged velocities are obtained from a hydrodynamic model.

(ii) The model must be able to compute suspended sediment transport in an unsteady flow field with reversed flows caused by the tides.

(iii) Although the sediment motion is primarily in the suspended mode, the settling velocity of the particles is high enough to cause strong stratification. The model must therefore, compute the net rate of transport of the sediment taking into account the fact that the sediment concentration near the bottom may often be very much higher than the average. The velocity of the sediment in such cases (transport rate) will, because of stratification, be lower than the sectionally averaged flow velocity.

(iv) The model must simulate the scouring and settling processes as time dependent phenomena and keep track of the bed profile and the availability of material to be scoured.

(v) A majority of the sediment material transported in the Delta is composed of silt, clay, and very fine sand. The settling velocities and resistance to scour of each of these size classes are sufficiently different so that their rates of transport need to be computed separately. Therefore, the model must be capable of handling a number of size fractions of sediment (at least three), including a cohesive component.

(vi) The model must account for aggregation and other special characteristics of cohesive sediments relating to their depositional, scour, and consolidation behavior.

4.4 Data Requirements

The minimum data required for the application of a model are as follows.

4.4.1 Sediment Inflows and Outflows

Sediment enters the system in suspension and as bedload via the following sources for which the data available are indicated.

(i) Sacramento River. Daily suspended sediment data are available from the USGS gaging station at Sacramento. Gradation analysis of the suspended sediment is made often enough to describe the composition sufficiently. The data has been collected since 1956 and the collection program continues.

(ii) San Joaquin River at Vernalis. Same as above.

(iii) Local drainage and Small Streams. No data available. This source is small and can be estimated. The lack of this data will not affect the overall analysis significantly.

(iv) Exchange with San Francisco Bay. The study area extends to the Chipps Island area at the upper end of the straits. Essentially, all of the sediment transported from the Delta to the Bay passes this point. Incoming tides (flood flows) bring with them some of the resuspended clay and silt. A recent study (1979-80) conducted by Kinnetics Lab for the San Francisco District of the Corps of Engineers included the measurement of suspended sediment concentrations at various depths at a number of stations in the Carquinez

Straits. This data is available on magnetic tape and can be used to provide the downstream boundary condition.

(v) Suspended Sediment Concentrations in the Exports. Measurements have been made by the USBR at the Delta pumping plant, Clifton Court intake, and at the Federal pumps for a period of one year. These measurements can be used to calibrate the model. Since the flow is unidirectional at the points of export the concentration need not be specified at these locations.

The bed load is a relatively small part of the total sediment load and enters primarily via the Sacramento River. Furthermore, most of the bed load is carried down the main stem of the Sacramento River. Computations of the bed material load transport can be made separately and the entire sediment balance established.

4.4.2 Bed Sediment Composition

In order to determine the potential for scour and the rate of scour, the composition by size fraction of the sediment on the bed at locations where scour may take place needs to be known. The size fraction and presence of clay will determine the critical shear stress for erosion and the rate of erosion when it occurs. Analysis of grab samples which are composite samples of the upper few inches of sediment will usually suffice. In locations where extensive scour may take place, and where the sediment composition changes with depth below the surface of the bed, core samples will be necessary so that the variation of sediment properties within the bed can be ascertained. Areas of potential scour can be identified by mathematical modeling of the flows in the channels by which process locations of scouring bed shear stress can be determined.

This process will of course be iterative since the resistance to scour depends on the sediment composition and size. Initial sampling locations are suggested in Plate 3.

4.4.3 Sediment Properties

The sediment properties that need to be specified are:

(i) Settling velocity of each size fraction. For the noncohesive fraction, settling velocity can be calculated based on size or measured directly, and for the cohesive component measured in the lab for various concentrations and salinities.

(ii) Critical shear stress for erosion. Same as above.

(iii) Consolidation Characteristics of the Cohesive Sediments. Measured in the laboratory.

4.4.4 Boundary Conditions for Hydrodynamic Modeling

All of the boundary conditions for the simulation of the hydrodynamics in the system are already available. The flow models have been in use for a number of years.

4.5 Scope of Study and Tasks

The study will involve the establishment of model inputs using existing data, the gathering of additional field data, laboratory testing, and the application of mathematical models for hydrodynamics and sediment transport within the Delta. The following specific tasks need to be undertaken.

4.5.1 Task 1 - Data Reduction

The data available under the headings described in Section 4.4 needs to be computerized in the few instances where this has not already been done, and then reduced to forms that enable graphical presentation and ready input to the mathematical model.

4.5.2 Task 2 - Field Data Gathering

Grab samples of surficial sediments on the bed of channels and embayments including Clifton Court need to be obtained for laboratory analysis. It is not anticipated that core sampling is necessary at this time. Should this study indicate locations of extensive scour, core samples can be obtained at such locations at a later stage.

4.5.3 Task 3 - Laboratory Testing

Laboratory testing will include:

(i) Particle size analysis of grab samples.

(ii) Flume tests for determination of critical shear stress for erosion and deposition and for the rates of these processes.

(iii) Settling and consolidation characteristics of the cohesive fraction.

4.5.4 Task 4 - Mathematical Modeling

The mathematical modeling will involve the setting up of the flow and sediment transport models, the design of the various conditions for which model runs will be made, and the establishment of the method for extrapolation of short term model simulations to long term effects. Model results need to be presented in concise graphical form where possible.

The recommended technical approach to accomplish these tasks and a schedule are presented in the next chapter.

5. TECHNICAL APPROACH AND SCHEDULE

The technical approach that can be used to undertake the tasks listed in the previous chapter is described here.

5.1 Task 1 - Data Reduction

This task will involve the development of high, low, and average year suspended sediment inflows at Sacramento and Vernalis using the digitized USGS data. In addition, the Kinnetics Labs measurements in the Carquinez Straits and the measurements of suspended sediment concentrations in the exports need to be reduced to a standard form from the magnetic tapes they are now on.

The task will involve the writing of simple computer programs for data reduction and plotting.

5.2 Task 2 - Field Data Gathering

Field data gathering will consist of sampling of bed material for laboratory analysis and a bottom survey of Clifton Court forebay. The locations at which grab samples of bed material are recommended are shown in Plate 3 (attached). These grab samples will be composed of a composite scoop of the upper six inches or so of bed material and need not be more than 1 Kg in dry weight. Greater quantities of sediment material, 40 Kg or so, need to be obtained at the locations shown on the Plate for erodibility testing.

Transects of Clifton Court forebay may be obtained with fathometer soundings and lead line measurements to determine the amount of deposition that has occurred there.

5.3 Task 3 - Laboratory testing

Particle Size Distribution. The particle size distribution of the surficial bed samples need to be analyzed by sieving and hydrometer measurements on the fines. The bed material distribution can then be mapped. It is likely that only a few different types of sediment distributions occur within the system.

Settling Velocity. The settling velocity of each of the noncohesive components can be measured directly by timing the rate of fall of individual particles in a column of still fluid. A number of such measurements will yield the median settling velocity for the silt, very fine sand, and fine sand components. The cohesive sediments must be handled differently. After separation from the silt and sand, hydrometer analysis (standard method) for settling velocity must be done at salinities of 0, 100, 500, 1000, 2000, 4000, and 8000 mg/ℓ. The critical salinity for aggregation and the relationship between salinity and settling velocity will thus be established. At salinities of 100 and 4000 mg/ℓ the relationship between sediment concentration and settling velocity can be established by performing hydrometer analyses on 1, 2, 4, 5, 8 and 10 g/liter initial sediment concentrations. For lower suspension concentrations of 50, 100, 200 and 500 mg/liter, pipette analysis needs to be conducted.

Consolidation Characteristics. The density variation with overburden pressure for cohesive sediments is measured by settling in a large diameter (8") cylinder. The method yields the density vs. depth of deposit of a particular cohesive sediment. Such measurements need to be made on two or three samples of the clay found in the system.

Erodibility Testing. The erodibility of each of the size fractions including the clay component can be measured in the rotating annular flume (13) which has the advantage that it uses a much smaller sample volume than a straight recirculating flume. Since the critical shear stress for erosion of clay sediments varies with overburden pressure, i.e., depth within the deposit, a bed must first be formed by deposition of a sufficient amount of sediment. Progressively increasing hydraulic shear stress is applied to such a bed while a number of measurements of suspended sediment concentration vs. time are made (9,11).

5.4 Task 4 - Mathematical Modeling

Hydrodynamic Modeling. The Fischer or Link-Node Models can be applied to the system to obtain the dynamic section averaged flow velocity in each channel. Typically model runs will be made for a complete tidal cycle with specified inflows at Sacramento and Vernalis, exports at the State and Federal projects, and the tidal elevations being specified near Chipps Island. Alterations to channel sections and operational strategies at the cross delta channel and Clifton Court intakes can be readily specified so that the flow field for any condition obtained to be input to the sediment model.

Sediment Modeling. The sediment model that is to be used needs to possess the features enumerated in Section 4.3 under the heading, "Mathematical Modeling." The data developed under the previous three tasks will provide all necessary information on the sediment inflows and outflows, composition of sediment on the bed, and the erodibility and depositional characteristics of the various size fractions. The suspended sediment transport in the channels is determined by the mass balance equation:

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(AU_s C)}{\partial x} = \frac{\partial}{\partial x}\left(AD_x \frac{\partial C}{\partial x}\right) + S \qquad 5.1$$

where A = area of cross-section of channel

C = section averaged suspended sediment concentration for particular size fraction

t = time

x = length along channel

U_s = sectionally averaged velocity of sediment not equal to sectionally averaged flow velocity in general

D_x = longitudinal dispersion coefficient

S = source/sink term accounting for erosion or deposition

Such an equation for each sediment size is solved to obtain the total sediment concentration. Note that the sediment velocity U_s, the dispersion coefficient D_x and source/sink term S is different for each size fraction.

The value of the average sediment velocity can be computed from the average flow velocity by assuming that fully developed flow and concentration profiles exist at all points in the system. The Rouse equation for suspended sediment distribution in a fully developed turbulent flow is:

$$c(y) = c_a \left(\frac{a}{d-a}\right)^{\zeta} \left(\frac{d-y}{y}\right)^{\zeta} \qquad 5.2$$

where a = some reference elevation at which the concentration c_a is known

d = depth of flow

$\zeta = V_s/kU_*$

V_s = settling velocity

k = von Karman's constant

U_* = shear velocity

The vertical velocity profile for a fully developed two-dimensional, free surface flow over a rough bed as proposed by many researchers varies only in the constants that are used and is of the general form:

$$\frac{U}{U_*} = \frac{1}{k} \ell n \; (y/k_s) + a_r \qquad 5.3$$

where U is the local longitudinal velocity, k is von Karman's constant, k_s is the effective roughness height, and a_r is a function of the boundary Reynolds number $R_* = U_* k_s/\nu$.

For a hydrodynamically smooth wall:

$$a_r = 5.5 + 5.75 \log \left(\frac{U_* k_s}{\nu}\right) \qquad 5.4$$

so that equation (5.4) becomes:

$$\frac{U}{U_*} = 5.5 + 5.75 \log \left(\frac{U_* y}{\nu}\right) \qquad 5.5$$

The criterion for smoothness is $R_* \leq 3.5$.

For rough walls:

$$a_r = 8.5 + 5.75 \log x \qquad 5.6$$

where x is a parameter whose variation with k_s is given by Einstein in his bedload function computation.

The effective rate of sediment transport or apparent sediment velocity U_s is then given by:

$$U_s = \frac{\int_0^d UCdy}{dc} \qquad 5.7$$

where d = depth of flow, and U as before is the average sediment velocity. Here it is assumed that there is no variation in the velocity and concentration profiles in the lateral direction. Since the concentration C is an unknown, non-dimensionalization of equations 5.2 and 5.3 are resorted to as detailed in Ariathurai (15) to compute U_s in equation 5.7. The principle used however, is that the shape of the concentration and velocity profiles are given by equations 5.2 and 5.3 and that the ratio of the average sediment velocity to the average flow velocity can therefore, be determined as shown in reference (15).

The source/sink term S is given by equations 2.2, 2.3 and 2.4 for cohesive sediments in which the bed shear stress τ_b is calculated from the shear velocity given by equation 5.5 according to:

$$\tau_b = \rho U_*^2 \qquad 5.8$$

For the silts and sands, the erosion and deposition rates E and D as proposed by Ariathurai (20), i.e.:

$$E = M \left(\frac{\tau_b}{\tau_{ce}} - 1\right) \left(\frac{C_{max} - C}{C_{max}}\right) \qquad 5.9$$

for $\tau > \tau_{ce}$

and

$$D = -V_s C_b \left(1 - \frac{\tau_b}{\tau_{cd}}\right) \qquad 5.10$$

for $\tau < \tau_{cd}$

where M = erosion rate constant obtained from measurements

τ_{ce} = critical shear stress for erosion

C_{max} = maximum concentration permitted in bed layer

C_b = sediment concentration in bed layer

V_s = settling velocity of sediment

The various constants that arise in these equations are obtained from the laboratory measurements described in the previous section.

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The solution of the mass balance equation 5.1 yields the concentration of each size fraction of sediment at each cross-section as it varies with time. Depending on whether erosion or deposition occurs, the bed profile is altered appropriately at each time step. The reader is referred to Ariathurai (20) for complete details of a model that embodies all the features described above.

In summary, the model inputs are:

(1) Geometry and sectionally averaged flow velocities for each time step.

(2) Concentration of sediment at points of inflow.

(3) Settling velocity, critical shear stress and erosion rate constant of size fraction.

(4) Initial bed profile.

The model outputs will be:

(1) Time history of local sediment concentration by size fraction.

(2) Changes in bed profile.

(3) Sediment outflows.

Separate calculations of bed load transport can be made for the Sacramento River by using a bed load function such as that proposed by Einstein (14). Since the bed load is a small fraction of the total load in the Delta and is restricted primarily to the Sacramento River main stem, a separate calculation can be made if necessary.

5.5 Schedule of Work

The recommended work plan and possible schedule to execute the tasks are presented in Figure 9. A cost estimate is appended to this report.

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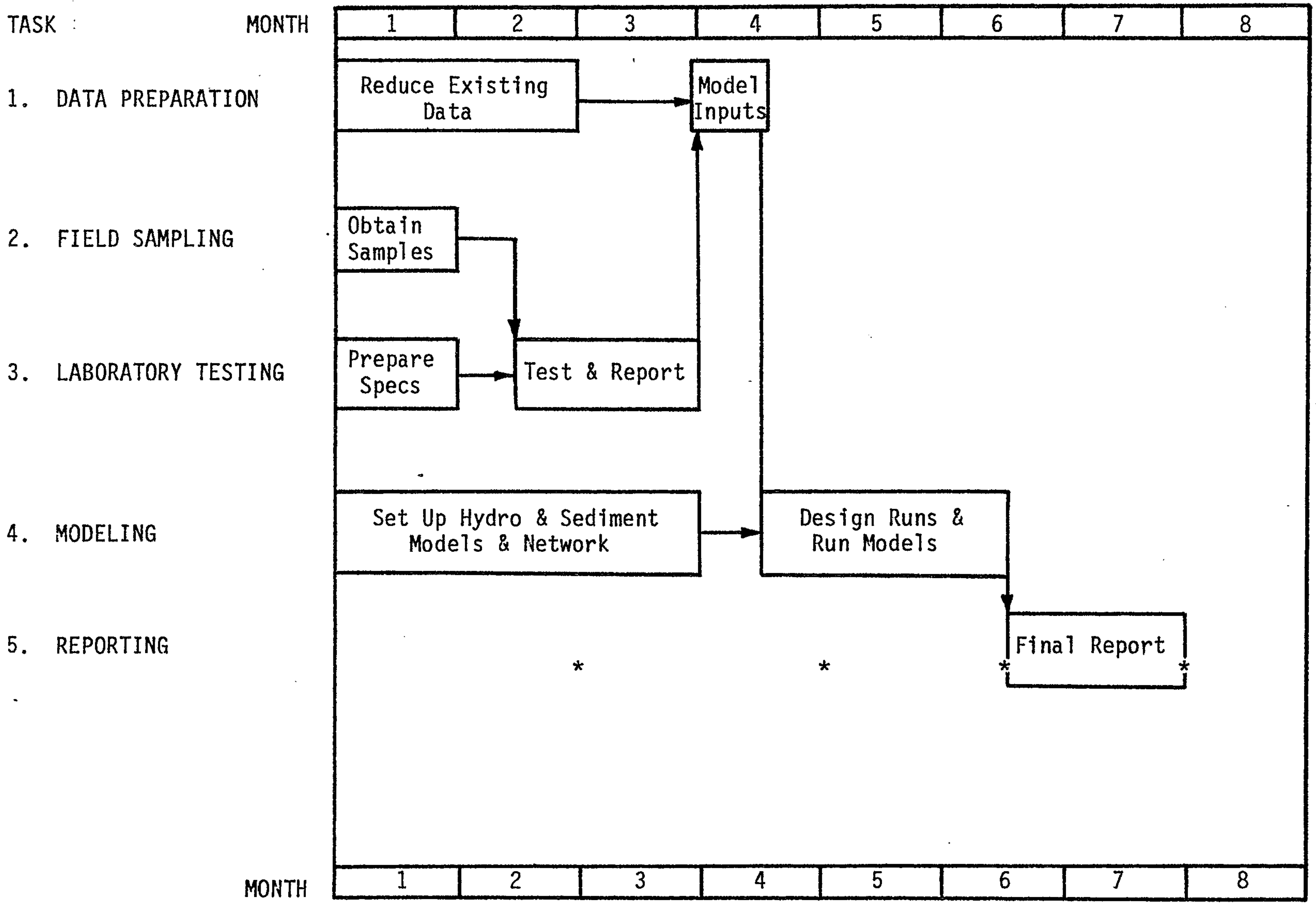

* Oral Presentations

FIGURE 9

WORK PLAN AND SCHEDULE

6. SUMMARY AND RECOMMENDATIONS

The existing data show that suspended sediment transport is the predominant mode of transport of sediments into and through the Delta. Diversion of Sacramento River flows into the Delta via the cross Delta channel has increased the water and sediment discharges in the upper Delta channels. Studies have shown that a substantial amount of sediment material is deposited in the Delta channels although the locations where deposition occurs or the rate of such deposition are not known. Futhermore, a significant quantity of fine sediments are pumped with the waters at the State and Federal projects. Velocities in the channels in the vicinity of the pumps are increased by the pumping during a part of the tidal cycle. It is possible that such velocity increases may cause scouring of the bed.

Due to the fact that flow reversals occur in most of the Delta channels and the velocities fluctuate signficantly in those that do not experience reversals, there will exist two types of channels with respect to erosion and deposition. The first will be channels that experience shoaling exclusively, and the second, those that experience both deposition and erosion depending on the phase of the tide. Changing tidal ranges and freshwater flows once again may alter the situation in some of the channels. A description of the flows in the channels at various times, and the sediment transport processes within the system can be obtained from a mathematical model that synoptically describes the flows and associated sediment transport processes.

The application of such a model to the system requires certain initial and boundary conditions that relate to water and sediment discharges into the system, sediment composition on the bed, and tides. Fortunately, a majority of the data required is already available as a result of the data acquisition and monitoring programs undertaken by DWR and the USGS. A plan for acquiring the additional data that is necessary has been presented in this report and is a relatively minor effort in terms of time and cost.

Model simulations will yield the suspended sediment concentrations, rates of scour and deposition, and the changes in bed profiles in each channel during the simulation period. Bank erosion and levee stability analyses will have to be conducted separately and are not included in this study.

Recommendations

The following recommendations are made as a result of this study:

1) It is suggested that DWR conduct a study based on the plan described in this report.

2) During the development of this study plan, DWR personnel prepared a list of existing data relevant to erosion, deposition and sediment transport in the Delta. It is recommended that the list be expanded to clearly identify sources, periods of record, and any other information that describes the data in detail.

3) The data requirements for conducting the study suggested here have been outlined. Some of the existing data resides on data bases established by other agencies, e.g., STORET. It is recommended that all required data be assembled on a single data base at DWR in order to expedite access.

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