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SEDIMENTATION AND SCOUR

Delta Impacts Staff Paper

Interim Report

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CONTENTS

Figures

Page

Tables

Plates

INTRODUCTION

This interim report discusses work completed and in progress for the Delta Sedimentation and Scour staff paper. The purpose is to present the results of a study to determine rates, amounts, grain sizes, and locations of sediment transport, erosion, and deposition caused by present water diversions and transfers. The Sacramento-San Joaquin Delta channels deliver water from the Sacramento River to Clifton Court Forebay (State Water Project) and to Tracy Pumping Plant (Federal Central Valley Project).

The Delta

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. They converge in the 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 upstream activities. These flows interact with the tides and are modified in quantity and quality as they pass through Carquinez Strait, San Francisco Bay, and the Golden Gate into the Pacific Ocean.

As a result of the State's enormous requirements for water, primarily for agriculture, reservoirs, pumping facilities, and conveyance systems have been built to redistribute water from areas of surplus in the north to areas of demand in the south. The U. S. Bureau of Reclamation's Central Valley Project, which began operation in the mid-1940s, and California's State Water Project, implemented in the 1960s, are engineering works designed to manage the State's water resources. Together these two systems have 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.

Modification of the Bay-Delta system and continuing human 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 percent in the last 100 years (Gilbert, 1917 and Nichols, 1971). Diking of lands within the Delta for agricultural use has reduced the inundated area to a small fraction of the original extent.

Great quantities of sediment transported by the rivers into the Bay and Delta move primarily as suspended load. More than 80 percent of the sediment load is transported in the winter. Of the estimated 5 million tons per year of sediment inflow to the Delta (Porterfield, 1978), about 80 percent originates from the Sacramento and San Joaquin river drainages; the remainder is contributed by local streams. Estimates of the amount of sediment deposited in the Delta vary from 15 percent (U. S. Army Engineer District, 1967) to 30 percent (Conomos, 1976); the balance moves into the San Francisco Bay system or out through the water project facilities.

Sediment circulation within the Bay-Delta system is complex due to the numerous interconnected channels, tidal flats, and bays, within which the interaction of fresh water flows, tides, and winds produce an ever-changing motion of sediments. 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 erosion of the bed and banks.

Over 90 percent of the sediment that enters the Delta is suspended sediment (Conomos, 1976) composed primarily (80 to 97 percent) of rock particles; the remainder is living and detrital organic 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 particles and, therefore, increasing salinity and reduction in flow velocity enhance sediment deposition.

The Delta is a dynamic system in which deposition and erosion in the channels are influenced by the effects of mining debris, reservoirs, floods, and droughts. Any significant changes in the flow patterns and sediment transport could have a substantial effect on commercial navigation, recreation, flooding, and levee stability. A drastic change in water quality could change natural vegetative growth, reduce fisheries and other wildlife, and affect use of water for domestic and irrigation purposes. Each of these changes would be accompanied by unknown socio-economic impacts.

Scope

Much of the proposed work was started under the Peripheral Canal Staff Paper program. The present program is the Delta Impacts Staff Paper program. Twenty-five years of data, worksheets, memoranda, reports, and other literature pertinent to sediment transport and water flow have been collected.

The scope of this staff paper includes describing the mechanics of deposition, erosion, and sediment transport and discussing the conditions and environmental factors affected by changes in salinity and hydraulic conditions. The staff paper will:

- Describe the methods used for the study.

- Identify present conditions of flow velocities and patterns and of suspended and bottom sediment distribution.

- Qualitatively discuss potential changes in the system caused by water transfer.

- Discuss mitigation measures and cost of such measures.

Any alterations to the natural environment disrupt the state of equilibrium that exists at the time of the alteration. Knowing the existing conditions provides a basis for monitoring the changes and for predicting what may happen given certain altered variables, such as increased flow or decreased velocities and differences in incoming sediment load. To establish this basis, specific questions were posed to focus the intent of the staff paper:

- Is (or will) erosion, deposition, and/or sediment transport taking place in Delta channels as a result of operation of the State and Federal water projects?

- Where and in what channels does erosion, deposition, and sediment transport take place?

- What causes erosion, deposition, and sediment transport?

- What quantities and sizes of sediments are moved?

- How are erosion, deposition, and sediment transport affected by the tidal cycle?

- What are the effects of erosion, deposition, and sediment transport, and to what extent?

- Is a computer model the best approach to analyze the data?

- Are the data now available to the Department sufficient to answer all the questions?

Much of the work herein is taken from a Resources Management Associates report (under DWR contract), which is reproduced as Appendix A.

Geology

The geologic history of California is complex. Following is a simplified description of the major events since the Triassic, about 2.3 million years ago, that formed the Delta, Sacramento Valley, and surrounding mountains. A relatively quiet, biologically diverse, marine environment existed as far inland as the area known today as Nevada. Most of California either did not exist or was under water. Abundant marine fossils suggest that the west coast of the continent was tectonically stable, with no high influx of sediments and no rapidly changing sea level. A rapid change would be a change in level of two or more centimeters per year.

In the late Jurassic (about 1.8 million years ago) the west coast area became tectonically active. The ocean floor was spreading as a result of renewed volcanic activity along the East Pacific Rise, an oceanic rift zone. A subduction zone, or trench, formed in response to the ocean floor abutting against continental crust. The oceanic crust was consumed at the trench as tectonic forces pushed the crust beneath the continental land mass. The crust heated and melted as it moved downward, then rose again, as molten rock through the continental crust, to eventually form the mountain chain known as the Sierra Nevada. Uplift of the rocks was part of this mountain-building process. Subsequent erosion washed sediments into the lowland region, which today is the Sacramento Valley.

As the oceanic crust was forced downward, the marine sediments that accumulated on the floor and in the trench were essentially scraped off onto the continental land mass. These rocks, which were intensely deformed, are now the Coast Ranges.

The Delta, a triangular shaped plexus of channels and islands, is the meeting point for the Sacramento, San Joaquin, and Mokelumne rivers. These channels and other local tributaries apparently were repeatedly incised and backfilled with each major climatic fluctuation, complicated by subsidence and isostatic adjustment of the land surface. The underlying deltaic deposits are sediments accumulated from the marine seas that periodically occupied the area and sediments from river systems draining the surrounding watersheds.

In the most recent natural development of the Delta, the river system formed a large number of islands. During flood stages, sediment-laden water rose above the natural channel banks and, in flowing outward, dropped the sediments, forming natural levees. From the levees, the surface gradient of each island dropped saucerlike toward the interior, which in most cases was below mean sea level. Water ponded in the islands, forming the ideal environment for the growth of tules. The decaying vegetation formed extensive peat deposits, which are intermixed with mineral soils carried in by periodic flooding. The islands have now been reclaimed for agricultural use through reinforcement of the levee system.

VARIABLES AFFECTING DEPOSITION AND EROSION

Sediment transport conditions are influenced by precipitation, soil saturation, vegetative cover, and land use practices in the watershed. Each channel has a geometry, suspended load, bedload, and grain size determined by the flow, the salinity, and the sediment characteristics. Water quality, human activities, and many more factors are involved in sediment transport. Determination of sediment transport rates is extremely complex, because many of the variables cannot be determined or must be expressed graphically.

> "The variables relate not only to available supply of the sediment but also to sizes, shapes, and densities of the particles; velocities of flow; channel widths, depths, and slopes; bank roughness and bed configuration; and density, temperature, and at times even chemical composition of the water. An average particle size or mean velocity may be an inadequate measure respectively of particle sizes of a sediment or of a velocity at a cross section, because the distribution about the average has significant effects. Most factors affecting sediment discharge change only with time and with distance along a channel but also with depth and with lateral distance at an individual cross section." (Graves, 1977).

The mechanics of sediment transport in either saline or tidally affected streams, such as the lower Sacramento River and the Delta, are even more complex than in fresh water streams.

> "The changes in the tide affect the place of deposition of the stream sediments. A stream transporting some sediment sizes at its full ability will begin to deposit some particles of these sizes where the stream is first slowed by the effect of the ocean level. The place of this first deposition may vary several miles and depends on whether the flow is affected by high or low tide. Thus, along an appreciable reach of tidal stream, sediment deposition may be intermittent. Also, some sediment deposited at high tides may be eroded from the streambed at low tides. Farther downstream, sediment may deposit slowly at low tide and much faster at high tide. Of course, the amount and place of deposition of sediment also vary with the discharge of the stream. If the streamflow is low, some fine sediment may even be carried back upstream while the tide is rising and be deposited before downstream flow begins again. Especially during floods, some fine sediment may be carried far out into the ocean or bay by the stream current." (Graves, 1977).

Modification of the system, such as diversions or channel changes, will alter the hydraulic processes until a new state of relative equilibrium is established. The consequences of change may be either detrimental or beneficial.

Erosion may occur when: (1) the velocity of flow in a channel is increased, (2) the sediment inflow to a channel in equilibrium is reduced, (3) predominance of flow in one direction is altered in a channel that experiences reverse flows. The rate of erosion depends on the composition of the material on the bed and banks and on the amount of change in the factors listed above. Erosion in the channels may cause:

- Bank or levee instabilities.
- A drop in water surface elevation, which may affect the pumping head and the tidal incursions.
- Additional sediments to be suspended in the waters, thereby increasing turbidity and causing accelerated deposition downstream.
- Flow changes in other channels by diverting more water.

Increased sediment concentrations in the water may:

- Affect water quality by altering the nutrient and toxicant levels in the water and by reducing the penetration of sunlight, also affecting benthic conditions and dependent biological productivity. These effects may be beneficial or detrimental depending on the changes.
- Increase the amount of sediments in the water exported. This may cause problems in the aqueducts and points of water release.

Deposition is caused by effects opposite to those for erosion. 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 and channel size. Deposition in the channels may cause:

- Reduction in capacity to transport water, which may result in levee instability and flooding.
- Clarification of waters and increased light penetration, which may cause more rapid growth of algae.
- Flow diversions and altered tidal incursions.
- Reduced capacity in forebays.
- A reduction in channel depth, affecting navigable waterways.
- Increased costs for dredging in boat harbors and navigable waterways.

MECHANICS OF SEDIMENT TRANSPORT

Physiochemical, mineralogical, and biological factors control the rate of transport, deposition, and resuspension of sediments. Sediment transport depends on hydraulic characteristics, bed configuration and roughness, current velocities, shear stress of the fluid, critical shear stress of bed materials, fluid properties, and channel depth.

The process of erosion and deposition includes several steps. Before erosion can occur, the particle must be detached from the position in which it rests. The velocity of flow in a channel must be high enough to detach the specific size particle. Once a particle is detached, it is subject to transport, and it may be transported until the velocity slows or until the flow can carry no more particles. At that time the particle may be deposited in a new location downstream from where it was recently detached. The entire process consists of three distinct phases: detachment, transport, and deposition.

The following discussion from the Resources Management Associates report explains the basic mechanics of sediment transport, emphasizing the differences between cohesive and noncohesive sediments. (Appendix A contains technical details, and Table 1 is a summary.)

Table 1

TRANSPORT FOR COHESIVE VERSUS NONCOHESIVE SEDIMENTS

	Cohesive	Noncohesive
Sediment Properties	Very fine particles. Exhibit colloidal properties. Flocculate. Resist erosion due to inter-particle bond.	Coarse particles. Resistance to detachment due to weight of particle. Do not flocculate.
Detachment	Resistance to detachment estimated by CEC, salt concentration, pH, SAR.	Particle size, density shape.
Transport	$Q_s = VC$ V = flow velocity C = sediment concentration Q_s = transport rate	$Q_s = V_sC$ V_s = sediment velocity C = sediment concentration Q_s = transport rate
Deposition	$\left.\frac{dC}{dt}\right\|_d = \frac{-PV_sC}{d}$ d = average depth through which particles settle t = time P = Probability of particles sticking to the bed	If $C > \frac{Q_s}{V_s}$

The presence of cohesive sediments is important to 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 flocculate and settle out much faster than the individual particles. Higher salt and higher 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 percent clay may exhibit properties similar to a pure clay, rather than the 95 percent noncohesive material it is composed of. Cohesive sediment properties and the study and quantification of transport processes have been undertaken only in recent years. Detailed descriptions of cohesive sediment transport are presented in many references.*

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, when studying water quality, it is necessary to quantify the transport of cohesive sediments.

The mechanisms of erosion, transport, and deposition of noncohesive sands 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. They are chemically inert, so they do not flocculate or exhibit ion exchange properties. Unlike clays, which consolidate under overburden pressure, sands maintain a relatively uniform density in deposits.

Critical Shear Stress for Detachment

When the hydraulic shear stress at the bed exceeds the resistance of the bed material to such shear, detachment of the particle occurs. The shear stress at the bed that is produced by flowing water depends primarily on the average velocity of flow, the depth, and the 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 detachment.

*Ariathurai, 1974 and 1978; Kandiah, 1974; Krone, 1962 and 1963; Migniot, 1968; and Partheniades, 1962.

The resistance to shear of cohesive sediments, on the other hand, depends 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:

- The surface charge density, which is a property of the clay mineral.
- The salt concentration of the surrounding water (attraction increasing with increasing concentration).
- The valence of the cations in solution (attraction increasing markedly with increasing valence).
- The temperature (attraction decreasing with increasing temperature).
- The separation (attraction decreasing rapidly with increasing distance).
- The pH of the surrounding water.
- The kind of anions in solution.

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 milliequivalents (me) of exchangeable cations held by 100 g of dry mineral. CEC is an effective measure of the activity of a clay, 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.

The total salt concentration and pH of the pore fluid strongly influence 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:

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

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

Together, the CEC of the clay, total salt concentration, SAR, and pH of the suspending water predominate in determining cohesion.

C-105051

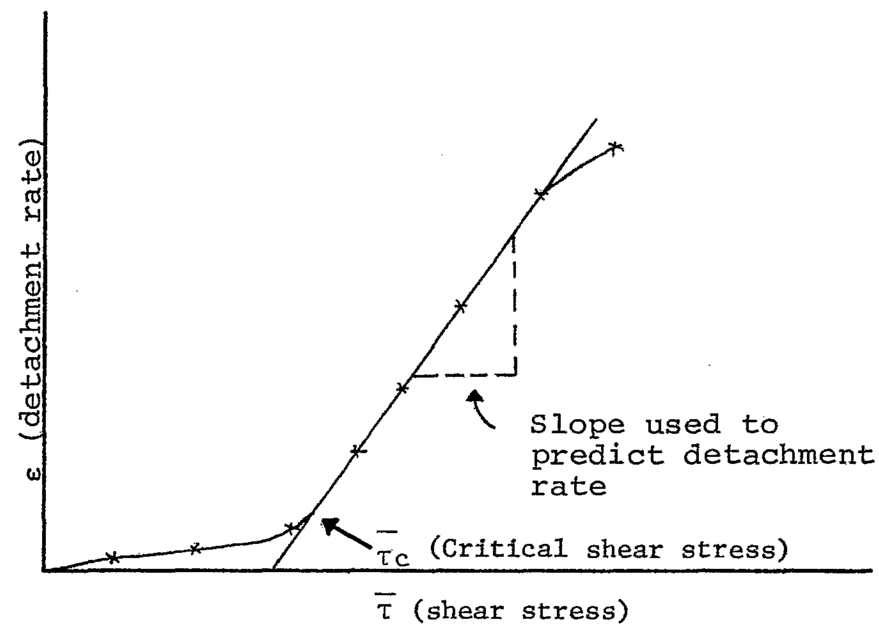
Empirical relationships between the critical shear stress for erosion of cohesive beds and the parameters mentioned above have been developed as a result of extensive laboratory and field testing.* The critical shear stress for detachment of a particular sediment can, therefore, be estimated by using these relationships if 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 (Krone, 1962), rotating cylinder apparatus (Ariathurai, 1978), or annular rotating flumes (Mehta, 1979) can be used to measure erodibility of cohesive and noncohesive soils. Undisturbed or remolded samples are used for these tests, which yield both the critical shear stress and the rate of erosion. Typically, erosion rate vs. mean hydraulic shear is stress plotted. Figure 2 is an example.

The plot 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.

Figure 2

MEASUREMENT OF CRITICAL SHEAR STRESS



*Ariathurai, 1978; Kandiah, 1974; Krone, 1962; and Partheniades, 1962.

C-105052

At bed shear stress just above critical value, detachment 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; 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 detachment rate if the erosive mechanism is surface erosion. At present, laboratory measurements must be made to obtain these parameters. The critical shear stress for rates of erosion may be measured in a flume for beds of relatively low strength. Stronger beds may be tested in a rotating cylinder apparatus by the method described in reference by Ariathurai (1978), although this method is not suitable for thin layers.

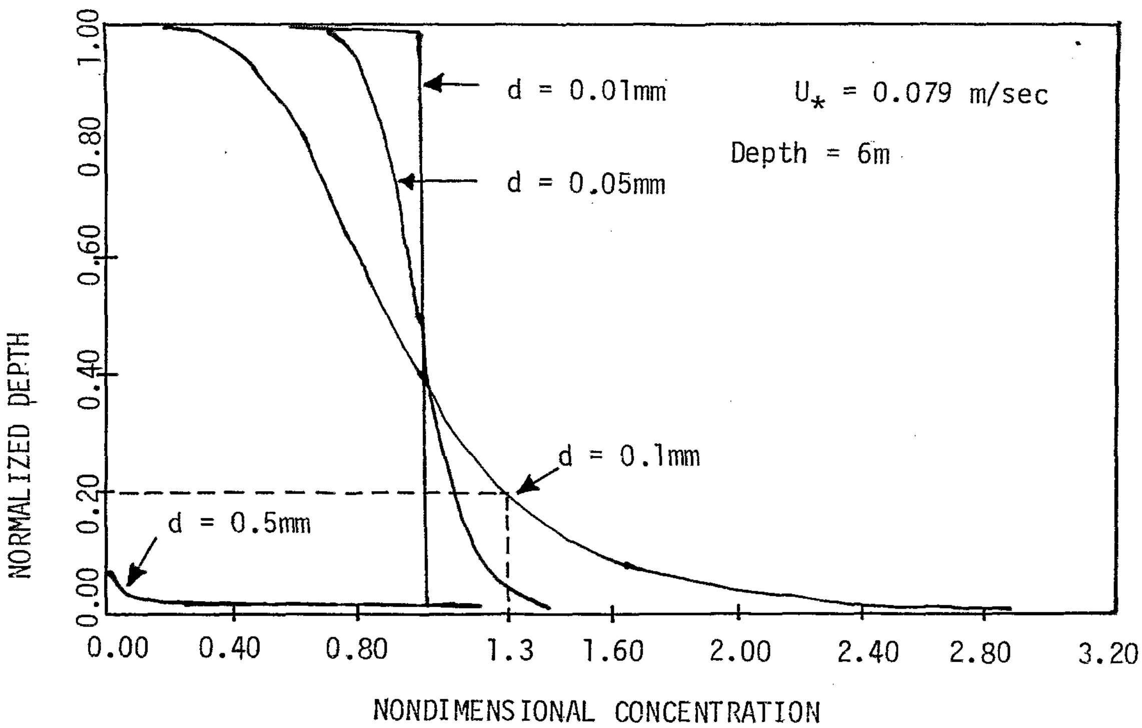
Transport

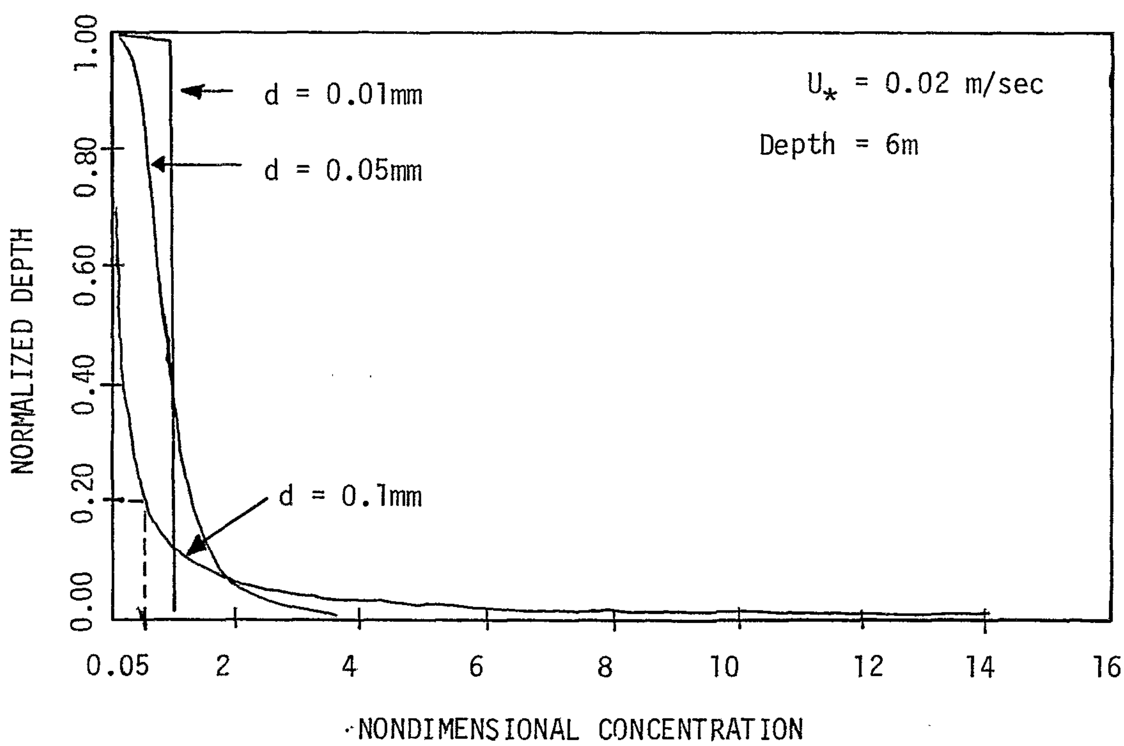
Sediments are transported as suspended load and as bed load. Particles are suspended when velocity of the particles is balanced by the upward mixing caused by turbulence. The bed load is carried in a thin layer within which particles slide, roll, and saltate (jump). This thin layer is close to the bed, and the particles within it intermittently rest on the bed.

Einstein, in developing his bed load function, defined the following terms:

> 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 thick, immediately above the bed. The thickness of the bed layer varies with the particle size.

The total sediment load is composed of the bed load and suspended load. The sediment sizes that make up each of these loads depend on the velocity 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_*) is shown in Figure 3. The smaller diameter particles are more or less uniformly distributed in the water column; the heavier particles are concentrated near the bed. Clays and silts are assumed to move entirely as suspended load; sands may move as suspended load or bed load.





Vertical Sediment Distribution
for Various Sizes

Example: At a depth of 0.2m and a particle size diameter of 0.1mm, the higher shear velocity of 0.079 m/sec has a higher nondimensional concentration of 1.3, compared to the lower shear velocity of 0.02 m/sec with a concentration of 0.5.

The suspended fraction is most commonly reported. Most field studies collect samples and analyze only for suspended sediment, because bed load sampling techniques are costly, difficult to execute, and have no standard method.

The rate of sediment transport is computed using the average flow velocity and sediment concentration. For unsteady flow conditions, the sediment velocity, which may be different than the average flow velocity, should be used.

Sediment transport equations are used to calculate the capacity of a particular flow to carry a particular sediment. If the sediment concentration falls below this capacity, bed material, if available, is detached and transported.

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 as or less than the critical shear stress for erosion, depending on the history of the bed surface.

The probability of cohesive particles sticking to the bed increases linearly with a decrease in the bed shear. 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 consolidate as the overburden increases and, as a consequence, increase in density and resistance to detachment (Ariathurai, 1980).

BASIC DATA SOURCES FOR FLOW AND SEDIMENT

Sources of data available for the Delta area vary from basic data collection programs to site-specific studies concerning water transfer facilities, water quality surveillance, and scour monitoring (see Plate 1). None of the studies has fully examined all aspects of sedimentation and scour, nor have the studies integrated the data in an overall analysis of erosion and deposition in the Delta channels. Consequently, the initial work for the staff paper was concentrated on locating and obtaining data; locating and evaluating reports that discuss erosion, deposition, sedimentation, scour, and flow velocity and quantity; and attempting to integrate the conclusions. Attention was focused on the longest period of data records and the most recent reports, because they presumably incorporate the earlier research and are founded on a greater data base. The data and reports are summarized below.

Publications

To evaluate sediment studies, it was necessary to review the types of data available. Historical sediment-yield values from the turn of the century are found in publications by Grunsky (1929) and Jones (1967). More recent sediment-yield values have been collected for the western tributaries of the Sacramento River by Jones, Hawley, and Crippen (1972), who published a compilation of data for 1941 through 1965. These studies provide the earliest estimates of Sacramento River sediment and document the sedimentological effects of hydraulic mining. Since it has been suggested that the Sacramento River is still exhibiting a decreasing trend in annual sediment yield that began at the close of hydraulic mining operations, it is important to review this information for sedimentation predictions.

The U. S. Army Corps of Engineers completed a Sacramento River Bank Protection Study in 1981, which supplies information on the type and source of sediments flowing into the Delta via the Sacramento River. DWR contracted with the University of California, Davis, and the U. S. Geological Survey from 1978 to 1982 to study sediment transport near the proposed Peripheral Canal intake near Hood (Kadir, 1983; USGS, 1983). Kadir's study supplies estimates of suspended sediment load and transport rates.

The California State Library provided pertinent references via NTIS, Compendex, GEOREF, and Water Resources Abstracts computerized literature searching programs. Many other reports were consulted for specific data and general information on sediment transport. These are listed in the references.

Gaging

Stream and sediment gaging stations are located throughout the Delta region. Table 2 lists locations and periods of record maintained by the U. S. Geological Survey. Although data are sparse, normal, critically dry, and wet periods are covered. The time covered by the data is extremely short for analyzing natural systems and for basing predictions on that analysis. These stream gaging data provide input for velocities in the channels for hydrodynamic modeling.

Table 2

USGS GAGING STATIONS

	Period of Record		
Station Location	Flow Discharge	Suspended Sediment	Turbidity
Sacramento River - "I" Street	1948-1979	1957-1979	1972-1979
Sacramento River - Freeport	1979-Date	1979-Date	1979-Date
Sacramento River - Rio Vista		1979-Date	1979-Date
San Joaquin River - Vernalis	1922-Date	1957-Date	1972-Date
Cosumnes River - McConnell	1941-Date	1965-1967	
Mokelumne River - Woodbridge	1924-Date	1975-Date	
Contra Costa Canal - Oakley	1950-Date		
Arroyo del Hombre - Martinez	1964-Date	1970-1971	
Delta-Mendota Canal - Tracy Pumping Plant	1957-Date		
Green's Landing - Courtland	1953-1958 1971-Date	1953-1958 1971-Date	

C-105057

The Geological Survey (USGS Water Supply Papers) data collection procedure and analysis are as follows:

> "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 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 concentrations 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."

Various other shorter term gaging programs have added to the data collection. The Corps of Engineers and the Geological Survey made periodic measurements of suspended sediment concentrations at a number of stations in and near Carquinez Strait in 1977. During 1973 and 1974, DWR and the Bureau of Reclamation measured suspended sediment of the water exports at the Banks and Tracy pumping plants and Clifton Court intake. The Geological Survey sampled suspended sediment and bed load from 1978 to 1981 along the Sacramento River near Hood for a study related to the Peripheral Canal. The Bureau of Reclamation (from 1968 to 1974) and DWR (from 1975 to present) have collected suspended sediment

C-105058

and bed load samples as part of the Delta Water Quality Surveillance Program. Sampling points for that program are located throughout the Delta, as are tide gaging stations.

Analysis of all the gaging data will enable the calculation of a sediment and flow balance for the system. Sediment concentration and size composition for suspended and bed load sediments will aid in the study of sediment transport processes and results of changes in the flow regimen.

Dredging

A regular activity in the Delta is channel dredging. Local districts dredge the inner channels for materials to stabilize the levees. The Corps of Engineers dredges certain channels to maintain a minimum depth for navigation. The Corps of Engineers has been dredging the Sacramento River near Rio Vista and the Stockton Deep Water Channel for many years, but has records only since 1966. Areas of repeated dredging delineate areas of deposition. Dredging data tell the amounts of sediment removed from the system.

Cross Section Surveys

Numerous cross section surveys have been conducted in the channels. In 1933, the Corps of Engineers measured 20 sections between Courtland and Sacramento; in 1968, DWR measured the same sections, plus sections in Miner, Georgiana, and Steamboat sloughs, Delta Cross Channel, and Sacramento and Mokelumne rivers near Walnut Grove. Since 1969, the DWR Scour Monitoring Program has documented changes in cross-sectional areas at 40 sites along the Old and Middle rivers system for evidence of erosion or deposition. The program has not attempted to identify or quantify causes of the changes, but has provided information on channel geometry and the possible effects of pumping in the southern Delta.

From 1978 to 1983, the Geological Survey surveyed channel cross sections on the Sacramento River near Hood for a special study relating to the Peripheral Canal. Department of Water Resources measured sections near Courtland, Isleton, and Rio Vista in 1979, and in the South and North Forks of the Mokelumne River and at the Delta Cross Channel in 1982.

Those cross sections with multiple surveying over a period of time provide evidence of past channel changes; all the cross sections provide a base for evaluating future conditions.

Aerial Photographs

Aerial photographs taken at periodic intervals allow visual estimates of deposition and erosion. Those taken after above normal or below normal water years should be particularly useful in determining regional scour and sedimentation history. With any aerial photographic interpretation, quantitative estimates of processes have to be fairly general.

Computer Programs

Several computer models are available as tools to reduce the complexity and quantity of calculations necessary to integrate Delta flows, sediment rates, and exports (see Table 3). These models use available data and interpolate between measurement sites to simulate the entire system. The models are also used to predict reaction of the system to changes.

Table 3

COMPUTER MODELS

Model Name	Model Type	Developed By
DELFLOW	Flow, Velocity	Hugo Fischer, UC Berkeley
DELSAL	Salinity	Hugo Fischer, UC Berkeley
DYNFLOW	Flow Rate, Velocity	Dept. of Water Resources
TVSALT	Salinity	Dept. of Water Resources
DAYFLOW	Flow Balance	Dept. of Water Resources

Using the U. S. Geological Survey flow and sediment data for the Sacramento River, which is on computer file, a series of computer plots were made (see Appendix B). The plots were grouped into three general sets: (1) suspended sediment versus time, (2) flow versus time, and (3) suspended sediment versus flow. These plots were analyzed to determine trends between the variables.

Various graphs, tables, charts, and maps have been made and evaluated using a combination of data sources.

Flow data appear to be sufficient to determine the hydrodynamics in the system. Sediment data are not sufficient to accurately model sediment transport. Resources Management Associates has recommended a field sampling program and laboratory analysis of collected samples.

SEDIMENT TRANSPORT IN THE DELTA

Resources Management Associates and the Department of Water Resources evaluated the existing data sources to obtain a preliminary indication of the sediment transport condition in Delta channels.

Sediment entering the Delta comes from:

- Sacramento River;
- San Joaquin River;
- Lesser streams and local drainage; and
- Return from the Bay with the tides.

Sediment is lost from the Delta by:

- Flows into San Francisco Bay;
- Sediment pumped with export water; and
- Removal by dredging.

The Delta is primarily a depositional environment, but variations of water and sediment inflow result in both deposition and erosion.

Figure 4 is a graph of daily discharge and suspended sediment load at Sacramento from 1956 through 1980.

Figures 5A and 5B are plots of the silt and clay fraction versus river discharge for Sacramento and San Joaquin rivers, developed from particle size analysis of suspended sediment samples. The Sacramento River plot indicates that most of the time more than 70 percent of the suspended sediment is silt and clay (<0.062 mm) for flows less than 40,000 cubic feet per second. Between 40,000 and 100,000 cfs, the silt and clay fraction varies from 30 to 95 percent. In general, as the flow increases, the percentage of larger particles in motion increases. Flows in the San Joaquin River are rarely more than 40,000 cfs. Most of the time, more than 50 percent of the suspended sediment is silt and clay.

Tabulated annual loads (see Table 4) indicate an average suspended sediment load in the Sacramento River to be 2,407,862 tons/year, and in the San Joaquin River to be 310,073 tons/year. In addition to the suspended load transported into the Delta, it is estimated that about 345,250 tons/year of bed load is transported by the Sacramento River, and 46,500 tons/ year by the San Joaquin River. The total annual average sediment loads are 2,753,112 tons/year for the Sacramento River and 356,573 tons/year for the San Joaquin River. Local drainage and direct runoff into the channels provide the rest of the sediment inflow to the Delta. Estimates of total sediment inflow from all sources vary from 4.5 to 5.2 million tons/year.

Table 4

DISCHARGE AND SUSPENDED SEDIMENT LOAD

Water Year	Sacramento River at Sacramento and Freeport Discharge (cfs-day)*	Sacramento River at Sacramento and Freeport Sediment (tons)	San Joaquin River at Vernalis Discharge (cfs-day)*	San Joaquin River at Vernalis Sediment (tons)
1957	6,649,750	1,472,218	727,079	--
1958	12,572,290	4,947,900	3,053,420	--
1959	5,926,540	1,726,335	626,967	--
1960	5,362,340	1,752,738	277,237	45,608
1961	5,745,260	1,943,117	220,419	23,532
1962	6,263,300	1,659,850	749,717	258,266
1963	10,227,330	2,946,188	1,417,970	344,823
1964	6,276,077	1,069,009	566,935	99,991
1965	9,383,250	4,070,458	1,913,340	555,112
1966	6,747,110	2,064,690	855,224	185,884
1967	12,038,810	3,287,674	2,803,498	515,572
1968	6,749,580	1,601,556	720,263	120,402
1969	12,613,200	3,491,335	5,079,110	--
1970	10,612,900	3,200,343	1,544,692	357,768
1971	11,469,610	3,161,669	894,910	189,987
1972	6,514,310	847,191	561,738	115,928
1973	9,348,930	2,452,465	1,196,399	372,698
1974	15,421,120	3,911,792	1,396,480	334,998
1975	9,950,479	2,878,060	1,419,050	346,175
1976	5,759,020	619,528	772,387	172,327
1977	2,777,030	219,680	209,982	35,934
1978	8,713,250	3,789,472	2,258,077	503,344
1979	6,524,686	1,606,642	1,318,140	268,617
1980	15,053,100	3,068,774	3,020,670	575,899
1981			890,070	188,671
TOTALS	208,699,272	57,788,684	34,493,774	6,511,536
ANNUAL AVERAGES	8,695,803	2,407,862	1,379,751	310,073

*cfs-day = The volume of water obtained through the continuous flow past a certain point, measured in cubic feet per second over a period of 24 hours.

Source: U. S. Geological Survey, "Water Resources Data for California", Volumes 3 and 4.

The bed material in the Sacramento River near Sacramento is medium sand, coarse sand, and fine sand, in order of occurrence. Progressing downstream, the fraction of fine sand increases, with a decrease in coarse sand. The material brought in by the San Joaquin River is finer sediment. Grab samples from Delta channels indicate that the surficial sediments are composed primarily of silt, silty sand, and, in areas of lower flow velocity, clayey silt. The embayments, sloughs, and back water areas in the western Delta contain more clay, because the salinity in these areas reaches the flocculating concentration of 1 to 2 gm/L. This distribution of bottom sediments is shown in Plate 2.

Data obtained in Carquinez Strait will aid in determining the total load carried into San Francisco Bay (see Appendix A). Estimates from previous studies indicate that about 70 to 80 percent of the sediment that enters the Delta is transported into the Bay. An estimated 15 to 30 percent of the sediments are deposited in the Delta channels (U. S. Army Engineer District, 1967, and Conomos, 1976). The remaining 5 to 7 percent is transported with water exports.

Flood tides from San Francisco Bay resuspend part of the sediment and transport the material back into the Delta. Subsequent ebb flows return a part of this sediment to the Bay. The net mass transferred seaward by the back and forth movement depends on the tide and the superimposed freshwater flows.

Suspended sediment measurements in the exports have been made by DWR and the Bureau of Reclamation (1973-74) (Arthur, 1976). Rough calculations of the Bureau's measurements indicate that 200,000 to 300,000 tons of fine sediments were exported with the 4 million acre-feet of water exported by the State and Federal water projects in water year 1973-74. The sediment transport in the southern Delta channels seems to vary seasonally, deposition occurring in winter and resuspension of part of this deposited material occurring in summer (Appendix A).

Dredging of channels in the Delta is another mechanism by which sediment material is removed from the system. Corps of Engineers figures (Table 5) indicate a 16-year annual average of 665,968 tons of sediment dredged from the Sacramento River near Rio Vista and 292,163 tons dredged from the Stockton Deep Water Channel (see Plate 1 for dredging locations). An unknown amount of material is dredged by local agencies and districts for levee stability work. The Corps of Engineers stockpiles the dredged material in land spoil areas. Some of this material is reused as landfill or construction material.

Sediment inflow and outflow to the system are shown in Table 6. The flow regime and transport of sediment vary seasonally and yearly. Annual averages of sediment transported give only a rough accounting of the system.

Table 5

Army Corps of Engineers
Annual Dredging

Year	Sacramento Deep Water Channel Cubic Yards	Sacramento Deep Water Channel Tons	Sacramento Deep Water Channel River Mile*	Stockton Deep Water Channel Cubic Yards	Stockton Deep Water Channel Tons	Stockton Deep Water Channel River Mile*
Prior to 1966	No Records Prior to 1966					
1966	2,220,000	3,296,700		401,688	596,507	7
1967	183,830	272,988		430,542	639,355	
1968	--			613,467	910,998	28-40
1969	890,554	1,322,473	7-14 35-42	473,961	703,832	37-40
1970	--			--		
1971	712,807	1,058,518	3-14	15,000	22,275	
1972	146,000	216,810	8-15	372,081	552,540	37-40
1973	--			--		
1974	1,065,324	1,582,006	26-33	--		
1975	314,300	466,736	9-15	--	Material dredged for highway fill U. S. Stockton	I-5 construction
1976	--			--		
1977	--			--		
1978	270,485	401,670	4-15	841,161	1,249,124	21-32 37-41
1979	--			--		
1980	--			--		
1981	1,372,110	2,037,583	33-42	--		
1982	1,083,600 cy as of 12-82 - in progress 35' project depth with 2,500,000 cy					
1983						
Total	7,175,410	10,655,434		3,147,900	4,674,631	
Annual Average	448,463	665,968		196,743	292,163	

*River mile from confluence of Sacramento and San Joaquin Rivers
Data Source: U. S. Army Corps of Engineers
Data given in cubic yards. Conversion to tons by: 1.5 tons/yd^3.
Dredge spoil analysis by USACE measured 110 lbs/ft^3 for bottom sediments (personal communication, John Rompala, USACE).
110 lbs/ft^3 = 1.5 tons/yd^3.

Table 6

Sediment Inflow and Outflow

Sediment Into Delta (annual averages - tons)

From:	Percentage	Suspended Load	Bedload	Total
Sacramento River	80	2,407,862	345,250	2,753,112
San Joaquin River		310,073	46,500	356,573
Local	20	1,740,000	260,000	2,000,000
Return from Bay	Minimal	--	--	--
Total	100	4,457,935	651,750	5,109,685

Estimated total = 4.5 to 5.2 million tons/year

Sediment Deposited in Delta

Estimated 15-30% = 0.7 to 1.6 million tons/year

Sediment Out of Delta (annual averages - tons)

	Percentage	Suspended Load	Bedload	Total
to San Francisco Bay (34, 8) 3/	70-80			3,150,000 to 4,160,000
with exports	5-7	200,000-300,000 2/		
by dredging:	13-15			
Sacramento River			665,970	
San Joaquin River			292,160	
Other Channels			?	

Estimated total = 4.5 to 5.4 million tons/year

1/ Bedload is estimated to be 15 percent as much as suspended load (34, 8).
2/ One year measurement 1973-74, not an annual average.
3/ References.

The local velocity plots in Plate 3 show the variation in velocity in various Delta channels during a mean tide with summer inflows from the Sacramento (16,430 cfs) and San Joaquin rivers, and with and without pumping by the State and Federal projects. The velocities shown were obtained from a link-node mathematical model simulation (U. S. Geological Survey, 1983). A similar run of the model was made for a winter condition during which the discharge in the Sacramento River was 100,000 cubic feet per second.

These model simulations show that the Delta Cross Channel near Walnut Grove diverts a significant amount of water and associated sediment into the channels in the northern part of the Delta. Because the sill level of the inlet control structure is at a higher elevation than the bottom of the Sacramento River, there is selective withdrawal of sediment into the Delta Cross Channel. The coarser bed load continues down the Sacramento River; 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 flow caused by diversion through the Cross Channel can cause deposition downstream.

Continual dredging occurs near Rio Vista. The deposition may be caused by the convergence of the Sacramento River with the Deep Water Channel, forming a wider channel and lower water velocity.

Flows induced by use of the Delta Cross Channel have affected the North Fork of the Mokelumne River by eroding a rather deep channel near New Hope. This erosion and the increased flow may have accelerated the need for riprap on the Mokelumne River levees. This may have improved flood control because of increased channel capacity of the North Fork of the Mokelumne River. Delta Cross Channel flows that go down the South Fork pass through Dead Horse Cut and impinge upon the Staten Island levee at a right angle. There have been complaints about the erosion of the bank in this area for many years.

Water that flows through the Delta Cross Channel, which has a predominantly silt and clay load of sediment, moves down the Mokelumne River, in which the flow is primarily undirectional. The flow velocities slow downstream and allow deposition. The water then reaches the San Joaquin River, and the flows and sediment loads of the Mokelumne River are augmented by discharge from the San Joaquin River because of reverse flows caused by tidal movement and a more complex network of channels.

The discharges and velocities in the channels south of the San Joaquin River are influenced significantly by exports at the State and Federal projects (Plate 3). Sediment deposition and gain from local drainage alter the amount and composition of the sediment transported in the channels. In addition, degradation or aggradation and widening or narrowing of certain channels (see Table 7) may be occurring due to the higher velocities caused by pumping. Increased diversion capability at Clifton Court involves an element of risk with respect to levee stability in the southern Delta.

Table 7

CHANGES IN CERTAIN DELTA CHANNELS

Channel ID	Thalweg	Width	Area
OR 143	Shallower	Wider	No Change
OR 153	Deeper	Narrower	Smaller
OR 157	Shallower	Wider	No Change
OR 160	Deeper	Narrower	No Change
OR 165	Shallower	Wider	Greater
OR 171	Shallower	Wider	Slightly Greater
OR 178	---	---	Greater
OR 195	Shallower	Wider	Greater
OR 200	Slightly Deeper	Narrower	Smaller
OR 208	No Change	No Change	No Change
MR 124L	No Change	Slightly Narrower	Slightly Smaller
MR 134R	Shallower	Narrower	Smaller
MR 134L	Shallower	No Change	Smaller
MR 142	No Change	No Change	No Change
MR 145	Shallower	Wider	Greater
MR 147	No Change	No Change	No Change
WC 197	Deeper	Slightly Narrower	Greater
VC 100	Shallower	No Change	Smaller
VC 500	No Change	Wider	Greater
NC 500	Shallower	No Change	Smaller
GL 100	No Change	No Change	No Change

Source: Based on data in DWR Memorandum Report, 1981.

Finally, water carrying suspended sediment enters Clifton Court Forebay, within which a portion of this material is deposited (Arthur, 1976). The rest is pumped into the Governor Edmund G. Brown California Aqueduct for conveyance southward. In the case of the Federal project, all of the suspended sediments enter the intakes and are pumped south.

According to the Resources Management Associates report, a substantial amount of sediment is deposited in the Delta channels. Because flow reversals occur in most of the Delta channels and the velocities fluctuate significantly in all channels, two types of channels exist with respect to erosion and deposition. Some channels experience deposition; others experience both deposition and erosion, depending on the phase of the tide. Changing tidal ranges and freshwater flows may alter the situation in some of the channels.

A standard method of analysis of sediment transport is to compile existing hydrologic and sedimentologic data and produce graphical representations of the rate of sediment transport per unit of discharge. These sediment discharge curves can then be used for extrapolation of different sediment transport regimes with variable flow rates. Graves (1977) tried this statistical method but found a significant decrease in the ratio of sediment to discharge over the historical period (1900-1976). He theorized that the major influence on the trend was human activities; first hydraulic mining, then damming of major tributaries. He further predicted that this general trend of decreasing sediment load would continue.

Other research, such as the Corps of Engineers 1981 Sediment Budget Study, agrees that the earliest sedimentologic records indicate a higher sediment to discharge relationship than now exists, but does not recognize a continuation of this process from the early 1930s to present. Thus, to evaluate these sediment transport estimates, it is necessary to identify and quantify the factors involved.

The most common influences on sediment transport are precipitation patterns and land use practices that may change sediment supply and streamflow characteristics. Historical precipitation may be statistically analyzed in terms of frequency, duration, and intensity. Historical land use, however, is not so easily resolved. The most important aspects of land use in relation to sediment transport are those aspects that influence runoff, erosion, and peak discharge.

As natural vegetation is removed for urbanization, farm land reclamation, or timber harvesting, the soil is compacted or made impermeable. This development increases runoff from precipitation as vegetative interception and soil infiltration are reduced. In turn, this runoff has enlarged erosive capacity and generates greater sediment yield. Urbanization also concentrates this runoff in gutters and sewers, leading to a faster watershed response time and higher peak flows. These increased peaks are often responsible for escalation of bank erosion, further supplementing the sediment load.

PROPOSED WORK

In its final report through a contract with DWR, Resources Management Associates recommended a study approach to answer the questions posed for this staff paper.

To determine the impact of exports on currents, salinities, and areas of scour and deposition, salinity and flow simulation results for each channel are needed. The dynamic output of flow at various points within the system is needed for high and low river flows, with and without exports, and for spring, mean, and neap tides. Simple computer programs can reduce and plot the collected data into usable form. DWR's DYNFLOW model and Fischer's DELFLO model can provide the hydrodynamic simulation for the channel conditions.

With flow data seeming to be sufficient, Resources Management Associates has recommended a field sampling program (detailed in Appendix A) to supplement the limited sediment data (see Plate 4). Grab samples of bed material should be analyzed for composition, particle size distribution, settling velocity for each size fraction, and consolidation characteristics of cohesive sediments. With this information, critical shear stress for erosion and deposition and rates for these processes can be determined.

Resources Management Associates recommends a mathematical model to integrate the data into meaningful and useful information to understand the sedimentation and erosion processes occurring in the Delta. Either of the hydrodynamic models can supply the average flow velocities in each channel. A sediment model needs to be developed that possesses these features:

1. 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.

2. The model must be able to compute suspended sediment transport in an unsteady flow field with reverse flows caused by the tides.

3. 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 much higher than the average. The velocity (transport rate) of the sediment in such cases will, because of stratification, be lower than the sectionally averaged flow velocity.

4. 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 detached.

5. 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 different enough that their rates of transport must be computed separately. Therefore, the model must be capable of handling at least three size fractions of sediment.

6. The model must be capable of handling aggregation and other special characteristics of cohesive sediments relating to detachment, deposition, and consolidation.

7. The model must account for bed profile and roughness.

The data developed from the field sampling and laboratory analysis will provide the information on sediment inflows and outflows, composition of sediment on the bed, and erodibility and depositional characteristics of the various size fractions. The suspended sediment transport in the channels will be determined by the mass balance equation (see Appendix A for equation details). The equation for each sediment size will be solved to obtain the total sediment concentration. 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 solution of the mass balance equation 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.

In summary, the model inputs are:

- ° Geometry of each cross section.
- ° Sectionally averaged flow velocities for each time step.
- ° Concentration of sediment at points of inflow.
- ° Settling velocity, critical shear stress, and erosion rate constant of size fraction.
- ° Initial bed profile.

The model outputs will be:

- ° Time history of local sediment concentration by size fraction.

- Changes in bed profile.

- 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 (1950). 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.

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

The budget now proposed for continuing the study will allow only field sampling and analysis to establish present conditions and a qualitative assessment of potential changes in the system. This limited study cannot produce the quantitative results of the mathematical model.

Physical Versus Mathematical Models

Use of models can facilitate reduction of data into more usable and understandable form. Choice of model type depends on length of study period, budget, and specific goals of the study.

The greatest advantage of a physical model is the visual display exhibiting the interplay of phenomena. Apart from how well it simulates the prototype, it is a real hydraulic system. Physical models are used when the hydrodynamic forces of the prototype are complicated such that a direct analytical approach is impractical. Even so, not all laws of dynamic similitude can be satisfied, such as for sediments, especially the cohesive fraction. Some properties are distorted in a physical model, so representation of these is inaccurate.

A mathematical model is a functional representation of the physical behavior of a system or process. By proceeding through the system, element by element, using the output of one as the input to the other and satisfying common boundary conditions, the complex behavior of the system can be evaluated. Computer techniques are capable of defining salinity gradients, direction of flows, and sectionally averaged velocities.

Unknown variables in a system are determined by calibration, by modeling an historical sequence of data and adjusting the unknowns to force the model output to match the prototype data. This technique has uncertain reliability when applied to significantly different conditions. Verification of a model uses historical data, so changes in the upstream watershed that affect the hydrology, such as land use, reservoir construction, and mining, must be accounted for when using the model for predictions.

To assure accuracy, both physical and mathematical models need field checking after the model is in use. A modeler must keep in mind the limitations of the models and how they relate to the prototype.

With the proper perspective, models can aid in assimilation and interpretation of data for a complex system such as the Delta.

Land Use Changes

Knowledge of historical land use changes in the Sacramento and San Joaquin watershed gives an understanding of the changing sediment transport of the rivers, which influences deposition and erosion in the Delta.

Streamflow data for the Sacramento River near Sacramento and Freeport are available for January 1904 to July 1915, June to November 1921, and October 1948 to present. Sediment transport was first estimated by G. K. Gilbert in 1917, but not until October 1956 were sediment measurements initiated on a continuous basis. Thus, general knowledge of the 1917 to 1956 land use is necessary to evaluate the earliest estimates, but more specific information can be useful in relating post-1956 data (see Table 8). Forecasts of development and growth in the Sacramento and San Joaquin watersheds will also be useful in predicting sediment transport processes during the operation of any water transfer alternative.

A detailed inventory of urban and rural areas would be ideal. Perhaps the most suitable approach, given time and overall project accuracy, is to divide the period of interest into major land use eras and document land use for these periods. Proposed time periods are:

1850-1930 - Hydraulic Mining Era (Mining from 1850-1884; effects seen in the Sacramento River at Sacramento until 1930.)

Delta Reclamation Period

1930-1945 - Central Valley Project (Started in 1933)

1945-1966 - Flow data gathering initiated
Post World War II
Growth Boom

Table 8

SACRAMENTO RIVER SEDIMENT BUDGET CHANGES
(1835 to Present)

1835-1850	Land grants from Spain and Mexico; start of Sacramento Delta development.
1850-1884	Hydraulic mining era: increased sediment load, flooding, and fan building; decreased stream velocity and sediment carrying capacity.
1852-1930	Delta reclamation period: levee building increased velocity and transportation; decreased overbank storage.
1862-1863	Great Flood year: massive flooding of the Great Valley.
1870-Present	Damming of Sacramento River and tributaries: impoundment of water and sediment, change in flow distribution over yearly cycle; therefore, changes in erosion and transport capacity.
1897	Maximum amount of debris from hydraulic mining at Sacramento from the American River.
1900	Half of Delta reclamation complete.
1905	Maximum amount of debris from hydraulic mining at Marysville from the Yuba and Feather rivers.
1911	Formation of the Debris Commission; proposal of Sacramento bypass and levee system.
1930	Delta reclamation essentially complete: bypasses and levees constructed. Bed of Sacramento River at Sacramento restored to pre-mining elevation after erosion of river deposits from hydraulic mining influence.
1933	Central Valley Project authorized.
1950-Present	Development: urbanization, increased runoff, peak transport capacity.
1951	Tracy Pumping Plant delivered water to upper San Joaquin Valley. Large flood year for Northern California.
1952-Present	Farming: changing land use, increased slope wash, runoff.
1955	Bed of Yuba River at Marysville restored to pre-mining elevation after erosion of river deposits from hydraulic mining influence.
1960	State Water Project started.
1962-1963	Large flood year for Northern California.
1964-1965	Large flood year for Northern California.
1966-Present	Channel dredging: U. S. Army Corps of Engineers.
1978	Corps of Engineers Sacramento River Chico Landing to Red Bluff Bank Protection Project: reduced bank erosion.
1983	Large flood year for Northern and Southern California.

C-105073

1956-1968 - Data Era (Both streamflow and sediment data collected.)

Large Dam Building Era in Sacramento Valley Watershed
State Water Project

1968-1982 - Recent, Highly Monitored Era (Very little damming of rivers.)

These divisions should yield some common sedimentologic trends. To determine land use during these periods, several resources should be used:

1. G. K. Gilbert, 1917. "Hydraulic-mining Debris in the Sierra Nevada", USGS Professional Paper 105. (A good description of the mining and effects on the regional sediment transport.)

2. J. Thompson, 1957. "The Settlement Geography of the Sacramento-San Joaquin Delta, California", PhD thesis, Stanford University Microfilms, 551 pp. (A narrative of settlement and development of the Delta region from the Indian period to 1957.)

3. California Regional Framework Study Staff, 1968. "Land and Water Areas". (Divides the State by counties into land area and water area.)

4. State Water Resources Board, 1955. "Water Utilization and Requirements of California", Vol. 1, Bulletin No. 2. (Breaks land use into areas of irrigated, urban and suburban, metropolitan, and unclassified.)

Four of the easiest divisions of land use are "irrigated farming", "urban and suburban", "unclassified" and "water", because these designations follow the notation of past DWR publications (George Sato, personal communication). Recent DWR land use inventories are not yet published but are available from individual districts on a county by county basis. An additional category, "dry farming", will be needed. Since these nonirrigated lands do not appear in the standard DWR publications, estimates will have to be based on the percentage of land in individual crops, such as wheat -- the major dry farm crop of the Central Valley.

Analysis of streamflow and sediment transport data is not complete without some consideration of all major watershed variables. One of the most significant of these is the increasing impoundment of water and sediment in reservoirs.

Development of massive water transfer and retention facilities in California has significantly altered both the flow and sediment regimes of the Sacramento River. Over 40 reservoirs have been constructed along the Sacramento River and its tributaries since 1870 (see Table 9). This constitutes a significant change in the

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Table 9

DAMMING OF SACRAMENTO RIVER AND TRIBUTARIES
(1870-Present)

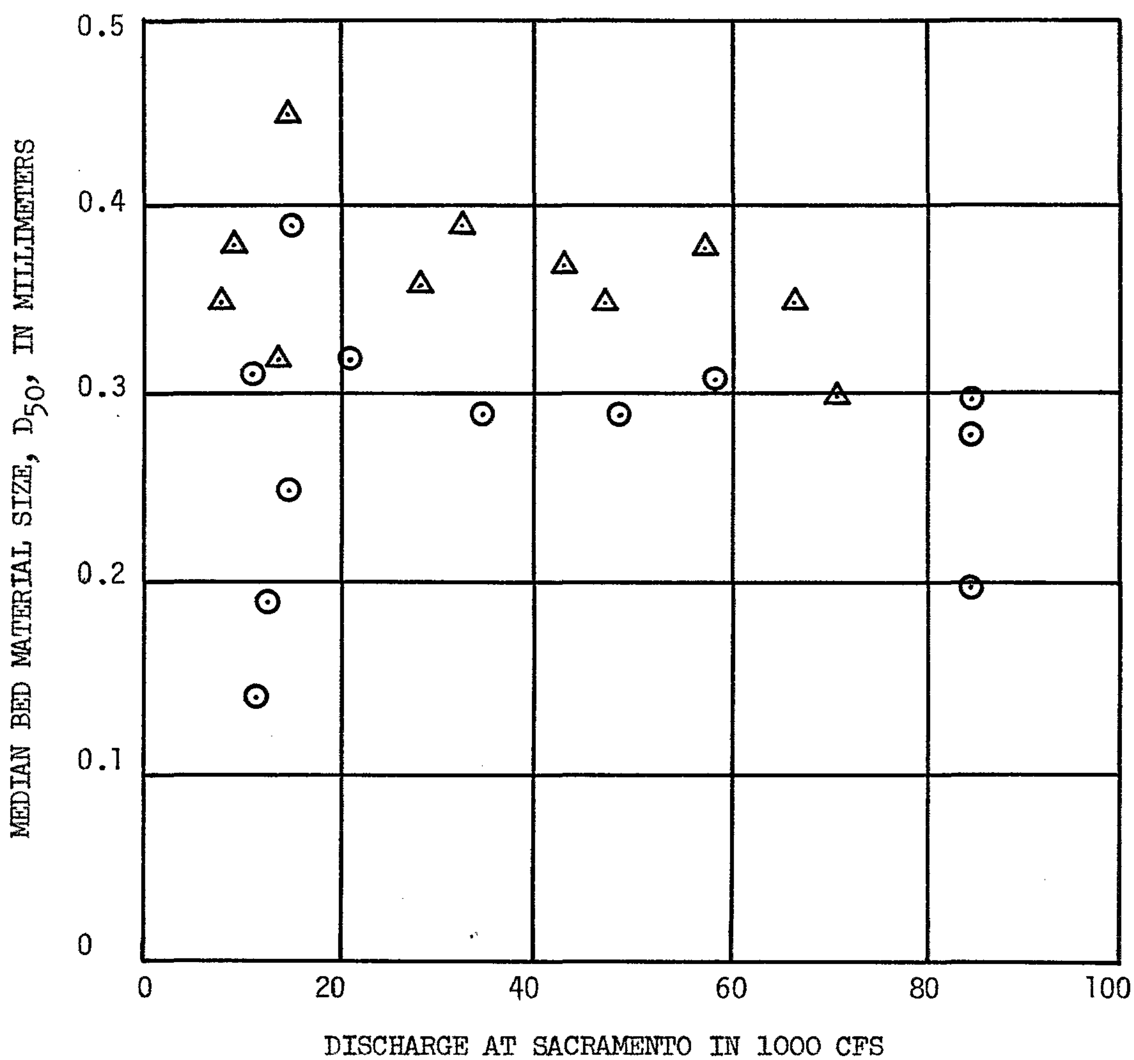
Year Complete	Reservoir or Dam	Year Complete	Reservoir or Dam
1870	Morning Star Reservoir	1956	Folsom Lake
1892	Round Valley Reservoir	1957	Monticello (Lake Berryessa)
1901	Lake Francis	1959	Ice House
1907	Kunkee	1961	Frenchman Lake
1910	East Park Reservoir	1969	Little Grass Valley Reservoir
1910	Clear Lake	1962	Lake Edson (Mark Edson)
1913	Lake Spaulding	1963	Whiskeytown
1915	Lake Mildred (Los Verjels)	1963	Black Butte Lake
1918	Magalia	1963	Camp Far West Reservoir
1924	Mt. Meadows (Indian Ole)	1963	Comanche Reservoir
1924	Butte Valley	1963	Union Valley
1926	Philbrook	1963	Virginia Ranch
1927	Concow	1964	Grizzly Creek
1927	Bowman Rockfill	1965	Jackson Meadows
1928	Lake Cambie	1965	Rollins Reservoir
1928	Stony Gorge Reservoir	1967	Slab Creek
1928	Bucks Storage and Diversion	1968	Oroville - trap efficiency 96% Estimated damming of 3,730 tons per day = 1,361,450 tons per year
1939	Lake Clementine		
1941	Englebright Reservoir	1970	New Bullards Bar Reservoir
1948	Scotts Flat	1984	Cottonwood Creek Reservoir - Dutch Gulch Lake Tehama Lake
1949	Shasta		
1950	Keswick		
1955	Sly Creek		
1955	Lake Natoma (Nimbus)		

watershed processes. Heavy rainfall and snowmelt, which normally contribute to flood flows, are restrained by dams, and the water is slowly released. This means lower peak flows and, in turn, reduced erosion below the dam.

At the same time, virtually all the coarse sediment and most of the fine sediment carried into reservoirs is deposited (see Figure 6). Large reservoirs, such as Oroville, have an estimated mean trap efficiency of 96 percent. Thus, very little of the previous natural sediment load is carried below the dam after it is built.

The effect of this watershed damming can be generally determined by a detailed indexing of the dams, their volume, capacity-inflow, watershed, and year completed. This information, in conjunction with actual reservoir sedimentation surveys and Brune's (1953) report, should provide a rough estimate of the average annual sediment trapped by reservoirs.

VARIATION IN MEDIAN BED MATERIAL SIZE
SACRAMENTO RIVER AT SACRAMENTO
(From USGS Records 1957 to 1970)



△ Measurements Made from 1957 to 1963

⊙ Measurements Made from 1964 to 1970

PREDICTION

An understanding of sediment transport processes within the Delta will aid in optimal design and management of new facilities within the system. Once the model for sediment transport in the Delta is established, calibrated, and verified, the model should:

- ° Provide data on erosion, sediment transport, and deposition under existing conditions so that DWR can evaluate alternative water transfer designs and operational strategies with respect to sedimentation.
- ° Assist in design and evaluation of mitigation measures for sediment related problems.
- ° Provide a basis for water quality assessment where quality is affected by sediment transport, such as turbidity generation, associated toxicant and nutrient transport, and habitat modification.
- ° Provide information to address the claims of landowners, harbor and navigational facility operators, and other agencies that operate within the system.
- ° Enable planned dredging, where necessary.

ESTIMATED COSTS OF SEDIMENTATION AND SCOUR EFFECTS

Awaiting model results and study completion.

MITIGATION MEASURES

Awaiting model results and study completion.

C-105080

DELTA WATER TRANSFER ALTERNATIVES

The sedimentation and scour analysis of any Delta water transfer alternative will depend heavily on conceptual or computer simulation of sediment transport throughout the Delta. The analysis of each water transfer alternative depends on obtaining adequate information for each alternative.

SUMMARY

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 Delta Cross Channel has increased the water and sediment discharges in the upper Delta channels. Resources Management Associates reports that a substantial amount of sediment is deposited in Delta channels, although the locations and rates of deposition are not known. Furthermore, a significant quantity of fine sediments is pumped with the water by the State and Federal projects. Velocities in the channels near the pumps are increased by the pumping during a part of the tidal cycle. It is possible that such velocity increases may cause erosion of the bed.

Resources Management Associates believes two types of channel exist with respect to erosion and deposition. The first are channels that experience deposition exclusively; the second are those that experience both deposition and erosion, depending on the phase of the tide. Changing tidal ranges and freshwater flows may alter the situation in some of the channels. A description of the flows in the channels at various times and of the sediment transport processes within the system can be obtained from a mathematical model that synoptically describes the flows and associated sediment transport processes.

Application of such a model to the system requires certain initial data and boundary conditions that relate to water and sediment discharges into the system, sediment composition on the bed, and tides. Some of the required data are already available as a result of the data acquisition and monitoring programs undertaken by DWR and the U. S. Geological Survey. A plan for acquiring the needed data has been presented in this report.

Model simulations could yield the suspended sediment concentrations, rates of erosion and deposition, and changes in bed profiles in each channel during the simulation period.

RECOMMENDATIONS

1. DWR should conduct an erosion, transport, and deposition study based on conclusions of the study by Resources Management Associates.

2. The data compilation started for this report should be expanded to identify sources, periods of record, and any other information that describes the data in detail.

3. Data maintained by different agencies should be assembled on a single data base at DWR.

4. DWR computer modeling results should be modified so that the results are easily accessible and usable.

GLOSSARY

Bed load. Sediment particles moving in the bed layer. This motion occurs by rolling, sliding and saltation.

Bed material load. That part of the total load which consists of grain sizes represented in the bed.

Cation exchange. The displacement of a cation bound to a site on the surface of a solid by a cation in solution.

Cohesive. Said of a soil that has relatively high shear strength when air-dried, and high cohesion when wet.

Colloid. Particle size range less than 0.00024 mm, any fine grain material in suspension.

Degradation and aggradation. Bed cutting and sedimentation during a relatively long period.

Deposition. The laying, placing of any material constructive process of accumulation such as the mechanical settling of sediment from suspension in water.

Detachment. Separation of transportable particles from their resting layer, usually by running water, raindrop impact, or wind.

Erosion. The processes whereby materials of the earth are loosened, dissolved, or worn away and simultaneously moved from one location to another by natural agencies such as weathering, solution, removal of material by running water, wave action, wind, moving ice.

Flocculation. The process by which a number of individual minute suspended particles are tightly held together in clot-like masses, or are loosely aggregated or precipitated into small lumps or clusters. The aggregates are commonly called "flocs".

Hydraulics. The aspect of engineering that deals with the flow of water or other liquids.

Hydrodynamics. The aspect of hydromechanics that deals with forces that produce motion.

Hydromechanics. The theoretical, experimental, or practical study of the action of forces that produce motion.

Prototype. The first thing or being of its kind; original; model; pattern.

Scour. Powerful and concentrated clearing and digging action of flowing water, air, or ice, especially during time of floods.

Scour and fill. Bed cutting and sedimentation during a relatively short period.

Sediment transport. The movement and carrying-away of sediments by natural agents after the sediment is detached; especially the conveyance of a stream load by suspension, saltation, solution, or traction.

Sedimentation. Process of forming or accumulating sediment in layers including erosion, transportation, deposition and consolidation of the materials.

Shear. A deformation resulting from stresses that cause or tend to cause contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact.

Shear stress. That component of stress which acts tangential to a plane through any given point in a body.

Shoal. To become shallow gradually.

Suspended load. Sediment particles carried in suspension for considerable period of time, free from contact with the stream bed; not the same as turbidity.

Tectonics. A branch of geology dealing with the broad architecture of the outer part of the Earth, that is, the regional assembling of structural or deformational features, a study of their mutual relations, origins, and historical evolution.

Total load. Made up of the bed material load and the wash load.

Transport. See Sediment transport.

Turbidity. The condition of opaqueness of reduced clarity of a fluid due to presence of suspended matter. A measure of the ability of suspended material to disturb or diminish the penetration of light through a fluid; not the same as suspended load.

Wash load. That part of the sediment load made up of grain sizes finer than the bulk of bed material, so, rarely found in the bed.

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C-105087

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