RESULTS FROM CSMW TASK 2

(Natural and Anthropogenic Turbidity)

TASK 2 – Gather studies that investigate the transport and depositional fate of fine-grained materials associated with natural and anthropogenic turbidity plumes; focus on what's currently known about the densities and duration of "natural" turbidity plumes, and similar information on plumes associated with beach nourishment or other sediment management activities.

BACKGROUND

The issue of "turbidity" related to marine/coastal environments falls into two main categories, natural and anthropogenic. If the subcategory of turbidity currents is excluded from the natural category, then the volume of research and literature for the anthropogenic category by far exceeds that for the natural category. Our research revealed little information for turbidity in the nearshore environment caused by the artificial placement of sand on beaches.

NATURAL TURBIDITY

Natural turbidity plumes in the marine environment generally fall into one of three distinct categories: 1) classical turbidity currents, which transport sediment from the shelf slope to the deep abyssal environment, 2) hypopycnal and hyperpycnal turbidity plumes at river mouths, and 3) storm-related turbidity plumes.

Classical turbidity currents are submarine phenomena that are responsible for transporting the majority of sediment to the oceanic basins. Usually triggered by earthquakes and slumping of oversteepened delta fronts or submarine canyon walls, bottom sediment is re-suspended increasing the density of the nearby water, which then flows down the continental slope, entraining more sediment as it goes. When it encounters a decrease in slope, its velocity slows allowing the suspended particles to settle. Since a large portion of the world's petroleum reserves occur in these mixed clastic deposits (turbidites), voluminous research and literature exist. Therefore, turbidity currents and turbidites are excluded from this literature search.

When sediment-laden river water enters the ocean, it can generate a "hypopycnal" plume (overflowing surface plume) or "hyperpycnal" plume (bottom-flowing plume). Hypopycnal plumes are more common since river outflows are typically fresh and warm relative to the ocean. Hyperpycnal plumes occur when the density of sediment-laden river water exceeds that of the ambient seawater and descends to the sea floor as a result of the excessive sediment load (Mulder and Syvitski, 1995; Parsons and others, 2001). Hyperpycnal plumes are predominantly seasonal and require unusually high sediment concentrations exceeding 40 kg m^3.

Smaller-scale storm-related turbidity plumes can also be generated by storm-wave re-suspension of either fine seafloor sediments in shallow marine environments or sediments along a wave-dominated beach or other shoreface.

ANTHROPOGENIC TURBIDITY

The primary sources of anthropogenic open-water turbidity are channel-maintenance dredging, disposal of dredged material, beach replenishment, aggregate mining, and coastal construction activities. The main environmental effects of increased turbidity levels from these operations are a reduction in penetration of light into the water column and suspended-sediment impacts on filter-feeding organisms and fish. Most studies have focused on maintenance dredging and disposal activities in enclosed waters such as estuaries, embayments, and navigational channels where there is a high percentage of fine-grained sediment (often 75% or more), which results in larger dispersion plumes than similar activities in offshore waters. Hitchcock and others (1999) cite numerous dredge-related plume studies from around the world in their report on benthic and surface plumes prepared for the U.S. Minerals Management Service. However, the largest inventory of research and literature on dredge-induced turbidity, was produced by the U.S. Army Corps of Engineers (USACE) through its Dredging Research Program (DRP), Dredged Material Research Program (DMRP), and Dredging Operations and Environmental Research Program (DOER) administered through the U.S. Army Engineer Research and Development Center (ERDC) and its predecessor, the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi.

Considerably less research has been conducted in unprotected offshore waters. Most of the available literature regarding suspended-sediment studies in the swash, surf, and nearshore zones has dealt with either the effect of turbidity on specific marine species and biosystems or on coarse-sand transport dynamics. This focus is largely because offshore disturbances generally produce fewer turbidity-related impacts since offshore sands tend to be coarser, cleaner, and have been winnowed of most clay and silt. In California and many other parts of the world, sands in high-energy offshore areas commonly contain less than 5 percent clay and silt (Nielsen, 1997). This is one reason beach-nourishment projects favor offshore borrow sites. The offshore hydrodynamic environment also favors prompt plume dispersion. Additionally, offshore organisms are more adapted to higher-energy natural sediment transport processes, which can create turbidity under normal conditions (storms, waves, etc).

Dredge and Material-Disposal Turbidity

Turbidity from marine dredging and disposal arises from disturbance of bottom sediments (benthic plumes), overspill of surplus or screened sediment mixtures from the surface dredge (surface plumes), and open-water disposal of dredged sediments (surface and benthic plumes). Generally overspill from spillways, screening, and open-water disposal generates a far greater quantity of suspended material and larger plumes than bottom disturbances (Herbich and Brahme, 1991; LaSalle and others, 1991; Herbich, 2000).

Turbidity is generally not an issue when dredging deposits of clean offshore sands with little fine-grained material. Studies also suggest that dredge-induced turbidity is of little concern in areas with high natural background levels of turbidity, such as at the mouth of estuaries, or in high-energy areas close to eroding coastlines since ecosystems are well-adapted to naturally high loads of suspended sediment caused by tides and wave action.

The majority of studies and monitoring efforts of dredge-induced turbidity has demonstrated that turbidity plumes are, more often than not, localized, spreading less than a thousand meters from their sources and dissipating to ambient water quality within several hours after dredging is completed (Schubel and others, 1978; Byrnes and others, 2003, LaSalle and others, 1991; McClellan and others, 1989; Pennekamp and Quaak, 1990). These results are characteristic of both offshore operations and those in enclosed waters.

Numerous observations and models by the USACE support the conclusion that dredge plumes are localized and of short duration. In one model of a turbid plume of re-suspended sediment generated by an operating hopper dredge in 90 meters of water in San Francisco Bay, a benthic plume extended 700-730 meters downcurrent from the dredge. In the immediate vicinity of the dredge, an overspill surface plume merged into the lower plume, becoming a single plume about 300 meters behind the dredge.

Infrequently, surface plumes can be visible for distances of many kilometers. In these cases, plumes are usually associated with enclosed waters with high fine-sediment content and strong tidal or riverine currents, which carry the plume marineward. In an instance of peak spring tidal velocities of 1.75 m/s, H.R. Wallingford reported that very fine sand could be carried up to 11 km from a dredging site (Hitchcock and others, 1999). Another extreme case was reported by Hitchcock and others (1999) wherein detailed monitoring associated with construction of the Storebaelt Link Bridge in Denmark detected suspended sediment up to 35 km from the source.

Measurements around properly operated dredges show that elevated levels of suspended bottom sediments can be confined to several hundred meters from the cutterhead location and dissipate exponentially towards the surface with little turbidity actually reaching surface waters (Herbich and Brahme, 1991; LaSalle and others, 1991; Herbich, 2000). In many cases, the suspended sediment concentrations are no greater than those generated by commercial shipping operations or during severe storms. Storms, floods, and large tides can increase suspended sediments over much larger areas and for longer periods than dredging operations, which makes it very difficult to distinguish between dredging-induced turbidity and that generated by marine natural processes or normal navigation activities (Pennekamp and others, 1996).

Both surface and benthic plumes are usually associated with marine disposal of dredged material (open-water pipeline discharges or hopper dredge releases). Upon release, the fines can behave either as a density current (dynamic plume), or mix with the water increasing turbidity throughout the water column (passive plume). In passive plumes, concentrations are generally low and sediment falls at the settling velocity of the single particles. In dynamic plumes, the bulk density of sediment-water mixture, relative to the ambient water, determines the rate of fall.

A dense, sediment-laden dynamic plume descends rapidly through the water column as a well-defined jet of high-density fluid, entraining ambient seawater as it falls. At the same time, a passive plume arises from turbidity-induced entrainment of sediment along the perimeter of the dynamic plume. It has been estimated that 95-99 percent of most discharged sediment loads descend to the bottom within 30 meters of the point of discharge with only the remaining few percent being stripped from the outside of the dynamic plume (Schubel and others, 1978; Neal and others, 1978).

In extremely strong current velocities and/or in deep water, where the bottom may be thousands of feet down, a descending dynamic plume may entrain so much water that it mixes entirely with the surrounding water and loses its integrity, thus becoming a passive plume. When this occurs, sediment concentrations become relatively low and fine particles usually stay in the water column for several hours, but may remain for as much as several days before settling out. The settling zone of the passive plume can cover several kilometers resulting in no significant bottom buildup.

Passive plumes will move away from the point of discharge by three separate mechanisms, all of which are a function of hydrodynamics and particle size and shape: advection by tidal currents; diffusion by turbulence; and settling. The fine particles in a plume are advected by the current and also undergo settling. Coarser sediments will be transported a lesser distance away from the point of discharge. Non-cohesive sediments, or those greater than sand size (>2mm) are generally considered to fall to the seabed immediately (Hitchcock and others, 1999). As the current velocity increases, advection becomes relatively more important in spreading the suspended sediment. Concentrations rapidly decrease with increasing distance downstream or downcurrent from the discharge point and laterally away from the plume center line due to settling and horizontal dispersion of the suspended solids (Bernard, 1978). Barnard (1978) presents a plot showing the relationship of suspended-solids concentrations along the plume centerline and distance down-current from several open-water pipeline disposal operations.

The duration of turbidity in water is largely based on the fall velocity of the sediment particles. Fall velocity depends on size, shape, and density of the particles as well as the fluid density, viscosity, and several other parameters. When a particle falls through water, it accelerates until it reaches its fall velocity, or the terminal velocity that a particle reaches when the retarding drag force on the particle just equals the downward gravitational force. While low concentrations of silt and clay (with diameters <0.03 mm) settle very slowly and cause more persistent plumes, under certain conditions, clay particles may collide to form aggregates or flocs with diameters of 0.1 to 2.0 mm. The formation of flocs increases settling velocity, which results in a more rapid decrease in suspended-sediment concentration with distance from the source (Barnard, 1978).

When a dynamic plume impacts the seafloor, it causes a horizontal, radially-spreading bottom surge outward across the seabed as a density underflow plume until its velocity and turbulence are sufficiently reduced to permit deposition. The greater the thickness and solids content of the layer, the greater the density flow effect. Generally, these underflow plumes originate as turbulent flows, characterized by chaotic motions and a billowing head just behind the leading edge and decay with deceleration to laminar underflow after spreading a short distance (Thevenot and others, 1992). Since turbulent underflows generally entrain ambient water, they grow vertically and tend to have lower concentrations than laminar underflows (Teeter, 2000a). The sediments ultimately form a low-gradient circular or elliptical fluid mud mound consisting of high-density (nonflowing) mud overlain by a surface layer of low-density (flowing) fluid mud (Barnard, 1978). Depending on the volume of material, these mounds can measure several feet thick (Holliday, 1978).

Tides also affect plume dispersion with plumes extending landward and seaward during the incoming flood tides and the outgoing ebb tides, respectively (Barnard, 1978).

Beach-Nourishment Turbidity

Suspended-sediment related issues are often a concern during beach-nourishment activities and afterward, while the new beach responds to the prevailing wave regime. Surprisingly, few attempts have been made to actually monitor and quantify turbidity conditions. Most of the literature regarding suspended sediments in the swash, surf, and nearshore environments addresses sand-transport dynamics and faunal effects rather than the distribution of re-suspended fine sediments. However, based on observations and the available studies, it is generally agreed that turbidity resulting from placement of sand on the beach face in beach nourishment and other sediment management projects is even more localized and transitory than offshore or enclosed-water operations. This is largely attributable to the use of nourishment material that is low in clay and silt and resembles as closely as possible the indigenous beach sand.

Generally, beach-nourishment projects on high-energy beaches quickly equilibrate with the current wave regime. Finer sediments are promptly winnowed from the nourishment material, causing only a short period of elevated turbidity. Parr and others (1978) noted that the silt and clay fractions were quickly winnowed from the nourishment material placed on Imperial Beach, California, and that after four months, the grain-size distribution of the nourishment fill was comparable to the indigenous beach sand.

In another study of beach nourishment on North Carolina beaches during 2001 and 2002, it was concluded that plumes caused by sand placement and de-watering on the beach face were small, short-lived, and did not create large increases in turbidity over background conditions (Versar, Inc., 2004). Sampling conducted immediately following nourishment and again one year later, demonstrated that turbidity generated by the pipeline discharge hugged the shoreline following the long-shore currents. While elevated turbidity spikes were associated with the discharge pipe itself, in most cases the plumes were not discernable from turbidity created by breaking waves in the surf zone a few hundred meters away or turbidity when dredging operations were temporarily shut down. Elevated suspended-sediment loads outside of the surf zone were rarely observed. Increases in turbidity detected during the second year of sampling were attributed to storm events and high surf conditions.

Perhaps one of the more definitive studies was conducted by the USACE between 1997 and 1999. During this period, the Corps completed one of the largest beach-nourishment projects on record, placing 19.39 million cubic meters of sand (<10% silt and clay) on 47 km of high-energy New Jersey beaches. Detailed sampling revealed little evidence of short-term elevated turbidity in the nearshore environment. Elevated turbidity was limited to a narrow swath (less than 500 m) in the swash zone in the immediate vicinity of the operation with a lateral extent on the order of several hundred meters. While discharge effluents ranged as high as 1048 g/l, observed concentrations decayed rapidly with dispersal through the surf zone to concentrations between <10mg/l to 34 mg/l, which are levels that many of the indigenous fish and invertebrate species experience in estuaries or during storm-induced turbidity (Burlas and others, 2001).

Post-storm monitoring of the swash, surf, and nearshore zones after hurricanes Dennis and Floyd in 1999 indicated that beach sediments at both recently filled and undisturbed beaches were equally susceptible to re-suspension. Suspended-sediment concentrations were generally comparable to slightly higher in the swash, surf, and near shore zones adjacent to the newly restored beaches as compared to undisturbed reference beaches. Only in a few samples from the swash zone of the nourished beach were suspended solids concentrations markedly elevated (Burlas and others, 2001).

DIFFICULTIES IN PLUME-PREDICTION AND MODELING

While many turbidity plumes have been qualitatively described both during and after dredging and beach-nourishment activities, it is difficult to ascribe the results of many studies in more than a general way. Few quantitative studies of short- and long-term plume behavior have been conducted. As a result, development of an accurate and universally applicable model of turbidity induced by dredging, beach nourishment, or other activities associated with largely cohesive sediments is considered nearly impossible (Pennekamp and others, 1996). This is largely because plumes, driven by tidal, wave, and current forces, can change dynamically over large spatial scales (both horizontally and vertically) and short time scales. Data collected at points in time at fixed locations are generally insufficient to rigorously assess the potential dispersion of suspended sediments. The development of widely applicable models is also hindered by the large number of parameters involved and the complications introduced by the dynamic temporal and spatial nature of plumes. Suspended-sediment dispersion is controlled by both operational parameters (dredge type and technique, method of overboard returns, speed) and the interaction of environmental parameters and physical properties. Water properties include depth, temperature, viscosity, stratification, and salinity; sediment properties include background levels of suspended solids, material composition, density, size, particle size distribution (individual grains or flocs), and solids concentration of the slurry; hydrodynamic forces include currents, waves, turbulence, all of which cause horizontal and vertical mixing; and other influences include buoyancy (entrapped air or gas), initial momentum on entering the water body, etc. The behavior and characteristics of a turbidity plume can only be evaluated if the complex interactions between the parts are taken into consideration.

Barnard (1978) offered one of the earlier methods of prediction of turbidity plumes from open-water sediment disposal activities requiring only six input parameters including dredge size, water depth, current velocity, sediment diameter or settling velocity, diffusion velocity, and the “age” of the plume to determine the worst case dimensions of the plume.

More recently, the USACE developed models and software in an effort to evaluate several aspects of suspended sediment behavior. The Dredging Research Program developed the PLUme MEasurement System (PLUMES) model (Kraus and Thevenot, 1992), which utilized commercially available broad-band acoustic Doppler current profiling equipment to measure sediment concentration and three dimensional (3-D) fluid velocity at dredging sites and to document the actual movement of sediment plumes.

The Dredging Research Program also developed the Short-Term FATE (STFATE) model (Johnson and others, 1993; Johnson and Fong 1993) as one module of the Automated Dredging and Disposal Alternatives Management System (ADDAMS) (Schroeder and Palermo, 1990). The STFATE software evaluates the short-term behavior of dredged material discharges in open water during and immediately after a surface discharge. The model was primarily designed to model disposed hazardous material mounds on the seafloor, but it can also be used to predict what portion of the discharge is dispersed as a passive plume. The model output includes a time history of the descent and collapse phases of the discharge and suspended-sediment concentrations for various particle-size ranges as a function of depth and time. At the conclusion of the model simulation, the thickness of the deposited material on the bottom is given.

The STFATE model was followed by development of the Long Term FATE (LTFATE) model (Scheffner and others, 1995). LTFATE modeling software was designed to assess the long-term fate and stability of dredged material disposal sites with an emphasis on seabed accumulations of disposed material.

More recently, the USACE, in conjunction with Applied Science Associates (ASA), developed the Suspended Sediment FATE (SSFATE) numerical modeling system to model suspended sediment plume behavior from dredging operations (Johnson and others, 2000). The software allows the running of multiple simulations in a short period of time so that alterative scenarios can be evaluated to determine those with the least potential for adverse environmental impact. The program evaluates sediment sources resulting from the operation of cutterhead, hopper, or clamshell dredges and differentiates the relative contribution of each type of suspended sediments to the water from bottom re-suspension and surface discharges. While this application is available to USACE staff, ASA has retained the distribution and marketing rights for non-USACE users. The model is currently undergoing upgrading following field testing, after which ASA intends to market the application.

Our research of the literature did not reveal reliability or success of these models as determined by any field-testing.

CGS RECOMMENDATIONS TO THE CSMW

- Follow up on the field testing and potential availability of the updated SSFATE model.

CSMW TASK TWO

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